

ELECTRICAL POWER SYSTEMS FOR MARS

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ABSTRACT

Electrical power system options for Mars Mission Modules and Mars surface Bases were evaluated for both near-term and advanced performance potential. The power system options investigated for Mission Modules include photovoltaics, solar thermal, nuclear reactor, and isotope power systems. Options discussed for Mars Bases include the above options with the addition of a brief discussion of open loop energy conversion of Mars resources, including utilization of wind, subsurface thermal gradients, and super oxides.

Electrical power requirements for Mission Modules were estimated for three basic approaches: (1) as a function of crew size; (2) as a function of electric propulsion; and (3) as a function of transmission of power from an orbiter to the surface of Mars via laser or r-f.

Mars Base power requirements were assumed to be determined by production facilities that make resources available for follow-on missions leading to the establishment of a permanently manned Base. Requirements include production of buffer gas and propellant production plants.

INTRODUCTION

The discussion of electrical power systems for the Mission Module considers a range of power requirements and power source options. Photovoltaics (PV) were selected for more detailed discussion. General performance characteristics of solar arrays and regenerative fuel cells are presented and weights for a 25 kW system are tabulated. Solar thermal (ST), nuclear reactor (RX), and isotope power system (IPS) are also considered.

The discussion of electrical power systems for a Mars/Phobos/Deimos base includes the above options in addition to methods of converting surface and atmospheric resources to electrical energy. Hybrid voltaic-isotope power systems and a nuclear reactor are selected for more detailed discussion.

MISSION MODULE

Power Requirements

Electrical power requirements are driven by crew size, electric propulsion options, and options to supply Mars surface power from a Mars Orbiter via laser or r-f transmission.

The crew size function is estimated to be 1.9 kW per person for life support systems. This leads to a 25kW Mission Module for a 6-person crew: 12 kW for life support and another 13 kW for subsystems and science. A 12-person crew requires 24 kW for life support and requirements for subsystems and science result in a 40 to 50 kW power system. Electric propulsion requiring multi-MW's dwarfs these requirements.

Laser transmission of power from a synchronous Mars orbit to the surface requires substantial technology development but is attractive because it may offer surface mobility and because of synergism with electric propulsion, i.e., surplus power is available from the electric propulsion power source after arrival at Mars. However, neither caveat is essential if an end-to-end efficiency of 6.3 percent can be achieved. For example, a 160 kW orbital power source could supply 10 kW of usable power to the surface if the transmitting antenna can be pointed with a 0.01 arc second accuracy. The diameter of the surface receiver would be 16 meters.

The viability of r-f transmission is dependent on the ratio of the square of transmission length to the area of the transmitter. Therefore, practical systems have either large size or modest transmission length. For example, the Space Power Satellite (Ref. 2) supplied 6.8 GW to an 85 km² ground rectenna from a 7.1 GW, 0.78 km² space antenna which orbited the Earth at 36,800 km. Attempts to scale this system into the MW range resulted in negligible power to the ground rectenna. Similar results may be expected for a Mars power satellite because synchronous orbit, 17,034 km, is of the same order as Earth synchronous orbit. However, synchronous orbit for Phobos was estimated to be 14 km. If such an orbit is possible, r-f transmission in the 10's of kW range may be practical.

Power Source Options

The following discussion places emphasis on, but is not limited to, a 25 kW manned Mission Module.

Four power system technologies shown in Figure 1 are considered to be good candidates for the Mission Module. PV is selected for detailed discussion as the most probable choice, although we caution that trade studies were not performed and that power source selection is strongly influenced by mission requirements. Possible merits and limitations of the alternate technologies are explained briefly.

ST systems relative to PV systems have approximately the same weight require one-half to one-third as much planform area and provide 80 to 90 percent thermal shielding. Shielding may be an advantage for certain Mission Module configurations if LOX/LH₂ propulsion is used. However, ST systems require a relatively large concentrator mirror that may require retraction or added structure to accommodate burn periods and possible artificial-g requirements (also added pointing complexity to achieve typical pointing accuracy of 0.1 degrees).

RX systems that do not require man rated shielding should be weight competitive with solar power systems at power levels greater than 25 kW. System weight of the SP-100 reactor (Ref.6) is 2800 kg (35 W/kg) at 100 kW. A 25 kW system, weighing 1700 kg is presented in the discussion of Mars Bases. Performance of very large reactors (1-10 MW) for nuclear electric propulsion is estimated to be 125 w/kg elsewhere in this paper.

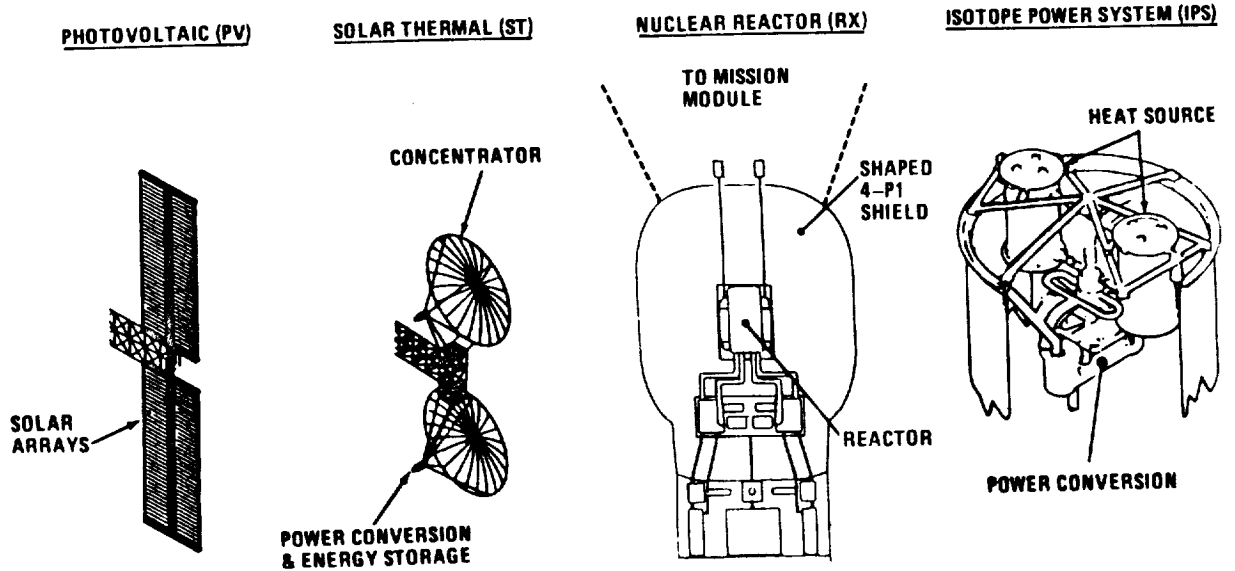
RX systems requiring man rated shielding are not competitive with solar power systems unless power levels of 400 kW to 1 MW are considered. System weight is estimated to increase from 15 MT (1 MT = 1000 kg) to 30 MT over a 10 kW to 400 kW power range. On this basis, performance is 13 W/kg at 400 kW and 35 W/kg at 1 MW. Redundancy requirements could further penalize RX performance even though typical designs utilize multiple fuel rods, heat pipes and converters.

IPS, using either dynamic or Alkali Metal Thermoelectric Converters (AMTC's), are presented in the discussion of Mars Bases. Performance does not exceed solar power systems for Mission Module application and cost, safety and availability considerations suggest that isotope power systems may be reserved for the more stringent environment on the surface of Mars.

Photovoltaic Design Values

Photovoltaics design values are tabulated in Table 1. The table lists seasonal solar intensity variation for Earth and Mars orbits.

FIGURE 1. MARS MISSION MODULE ELECTRICAL POWER SYSTEM OPTIONS



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TABLE 1. PHOTOVOLTAIC DESIGN VALUES FOR MISSION MODULE

	<u>EARTH</u>	<u>MARS</u>
SOLAR INTENSITY		
PERIHELION	1399 W/M ²	708.8 W/M ²
AVERAGE	✓ 1353	✓ 582.8 (.43 RELATIVE)
APHELION	1309	487.0
SOLAR CELL DEGRADATION		
LEO ASSEMBLY	.95	
MARS ARRIVAL		.9
LEO RETURN	.87	
SOLAR ARRAY PERFORMANCE		
Si PLANAR		
W/M ²	120-155** (150) ✓	X.43 RELATIVE INTENSITY
W/KG	75-144 (100) ✓	X1.09 LOWER TEMP
KW/M*	37	X COS 20° OFF POINTING
\$/W	46-100	
GaAs CONCENTRATOR		
W/M ²	150-133	1° POINTING
W/KG	25-41	
KW/M*	54-38	
\$/W	30-166	

* LAUNCH PACKAGING EFFICIENCY IN UNITS OF KW PER METER OF STS ORBITER PAYLOAD BAY
 ** INCREASE FROM 155 W/M² TO 200 W/M² IF GaAs
 ✓ REFERENCE SELECTION

Selected values are 1353 W/m^2 in Earth orbit and 582.8 W/m^2 in Mars orbit. Degradation from solar radiation is estimated to be 0.95 to 0.87 for two-year round trips. Table 1 also tabulates a range of performance values for state-of-the-art Si-planar and GaAs concentrator (1 degree pointing required) solar array designs. Earth performance values of 150 W/m^2 and 100 W/kg for a Si-planar array are selected for the analysis assuming simple retraction for burn periods and 20 degree pointing capability to accommodate artificial-g or other orientation constraints. Accounting for reduced solar intensity, degradation and temperature performance at Mars is 63 W/m^2 and 42 W/kg .

Energy Storage

Energy storage options required by PV systems, if full Sun operation is not possible, include regenerative fuel cells (RFC), fused salt batteries, and flywheels. RFC's are selected for analysis assuming energy storage must accommodate both a highly elliptical orbit at Mars such that the Mission Module is in the Sun for 20 hours and in shadow for 4 hours (worst case) and a circular orbit at Earth with 1 hr sun and 0.6 hr shadow periods. RFC's have a particular advantage in handling either 4 hours Mars shadowing or 0.6 hour LEO shadowing because fuel cell size remains the same for either shadow period. However, the electrolyzer unit must be sized for LEO operation and H_2O and H_2/O_2 tanks must be sized for longer occultation periods at Mars. RFC performance for LEO application is typically 15 to 45 Wh/kg depending on whether the system is optimized for weight or efficiency. Compromises are necessary for dual use at both LEO and Mars: electrolyzer sized by LEO and tanks sized by Mars. Resulting performance, for an efficiency optimized system, is 19 Wh/kg at LEO and 125 Wh/kg at Mars ($19 \times 4 \text{ hr}/0.6 \text{ hr}$).

Energy storage is probably not required for large PV or ST propulsion systems because the penalty for not thrusting during occultation periods at Earth or Mars orbit is minimal.

Photovoltaics--Regen Fuel Cell Performance

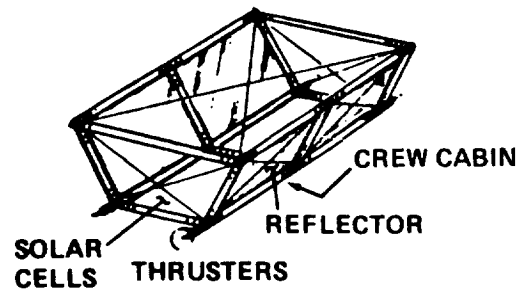
The weight of a state-of-the-art 25 kW PV system, with and without energy storage requirements, is tabulated in Table 2. Note that the solar array is oversized in the RFC option to recharge the electrolyzer and in the PV only option to overcome distribution losses. The performance range is 13 to 35 W/kg.

TABLE 2. 25 KW, PV SYSTEM – MARS ORBIT

<u>COMPONENT</u>	<u>PV-RFC</u>	<u>PV ONLY</u>
SOLAR ARRAY		
POWER	40 KW	30 KW
AREA	650 M ²	475 M ²
WEIGHT	980 KG	710 KG
RFC AND TANKS	930 KG	0
	1910 KG (13 W/KG)	710 KG (35 W/KG)

FIGURE 2: PHOTOVOLTAIC ELECTRIC PROPULSION (PEP)

	WEIGHT (MT)
SOLAR ARRAY	333
SOLAR PANELS	230
CONCENTRATOR	33
STRUCTURE	51
DISTRIBUTORS	11
OTHER	8
THRUSTER ASSEMBLY	189
THRUSTERS	24
POWER PROC.	2
BATTERIES	154
OTHER	9
TANKS (DRY)	85
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An advanced Photovoltaic Electric Propulsion (PEP) system is shown in Figure 2 along with a weight tabulation (Ref. 1). This conceptual design, part of the Space Power Satellite (SPS) studies (Ref. 2), transferred a 6860 MT cargo from 486 km Earth orbit to GEO in 120 days. The PEP concept is considered to be applicable to Mars missions as an alternative to Nuclear Electric Propulsion. Power, 309 MW, for the ion thrusters was provided by a 2 to 1 GaAs concentrator solar array weighing 333 MT (930 W/kg). Overall dimensions of the PEP was 1500 M x 1400 M planform area x 606 M concentrator height and the total dry weight was 607 MT. NaS batteries, 155 MT, were utilized to accommodate maximum LEO gravity gradient torques during occultation periods but may not be required for Mars missions. A specific weight of 930 W/kg, based on LEO to GEO intensity, would be reduced to approximately 400 W/kg at Mars.

The analyses of Mission Module power systems reaches the following conclusions: (1) Requirements for crew delivery modules are 25 to 50 kW; (2) Electric propulsion requires multi-MW's; (3) Laser transmission is practical in the 100's of kW range but r-f transmission requires GW's; (4) Several power system technologies are available to accommodate a variety of mission objectives and power levels; (5) State-of-the-art performance referenced to Mars orbit is 13 to 35 W/kg for 10-100 kW systems; and (6) Performance of large, MW electric propulsion systems is 100 to 400 W/kg.

MARS BASE

The production of electrical power on the Mars surface is considered to be difficult, and existing terrestrial and space power system technology development programs do not address environmental and operational constraints unique to Mars. Because the potential to produce energy from surface or atmosphere constituents of Mars is not well understood, a basic approach to power generation cannot be clearly established. Compounding the difficulty are considerations of fixed or mobile bases at Mars, Phobos, or Deimos, each having a variety of growth scenarios.

The possibility of supplying electrical power from either the conversion of Mars surface and atmospheric constituents or the collection of solar energy is briefly explored. Two conventional power systems, a

10 kw PV-IPS system and a 25 kW RX system are presented for the purpose of investigating first-order design constraints.

Open loop energy conversion, similar to Earth power plants, would be the preferred method of power generation at Mars if a readily available source of fuel, such as superoxides, can be extracted from the surface. However, the present understanding of in-situ fuel production of e.g., CH_4 and O_2 from the atmosphere and surface, as described by Ash (Ref. 4), while useful to store energy for intermittent power generation, is not practical for steady state operation; 6 kWh/kg input required energy to the process plant and only 1 kWh/kg is converted to electrical energy by a fuel cell or generator.

LOX and LH_2 can be brought from Earth and converted to electrical energy by a fuel cell with a conversion efficiency of 2.5 kg/kWh. Reactant and tank weight make this approach unacceptable for operation beyond a few weeks.

Cursory investigation of wind or subsurface thermal energy sources initiated that these did not appear to be a readily available solution for either Mars, Phobos or Deimos. Mars windmills do not appear to be practical because the atmosphere is very thin (0.008 atm) and nominal wind speed is moderate (2 to 7 m/s). Subsurface thermal energy production (geothermal equivalent) may be possible at certain sites at Mars.

ST systems were not considered in detail but may be a competitive option if they can be manufactured from natural resources at Mars.

Photovoltaic Design Values for Mars Base

Photovoltaic systems for a Mars Base are considered with reference to Table 3. A nominal solar intensity value, 582.8W/m^2 , is modified by several factors at the Mars surface: (1) increased performance over Earth orbit because the solar array operates at about -20°C instead of typical LEO, temperatures of 70°C ; (2) radiation degradation, 5 percent after initial deployment and 10 to 20 percent after 15 or 20 years; (3) a 20 percent allowance for dust obscuration and abrasion; and (4) a 50 percent weight improvement over typical self-deployed solar arrays designed for LEO assuming manned or simple spring deployment. Simple deployment also implies that the solar array be deployed flat along the surface. The performance penalty is 0.53 at 30° latitude and 0.614 if the array is

located at the equator or is tilted to compensate for higher latitudes. Performance of a flat array at 30° latitude is 28 W/m^2 and 28 W/kg as compared with LEO performance of 150 W/m^2 and 100 W/kg .

Two additional considerations are included in Table 3. First, the time available to collect solar energy on Mars is approximately 50 percent of the 24.62 hr. rotation period. The percentage was modified slightly because solar arrays are not useful for morning and evening sun angles below 15° . Secondly, dust storms were assumed to totally obscure the Sun for 60 days of the 687-day Martian year. These factors reduce performance to 12 W/m^2 or 12 W/kg on an annual basis. Detailed solar radiation data can be found in reference 7.

Solar energy collection at Phobos and Deimos is only slightly better than solar collection at Mars. Both moons orbit with the same side facing Mars. Also, Phobos is obscured by Mars for 0.9 hr. of a 7.65-hr orbit while Deimos is obscured by Mars for 1.5 hr. of a 30.6-hr orbit.

Point Design Power Requirements

Early outposts, or even an initial outpost, may place processing plants into operation in preparation for future missions. Power estimates assumed for this analysis are tabulated in Table 4. The processing plant produces Ar/N_2 buffer gas (carbon leakage make-up for next crew); water and compressed CO_2 for a greenhouse; and CH_4/O_2 propellants for surface and/or return vehicles in preparation for an 8-person crew planning 45 or 350 day stay times. Power requirements, 5 to 25 kW, matched 4 to 6-person crew requirements, 10 to 25 kW, and are considered to be reasonable for early missions. Power levels are modest because the power is furnished over the 400-day interval between missions (low power but high energy). The implication to power design is that long life, unattended, systems will be required.

Requirements for production of Ar/N_2 buffer gas are $0.5625 \text{ kWh/man-day}$ yielding requirements of 200W to 1.5 kW. Compression of CO_2 from 0.008 to 0.1 atm for the greenhouse requires 0.027 kWh/kg . If the greenhouse requires 10 kg/day, 112 W of compressor power is required (Ref. 3). Water is extracted from the soil at 9.3 kWh/kg (Ref. 4) or from the atmosphere at 42 kWh/kg (Ref. 3). The power requirement range is 2.7 to 12 kW to supply 7 kg/day. Production of CH_4 and O_2 in quantities of 330 to 12,000 kg requires 2.1 to 7.5 kW of electrical power (Ref. 5).

TABLE 3. PHOTOVOLTAIC DESIGN VALUES AT MARS

SOLAR INTENSITY	582.8 W/M ² (.43 RELATIVE TO EARTH ORBIT)
TEMP. CORRECTION	1.09 RELATIVE TO EARTH ORBIT
DEGRADATION	.95
OBSCURATION	.80 DUST/SPECTRAL RESPONSE
GEOMETRY	.53 FLAT ARRAY/NO ORIENTATION 30° LATITUDE/15° MIN SUN SINGLE
STRUCTURE	1.5 SIMPLE DEPLOYMENT
REF. LEO PERFORMANCE	150 W/M ² AND 100 W/KG
MARS PERFORMANCE	28 W/M ² AND 28 W/KG
DAY/NIGHT TIMES	
ROTATIONAL PERIOD	24 HR, 37 MIN, 23 SEC
SUN TIME, EQUATOR	50%
USABLE SUN TIME	11.89 HRS, 15° TO 165° SUN ANGLE
ENERGY STORAGE TIME	12.73 HRS
ANNUAL POWER AVAILABILITY	
ORBITAL PERIOD	687 DAYS
DUST STORM OBSCURATION	60 DAYS

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TABLE 4. EARLY MARS BASE POWER REQUIREMENTS

	POWER (KW)
● Ar/N ₂ BUFFER GAS	
- STORED FOR 8-MEN CREW	
- 45 DAY OR 350 DAY STAY TIMES	.2 TO 1.5
- 202 TO 1575 KG STOCKPILE	
- CONVERSION ENERGY 9.4 KWH/KG OF AR/N ₂	
● H ₂ O FOR GREENHOUSE	
- 7 KG/DAY REQUIREMENT	
- CONVERSION ENERGY	2.7 TO 12
- 9.3 KWH/KG FROM SOIL	
- 42 KWH/KG FROM ATMOSPHERE	
● CO ₂ COMPRESSED FROM 0.008 ATM TO .1 ATM FOR GREENHOUSE	
- 10 KG/DAY REQUIREMENT	.1
- CONVERSION ENERGY OF .027 KWH/KG	
● CH ₄ AND O ₂ IN SITU PROPELLANT PRODUCTION	
- 3330 KG TO 12,000 BY REQUIREMENT	2 TO 8
- CONVERSION ENERGY 6 KWH/KG	<u>5 TO 25 KW</u>

A 10 kW Photovoltaic/Isotope Power System

A reference design is defined for the purpose of exploring first order system considerations. Three combinations of PV and IPS power systems to supply 10 kW to an initial Mars Outpost are shown in Figure 3. Liberty is taken in interpreting the 10 kW requirement. The requirement is assumed to be satisfied if day/night loads are unbalanced to provide 12 kW of day power and 7 kW of night power. Unbalanced loading favors PV designs by minimizing energy storage requirements. Although a regenerative fuel cell was selected for this analysis, inertial energy storage and high performance batteries, such as NaS and Li, should be investigated.

The use of IPS was minimized based on the assumption that isotope inventory should be minimized for cost, availability and safety reasons. These considerations tend to limit IPS to a few Kw output. Performance numbers are based on typical 20 to 30 percent dynamic converter efficiencies of existing Organic Rankine or Brayton cycle converters. Static Alkali Metal Thermoelectric Converter (AMTEC) or dynamic Stirling cycle engines may achieve 30 to 40 percent efficiency.

The first design supplies 10 kW from a solar array and 5 kW from a RFC energy storage system. IPS supplies 2 kW of continuous power to satisfy the 12 kW day and 7 kW night power requirement. A series of concerns emerge from this design.

First, an 860 sq. meter solar array, 20 percent of a football field, must be deployed. Crew capability to deploy the solar array is unknown and because existing technology deals only with free-flyer deployment, there is little basis for evaluating spring loaded or other unmanned deployment alternatives.

Secondly, existing RFC technology emphasizes LEO Space Stations utilizing low pressure (150 psi) and high temperature (100⁰ C) H₂ and O₂ gas storage. Tank size, for these conditions is prohibitive for 12-hour energy storage requirements at the Mars surface. Cool-down to 20 degrees C and operation of the electrolyzer unit at 400 psi is assumed in projecting a packaging volume of 5 cu. meters for the total PV-IPS system. Package volume for the solar array is estimated to be 550 W/cu. meter.

Heat rejection requirements for the IPS and fuel cell portion of the RFC, 11 kWt, may be a major system level factor. Thermal control will be presented in other papers, however, in-house discussion suggests that requirements will be modest under normal conditions but possibly severe during large dust storms.

A final design option utilizes a 5 kW solar array without a RFC, and a 7 kW IPS to supply 12 kW day loads and 7 kW night loads. Performance is reduced slightly from 6.3 w/kg to 6.1 W/kg but solar array area is reduced from 860 to 210 sq. meters and packaging volume is reduced from 5 to 2.5 cu. meters. Heat rejection increases from 11 to 25 kWt.

Power requirements for the Initial Outpost were estimated previously to be in the 10 to 25 kW range. Results from the 10 kW PV-IPS system study were indication that a more optimistic approach should be investigated for 25 kW systems. Accordingly, a RX concept is selected for analyses.

A 25 kW Nuclear Reactor Power System

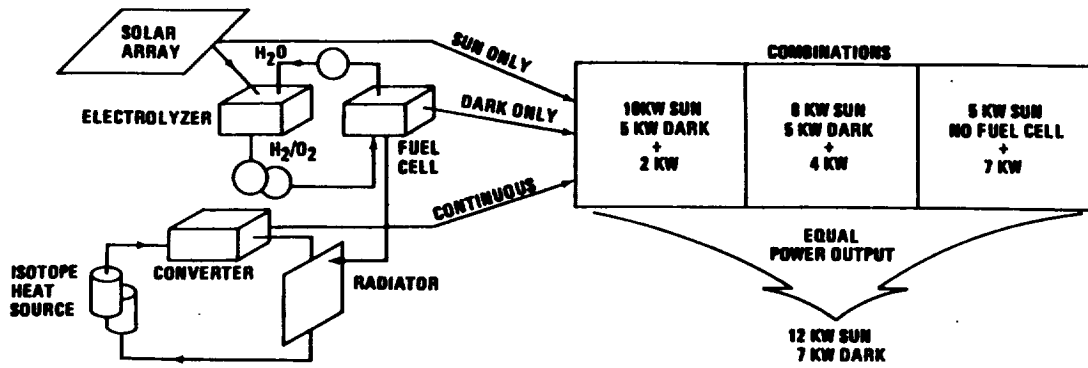
The RX concept depicted in Figure 4 requires a hole to be excavated, at say 50 meters from the Outpost; that a "reactor sled" be towed into the hole by an existing surface vehicle; and that the power system be connected electrically to the Outpost by a tether.

A weight tabulation, based on the on-going SP-100 program (Ref. 6), is included in Figure 4. The weight is 1700 kg or 15 W/kg. Performance more than doubles that of the hybrid PV-IPS system and should therefore be given consideration for the initial outpost. The largest weight contribution to the system is a 700 kg instrument rated shield. If the shield can be eliminated altogether, e.g., by excavating a right angle hole or burying the reactor, performance increases to 25 W/kg. Although this performance is inviting, consideration must be given to potential nuclear contamination of Mars, the lack of redundancy, heat rejection during dust storms, and requirements for power while the reactor is being placed in operation. Also, the SP-100 reactor is expected to use refractory metals which would be unacceptable in the CO₂ atmosphere of Mars. Refractory metals would not be a problem on Phobos or Deimos.

SUMMARY

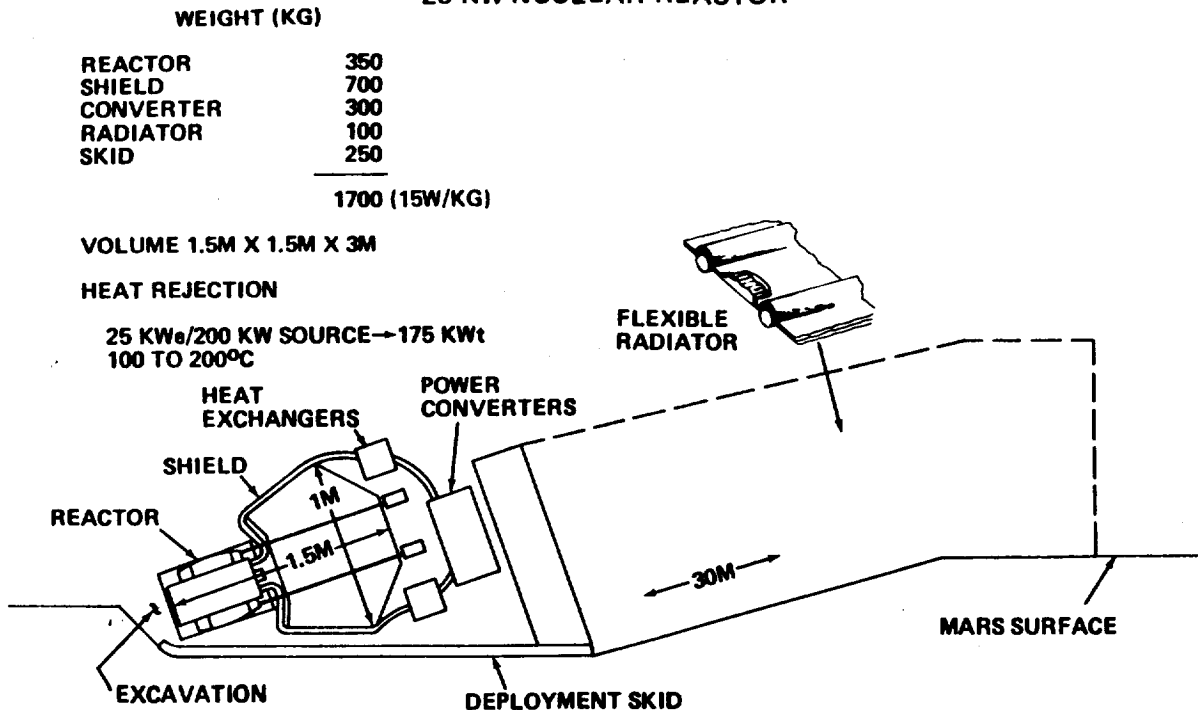
Several power source technologies were evaluated for Mission Module application: (1) Photovoltaics (PV), (2) Solar thermal (ST), (3)

FIGURE 3. ELECTRICAL POWER FOR MARS LANDER
PHOTOVOLTAIC + REGEN FUEL CELL + ISOTOPE



SOLAR ARRAY AREA	860M ²	600M ²	210M ²
SYSTEM MASS	1580 KG	1610 KG	1630 KG
SYSTEM VOLUME	4.8M ³	3.9 M ³	2.5M ³
HEAT REJECTION	11KWt	16KWt	25KWt

FIGURE 4. ELECTRICAL POWER FOR MARS LANDER
25 KW NUCLEAR REACTOR



Nuclear reactors (RX), and (4) Isotope power systems (IPS) with either dynamic cycle or AMTEC engine energy conversion. Performance of a 25 kW state-of-the-art PV-regenerative fuel cell system was estimated to be 13 W/kg and performance for an advanced 309 MW photovoltaic electric propulsion system was estimated to be 400 W/kg. The state-of-the-art systems PV, ST, RX and IPS, require modest development to satisfy early missions, whereas large, advanced high performance systems, necessary for electric propulsion, require significant development.

The same power source options were evaluated for a Mars/Phobos/Deimos Base. Performance ranged from 6 W/kg for a 10 kW PV-IPS hybrid system to 25 W/kg for a 25 kW RX system. Requirements of long life, unattended systems were hypothesized assuming early, or even initial, mission objectives to operate in-situ production plants (5 to 25 kW power level). Reduced solar intensity, self-deployment over rough terrain, 0.3 gravity, CO₂ atmosphere, wind, dust storms, long night periods, etc., were considered to pose severe design challenges which are not being addressed by existing power technology programs. Energy systems to convert Mars resources to electrical power super oxides, CH₄/O₂, and subsurface thermal gradients should also be investigated.

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