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Power Generation Technology Options for a Mars Mission

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POWER GENERATION TECHNOLOGY OPTIONS FOR A MARS MISSION

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SUMMARY

The power requirements and resultant power system performances of an aggressive Mars mission are characterized. The power system technologies discussed will support both cargo and piloted space transport vehicles as well as a six-person crew on the martian surface for 600 days. The mission uses materials transported by cargo vehicles and materials produced using in-situ planetary feed stock to establish a life-support cache and infrastructure for the follow-on piloted lander. Numerous power system technical options are sized to meet the mission power requirements using conventional and novel solar, nuclear, and wireless power transmission technologies for stationary, mobile surface, and space applications. Technology selections will depend on key criteria such as mass, volume, area, maturity, and application flexibility.

INTRODUCTION

NASA is currently in the process of identifying and quantifying mission architectures and technology options for a manned Mars mission. The baseline mission architecture envisions landing six astronauts on the martian surface by the first decade of the next century and providing the capability for in-situ production, bioregenerative life support, surface habitation and mobility, emergency power, and lift-off propellants for Earth return. These goals will be accomplished with a range of power system options that use both conventional and novel technologies to satisfy these diverse requirements.

This report provides a brief description of the current mission requirements and presents a preliminary performance evaluation of a variety of space and surface power technology options from the standpoint of power system mass, volume, and deployed area.

MISSION REQUIREMENTS

The mission architecture calls for a "split" mission concept in which cargo and piloted vehicles are launched separately. A series of three cargo vehicles will be launched to Mars in 2-month intervals starting in late 2007. The cargo vehicles will have sufficient material and power capability to autonomously emplace an infrastructure capable of supporting six astronauts. Upon confirmation that the infrastructure and a cache of life-supporting, in-situ products are in place, a piloted Mars transfer vehicle (MTV) will follow at the next opportunity.

The first two cargo vehicles will deliver a habitat, a bioregenerative chamber for food production, a plant to produce water, a plant to produce methane and oxygen, oxygen and buffer gases, two unpressurized rovers, one pressurized rover, the power system(s) with cable-captive or wireless power transmission, and cache storage capabilities to the martian surface. The third cargo vehicle will deliver the Earth return vehicle (ERV) to martian orbit where it will remain awaiting crew ascent, rendezvous, and subsequent trans-Earth insertion. The piloted MTV contains a transit habitat that is ultimately placed on the martian surface with the six astronauts inside. This transit habitat will expand the livable quarters on the surface beyond that available through a previous cargo vehicle landing.

Table I shows the current mission power and duration requirements of the space and surface application elements. Space elements include the cargo and piloted vehicles required to accomplish the Earth-Mars surface-Earth transition; surface mission elements include life support, in-situ resource utilization, rovers, and methane production.

Three of the surface infrastructure elements that may use methane-based power are the habitat/bioregenerative chamber and both manned rovers. In the event of a power system failure for the habitat/bioregenerative chamber, the methane-based power system is a possible source of emergency backup power. A 5- and a 60-day emergency period were analyzed.

Space power levels range from 2.5 kWe for the cargo vehicle to 30 kWe for the manned MTV and ERV, and durations range from minutes to hundreds of days. While awaiting arrival of the crew in Mars orbit, the ERV is designated as an orbiter and requires 5 kWe for 515 days.

Individual surface elements require power levels up to 120 kWe with durations ranging from hours to years. However, in some instances, because of the anticipated proximity of these elements and the potential centralized power system capability, selected mission elements have been combined to create a higher load requirement. These combinations will be discussed in the Technology Options section.

The 10-kWe pressurized rover will be capable of 500 km sorties lasting 20 days with two to three astronauts on board. The two 4-kWe unpressurized rovers will only operate for 10 daylight hours, with a range of 15 to 20 km per sortie.

The in-situ resource utilization (ISRU) plant will produce a cache of water, oxygen, and buffer gases for crew life support. The ISRU plant will be capable of several separate processes powered by a single 120-kWe power plant and will produce a 600-day life support prior to the arrival of the crew on the martian surface.

The methane plant produces a cache of methane and oxygen that can provide propellants for Mars surface lift-off capability or for an energy source for the habitat, bioregenerative chamber, and rovers. The manufacturing process uses hydrogen imported from Earth and in-situ carbon dioxide from Mars' atmosphere to produce water and methane. Electrolysis of water produces usable oxygen and recyclable hydrogen. A 40-kWe plant can produce sufficient products to provide up to 60 days of emergency power for the habitat and bioregenerative chamber, and can produce 4 and 10 kWe for the unpressurized and pressurized rovers, respectively.

TECHNOLOGY OPTIONS

The power technologies examined included systems for operational power in table II and methane-based power in table III. Both tables display the mass, deployed area, volume, power system application, and required power level of these technologies. Reactor- and isotope-based power systems comprise the nuclear technologies, and photovoltaic arrays and solar concentrators, with and without energy storage, comprise the nonnuclear category, including primary electrochemical energy storage.

Nuclear reactor power systems are based on SP-100 reactors and Stirling cycle thermal-to-electric conversion technologies; however, over the range of power levels shown, the mass, area, and volume values are representative of other SP-100 systems using Brayton or thermoelectric conversion. Reactor power systems have been used to provide operational power for multiple load applications. For these applications, all reactor power systems have been arbitrarily located 2 km away from the nearest load. In addition, reactor power systems include an integral 4π radiation shield designed to limit human exposure to 5 rem/yr at a distance of 2 km.

The largest multiple load application (270 kWe) was powered by a 520-kWe SP-100/Stirling cycle power system using a wireless power transmission system based on microwave technology. Discounting the increased load requirement discussed below, a key feature of this concept is that the location of loads and the power system are not constrained by a fixed cable length. The 270-kWe total load for this power system includes the methane and ISRU plants, a habitat/bioregenerative chamber, and an additional 25-kWe habitat to quantify the extent to which diverse loads can be accommodated. All loads can be located at diverse locations up to 14 km, the maximum lineof-sight distance for a 10-m-high antenna and a 5-m-high rectenna. The wireless transmission power system includes a 20 000-kg, 520-kWe SP-100/Stirling power generator and a 5400-kg 100-GHz microwave transmitter subsystem with individual antennas and rectennas for each load. The other multiple load application of 160 kWe is supplied by a 180-kWe SP-100/Stirling cycle power system using a high-voltage insulated cable transmission.

The nuclear dynamic isotope power systems (DIPS) are based on general purpose heat source (GPHS) technology with small Stirling cycle engines. DIPS-powered space and surface applications were limited to low power levels with high energy requirements to limit the Earth launch inventory of plutonium. The human-rated gamma radiation shield for rover applications was sized to limit exposure to 5 rem/yr whereas the cargo vehicle application did not require a shield. Also, the potential portability of a DIPS could permit additional operational or emergency applications, such as habitat emergency power.

The solar-based power systems include a range of photovoltaic (PV) technology options for surface and space applications and a solar dynamic (S/D) option for space applications only. Photovoltaic system options using GaAs cell technology have been considered with fixed, tracking, and tent arrays. Electrochemical storage options included high-energy-density NaS batteries for short-duration applications and H_2/O_2 regenerative fuel cells (RFC) for long-duration applications. A nonregenerative H_2/O_2 primary fuel cell (PFC) was also considered for the short sortie and daylight-only requirement for the unpressurized rover.

Methane-based power applications and technologies use the previously stored methane and oxygen cache to generate electricity with three different conversion options (table III) and the Stirling cycle option uses external combustion of methane and oxygen. The proton exchange membrane fuel cell (PEM FC) and solid oxide fuel cell (SOFC) technologies use an H_2 reformer. The hydrogen is then combined with oxygen to operate the fuel cell. The mass and volume of these options are strongly dependent on the operating duration of the specific application because of reactant storage tank requirements.

CONCLUDING REMARKS

This report has presented preliminary estimates of the mass, volume, and deployed area for many power system technologies as applied to numerous discrete elements of a manned Mars mission. Selection of a power system technology for a specific mission element will depend on further mission requirements and power system design definitions. Even though the down selection to fewer technologies may be desirable, it may be premature, given the technology maturation rate, the ever-changing political environment, and flux of mission requirements. In fact, the power system technology trade-space may have to be expanded as technologies emerge from the laboratory.

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TABLE I.—SPACE AND SURFACE ELEMENT REQUIREMENTS

Space mission element	Power, kWe	Duration	Surface mission element	Power, kWe	Duration
Cargo vehicle			Habitat (crew of six)	25	> 6 yr
Earth orbit	2.5	5 days	Habitat (standby mode)	4	(a)
Trans-Mars insertion	2.5	2 hr			
Cruise to Mars orbit	2.5	339 days	Bioregenerative chamber	15	> 6 yr
Mars orbit insertion	2.5	2 hr			
Mars orbit to Mars surface	(a)	(a)	Pressurized rover	10	20 days
Mars tranfer vehicle (MTV)					
Earth orbit	30	1 day			
Trans-Mars insertion	30	30 min	Unpressurized rover	4	10 hr
Cruise to Mars orbit	30	180 days			
Mars orbit insertion	30	11 min			
Earth return vehicle (ERV)					
Trans-Earth insertion	30	10 min	In-situ resource utilization	120	2 yr
Cruise to Earth orbit	30	180 days	ISRU plant		
Earth orbit insertion	30	(a)	ISRU storage	6	> 6 yr
Earth orbit to Earth surface	(a)	(a)			
Orbiter (part of ERV)			Methane plant	40	1 yr
Mars orbit	5	515 days	Methane plant storage	1.3	As needed

[a]To be determined.

TABLE II.–OPERATIONAL TECHNOLOGIES

Power, kWe	Application	Technology	Mass, kg	Area, m^2	Volume, m^3
		Nuclear			
270	Habitat/bioregenerative chamber/ISRU/ Optional habitat/methane plant	SP-100/Stirling/microwave[a]	25 400	920	120
160	Habitat/bioregenerative chamber/ISRU	SP-/Stirling[b]	14 000	320	42
30	MTV or ERV/ERV's orbiter	SP-/Stirling	2 600	40	23
2.5	Cargo vehicle	DIPS	230	6	4
4	Unpressurized rover	DIPS	460	16	9
10	Pressurized rover	DIPS	1 100	33	18
		Nonnuclear (solar-based)			
40	Habitat/bioregenerative chamber	PV(Fxd)/RFC[b,c]	27 000	15 000	820
40	↓	PV(Trk)/RFC[b,c]	19 000	11 000	390
40	↓	PV(Fxd)/NaS[b,c]	26 000	12 000	640
40	↓	PV(Trk)/NaS[b,c]	21 000	9 200	320
120	ISRU plant	PV(Fxd)/RFC[d]	30 000	12 000	690
120	ISRU plant	PV(Fxd)/NaS[d]	20 000	7 200	340
10	Pressurized rover	PFC	6 500	13	29
10	Pressurized rover	PV(Fxd)/RFC[d]	2 900	1 200	66
10	Pressurized rover	PV(Trk)/RFC[d]	3 700	930	51
4	Unpressurized rover	PFC	160	6	1
4	Unpressurized rover	PV(Fxd)[d]	150	100	5
4	Unpressurized rover	PV(Tent)[d]	58	40	1
2.5	Cargo vehicle	PV(Trk)[e]	79	47	2
30	MTV	PV(Trk)[e]	960	560	28
30	ERV/ERV's orbiter	PV(Trk)/NaS[e,f]	1 000	560	28
2.5	Cargo vehicle	S/D[e]	69	22	0.01
30	MTV	S/D[e]	860	280	.23
30	ERV/ERV's orbiter	S/D-TES[e,f]	950	280	.23

[a]Includes rover recharge power.
[b]Power system used for a methane plant prior to habitation.
[c]Sized for global dust storm insolation.
[d]Sized for hazy day insolation.
[e]Sized for Mars orbit insolation.
[f]Orbiter portion requires energy storage for a 5-kWe, 41-min eclipse of a 123-min orbit.

DIPS	Dynamic isotope power system
ERV	Earth return vehicle
Fxd	PV array with fixed orientation
ISRU	In-situ resource utilization
MTV	Mars transfer vehicle
NaS	Sodium/sulfur battery
PFC	H_2/O_2 primary fuel cell
PV	Photovoltaic array
RFC	H_2/O_2 regenerative fuel cell
S/D	Solar dynamic
Tent	Fixed PV array in tent configuration
TES	Thermal energy storage
Trk	Sun-tracking PV array

TABLE III.—METHANE-BASED POWER TECHNOLOGIES

Power, kWe	Time, hr	Application	Conversion technology	Mass, kg	Volume, m^3
4	10	Unpressurized rover	PEM FC[a]	150	0.15
4	10	Unpressurized rover	Stirling	180	.29
4	10	Unpressurized rover	SOFC[b]	120	.18
10	480	Pressurized rover	PEM FC[a]	4 200	11
10	480	Pressurized rover	Stirling	13 000	35
10	480	Pressurized rover	SOFC[b]	5 000	14
40	120	Habitat/bioregenerative chamber	PEM FC[a]	5 000	12
40	120	↓	Stirling	13 000	35
40	120	↓	SOFC[b]	5 600	15
40	1440	↓	PEM FC[a]	48 000	130
40	1440	↓	Stirling	150 000	420
40	1440	↓	SOFC[b]	58 000	170

[a]PEM FC, proton exchange membrane fuel cell.
[b]SOFC, solid oxide fuel cell.

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