35851/
p 13

NASA Technical Memorandum 106606

Solar-Electrochemical Power System for a Mars Mission

Colleen A. Withrow and Nelson Morales
Lewis Research Center
Cleveland, Ohio

December 1994

National Aeronautics and
Space Administration

SOLAR-ELECTROCHEMICAL POWER SYSTEM FOR A MARS MISSION

Colleen Withrow and Nelson Morales
National Aeronautics and Space Administration
Lewis Reseach Center
Cleveland, Ohio 44135

SUMMARY

This report documents a sizing study of a variety of solar electrochemical power systems for the intercenter NASA study known as "Mars Exploration Reference Mission." Power systems are characterized for a variety of rovers, habitation modules, and space transport vehicles based on requirements derived from the reference mission. The mission features a six-person crew living on Mars for 500 days. Mission power requirements range from 4 kWe to 120 kWe. Primary hydrogen and oxygen fuel cells, regenerative hydrogen and oxygen fuel cells, sodium sulfur batteries, advanced photovoltaic solar arrays of gallium arsenide on germanium with tracking and nontracking mechanisms, and tent solar arrays of gallium arsenide on germanium are evaluated and compared.

INTRODUCTION

The Mars Exploration Reference Mission, an intercenter NASA study, required that power systems be sized for a variety of surface systems and space transport vehicles. This report documents only the solar and electrochemical power systems considered. Sizing of other power systems such as nuclear and beam power systems is documented in another report (ref. 1). Power systems were sized for seven separate elements: a surface habitat-greenhouse, an in situ resource utilization plant (ISRU), a methane plant, a pressurized rover, an unpressurized rover, an unmanned cargo vehicle, and a piloted vehicle. Eight power systems were considered for the seven elements. The power systems analyzed for each element are listed in table I.

MISSION DESCRIPTION

The objective of NASA's Mars Exploration Reference Mission is to identify mission architecture and technology options that will place humans on the surface of Mars to perform scientific studies and advance the capabilities of humans in space. The astronauts will study surface materials to discover potential resources, learn about the geological and climatic history, and investigate the possible presence of life on the planet. The mission will send a crew of 6 to the Martian surface for about 500 days. The surface infrastructure includes a surface habitat with an attached bioregenerative chamber (greenhouse) capable of growing 50 percent of the food and revitalizing breathing air. Also, one pressurized rover and two unpressurized rovers will be used to achieve the exploration objectives both locally and regionally (Bozek, J.M.; and Cataldo, R.L.: Presentations to Lewis Research Center Mars Exploration Study Team; Feb. 1993; Duke, M.B.: Mars Reference Program; Presented by NASA/Johnson Space Center to Code XA, NASA Headquarters; Feb. 1993).

The mission begins with three unmanned cargo vehicles launched at three-month intervals starting in 2007. The cargo flights take 344 days each. The first cargo flight carries to the Martian surface the in situ resource utilization and methane plants with their power supplies, and an unfueled ascent vehicle, and leaves a fueled trans-Earth stage vehicle in the Mars

TABLE 1.—POWER SYSTEM APPLICATIONS SIZED

	Habitat-greenhouse	ISRU[a]	Methane plant	Pressurized rover	Unpressurized rover	Cargo vehicle	Piloted vehicle
Regenerative fuel cell with nontracking array	X	X	X	X			
Regenerative fuel cell with tracking array	X	X	X				
NaS batteries with nontracking array	X		X	X			
NaS batteries with tracking array	X		X				
Primary fuel cell				X	X		
GaAs/Ge tent array					X		
GaAs/Ge nontracking array					X		
GaAs/Ge array wing						X	X

[a] In situ resource utilization plant.

orbit for crew return. The methane plant produces the fuel and oxidizer for the Mars ascent vehicle. Prior to the astronauts leaving the Earth's surface, the successful transfer of fuel will be confirmed. The second cargo vehicle delivers one habitat unit. After arrival at the surface of Mars, the habitat will be confirmed as ready for use prior to crew launch from Earth. The third cargo flight carries the pressurized rover, bioregenerative chamber, scientific experiments, consumables, and other hardware.

The piloted vehicle carries the crew of six within a transit habitat, in which the crew lives on the trip to Mars and subsequently lands on the surface. The piloted vehicle will reach Mars in 120 to 180 days, depending on launch opportunity. Upon completion of the mission, the astronauts use the ascent vehicle to return to the trans-Earth stage vehicle that has been orbiting Mars since the first cargo flight. The return flight to Earth takes 150 days.

TABLE II.—POWER SYSTEM CHARACTERISTICS

	Fuel cells		Batteries	Surface arrays	Spacecraft arrays
	PFC[a]	RFC[b]	NaS	GaAs/Ge	GaAs/Ge
Fuel cells					
Current density	215 to 1075 mA/cm^2	215 to 1075 mA/cm^2	(c)	(c)	(c)
Cell active area	0.092 m^2	0.092 m^2			
Operating pressure	0.4 MPa	0.4 MPa			
Operating temperature	355 K	355 K			
Round trip efficiency	~61% (discharge only)	~58%			
Electrolyzer					
Current density	(c)	215 mA/cm^2	(c)	(c)	(c)
Cell active area		0.092 m^2			
Operating pressure		2.2 MPa			
Operating temperature		355 K			
Tanks					
H_2 and O_2 tank pressure	20.7 MPa (3000 psia)	20.7 MPa (3000 psia)	(c)	(c)	(c)
H_2O tank pressure	2.2 MPa (315 psia)	2.2 MPa (315 psia)			
Tank safety factor	4	4			
Radiator					
Emissivity (effective)	0.595	0.595	(c)	(c)	(c)
Specific mass	5 kg/m^2	5 kg/m^2	5 kg/m^2		
Rejection temperature	355 K	355 K	293 K		
Sink temperature	210 K	210 K	(c)		
Battery					
Cell capacity (at 100% depth of discharge)	(c)	(c)	54.7 Ah	(c)	(c)
Operational (depth of discharge)			80%		
Operational temperature			623 K		
Round-trip efficiency			~80%		
Arrays					
Array dimension	(c)	(c)	(c)	10 m x 1.5 m	Undetermined
Overall efficiency				15.4%	13%
Cell efficiency				20%	18%
Packing factor				82%	(c)
Electric losses				95%	
Thermal effects				99%	
Day/night operating time					
Tracking array	(c)	13.9 hr at night	13.9 hr at night	10.7 hr in day	(c)
Nontracking array	(c)	16.9 hr at night	16.9 hr at night	7.7 hr in day	(c)

[a] Primary hydrogen-oxygen fuel cells.
[b] Regenerative hydrogen-oxygen fuel cells.
[c] Not applicable.

SOLAR POWER TECHNOLOGY REQUIREMENTS AND DESIGN FEATURES

Several different power technologies were combined to meet the requirements of the Mars Reference Mission. Advanced photovoltaic solar arrays (APSA) (ref. 2) composed of gallium arsenide/germanium (GaAs/Ge) were chosen as a power source because of their high efficiency. Hydrogen-oxygen fuel cells and sodium sulfur (NaS) batteries were chosen as the energy storage devices due to their high energy densities. These technologies should be available in the time frame of the Mars mission.

In this study, the Mars surface photovoltaic (PV) arrays consisted of a blanket, frame, and tracking mechanism (for sun-tracking solar arrays). An array dimension of 1.5 m by 10 m was assumed for convenience. The blanket included GaAs/Ge solar cells connected in series with parallel strings to supply the power required. Gallium arsenide solar cell technology makes possible a smaller array than an array with silicon solar cells because of its higher efficiency (20 percent compared to 14.5 percent), and it also offers more resistance to radiation and temperature degradation. The GaAs/Ge solar array efficiency is 15.4 percent, which takes into consideration 20 percent cell efficiency, 82 percent packing factor, 95 percent electric losses, and 99 percent thermal effects. The GaAs/Ge solar cells are assembled on an APSA blanket which is very light compared to rigid modules. Table II contains a summary of PV array characteristics, along with the characteristics of the other power systems considered in this study.

Solar arrays were designed for both orbital and surface environments. Transit vehicle arrays were sized for the worst case orbital scenario, with Mars at aphelion. Solar arrays for the surface were designed for various atmospheric conditions that ranged from a hazy day to a global dust storm. Dust storm effects can be defined in terms of the opacity of the atmosphere. Atmospheric opacity is measured in terms of the optical depth, which is defined as the logarithm of the attenuation of the direct component of a beam that is perpendicular to the surface penetrating the atmosphere (ref. 3). Optical depth values used in this study were 6 (global dust storm), 1 (local dust storm) and 0.4 (hazy day). Table III contains the assumed optical depths that were used to size the solar arrays for the various surface applications. Surface location (latitude), surface albedo, and insolation variation were considered, in addition to dust storms, in sizing the arrays for the surface (refs. 4 to 9).

TABLE III.—ASSUMED OPTICAL DEPTHS AND POWER REQUIREMENTS FOR SURFACE APPLICATIONS

Application	Power requirement	Optical depth assumed	
Surface habitat-greenhouse	49 kWe	6	global dust storm
In situ resource utilization plant (ISRU)	120 kWe	0.4	hazy
Methane plant	40 kWe	0.4	hazy
Pressurized rover	10 kWe	1	local dust storm
Unpressurized rover	4 kWe	0.4	hazy

Two types of solar arrays were considered for surface applications, sun-tracking and nontracking. Sun-tracking solar arrays follow the sun so that the solar array surface is always perpendicular to the sun's rays. A 10° start-power angle[a] was assumed, which resulted in 10.7 hr of array operation and 13.9 hr of energy storage operation on a Martian day of 24.6 hr.

Nontracking solar arrays do not follow the sun, and the output power varies with the position of the sun. For nontracking solar arrays, the array operation was 7.7 hr, and the energy storage operation was 16.9 hr, because a 30° start-power angle was assumed. Consequently, there will be an energy loss of approximately 13 percent of the maximum energy (maximum energy is obtained when the start angle is 0°) when nontracking solar arrays are used.

In tables IV to X the blanket area given for each system is only the total area of the array blankets and does not include any spacing for deployment in the array fields. Array field area was not shown in the tables because the field size varies relative to the space between the arrays and the layout of the field (number of rows and columns). At this time the preferred layout is not known. However, an example of an array field area is described here for the habitat-greenhouse (table IV). The tracking arrays are assumed to have each row placed at a distance of approximately 9 m from array center to array center to avoid one row of arrays shadowing the next row of arrays. For the nontracking arrays, each row of arrays is spaced 3 m apart to allow for movement around the arrays by the crew or deployment vehicles. This leads to a field area of 53 000 m^2 for a blanket area of 7575 m^2 with tracking arrays. For nontracking arrays, a field area of 56 000 m^2 is needed for a 16 037 m^2 blanket area. Both examples are for the 40 kWe power system of the habitat-greenhouse.

---

[a] Start-power angle is the angle the sun's rays make with the horizon, and at which the solar arrays will start producing power.

Two types of energy storage systems were selected, fuel cells and batteries. Primary hydrogen-oxygen fuel cells (PFC) with high-pressure storage, and regenerative hydrogen-oxygen fuel cells (RFC) with high-pressure storage were selected as examples of a high energy density storage technology. Fuel cells with cryogenic storage were not considered because of the complexity involved for the liquefaction plant to supply the cryogens and because the technology might not be available on the large scale needed during the timeframe of this project. The battery choice was sodium sulfur (NaS) because of its high energy density and the fact that it is representative of an emerging technology. The battery and RFC will utilize a solar array for recharge power.

The PFC and RFC cell block diagram is shown in figure 1. The fuel cell is an electrochemical device that converts hydrogen and oxygen into water and electricity. An RFC adds an electrolyzer to regenerate the reactants from the water produced by the fuel cell, thus creating a closed loop system. The components within the dotted lines of figure 1 are for the PFC and the entire diagram represents the RFC. Both the PFC and RFC use high-pressure gas storage, which is at 20.7 MPa (3 000 psia) with a tank safety factor of 4. The round-trip efficiency for the RFC is approximately 58 percent while the PFC discharge efficiency is approximately 61 percent. The system components for the PFC are the fuel cell stack, the reactants, tankage for the oxygen, hydrogen, and water, and the radiator. The RFC includes all of the components in the PFC plus an electrolyzer. A summary of the characteristics for both fuel cells are shown in table II. In subsequent tables in this report, the RFC sizings include the fuel cell, electrolyzer, tanks, and reactants. The RFC radiator is part of a radiator category which includes the fuel cell and the electrical power management and distribution (PMAD) radiator. The array category includes the PV arrays and PMAD subsystems.

The Na/S battery system components include the battery, radiator, PMAD, structure, and solar arrays. The Na/S battery has a round trip efficiency of 80 percent. The Na/S battery characteristics can be seen in table II. In subsequent tables showing the battery sizes, the category of battery includes the battery and its radiator. The radiator category is only the radiator required for the PMAD system. The PMAD mass and volume are included as part of the PV array.

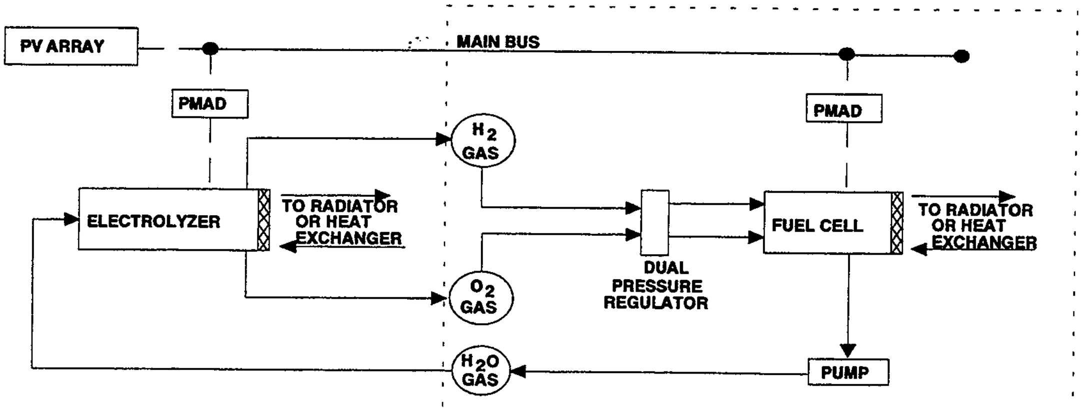


Figure 1.—Regenerative fuel cell with gaseous storage (primary fuel cell within dotted lines).

MARS SURFACE SYSTEMS

Power systems were investigated for five separate surface systems: a surface habitat-greenhouse, an in situ resource utilization plant (ISRU), a methane plant, a pressurized rover, and an unpressurized rover.

Surface Habitat-Greenhouse

The initial Mars habitat is configured to accommodate basic habitation needs, establish miscellaneous surface equipment and science instruments, and provide for a surface operations network for later missions. The habitat is designed to house a 6-person crew for 500 days. The surface habitat and greenhouse have a combined power system because they are fully integrated to form the environmental control and life support system (ECLSS). The ECLSS power system will produce 40 kWe, of which 25 kWe is for the habitat and 15 kWe is for the greenhouse. The ECLSS power system is required to produce 4 kWe during the first year of operation, which is deemed necessary for housekeeping. During the second year the power level is increased to 19 kWe to prepare the ECLSS for crew arrival. When the astronauts arrive, the full 40 kWe is required.

To accommodate the fluctuating power level, the RFC and batteries have a 10-kWe incremental stack or module size. The RFC has a total of five 10-kWe fuel cell/electrolyzer systems, with one of the five systems reserved as a spare. The four operating RFC's share two tanks each of hydrogen, oxygen, and water. There are two radiators in the system. The radiators are used both for the fuel cell and the PMAD subsystems. The tanks and radiators were split in half to allow for redundancy so that the astronauts would have half of the power required in the event of a meteoroid puncture. The power system has only one battery module or RFC stack active during the first year to produce the 4 kWe. In the second year, a second stack or module is activated to produce a total of 19 kWe and then all 4 RFC stacks or battery modules are activated to produce the 40 kWe.

Habitat power is required continuously, even in the worst atmospheric conditions. Therefore, the solar arrays were sized for global dust storm conditions. Tracking and nontracking solar arrays were examined. The arrays were sized to supply 40 kWe to the habitat and greenhouse and to recharge the batteries or fuel cells during daylight hours. Because the increased length of time the RFC with nontracking arrays is required to run (additional three hours over the tracking array system) the RFC nontracking system requires 150 kWe to recharge, while the tracking system only requires 88 kWe. The NaS-battery nontracking system requires 110 kWe to recharge the batteries, while the tracking system only needs 65 kWe to recharge. In general, NaS batteries requires less recharge energy than RFC cells for the same discharge energy because NaS round-trip efficiency is higher (80 percent compared to 58 percent).

Table IV shows the sizes of various 40-kWe surface habitat and greenhouse power systems. The NaS batteries with nontracking arrays are the heaviest of the four systems considered, with the RFC with nontracking arrays being only 1800 kg lighter. The lightest system was the RFC with tracking arrays. In the RFC system with tracking arrays, the RFC only made up 17 percent of the total system mass, while the arrays made up 79 percent because of the large amount of array power required to recharge the fuel cells and the high optical depth used to size the solar arrays. The array blanket area doubled between the tracking and nontracking systems with RFC's. The nontracking array system has 1070 arrays (1.5 m by 10 m each) to recharge the fuel cells and this requires an array field about 56 000 m^2 (about 13.9 acres or 5.6 ha). The tracking array system has only 505 arrays, but requires a 53 000 m^2 array field. Although the nontracking system requires twice as many arrays as the tracking system, it only requires 3000 m^2 more array field area because of the increased separation distance between the tracking arrays.

The NaS batteries make up 39 percent of the nontracking array system total mass, while they make up 49 percent of the tracking system mass. The nontracking system requires 845 arrays to produce the 40 kWe for the habitat and to recharge the batteries, which covers about 45 000 m^2 of array field area, while the tracking system requires 415 arrays and 43 000 m^2.

If the arrays were sized for hazy day conditions (optical density of 0.4) instead of global dust storm conditions (optical density of 6.0), the mass of the tracking arrays for the RFC-based system would be 2876 kg (compared to the 10 636-kg array portion of the 11 347-kg PV array and PMAD combinations), and the blanket area would be 2048 m^2 (compared to 7575 m^2). However, because the life support system requires continuous operation, the power system must be sized for the worst case, which is a global dust storm.

TABLE IV.—40-kWe SURFACE HABITAT-GREENHOUSE POWER SYSTEMS

Power system	RFC with nontracking array			RFC with tracking array			NaS with nontracking array			NaS with tracking array		
	Mass, kg	Volume, m^3	Blanket area, m^2	Mass, kg	Volume, m^3	Blanket area , m^2	Mass kg	Volume, m^3	Blanket area, m^2	Mass, kg	Volume, m^3	Blanket area, m^2
RFC	3 812	7	--------	2 440	5	-------	--------	-----	--------	--------	------	-------
Radiator	586	7	106	478	6	88	23	0.27	4	16	0.19	3
Battery	--------	-----	--------	--------	-----	-------	10 700	6	--------	8 785	5	-------
Array	21 538	802	16 037	11 347	379	7 575	17 013	633	12 670	9 314	311	6 218
Total	25 936	816	16 143	14 265	390	7 663	27 736	639	12 674	18 115	316	6 221

In situ resource utilization (ISRU) plant

The in situ resource utilization plant (ISRU) will make a 600-day cache of oxygen, water, and buffer gasses prior to the astronauts' departure from Earth. It requires a continuous (day/night) 120-kWe power level. Two power systems were analyzed for the ISRU plant, an RFC with tracking arrays and an RFC with nontracking arrays. To obtain the 120-kWe power level with redundancy, five 30-kWe RFC's were used (one reserved for a spare), along with three tanks each of hydrogen, oxygen, and water, and three radiators. The arrays were sized for hazy day conditions (optical density of 0.4) because it is not essential to operate during dust storms.

Table V shows the breakdown of mass, volume, and blanket area for the two power systems for the 120-kWe ISRU plant power system. The total mass of the RFC with tracking arrays is 59 percent of the total mass of the RFC with nontracking arrays and the blanket area of the RFC with tracking arrays is about 50 percent of the area of the nontracking arrays.

TABLE V.—120-kWe IN SITU RESOURCE UTILIZATION PLANT POWER SYSTEMS

Power system	RFC with nontracking array			RFC with tracking array		
	Mass, kg	Volume, m^3	Blanket area, m^2	Mass, kg	Volume, m^3	Blanket area, m^2
RFC	12 285	18	--------	7 490	14.9	------
Radiator	1 742	22	316	1 431	18.5	264
Array	19 629	646	12 910	10 762	307.3	6 145
Total	33 656	686	13 226	19 683	340.7	6 409

Methane Plant

Along with the ISRU plant, a methane plant is placed on the surface to produce a cache of methane and oxygen that can provide propellants for Mars surface liftoff capability. It can also be used as an energy source for the rovers and the habitat-greenhouse. Hydrogen brought from Earth and carbon dioxide from the Mars atmosphere is processed to produce water and methane. The methane is used to fuel the ascent vehicle while the water is electrolyzed to produce hydrogen and oxygen for use in the rovers and to provide up to 60 days of emergency power for the habitat-greenhouse.

The methane plant requires a 40-kWe power system and is only required to operate during hazy day conditions. Both RFC's and NaS batteries with tracking and nontracking arrays were considered for the methane plant. Table VI shows the breakdown of mass, volume, and blanket area for the four power systems. The RFC with tracking arrays is the lightest mass at 6507 kg, less than half the mass of the other three systems.

TABLE VI.—40-kWe METHANE PLANT POWER SYSTEMS

Power system	RFC with nontracking array			RFC with tracking array			NaS with nontracking array			NaS with tracking array		
	Mass, kg	Volume, m^3	Blanket area, m^2	Mass, kg	Volume, m^3	Blanket area, m^2	Mass, kg	Volume, m^3	Blanket area, m^2	Mass, kg	Volume, m^3	Blanket area, m^2
RFC	3 812	7	--------	2 440	5	--------	---------	------	-------	--------	--------	--------
Radiator	586	8	106	480	6	91	23	0.3	4	16	0.2	3
Battery	-------	----	-------	--------	----	--------	10 700	6	-------	8 785	5	--------
Array	6 594	217	4 337	3 587	102	2 048	5 208	171	3 426	2 945	84	1 681
Total	10 992	232	4 443	6 507	113	2 139	15 931	177.3	3 430	11 746	89.2	1 684

Pressurized Rover

The pressurized rover is used for traversing the surface of Mars for distances of approximately 500 km with a crew of 2 or 3. The rover is expected to have a maximum sortie of 5 days out to the site, with 10 days allowed at the site, and then another 5 days to return to the base. The 20-day sortie is expected to have an average power level requirement of 10 kWe. One requirement for this rover is that it be able to operate in local dust storm conditions. The astronauts would not venture out during global dust storms. The rover will also serve as a temporary habitat in the event of a main habitat failure. In fact, the rover's power system could augment the main power system, if required.

PFC's, RFC's and NaS batteries were considered for this application. The RFC and batteries also included nontracking solar arrays for recharging during the sortie. The PFC would be recharged back at the main base after the 20-day sortie. Solar arrays were sized for local dust storms (optical density of 1) based on the nature of this rover. Tracking arrays were not considered for the rovers because the tracking mechanism for the arrays used in this study has only one axis rotation which would make it difficult to track the sun while the rover is moving across the surface of Mars.

The mass, volume, and blanket area of the systems options can be seen in table VII. The RFC with nontracking arrays is the lightest system at a total mass of 2813 kg, while the NaS battery is next at 3617 kg, and the PFC is the heaviest at 6492 kg. The PFC requires the smallest volume of 29 m^3, while the RFC with nontracking arrays is the largest at 66 m^3. The RFC required 37.4 kWe to recharge, while the battery required 27.5 kWe. The blanket area for the RFC nontracking and Na/S nontracking arrays is 1 248 m^2 and 989 m^2, respectively, which is judged an impractical area to pull behind or mount on top of the rover.

TABLE VII.—10-kWe PRESSURIZED ROVER POWER SYSTEM

Power system	RFC with nontracking array			PFC			NaS with nontracking array		
	Mass, kg	Volume, m^3	Blanket area, m^2	Mass, kg	Volume, m^3	Blanket area, m^2	Mass, kg	Volume, m^3	Blanket area, m^2
Fuel cell	809	2	------	6 427	28	----	2 140	2	----
Radiator	146	2	27	65	1	13	6	0.07	1
Battery	------	---	------	------	----	----	------	------	----
Array	1 857	63	1 248	------	----	----	1 471	49	989
Total	2 813	66	1 275	6 492	29	13	3 617	51	990

Unpressurized Rover

Two unpressurized rovers are used for local sorties during daylight hours with a maximum range of 15 to 20 km. Each rover is capable of one sortie per day and operates during hazy or clear days, but not during dust storms, and it requires 4 kWe for the entire mission. Each sortie consists of traveling 3 hr out to the destination site, remaining for 4 hr at the site, and then, returning in 3 hr to the habitat.

Three power systems were analyzed for this rover: a PFC, a GaAs/Ge tent array, and a GaAs/Ge nontracking array (ref. 10). No recharging systems were selected because of the short duration of the mission and the assumption that the fuel cell could be recharged by another source back at the main base. The arrays were sized for hazy day conditions.

Table VIII shows the breakdown of the systems analyzed. The tent array is the lightest system at 53 kg, with the smallest volume (1 m^3). The blanket area for the tent array is small enough to be carried either on the rover or on a small cart pulled behind the rover. The PFC was the heaviest at 157 kg.

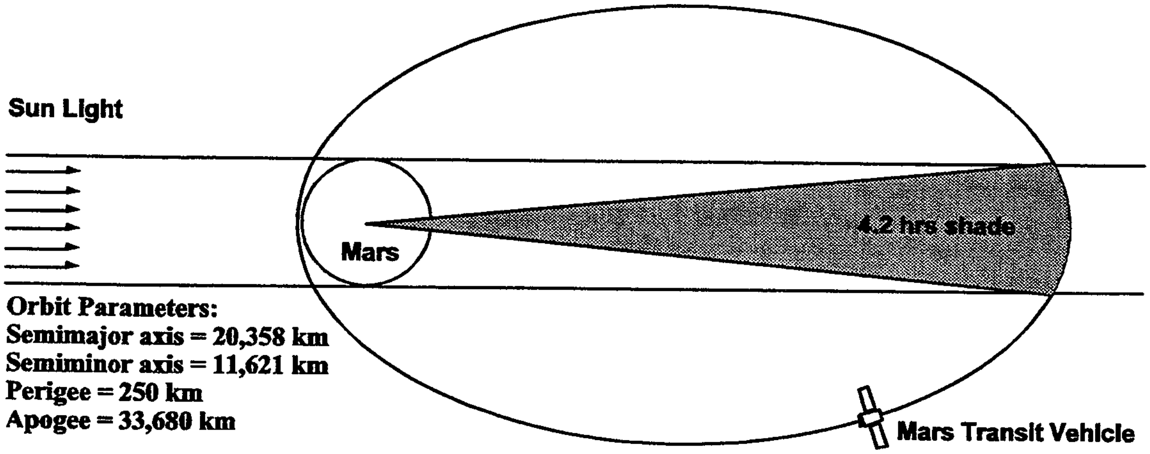
TABLE VIII.—4-kWe UNPRESSURIZED ROVER POWER SYSTEM

Power system	PFC			GaAs/Ge tent array			GaAs/Ge nontracking array		
	Mass, kg	Volume, m^3	Blanket area, m^2	Mass, kg	Volume, m^3	Blanket area, m^2	Mass, kg	Volume, m^3	Blanket area, m^2
Fuel Cell	130	0.34	--	------	----	--------	-------	-----	----
Radiator	27	0.39	6	0.61	0.01	0.10	0.61	0.01	0.10
Array	----	-----	--	53	.92	18	140	5	92
Total	157	1	6	53	1	18	141	5	92

MARS TRANSIT VEHICLES

Two types of transit vehicles are included in this study: the Mars cargo vehicle and the Mars piloted vehicle. Both vehicles are powered by PV arrays with RFC's as the energy storage system. Each spacecraft solar array wing consists of two flexible blankets of GaAs/Ge attached to a deployable mast. The overall array efficiency is 13 percent with a cell efficiency of 18 percent (ref. 2). The 15.4 percent array efficiency shown in table II for surface arrays was reduced to 13 percent due to array design differences between spacecraft and surface applications.

When the vehicles are launched from Earth, the RFC will provide power until the solar array wings are deployed. The arrays will power the vehicles and recharge the RFC until the vehicles approach Mars orbit capture, at which time the arrays will be retracted to facilitate orbit capture and the RFC will be used. After the orbit capture is completed, the arrays will redeploy and the vehicles will orbit Mars until the RFC is completely recharged. At that time, the solar arrays on the vehicles landing on the surface will be retracted again, and the RFC will provide the power for the descent to the surface. When the vehicles land, the arrays will be redeployed so that they can provide power and recharge the RFC. The RFC system was designed for a 20 percent energy reserve to allow for extra time to deploy the solar arrays after the vehicle has landed and to handle any unexpected events.



Orbit Parameters:
Semimajor axis = 20,358 km
Semiminor axis = 11,621 km
Perigee = 250 km
Apogee = 33,680 km

Figure 2.—Mars transit vehicle trajectory for worst case shade scenario (4.2 hr shade time).

Figure 2 shows a schematic of the Mars orbit trajectory. The vehicles will be in an elliptical orbit with a perigee of 250 km, an apogee of 33 680 km, and a period of 1 sol (1 Martian day, approx. 24.6 hr). The shade time varies as Mars moves around the Sun and the orbit precesses around Mars. The maximum shade time, 4.2 hr, occurs when Mars is at aphelion and the semimajor axis of the Mars orbit is aligned with the semimajor axis of the vehicle orbit.

Two different Mars orbit scenarios were analyzed for recharging the RFC prior to descent. The first scenario allows the RFC to recharge during 7 orbits, which minimizes the size and mass needed for the power system. For comparison, a second scenario was also analyzed by using only 1 orbit to recharge the RFC. One-orbit recharge would make a larger power system necessary, but would minimize the time required in Mars orbit.

Mars Cargo Vehicle

The Mars cargo vehicles will be used to transfer the surface elements, that is, habitat-greenhouse, rovers, ISRU plant, methane plant, ascent vehicle, and Earth return vehicle. A total of three cargo vehicles will be used for separate launch opportunities. The vehicles are required to land within close proximity to each other. The power required for each cargo vehicle is a constant 5 kWe for the entire trip. Figure 3 shows the power requirements and power system operational strategy for the cargo vehicles.

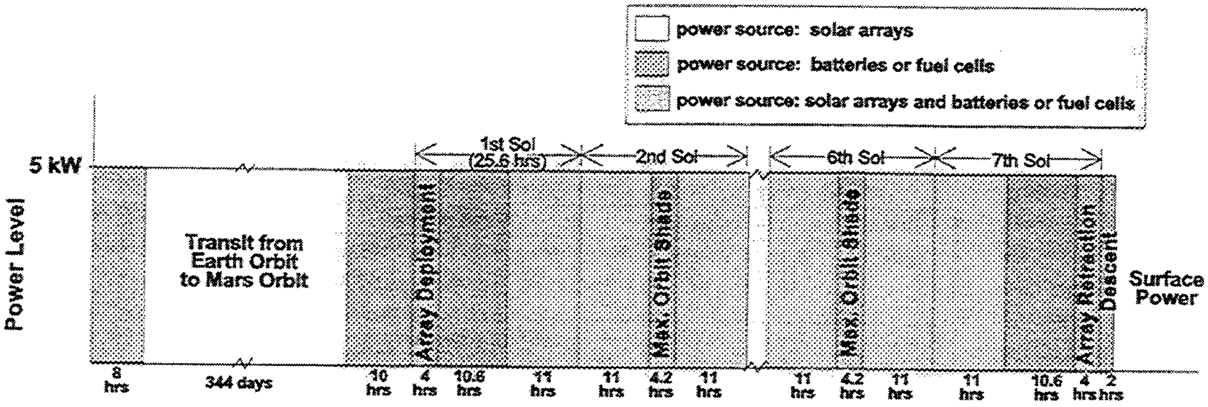


Figure 3.—Mars cargo vehicle power requirements and system operational strategy.

Table IX shows the results of the comparison between one orbit and seven orbits for RFC recharge. The 7-orbit recharge case is 65 percent of the total mass of the 1-orbit case and 57 percent of the blanket area. The difference is due to the length of time the arrays have to recharge the fuel cell. If the RFC is to be recharged in one orbit, more power from the array is required.

TABLE IX.—5-kWe CARGO VEHICLE WITH FUEL CELLS AND ARRAYS—POWER SYSTEMS FOR 1- AND 7-ORBIT RFC RECHARGE SCENARIO

Power system	1-orbit recharge			7-orbit recharge		
	Mass, kg	Volume, m^3	Wing area, m^2	Mass, kg	Volume, m^3	Wing area, m^2
Fuel cell	398	0.498	----	347	0.456	----
Radiator	76	0.971	14	49	0.653	9
Array	795	-------	246	431	-------	138
Total	1269	1.469	260	827	1.109	147

Mars Piloted Vehicle

One piloted vehicle will deliver a crew of six. The vehicle will deliver some cargo and will include a transit habitat. This vehicle is required to descend to a site close (within a 1-km distance) to the habitat-greenhouse.

The piloted vehicle power level is 30 kWe. This power level will remain constant from Earth departure until Mars orbit capture. Upon Mars orbit capture, the power level will be lowered to 15 kWe. Figure 4 shows the power requirements and power system operational strategy of the piloted vehicle using seven orbits for RFC recharge.

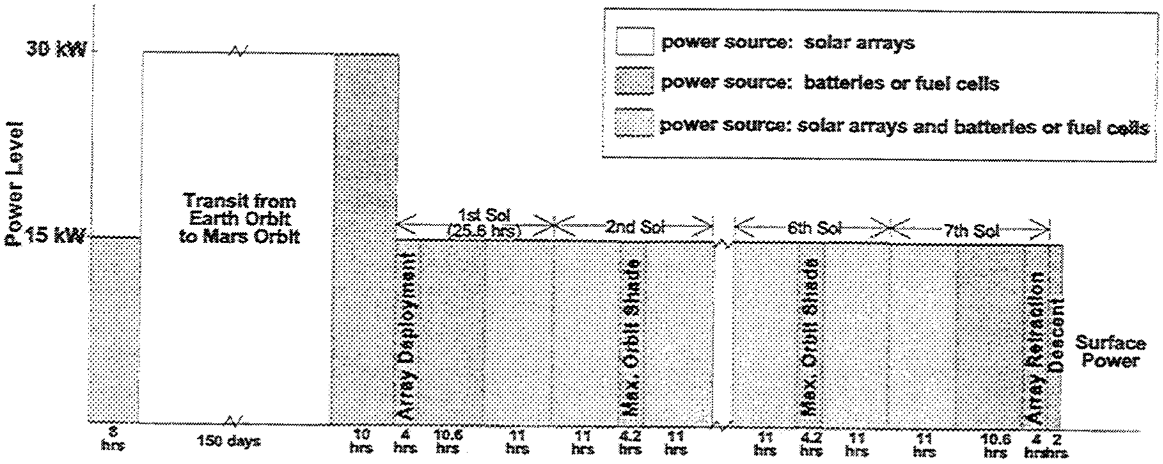


Figure 4.-Mars piloted vehicle power requirements and system operational strategy.

Table X shows the results for the piloted vehicle for both 1- and 7-orbit RFC recharging. The total mass for the 7-orbit case is 63 percent that of the 1-orbit case and 58 percent of the blanket area. The array mass and blanket area almost doubles when the RFC is required to recharge in 1 orbit instead of 7.

TABLE X.—PILOTED VEHICLE WITH FUEL CELLS AND ARRAYS—
POWER SYSTEMS FOR 1- AND 7-ORBIT SCENARIOS

Power system	1-orbit recharge			7-orbit recharge		
	Mass, kg	Volume, m^3	Wing area, m^2	Mass, kg	Volume, m^3	Wing area, m^2
Fuel Cell	1481	0.194	----	1102	3.83	----
Radiator	259	3.260	47	190	1.55	35
Array	2971	-------	918	1682	----	520
Total	4711	3.454	965	2974	5.38	555

CONCLUDING REMARKS

When selecting power system technologies, self deployment, safety concerns, mass, volume, and area estimates must be evaluated. The photovoltaic/energy storage system has challenges due to the low solar intensity on the Martian surface and the need to deploy the power system by telerobotic methods. Mars is located at approximately 1.6 au and its solar intensity above the Mars atmosphere is approximately 2.5 times less than the solar intensity of Earth. In addition, Mars dust storms reduce significantly the insolation and provide potential hazards because of dust accumulation on the solar arrays and possible erosion of the coverglass by the strong wind-driven dust. Therefore, the solar arrays must be designed to overcome these adversities. Oversized solar arrays and array tilting are two methods that might overcome these potential issues.

The habitat-greenhouse solar arrays must be sized to operate under the worst circumstances (global dust storms) because the habitat needs to operate constantly in all atmospheric conditions. Consequently, the habitat requires a large area of solar arrays. This is a concern because the power system must be deployed before humans are present on the surface of Mars. The RFC's have a lighter mass than the sodium sulfur batteries, but the batteries require a smaller array field (about 20 percent less). Therefore, a choice must be made between area and mass when deciding which power system to choose. The in situ resource utilization plant and methane plant have the same issues as the habitat-greenhouse.

The pressurized rover requires a large solar array area because the solar arrays need to be sized for local dust storms rather than hazy day conditions. This requirement was necessary because this rover is designed for a 20-day journey, and it is hard to predict the local dust storms. Thus, an onboard array to power the rover appears to be impractical. Conversely, the solar array for an unpressurized rover is relatively small and can probably be mounted on the rover because the power level is low and the rover will operate only in hazy or better conditions. The major issue with using the solar arrays is making sure that the rover is always in sunlight. This could be a concern if mountains are nearby that would cast shadows on the arrays. The unpressurized rover may require some type of energy storage backup for use when the solar arrays are in a shadow.

Finally, a trade-off between power system mass and stationkeeping fuel mass is required when analyzing the number of orbits required to recharge the RFC's for the piloted and cargo vehicles. If the number of orbits is reduced, the mass and blanket area of the power system increase while stationkeeping fuel mass decreases.

The mass, volume, and area for the power system options presented herein can influence the vehicle configuration. As the mission requirements mature, the power system technology options will be reduced or may even influence mission requirements.

REFERENCES

1. Bozek, J.M.; and Cataldo, R.L.: Power Generation Technology Options for a Mars Mission, Proceedings of the 11th Symposium on Space Nuclear Power and Propulsion 1994.
2. Rauschenbach, H.S.: Solar Cell Array Design Handbook: Van Nostrand Reinhold Company, New York, 1980.
3. Green, M.A.: Solar Cells: Operating Principles, Technology, and System Applications. Prentice-Hall, Inc. Englewood Cliffs, New Jersey, 1982.
4. Appelbaum, J.; and Flood, D.J.: Solar Radiation on Mars. Solar Energy, vol. 45, no. 6, pp. 353 to 363, 1990.
5. Appelbaum, J.; and Landis, G.A.: Photovoltaic Arrays for Martian Surface Power. 43rd Congress of the International Astronautical Federation, (IAF) 29th Plenary Meeting of the Committee on Space Research COSPAR, August 28 to September 5, 1992.
6. Appelbaum, J.; and Landis, G.A.: Solar Radiation on Mars—Update 1991. NASA TM-105216, 1991.
7. Katzan, C.M.; Brinker, D.J.; and Dress, R.: The Effects of Lunar Dust Accumulation on the Performance of Photovoltaic Arrays. Space Photovoltaic Research and Technology 1991 Proceedings of a Conference (SPRAT XI). May 7 to 9, 1991.
8. Landis, G.A.; and Appelbaum, J.: Photovoltaic Power Options for Mars. Space Power. vol. 10, no. 2, pp. 225 to 238, 1991.
9. Perez-Davis, M.E.; Galer, J.R.; Kress, R.; and Grimalda, J.P.: Simulation of Martian Dust Accumulation on Surfaces; 16th AIAA-NASA/ASTM/IES Space Simulation Conference, Albuquerque, New Mexico, November 5 to 8, 1990.
10. Colozza, A.J.; Design, Optimization, and Analysis of a Self-Deploying Tent Array. NASA CR-187119, June, 1991.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	**2. REPORT DATE** December 1994	**3. REPORT TYPE AND DATES COVERED** Technical Memorandum

4. TITLE AND SUBTITLE

Solar-Electrochemical Power System for a Mars Mission

5. FUNDING NUMBERS

WU–233–03–05

6. AUTHOR(S)

Colleen A. Withrow and Nelson Morales

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–8885

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–106606

11. SUPPLEMENTARY NOTES

Responsible person, Colleen A. Withrow, organization code 5440, (216) 433–7006.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories 20, 44, 66 and 91

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

This report documents a sizing study of a variety of solar electrochemical power systems for the intercenter NASA study known as "Mars Exploration Reference Mission." Power systems are characterized for a variety of rovers, habitation modules, and space transport vehicles based on requirements derived from the reference mission. The mission features a six-person crew living on Mars for 500 days. Mission power requirements range from 4 kWe to 120 kWe. Primary hydrogen and oxygen fuel cells, regenerative hydrogen and oxygen fuel cells, sodium sulfur batteries, advanced photovoltaic solar arrays of gallium arsenide on germanium with tracking and nontracking mechanisms, and tent solar arrays of gallium arsenide on germanium are evaluated and compared.

14. SUBJECT TERMS

Mars; Power; Solar; Electrochemical

15. NUMBER OF PAGES

13

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT**

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102