POWER SYSTEMS FOR HUMAN EXPLORATION MISSIONS

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Robert L. Cataldo
Lewis Research Center

Power system options were reviewed for their appropriateness to meet mission requirements and guidelines(1). Contending system technologies include: solar, nuclear, isotopic, electro- chemical and chemical. Mission elements can basically be placed into two categories; in-space transportation systems, both cargo and piloted; and surface systems, both stationary and mobile. All transportation and surface element power system requirements were assessed for application synergies that would suggest common hardware (duplicates of the same or similar design) or multi-use (reuse system in a different application/location), wherever prudent.

GENERAL REQUIREMENTS

Power systems, defined as a life critical function, falls under a fail operational/fail operational/fail safe (FO/FO/FS) functional redundancy risk approach. A power system strategy incorporating redundant, back up and dual-function systems are utilized to satisfy this mission risk approach. Also the adopted mission abort philosophy is to utilize the Mars Base as a "safe haven" since a significant infrastructure of shelter, power, life support and consumables, return flight propellants will already exist.

Thus, a 600-day supply of life support gases and water, along with the ascent vehicle propellants (CH_4 and O_2), will be generated and stored before committing to the piloted mission scheduled for the following opportunity, some 750 days later. A significant requirement on the power system will be a design that can be self-deployed or telerobotically deployed within a short period of time. The initial power system output is therefore dictated by the total energy needed to produce and store the cache of life support and propellants and the available operating time. Of the 750 days between missions, only 480 days are available to produce power based on 210 days of transit and 60 days for robotic deployment of surface systems.

TRANSPORTATION SYSTEM REQUIREMENTS

The mission transportation elements that require power are: Transit Habitat (TH), Mars Transfer Vehicle (MTV), Mars Lander (ML), Ascent Vehicle (AS), and Earth Return Vehicle (ERV).

Power requirements for the six person crew Transit Hab for both nominal and "power down" emergency mode are shown in Table 1. The life support system (LSS) is a major constituent of the 30 kWe. The LSS is based on a partially closed air and water system design that performs the following functions: CO_2 reduction; O_2 and N_2 generation; urine processing; and both potable and hygiene water processing. The derated "emergency mode" value is based on the LSS operating in an open loop mode and reductions in non-critical operations. A TH is used for both outbound and inbound flights. However, the outbound TH's are landed on Mars and become part of the Base's living quarters. The Earth return TH is sent on the previous opportunity aboard the ERV and remains in transit and Mars orbit for almost 5 years.

TABLE 1. Nominal and emergency transit habitat power estimates

ESTIMATED MARS TRANSIT HABITAT POWER REQUIREMENTS (kWe)			
ELEMENT	MODE		NOTES:
	NOMINAL	EMERGENCY	
LIFE SUPPORT SYS. (LSS)	12.00	8.00	OPEN LOOP IN EMER. MODE
THERMAL CON. SYS. (TCS)	2.20	2.20	
GALLEY	1.00	0.50	EMERGENCY VALUES:
LOGISTIC MODULE	1.80	1.80	DERATED FROM NOMINAL
AIRLOCK	0.60	0.10	WHERE DEEMED
COMMUNICATIONS	0.50	0.50	APPROPRIATE
PERSONAL QUARTERS	0.40	0.00	
COMMAND CENTER	0.50	0.50	VALUES ADAPTED FROM
HEALTH MAINT. FAC. (HMF)	1.70	0.00	NAS8-37126, "MANNED
DATA MGT SYS	1.90	0.80	MARS SYSTEM STUDY"
AUDIO/VIDEO	0.40	0.10	
LAB	0.70	0.00	
HYGIENE	0.70	0.00	
S/C UTILITY POWER	5.00	5.00	
TOTAL	29.40	19.50	

The spacecraft base power load for vehicle avionics, communications, and the propulsion system is estimated at 5 kWe. This value is also assumed for cargo only vehicles.

The MTV uses a nuclear thermal rocket (NTR) for the trans-Mars injection propulsion only and an aerobrake (A/B) for Mars orbit capture and entry. The baseline power system for the NTR-A/B configured MTV is photovoltaic arrays and regenerative fuel cells for energy storage. Figure 1 shows a power vs. time profile for the Mars transit.

The array is designed to produce the required 30 kWe in Mars orbit (worst case 1.67 AU). The energy storage system is sized to provide power before and after Mars orbit capture during the following maneuvers: attitude control, array retraction, orbit capture, array extension and orbit eclipse, as shown in Figure 1. It is currently assumed that the TH can be safely "powered down" to 20 kWe during these mission phases to save RFC mass and volume. The RFC and array remain with the TH/lander and are utilized on the surface.

Based on the size of the energy storage system, eclipse power and the available power from the array, it will take 7 orbits before the RFC is fully charged. The RFC delivers power when the array is retracted during entry, descent and landing. The RFC can deliver 20 kWe for 24 hours after landing and is the prime power source for the lander/TH and crew. The RFC could also provide power for moving the habitat from the landing site to its final emplacement location, assuming no solar array deployment. The ERV solar array/RFC will become part of the back up power system for the habitats upon final emplacement.

Another option under consideration is the "all NTR" concept, where the propulsion system is also used for the Mars capture and trans-Earth injection maneuvers. The reactor therefore, would be configured to produce power as well as propulsion. Power would be required to maintain LH_2 boil-off to acceptable levels, thus the NTR engine in the power-mode would produce 40 kWe; 30 kWe plus 10 kWe for propellant refrigeration. Only refrigeration power is needed while in Mars orbit, however full TH power would be required for Earth return.

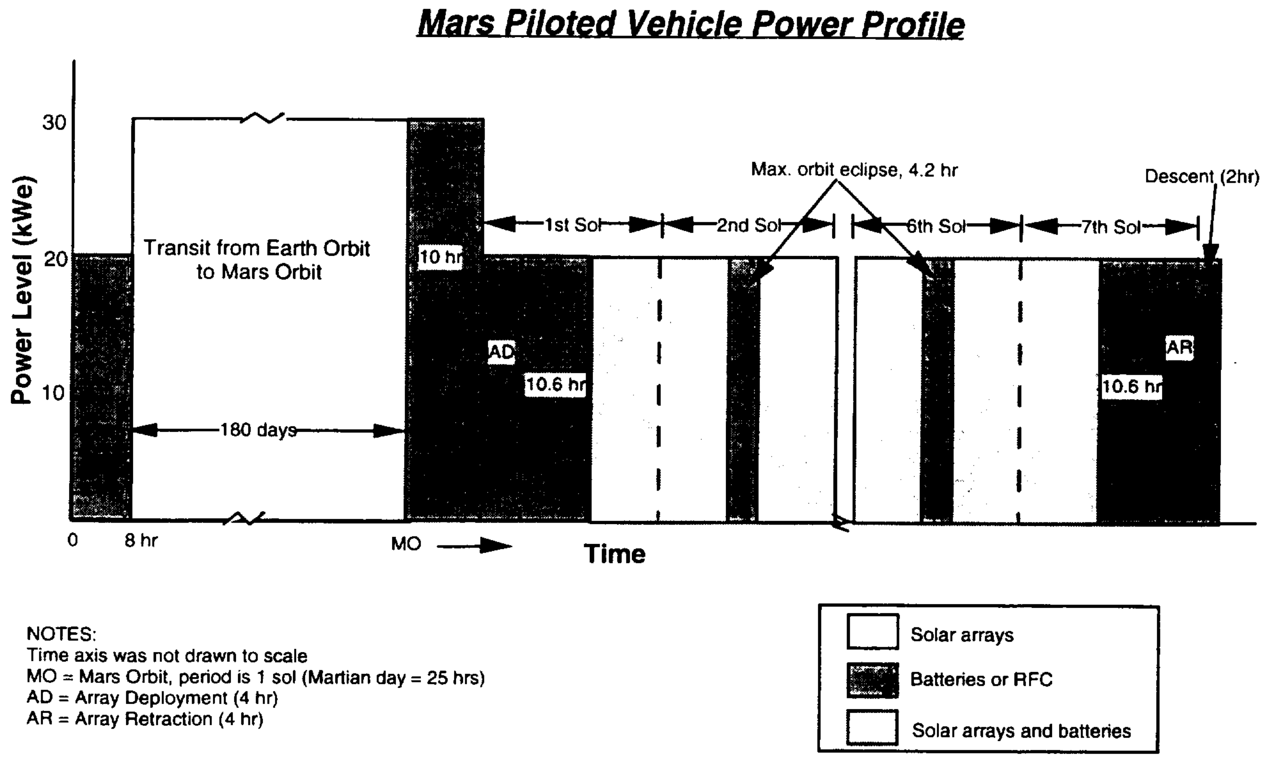

FIG. 1. MTV Power Profile

SURFACE SYSTEMS REQUIREMENTS

Significant design requirements are placed on all the surface equipment delivered on the initial cargo flights. Each system must be deployed to their respective locations and function autonomously for almost two years. These two requirements could greatly impact the design and selection of the power system. Crew safety and well being demands reliability and robustness in all surface elements. Risk is also mitigated by backup and redundant systems or systems that can perform multiple functions.

Habitation, Life Support And Propellant Production And Operations

A particular challenge to the power system and other surface assets is their deployment and set-up on the planet surface. The power system, LSS cache plant and propellant fuel plant must be deployed without direct human intervention. They therefore must be self-deployed or most likely deployed in a supervisory, tele-operated mode from Earth. For example, a command will be given for a "safe" maneuver depending on vision capability and line of sight limitations, then an operator will wait for conformation of the completed task. This sequence could take up to 40 minutes (speed of light delay) plus the actual time to perform the task. This could be a significant design factor the power system.

To best determine the type and design of the power system, an estimated power profile, was determined and is shown in Figure 2.

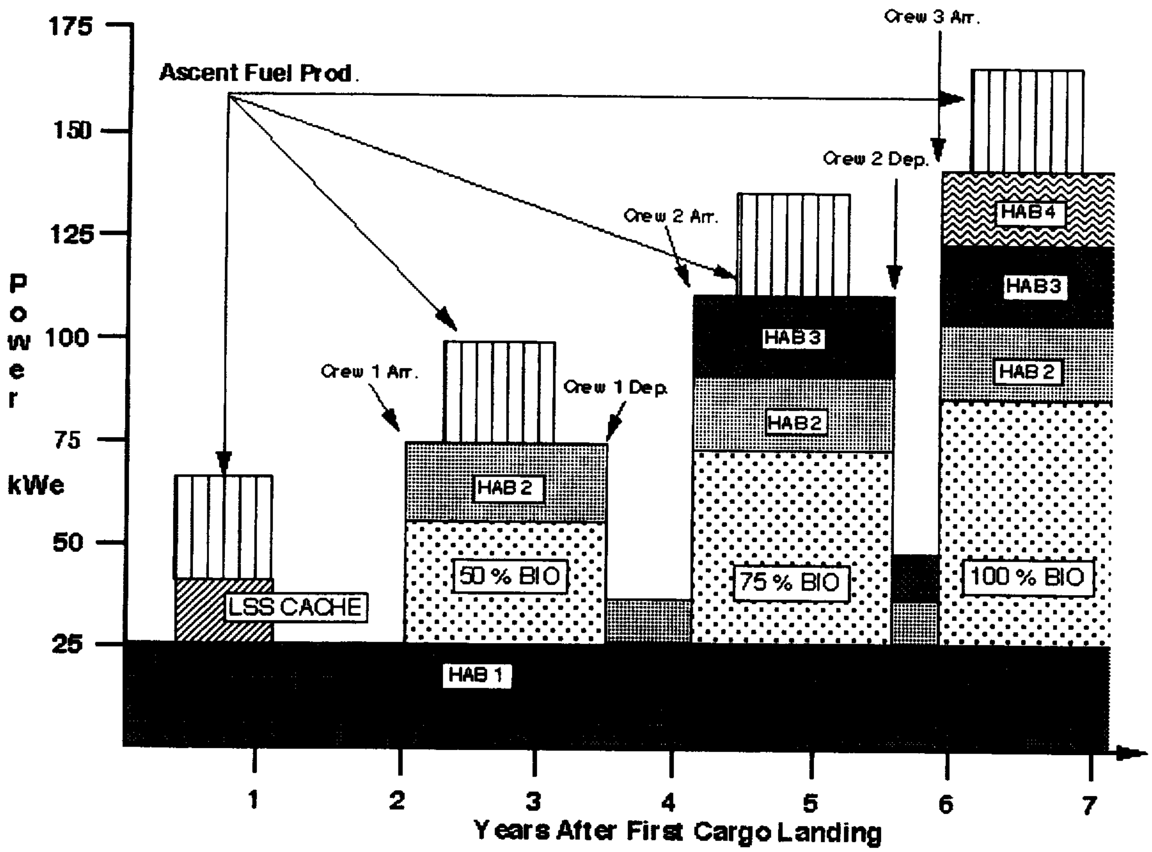

FIG. 2. MARS SURFACE POWER PROFILE

Figure 2 shows the estimated power levels and time sequencing for the various surface elements. The power system must be one of the first elements deployed because it must provide power to produce the life support cache and ascent vehicle propellants, prior to the first crew launch. Approximately 370 days will be available to produce the required cache. However, this will be reduced by the time to deploy the power system. With an estimated power system deployment time of 30-60 days, about 320 days remain for producing these products. The initial 60 kWe power level was determined by the required energy and production time. Power levels approach 160 kWe as the outpost reaches full maturity of increased habitation volumes and life support capability.

Two types of power systems were evaluated to meet the evolutionary power requirements of the base; nuclear and solar. Table 2 shows estimated mass, volume and area. A brief description of each system follows.

The nuclear power system is configured for remote deployment and is integrated with a mobile platform. The entire system is tele-deployed from the landing site (trailing distribution cables) to a site about 2 km from the base. No assembly is required, however, deployment of the radiator panels, either self-deployed or with the aide of a rover arm, is necessary. It is planned to utilize the pressurized rover (or its power cart) for this task. Power from the rover will be used for startup heating (eliminating batteries) and obtain operating conditions. The nuclear power system will be capable of delivering the full base needs of 160 kWe. A second system is delivered and deployed to satisfy the fail-ops mission requirement, but will not be turned on unless required. The mass of this system is higher than technically achievable because of the low temperature design parameter selected for Mars surface application.

TABLE 2. Surface power system options characteristics

MAIN POWER SYSTEM	TYPE	MASS (MT)	VOLUME (m^3)	AREA (m^2)
160 kWe	NUCLEAR- SP-100 type, low-temp, stainless steel, dynamic conversion, 4-Pi shielding	14	42	321 radiator area
120 kWe	SOLAR- tracking, O.D. = 0.4	19.6	341	6,400 array area 45,000 field area
	SOLAR- non-tracking, O.D. = 0.4	33.5	686	13,000 array area 39,000 field area
BACKUP (40 KWe)	SOLAR- tracking, O.D. = 6.0	14	390	7,600 array area 53,000 field area
	SOLAR- non-tracking, O.D. = 6.0	26	816	16,000 array area 48,000 field area
EMERGENCY	USE PRESSURIZED ROVER POWER SYSTEM (SEE TABLE 3)			

A solar power system requires array panels to supply the main base load and recharge the energy storage for nighttime operations(2). The system was sized to produce required power at winter diurnal cycles, at the equator. The backup habitat power system was designed to operate at "worst case" global dust storm conditions, or an optical depth (O.D.) equal to 6.0, since these conditions could be present at the Base when an emergency power situation arose. The ISRU plant was not considered a life critical function and therefore designed to produce full power at an optical depth of 0.4 or a "clear Mars sky." Both sun tracking and non-tracking arrays were evaluated. The sun tracking array total land area is greater that the non-tracking because of the required panel spacing needed to eliminate shadows from one panel upon the other.

Optical depth, or the intensity of the Sun reaching the surface of Mars, has a significant impact on system size and mass. For example, if the entire 160 kWe were solar generated, the array field would encompass about 11(O.D. =.4) to 40 (O.D. =6.0) football fields. In addition, the the need for prompt telerobotic emplacement of the array panels and interconnectiong cables would present a significant challenge. Dust erosion, accumulation and wind stresses on the array panels raise power system lifetime issues. However, use of the "in-space" array and fuel cell power system is anticipated for the habitat emergency/backup power systems, which could be stowed until needed.

The power management, transmission and distribution masses (@ 95% eff.)have been included in each of the system sizing estimates. Transmission cable masses were calculated using 500 V due to the Paschen breakdown limit associated with Mars' atmospheric pressure.

Surface Mobility

Another application needing power is rovers. Three types of rovers have been identified, long-range pressurized, local unpressurized and long range robotic. Several options, including regenerative fuel cells, combustion engines and isotope for powering these rovers were evaluated.

Requirements for the long-range pressurized rover are as follows: a crew of 2-3, 500 km range, 5 days out-10 days at site-5 days back. Power estimates for this rover is 10 kWe.

TABLE 3. Rover Power System Characteristics

Power System	Mass (MT)	Volume (m^3)	Area (m^2)	Mass (MT)	Volume (m^3)	Area (m^2)
	Regional Rover			Local Rover		
Dynamic isotope	1.1	10	33	0.5	4	16
Photovoltaic/RFC	2.8	66 (RFC-4) (PV-62)	1,275	recharge by refueling		
Primary Fuel Cell	6.5	29	13	.160	1	6
Methane ICE	12	36	n/a	.160	0.4	n/a

It is anticipated that the pressurized, regional rover or its power system would be used to assist in the deployment of the main power system, situate future habitat modules, and serve as back-up, emergency power when required. It is desirable that the rover power system be mounted on its own cart. This would add considerable versitility to its use when the rover is not on a sortie. Table 3 shows the estimated mass, volume and array or radiator area for the four power system options listed.

The dynamic isotope power system (DIPS) was chosen for its low mass and significantly lower radiator size compared to the photovoltaic array area. The ^{238}PU isotope has a half life of 88 years and can be the same design as the flight proven RTG. However, the quantity and cost are issues to be addressed and could be justifiable for a sustained base occupancy. The isotope fuel would be reloadable into other power units in the event of a failure, thus preserving its utility for subsequent missions. Another feature of isotope fuel is that it does not need to be recharged and is always ready as a back-up, emergency power source independant of solar availability or atmospheric conditions. For example, this flexibility is utilized in providing power for the positioning of each crewed transit habitats from their landing sites to the main habitation locale. The small amounts of radiation emited (primarily alpha and gamma rays) by ^{238}PU is mitigated by a small heat source end cap shield and distance ($1/d^2$ attenuation) to the crew.

Methane is a possible fuel for the rover since the propellant plant could produce additional fuels, given extra hydrogen is brought from Earth. Methane could be used in an appropriately designed fuel cell. The reactant water would be returned and fed through an electrolizer to capture the hydrogen. However, once you have electrolized the water into H_2 and O_2, which the fuel cell acually uses to operate, it is not prudent from an energy utilization standpoint to make methane again. Although the issue of storing and maintaining reactants on the rover would need further study. A methane burning engine could be used to operate the rover, however, combustion materials would need to be collected to reclaim the H_2.

The photovoltaic/RFC power option seems impractical for the regional rover due to the large array area. The arrays were sized to provide required power output during a local dust storm, anticipating suspended operations during the global dust storm season.

The local rover is unpressurized like the Apollo LRV. It would function to transport the crew 10's of kilometers, 3 hours out and back, and 4 hours at the site. The primary fuel cell would meet the local rover rquirements at less mass than other options. The power system design characteristics assumes refueling after every sortie.

SUMMARY

A power system strategy was adopted that satisfied mission requirements for power availability and reliability by utilizing several different technologies and functional redundancy of several elements. The power system selected for surface operations is a SP-100 type reactor system capable of producing 160 kWe. This option was selected based on its high power capability at reduced mass and volume, less deployment issues and its insensitivity to changes in operating environment, i.e., latitude, atmospheric sunlight attenuation, seasonal variation of day/night ratio. The selection of nuclear power for this mission is a major concern due to its historic socio-political nature. In addition, DOE's SP-100 and other space nuclear power programs have been terminated.

Back-up, emergency power is provided by the MTV photovoltaic/RFC power system. This is the same system used in Mars transit and provides power during descent. taken to and the isotope power system of the regional rover. This strategy maximizes power availability with the least amount of hardware through functionally redundant componets.

REFERENCES

(1) Human Exploration of Mars: The Reference Design Mission of the NASA Mars Exploration Study Team, Hoffman, S., Kaplan, D., NASA SP 6107, July, 1997

(2) Solar-Electrochemical Power System for a Mars Mission, Withrow, C., Morales, N., NASA TM 106606, December, 1994.