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A Solar Power System for an Early Mars Expedition

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SUMMARY

As NASA looks at missions that will expand human presence in the solar system, the power requirements for such missions need to be defined, developed and analyzed. One mission under consideration consists of a 40 day manned Mars surface expedition to perform science experiments. The mission time was centered around an aerocentric longitude (Ls) of 90° (the northern hemisphere summer solstice) to lessen the probability of an occurrence of a local or planetary dust storm. These storms significantly reduce the amount of available solar energy that reaches the surface. The mission site was arbitrarily located at the Martian equator. The power requirements were assumed to be 40 kWe for life support and experiment power during the Martian day and 20 kWe for life support during the Martian night, which is the power level envisioned for use by an early exploration mission.

A solar energy system consisting of roll-out amorphous silicon arrays and a hydrogen-oxygen regenerative fuel cell energy storage system was chosen for the study. The power available from a roll-out array, when plotted against time, approaches a cosine-like curve and depends on both array area and the amount of solar irradiance impinging on its horizontal surface. The array is sized to provide at least 20 kWe when the sun is 12.5° above the horizon and ramp up to 140 kWe peak power at Martian noon. In this configuration, the array is capable of supplying 40 kWe continuously to the user for the majority of the Martian day while supplying the excess energy to the electrolyzer portion of the energy storage system. Since the power delivered from the array varies continuously with time, the electrolyzer stacks are brought on-line as power becomes available. The fuel cell is sized to provide 20 kWe of continuous power during the Martian night and when the sun angle is below 12.5°. A roll-out, pumped loop radiator system is used to dissipate the waste heat produced by the fuel cell. The power management and distribution system inverts the power from the individual solar array sub-modules and the fuel cell stacks and connects them to a 440 V ac single phase 20 kHz main bus. This bus attaches both to the scientific users and to down converter/ rectifiers connected to the electrolyzer stacks. The total power system is comprised of 80 individual solar array modules with an integral bus and three energy storage modules consisting of fuel cell and electrolyzer stacks, reactant storage tanks, and a roll-out radiator. Power system mass, stowed volume, and deployed area were determined. Day/night power splits of 40/10, 40/30, and 40/40 kWe were also considered to determine the impact of a range of nighttime power requirements on the baseline system.

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INTRODUCTION

As outlined by the NASA Office of Exploration (ref. 1) several Mars mission scenarios are under consideration which will require lightweight, compact power sources. For one of these scenarios, which outlined an early manned expedition to Mars, a photovoltaic array with energy storage was identified as the candidate power system. The tasks described in this scenario were examined to determine the power requirements for this mission. These requirements then were used as the basis for a power system design which considered lightweight photovoltaic arrays and advanced energy storage systems.

MISSION ASSUMPTIONS

NASA's Office of Exploration 1988 Report Case Study 2 (ref. 1) provides the mission profile for this study. Case Study 2 is a human expedition to Mars consisting of an eight member crew departing from Earth in the year 2007. Four members of the crew will land on the surface while four stay in the orbiting spacecraft. A deployable photovoltaic power array with regenerative fuel cell storage for the Martian night is required to support 20 days of operations. This requirement was doubled to 40 days of operation to allow for problems and delays. After consideration of the power requirements of the tasks described for this mission, a 40/20 kWe day/night split was determined to be an appropriate power. Day/night power splits of 40/10, 40/30, and 40/40 kWe were also identified as alternatives to determine the impact of differing nighttime power requirements.

The landing site latitude chosen for this mission was the Martian equator. This latitude provides a local sun/shade cycle of 12.3/12.3 hr. The time of landing was chosen to minimize the probability of encountering local or global dust storms. From previous studies (ref. 2), it was found that few (if any) dust storms occur during the southern hemisphere Martian winter (aerocentric longitude of 90°). At this time of year, the surface day/night temperature variation is 260/173 K respectively while the average surface temperature is 205 K. The Martian atmosphere is composed mostly of carbon dioxide and has an ambient atmospheric pressure on the Martian surface of 7.79 mbars at $L_s = 90°$. Dust particles, probably clay silicates, are carried through the atmosphere by the surface winds. These dust particles have a mean radius of about 2.5 μm. The main effect of these dust particles is to increase the atmospheric optical depth. Because of the dust and the Martian atmosphere, there is a diffuse component of solar insolation which adds about 10 percent to the direct component of solar insolation throughout the day. This affects solar array performance and is accounted for in the solar irradiance model.

PHOTOVOLTAIC ARRAY SUBSYSTEM

The power produced by the solar array needs to fulfill both the daytime power requirements and the excess power required for storage for use at night. Due to its light weight and stowability (refs. 3 and 4) a rollout amorphous silicon photovoltaic array concept was studied for this daytime power production. The solar array needs to produce 40 kWe continuously for the majority of the day as well as the additional excess power that will be stored for nighttime use.

The power available from the rollout array, when plotted over the Martian day, approaches a cosine-like curve (fig. 1) and depends on the array area and operating temperature as well as the amount of available solar irradiance. The solar irradiance available during the Martian day was calculated using a model developed at the NASA Lewis Research Center (ref. 5). The array is sized to produce 20 kWe when it turns on at 0.85 hr after sunrise (when the sun is 12.5° the horizon). A variety of array turn on times were considered. A turn on time of 0.85 hr after sunrise allows the production of sufficient power for both the daytime user power and the power that is stored for nighttime use without causing the array to be greatly oversized. Forty kWe are available to the user at 1.43 hr after sunrise for 9.4 hr. The maximum power available from the array is 152 kWe at noon.

The solar array blanket consists of 80 modules. Each module contains 733 strings in parallel with 73 cells in series in each string (fig. 2). Integral power conditioning is included in each module which connects to a main bus (fig. 3). The 50 μm thick blanket is made of 2 cm by 3 cm p/i/n amorphous silicon cells on aluminum and polyamide substrates, with silver paste interconnectors and an indium tin oxide top contact (fig. 4). These cells operate at the Mars surface temperature and have a cell efficiency of 13.8 percent at Mars noon. When taking into account the array packing factor of 91 percent, the interconnection efficiency of 95 percent and the power conditioning efficiency of 93 percent, the overall array efficiency is 11.9 percent (based on total array area on Mars at noon). The total array covers 2822 m^2 when deployed and has a blanket mass of 177.6 kg. A summary of the array characteristics is given in table I.

FUEL CELL/ELECTROLYZER SUBSYSTEM

An energy storage subsystem is required to provide power to the base during the Martian night. Several advanced energy storage subsystems were considered for this application: silver-zinc, sodium-sulfur, and secondary lithium batteries, and hydrogen-oxygen alkaline regenerative fuel cells (RFC's). Hydrogen-oxygen regenerative fuel cells were chosen over the advanced battery systems due to the high specific energy density exhibited for long storage periods.

The primary components of the RFC subsystem include a fuel cell unit, an electrolysis unit, reactants, and reactant tankage (fig. 5). During the night portion of a mission, gaseous hydrogen and oxygen are delivered to the fuel cell unit at regulated pressure. Electrical power and heat are generated as the hydrogen and oxygen combine to form water. The water leaves the fuel cell stack and is stored in a tank while the heat is dissipated via a radiator. During the daylight portion of the mission, the stored water is pumped to an electrolysis unit, which is supplied with electrical power from an outside source (the photovoltaic array) to electrolyze the water and regenerate the gaseous hydrogen and oxygen reactants.

For this mission, the fuel cell was required to provide 20 kWe continuously during the Martian night and when the sun angle was less than 12.5°. The total operation time for the fuel cell was 14 hr. The reactants were regenerated during the time when the output power from the array exceeded 40 kWe, the daytime power required by the base. As can be seen from the power profile (fig. 1), 9.4 hr were available for electrolyzer operation.

The RFC subsystem was modeled using a code that was developed at NASA Lewis (ref. 6). The code calculates mass and performance characteristics based on input design parameters, which, for this study, were set to state-of-the-art values. The RFC operating conditions are shown in table II. The reactants were stored in spherical tanks made from filament-wound Kevlar 49/epoxy matrix. Based on data from the Lawrence Livermore Laboratory (ref. 7), the rupture stress of this type of material is approximately 931 MPa(135 000 psi). A working stress of 233 MPa (33 750 psi) was used for modeling the tanks. A 10 mm titanium liner was included in the hydrogen and oxygen tanks to reduce the diffusion of gas through the tank wall. The reactants were stored at the electrolyzer operating pressure of 2.2 MPa (315 psi).

In previous studies (ref. 8), the electrolyzer was sized based on constant input power from a sun-tracking array. In this case, all electrolyzer cells can be brought on-line at full power at the same time. However, as was discussed previously, the power generated by the roll-out array as a function of time approaches a cosine curve. In order to accommodate this power profile, an operating scheme was devised where the electrolysis cells would be divided into stacks with each stack being brought on-line at full power as power became available. Three stacks were chosen, representing an optimum point which minimizes the total number of cells required while utilizing as much of the excess array power as possible.

A roll-out, pumped loop radiator system was used to dissipate the waste heat produced by the fuel cells. The material chosen for the radiator was mylar with an insulated back-side. This allows the radiator to be compacted into a small volume for stowage. Deployment will be accomplished by simply rolling it out on the Martian surface. The working fluid chosen was water, which will initially be stored in the water reactant tank. The radiator characteristics are given in table III.

Since three electrolysis stacks were required to regenerate the reactants, it was decided that three RFC modules would be used to meet the 20 kWe mission power requirements in order to allow for system modularity and ease in stowage and deployment. Each module is rated for 6.7 kWe and consists of a fuel cell stack, an electrolysis stack, reactants and associated tankage, and a roll-out radiator. A mass and volume breakdown for one module is given in table IV.

POWER MANAGEMENT AND DISTRIBUTION

Power management and distribution components to connect the power from the photovoltaic array, fuel cell and electrolyzer components to a main bus of 440 V ac, single phase, 20 kHz were added to the system (fig. 6). A summary of the component masses is shown in table V.

SUMMARY OF RESULTS

This concept for a Mars power system (fig. 7) uses a rollout amorphous silicon photovoltaic array and a hydrogen-oxygen regenerative fuel cell energy storage system to provide 40 kWe to the users for 9.4 hr during the day and 20 kWe for the remainder of the Martian day and night. The total mass of the system is 3170.6 kg and the stowed volume is 49.66 m^3. A summary of the total system mass broken down by subsystem is given in table VI.

The impact of different nighttime power requirements of 10, 30 and 40 kWe on the system was also studied. The time at which the array turned on at 20 kWe was varied for each case so that sufficient power was provided for both the day and nighttime power requirements without causing the solar array to be greatly oversized. The system mass breakdowns for these various day/night power splits are compared with that of the baseline system in figure 8.

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TABLE I - ARRAY CHARACTERISTICS

Array module	
Cell efficiency, percent	13.8 (Mars surface)
Deployed area, m	1.53x23.05
Peak power, kWe	1.9 (Mars noon)
Peak voltage, V	48
Peak current, A	40
Stowed volume, m^3	0.055
Blanket mass, kg	2.22
Array blanket	
80 Modules	
Overall efficiency, percent	11.9 (Mars surface)
Deployed area, m	46.7x61.3
Blanket specific mass, kg/m^2	0.063

TABLE II - RFC OPERATING CONDITIONS

Fuel cell	
Power output, kWe	20 continuous
Current density, mA/cm^2	161
Cell active area, m^2	0.093
Operating pressure, MPa	0.4
Operating temperature, K	355
Electrolyzer	
Power input, kWe	75.8 total
Current density, mA/cm^2	215
Cell active area, m^2	0.093
Operating pressure, MPa	2.2
Operating temperature, K	355
Round trip efficiency, percent	61.5

TABLE III - RADIATOR CHARACTERISTICS

Emissivity	0.7
Specific mass, kg/m^2	4.3
Radiator surface temperature, K	325
Sink temperature, K	250
Radiator area, m^2	42 total

TABLE IV - RFC SUBSYSTEM MASS BREAKDOWN (PER MODULE)

Component	Mass, kg
Fuel cell stack	91.6
Ancillaries	7.7
Electrolyzer stack	182.4
Ancillaries	56.1
Reactants	43.6
Reactant tanks	
Hydrogen	75.2
Oxygen	39.2
Water	0.7
Radiator	60.2

TABLE V - PMAD SUBSYSTEMS MASS BREAKDOWN

80 Ribbon cable edge connectors for array modules, kg	80
80 Invertor modules for array modules, kg	560
3 Invertor units for fuel cell stack, kg	60
3 Down converter/rectifier units for electrolyzer stacks, kg	45
3 Pallets for RFC units, kg	177
Main bus (transmission line), kg	300
User interface, kg	100

TABLE VI - TOTAL MASS SUMMARY

Array blanket mass, kg	176
Energy storage mass, kg	1670.4
PMAD mass, kg	1322
Total system mass, kg	3168.6

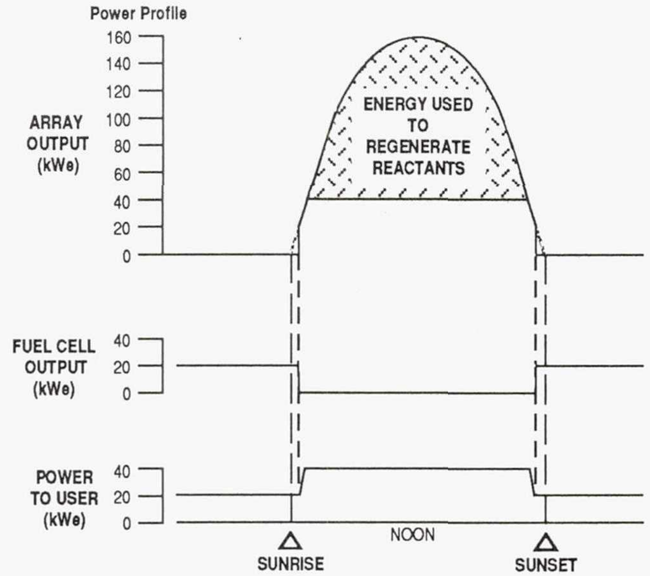

Figure 1.—Power profiles.

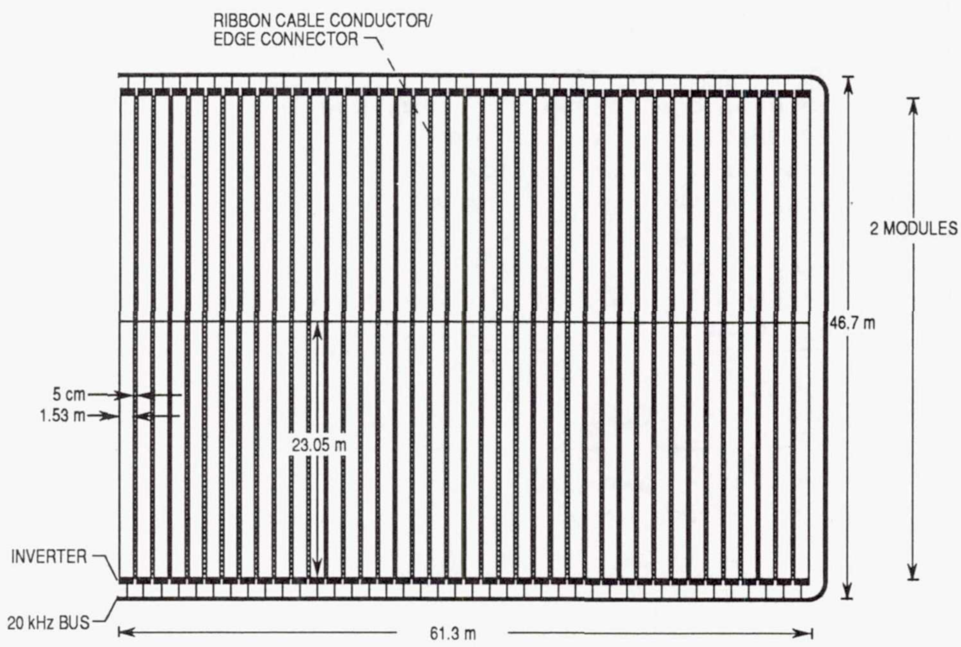

Figure 2.—Solar array layout.

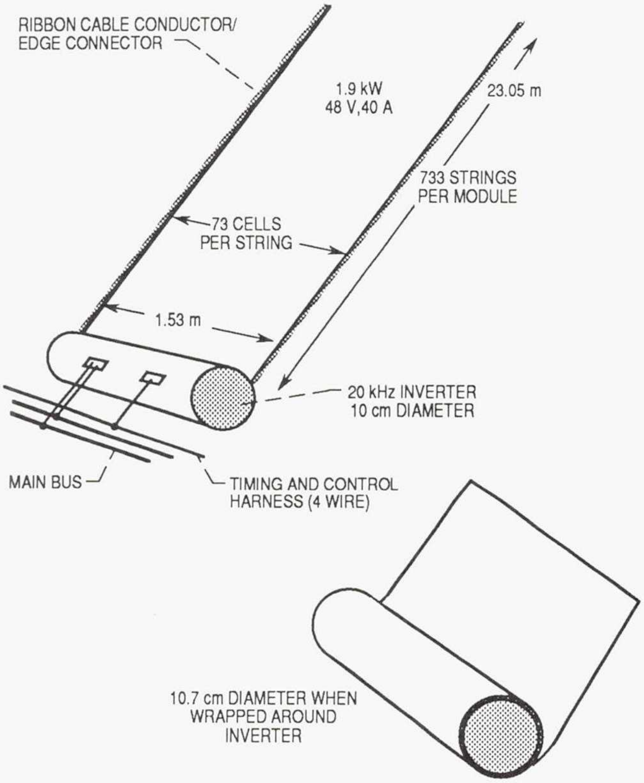

Figure 3.—Solar array module.

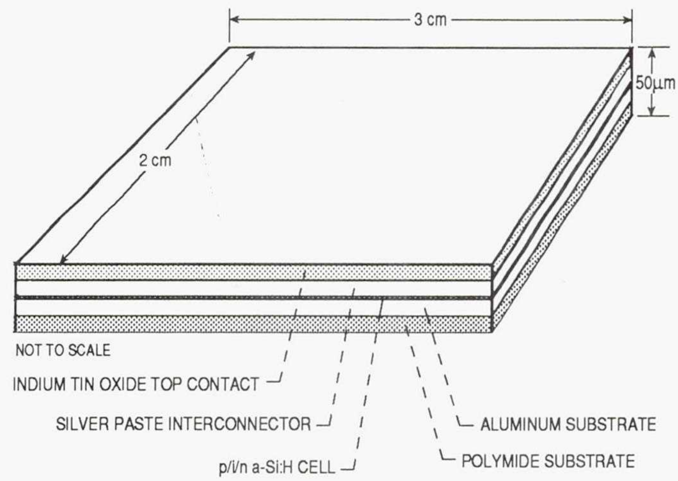

Figure 4.—Cutaway showing array layers in one cell.

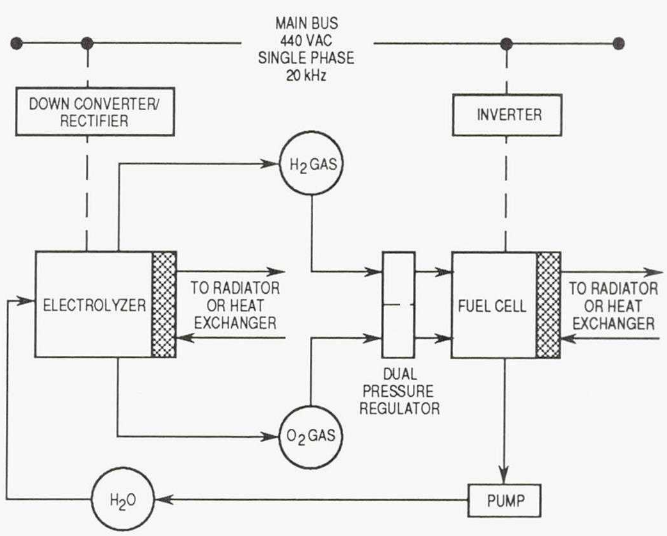

Figure 5.—Block diagram of RFC subsystem.

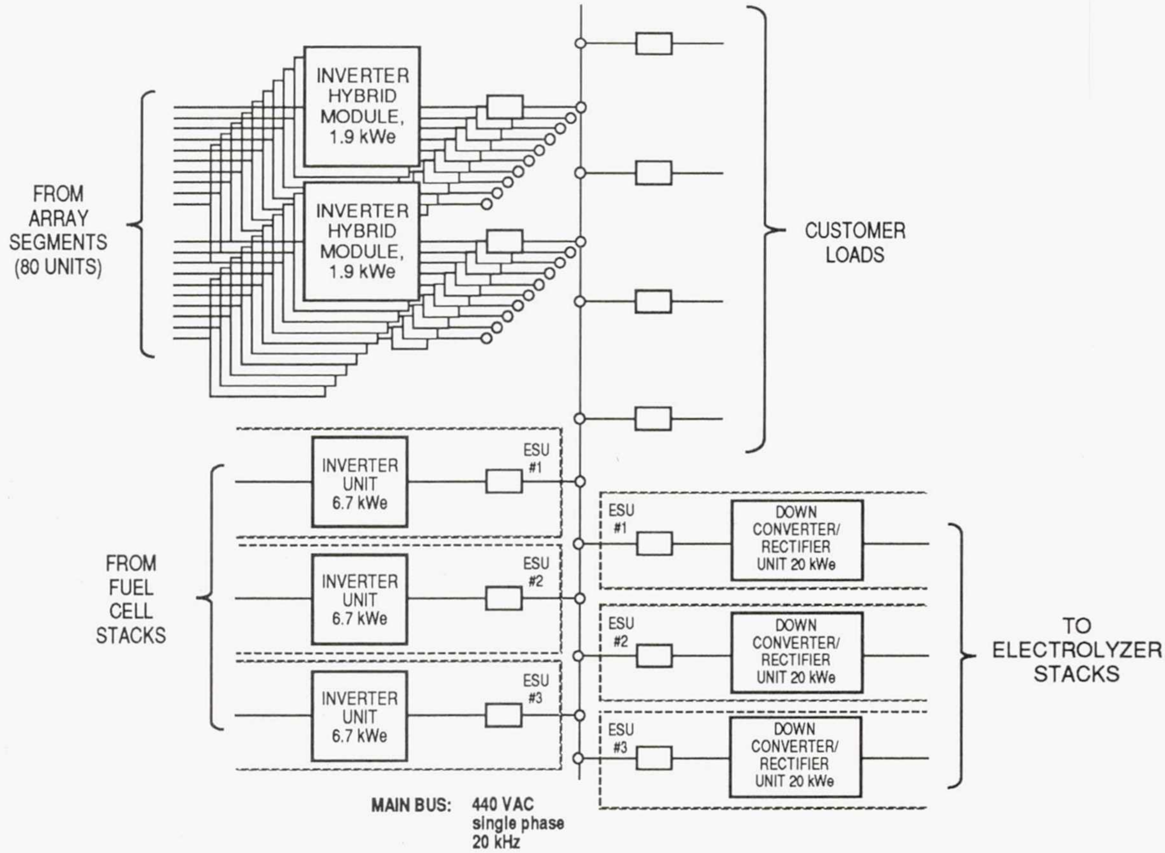

Figure 6.—Power management and distribution layout.

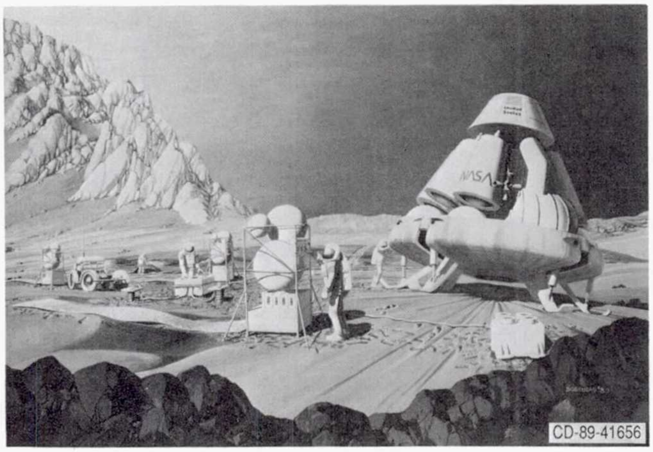

Figure 7.— A solar power system for an early manned Mars expedition.

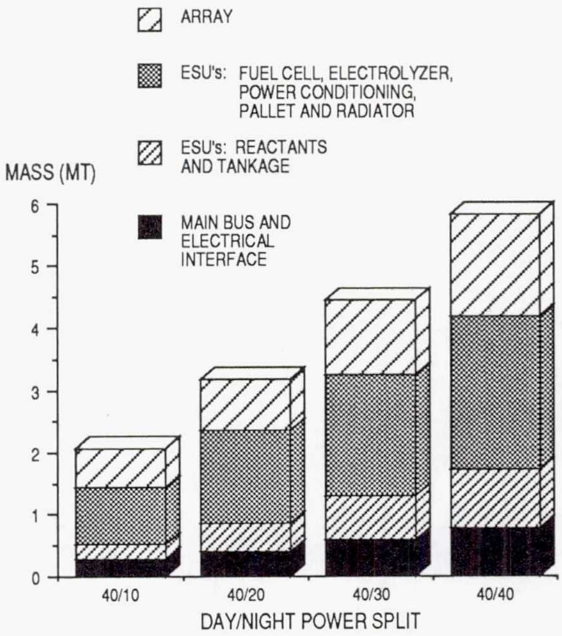

Figure 8.—System mass breakdown.

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15. Supplementary Notes

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16. Abstract

As NASA looks at missions that will expand human presence in the solar system, the power requirements for such missions need to be defined, developed and analyzed. One mission under consideration consists of a 40 day manned Mars surface expedition to perform science experiments. The mission time was centered around an aerocentric longitude (Ls) of 90° (the northern hemisphere summer solstice) to lessen the probability of an occurrence of a local or planetary dust storm. These storms significantly reduce the amount of available solar energy that reaches the surface. The mission site was arbitrarily located at the Martian equator. The power requirements were assumed to be 40 kWe for life support and experiment power during the Martian day and 20 kWe for life support during the Martian night, which is the power level envisioned for use by an early exploration mission. A solar energy system consisting of roll-out amorphous silicon arrays and a hydrogen-oxygen regenerative fuel cell energy storage system was chosen for the study. The power available from a roll-out array, when plotted against time, approaches a cosine-like curve and depends on both array area and the amount of solar irradiance impinging on its horizontal surface. The array is sized to provide at least 20 kWe when the sun is 12.5° above the horizon and ramp up to 140 kWe peak power at Martian noon. In this configuration, the array is capable of supplying 40 kWe continuously to the user for the majority of the Martian day while supplying the excess energy to the electrolyzer portion of the energy storage system. Since the power delivered from the array varies continuously with time, the electrolyzer stacks are brought on-line as power becomes available. The fuel cell is sized to provide 20 kWe of continuous power during the Martian night and when the sun angle is below 12.5°. A roll-out, pumped loop radiator system is used to dissipate the waste heat produced by the fuel cell. The power management and distribution system inverts the power from the individual solar array sub-modules and the fuel cell stacks and connects them to a 440 VAC single phase 20 kHz main bus. This bus attaches both to the scientific users and to down converter/rectifiers connected to the electrolyzer stacks. The total power system is comprised of 80 individual solar array modules with an integral bus and three energy storage modules consisting of fuel cell and electrolyzer stacks, reactant storage tanks, and a roll-out radiator. Power system mass, stowed volume, and deployed area were determined. Day/night power splits of 40/10 kWe, 40/30 kWe, and 40/40 kWe were also considered to determine the impact of a range of nighttime power requirements on the baseline system.

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