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Mars Power System Concept Definition Study (Task Order No. 16)

Volume 1 - Study Results

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FOREWORD

This report documents the work performed by Rockwell International's Rocketdyne Division on NASA Contract No. NAS3-25808 (Task Order No. 16) entitled "Mars Power System Definition Study." This work was performed for NASA's Lewis Research Center (LeRC). The NASA LeRC Task Order Contract Technical Manager was Mr. William A. Poley and the Specific Task Manager was Mr. Robert Cataldo. The Rocketdyne project engineer was Mr. James M. Shoji.

The report is divided into two volumes as follows:

- Volume 1 - Study Results

- Volume 2 - Appendices

The results of the power system characterization studies, operations studies, and technology evaluations are summarized in Volume 1. The appendices include complete, standalone technology development plans for each candidate power system that was investigated.

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<u>VOLUME 1</u>

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AI	=	Artificial Intelligence
AMTEC	=	Alkali Metal Thermoelectric Converter
BIPS	=	Brayton Isotope Power System
BRU	=	Brayton Rotating Unit
C-C	=	Carbon-Carbon
CBC	=	Closed Brayton Cycle
CIS	=	Copper Indium Diselenide
D	=	Day
DIPS	=	Dynamic Isotope Power System
EM	=	Electromagnetic
EMU	=	Extravehicular Mobility Unit
EOL	=	End-of-Life
EVA	=	Extravehicular Activity
FLO	=	First Lunar Outpost
FU	=	Flight Unit
GaAs/Ge	=	gallium arsenide on germanium base photovoltaic cell
GES	=	Ground Engineering System
GPHS	=	General Purpose Heat Source
HP	=	High Pressure
HSA	=	Heat Source Assembly
LMCR	=	Liquid Metal Cooled Reactor
LP	=	Low Pressure
MEV	=	Mars Excursion Vehicle
N	=	Night
NaS	=	Sodium Sulfur
OSR	=	Optical Solar Reflector
P	=	Peak
PCU	=	Power Conversion Unit
PEM	=	Proton Exchange Membrane
PP&C	=	Power Processing and Control
PV	=	Photovoltaic
QU	=	Qualification Unit
RFC	=	Regenerative Fuel Cell
RTG	=	Radioisotope Thermoelectric Generator
SC	=	Stirling Cycle
SEI	=	Space Exploration Initiative
SUPER	=	Survivable Power Subsystem
TAC	=	Turboalternator-Compressor
TE	=	Thermoelectric
TFE	=	Thermionic Fuel Element
TRL	=	Technology Readiness Level

1.0 SUMMARY

A preliminary top level study was completed to define power system/subsystem concepts applicable to Mars surface power system applications. It was not the purpose of this study to determine optimum power systems and architectures. Prior to selecting a power system architecture for Mars surface applications, many elements must be evaluated. This study determined power system technology level, system mass, deployment requirements and servicing requirements which will aid in selecting an architecture. Rocketdyne did not determine system architecture life cycle cost due to the limited nature of the study.

Power system requirements were defined based on the Rocketdyne Task Order 10 (Commonality Subtask) study (Ref. 1). Power system concepts with high commonality (applicable for both lunar and Mars missions) were selected as a result of screening criteria. These power systems included closed Brayton cycle (CBC) dynamic isotope power systems (DIPS), Proton Exchanger Membrane (PEM) regenerative fuel cells (RFC), sodium-sulfur (NaS) batteries, gallium arsenide on a germanium substrate/copper indium diselenide (GaAs-Ge/CIS) photovoltaic (PV) array with PEM RFCs or NaS batteries, Driver Fuel In-core thermionic fuel element (TFE) and SP-100 thermoelectric (TE) reactor systems.

Design influencing factors (primarily environmental) were identified for specific power systems and for Mars power systems in general. A preliminary mass and radiator area tradeoff study was done to compare the reactor concepts. The impact of design concepts which protected the reactors (vacuum enclosure or lower temperature operation to eliminate the use of refractory materials) from the Martian environment were evaluated. The TI reactor concept had a somewhat lower mass for many cases. The SP-100 thermoelectric power system is also a viable option for Mars applications. Modification of SP-100 for Mars (either enclosure or low temperature operation) will be studied in a large General Electric study to be funded by NASA. Additional studies are required to determine the optimum reactor concept for Mars applications.

Each power system concept was characterized for applicable missions on the basis of preliminary design studies. Power system requirements were defined in an earlier Rocketdyne

study for NASA-Lewis (Ref. 1). The results are summarized in Table 1. It should be noted that not all power systems can be used for all the applications. For most cases, either a DIPS or reactor power system resulted in the lowest mass, volume, and area. Modular 2.5 kWe DIPS were assumed in this study. Sodium sulfur batteries were assumed for DIPS peaking power. These assumptions resulted in the Payload Unloader power system having a higher mass than the Unpressurized Rover power system for DIPS.

Other study subtasks included examination of emplacement/deployment requirements for power systems, maintenance/servicing requirements, and operations concepts (startup and shutdown).

Example power system architectures were defined which provided high commonality. These architectures included the following: (1)predominantly PV/NaS batteries; (2)predominantly PV/PEM RFC; (3)CBC DIPS and SP-100 TE reactor; and (4)CBC DIPS and Driver Fuel In-core TFE reactor. The reactor architectures had total masses which were a factor of two lower than those for the PV system architectures, as seen in Table 2. Thus, high commonality does not always result in low architecture mass.

System/subsystem technology maturity levels were assessed for each screened concept. Technology development roadmaps were prepared for each candidate power system (see appendices). Concept development times and schedules were determined. Results of this effort are summarized in Table 3.

An example of an integrated development plan (schedule) was completed for the DIPS and TI reactor architecture to determine the overall development strategy in this case. Development and deployment schedules were developed to determine the time phasing strategies required for meeting the mission requirements.

TABLE 1. - POWER SYSTEM MASS STUDY RESULTS

Application	DIPS*	RFC**	NaS Batteries**	PV/RFC	PV/NaS Batteries	SP-100 TE Reactor	Driver Fuel In-core TFE Reactor
M1 - Communications (0.9 kWe)	352			303	310		
M2 - Surface Power (25 kWe)	3,520			7,401	8,617	3,210	2,680
M3 - Emergency Power (12 kWe)	1,760			3,679	4,138		
M4 - MEV Servicer (10 kWe)	1,408			3,119	3,448		
M5 - Surface Power (75 kWe)				23,228	25,864	4,960	4,125
M6 - Unpress. Rover (5 kWe)	704						
M7 - Payload Unloader (3/10 kWe)	779	1,076	886				
M8 - Teleoperated Rover (0.15/1.5 kWe)	352						
M9 - Pres. Rover (onboard power-7 kWe)	1,056	1,568	1,599				
M9 - Pres. Rover (cart power:5-12 kWe)	779 (5 kWe)	3,882 (12 kWe)	11,540 (12 kWe)				
M10 - Regolith Hauler (3/15/1.5 kWe)	1,056	1,009	991				
M11 - Mining Excavator (22/40/10 kWe)	3,711	4,912	5,081				

*Includes NaS battery for peaking power.
**Includes base PV system growth mass penalty.

TABLE 2. - POWER SYSTEM ARCHITECTURE MASS COMPARISON

Architecture	Mass (kg)*
1-Highly PV/NaS battery	85,972
2-Highly PV/RFC	69,449
3-DIPS and SP-100 reactor	31,461
4-DIPS and TI reactor	29,036

*No replacement systems included.

TABLE 3. - POWER SYSTEM ESTIMATED DEVELOPMENT TIMES

Power System	Estimated Development Times (yrs)*
CBC DIPS	6
PEM RFC	6.75**
NaS battery	7
GaAs-Ge/CIS PV array/PEM RFC	6.75**
GaAs-Ge/CIS PV array/NaS battery	7
Driver Fuel In-core TFE reactor	7.5
SP-100 TE reactor	13.5

*To launch; assumes no prior/parallel development.
**Additional time for demonstration of component life may be required.

Specific outputs from this study include power system requirements, screened power system candidates, power system applicability, power system characteristics, potential maintenance needs, startup/shutdown procedures, technology development plans, high commonality power system architectures, architecture masses, integrated development plans, and deployment schedules.

2.0 INTRODUCTION

The general scope of this task was to define various power system concepts including: generation, conversion, storage, thermal management, and power conditioning of the electric power, capable of supporting manned Mars surface missions. It is currently envisioned (Ref. 2) that manned Mars missions could begin taking place in the 2010-2016 time frame. A scenario for such a Mars program includes two phases: the Expedition Phase and then the Emplacement Phase. Possibly three expeditions to different locations would occur with a crew of four to six, lander habitat, and ancillaries to support 30-90 day stay times. The Mars outpost could evolve similar to that of the lunar outpost which includes these major elements: habitat, power production and distribution, in-situ resource utilization facility, construction and mining vehicles, pressurized and unpressurized crew transport, science packages, and communication system eventually supporting crew stay times of a full Martian year.

The power requirements used in this task were those generated for the 90 Day Study, November 1989 (Refs. 3-5). NASA's 90 Day Lunar/Mars Study, defined reference mission scenarios as well as reference power systems for each application. NASA and the Synthesis Group are investigating various approaches to developing power systems to meet humankind's renewed effort to explore and eventually colonize the Moon and Mars. Of key interest is the reduction in the rather significant costs of this effort. The life cycle cost, including development, transportation, and operating costs, must be minimized if this ambitious endeavor is to be realized. In order to achieve this goal, it is necessary to evaluate different development approaches. Power system mass is one criterion which must be evaluated in order for the optimum power systems to be developed. Minimizing power system mass will reduce the Mars transportation costs. NASA also needs to have an integrated approach to power system development to minimize development effort and costs. Deployment, startup/shutdown, and maintenance/servicing procedures need to be designed to minimize risk to personnel and to insure power system availability prior to launch of piloted missions.

3.0 TECHNICAL DISCUSSION

The technical discussion includes sections on the study groundrules, power system requirements, concept selection, influencing factors on power system design, concept characteristics, deployment approach, startup and shutdown, maintenance/servicing requirements, technology development plans/schedules, integrated development strategies, and time phasing strategies.

3.1 GROUNDRULES

The term "architecture" was used in this study to refer to a specific set of power systems (one concept for each application) which met all of the application scenario requirements. Power system concepts were evaluated primarily at the system and subsystem level. Key subsystems included the energy source, power conversion unit (PCU), energy storage, heat rejection, and power processing and control (PP&C). Only certain subsystem technologies were considered as a result of a prior screening study (Ref. 1). Technologies were selected which are currently under development or which have the potential for high commonality.

Examples of potential power system architectures were compared. These architectures were based primarily on commonality ratings (Ref. 1). Optimization studies of these architectures were not conducted.

Study results are based on the following assumptions:

- the impact of recharging mobile systems on the base power system mass was included;

- the impacts of the charging time on the electrolyzer and radiator masses were included;

- the effect of power system mass on vehicle power requirements or speed was neglected;

- systems were designed to provide both nominal and peak power, if applicable (DIPS uses NaS battery for peak power; PEM RFC designed to work at off-design conditions);

- startup power provided by lander or existing systems;

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- no redundancy included (depends on life requirements, reliability requirements, and design approach);

- no replacement systems were included (all systems treated equally);

- power distribution was not considered (application and power system dependent; see Ref. 6 for discussions of power distribution systems); and

- reactors are buried to satisfy personnel shielding requirements (for system mass calculations).

Additional assumptions used for the characterization studies are summarized in Tables 4-7. Table 4 summarizes key Mars environmental assumptions. Table 5 summarizes design and performance assumptions for PV systems. Table 6 summarizes DIPS assumptions. Table 7 summarizes assumptions for TI reactor systems.

TABLE 4. - MARS ENVIRONMENTAL ASSUMPTIONS (Refs. 17 & 25)

Parameter	Value
Surface insolation (integrated energy input over day), kW-h/sq m/day	1.1*
Maximum radiator sink temperature, °K (absorptivity=0.22, 420 °K radiator temperature)	249 (vertical without cover) 184 (vertical with cover) 172 (horizontal)
Air temperature range, °K	165-237
Wind velocity, m/s	2-7 (Viking sites); 15-50 for local dust storms; 10 for global dust storms
Gravity, g's	1/3
Atmosphere composition	95.32% CO_2, 2.7% N2, 1.6% Ar, etc.
Earth-Mars opposition distance, km	5.6×10^7 to 10.1×10^7

*Minimum value used based on worst aerocentric longitude day and global dust storm effects (Ref. 8).

TABLE 5. - PV SYSTEM ASSUMPTIONS

Parameter	Value
PP&C Subsystem:	
•PP&C, kg/kWe	7.5
•Array to bus transmission efficiency, %	97
•Bus to energy storage unit transmission efficiency, %	99.5
•Voltage regulator efficiency, %	95
•Diode efficiency, %	99
Thermal Management Subsystem:	
•Radiator type	C-C heat pipe
•Radiator mass, kg/m^2	2.8-4.3
•Radiator orientation	vertical
Energy Storage Subsystem:	
•NaS battery technology level	nearterm
•Output voltage, V	120
•Battery charging voltage, V	170
•Battery depth of discharge, %	80
•Battery roundtrip efficiency (w/o PP&C), %	70.4
•RFC and battery life, yrs	5 *
PV Array Subsystem:	
•Orientation	horizontal, non-tracking
•Cell temperature, °K	300
•Cover glass thickness, mm	0.025
•Cell efficiency, %	20.6
•Array efficiency, %	16.5
•Packing factor, %	80
•Blanket specific mass, kg/sq m	0.633
•Structure specific mass, kg/sq m	0.1
•Net specific output power, W/sq m	11.75
•Specific mass (array+structure), kg/kWe	62.4

*2.5 years for fuel cell and electrolysis cell stacks

TABLE 6. - DIPS DESIGN ASSUMPTIONS

Parameter	Value
•Module power level, kWe	2.5
•Peak PCU temperature, °K	1133
•Peak PCU pressure, N/sq m	5.3×10^8
•Net efficiency, %	21.6
•Minimum energy storage (for startup), kW-hr	3
•Aluminum tube and sheet (pumped loop) radiator mass, kg/sq m	7.3

TABLE 7. - TYPICAL THERMIONIC REACTOR POWER SYSTEM DESIGN ASSUMPTIONS

Parameter	Value or Description
Performance:	
Nominal Power	40 kWe EOL; scalability between 10 and 100 kWe
Lifetime	10 yr
Packaging	Titan IV/Centaur payload fairing with a 7 m long x 4.5 m diameter payload; evaluate 13 m long payload
Separation distance	5 m to 15 m
Mass	Minimum consistent with requirements
Payload Interactions:	
Dose plane	4.5 circular diameter
Neutron dose	10^{14}-10^{15} nvt (1 MeV equivalent)
Gamma dose	10^6-10^7 Rad (Si)
Thermal flux	0.14 W/cm^2
Startup and Shutdown:	
Startup time	24 h; evaluate impact of 15 min startup
No. startup/shutdowns	At least 10
Reliability:	95% for 10 yr
Environment	Natural space-debris, meteorites, thermal cycles, Van Allen belts, cosmic, reactor induced radiation
Single point failures	Identify and determine system impact
Safety	Subcritical under all credible launch accident scenarios; pass INSRP review
Testability	
Qualification/Acceptance launch environment	Identify test program to meet MIL-STD-1540B Titan IV/Centaur launch vehicle

3.2 REQUIREMENTS DEFINITION

The first step was to identify the activities requiring separate power supplies. Once these activities were identified, then power system requirements were determined. This information was taken from the Rocketdyne Power System Commonality Study (Ref. 1). Table 8 lists the Mars power system applications and their requirements. Eight-hour work shifts were assumed for human operated vehicles.

Mars power requirements spanned a range from 0.9 to 75 kWe. The portable system power requirements were assumed to be the same for both lunar and Mars applications (i.e., gravity differences were not factored into this study). Base and some portable system energy storage requirements were greatly reduced for Mars applications due to the shorter night time period (12 hours versus 354 hours).

The bases and exploration sites were assumed to be near the equator. Thus, the day and night times were assumed to be equal. Recharge times for energy storage systems are shown in Table 9. A recharging time of 12.3 hours was assumed for the fixed RFCs using non-tracking PV arrays. PV arrays were sized based on the integrated energy input over the daylight hours. In actual practice, there will no power input to the electrolyzer for sun angles of less than 30 degrees or greater than 150 degrees. The average powers to the electrolyzer will be higher in practice than assumed in this study but the impact on the PV/RFC system mass will be small.

Duty cycles for portable applications were based primarily on previous NASA studies (Refs. 3, 4, and 7). Portable vehicle energy storage systems are assumed to be recharged by the base power system. A short recharge time of 2 hours (Ref. 3) was originally selected for the pressurized rovers to provide the crew "safe haven" in the event of a habitat failure. However, the power system mass studies showed that a 2-hour recharge time would be an excessive mass penalty (large radiator) for PEM RFC power systems and an excessive increase in the base power system. Figure 1 shows the effect of charge time on the rover mass (including the increase in base power). To reduce the recharging power to a more reasonable level, the recharge time for the pressurized rovers was assumed to equal the on time of 8 hours.

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If the rover power system is discharged at the time when the crew needs a safe haven, then the emergency power system can provide power to the pressurized rover. An equal discharge and recharge time is also assumed for the portable power systems which do not operate continuously (i.e., payload unloader, regolith hauler, and mining excavator). This analysis only holds true for rovers powered by energy storage. Other systems like DIPS could have different operating regimes.

TABLE 8. - MARS APPLICATIONS AND POWER SYSTEM REQUIREMENTS

Appli-cation No.	Description	Miss-ion Phase *	IOC	Life (yrs)	Power - Nominal/ Peak/ Standby (kWe)	Time - Nom./ Peak/ Stand-by (hrs)**	Oper-ating Time	No. of Units ***
FIXED POWER:								
M1	Communications	EX	2016, 2018, 2020	15	0.9		D/N	3
M2	Base Power	EX	2016, 2018, 2020	15	25		D/N	3
M3	Emergency Power	EMP	2022	15	12		D/N	1
M4	MEV Servicer	EMP	2022	15	10		D/N	1
M5	Base Power	EMP	2022	15	75		D/N	1
MOBILE POWER:								
M6	Unpress. Rover with Power Cart	EXP	2016, 2018, 2020	4	5+	24.65	D/N	5
M7	Payload Unloader	EMP	2022	15	3/10	7/1	D	3
M8	Telerobotic Rover	CON	2024	15	0.15/1.5	24.42/0.23	D/N	1
M9	Pressurized Rover, Power Cart for Rover	CON	2026	15 15	7 12++	8 96	D/N D/N	1 1
M10	Regolith Hauler	OP	2030	15	3/15/1.5	5.6/1/1.4	D	1
M11	Mining Excavator	OP	2030	15	22/40/10	5.6/1/1.4	D	1

NA - information not available. D=day, N=night.
*EXP=Exploration Phase, EMP=Emplacement Phase, CON=Consolidation Phase, OP=Operations Phase.
**24 hour cycle for mobile power systems except for M11.
***Does not include replacement units which may be required for power systems not meeting the life requirement.
+Actual rover requirements are 2(nominal)/3(peak)/0.3(standby) kWe. A requirement of 5 kWe was selected by NASA (Ref. 3) to provide night habitat power prior to delivery of main base power system and also recharging for payload unloader.
++Cart power. Can be 5 kWe if isotope power system used for onboard power.

TABLE 9. - MARS PEM RFC POWER SYSTEM RECHARGING REQUIREMENTS

Application No.	Description	Recharge Time (hrs)	Bus Power To Electrolyzer (kWe)
	FIXED POWER:		
M1	Communications	12.3	2.2
M2	Base Power	12.3	63.
M3	Emergency Power	12.3	31.6
M4	MEV Servicer	12.3	26.5
M5	Base Power	12.3	200.5
	MOBILE POWER:		
M6	Unpressurized Rover with Power Cart	NA	NA
M7	Payload Unloader	8	9.8
M8	Telerobotic Rover	NA	NA
M9	Pressurized Rover,	8	17.5
	Power Cart for Press. Rover	96	28.0
M10	Regolith Hauler	8	10.2
M11	Mining Excavator	8	55.5

NA=not applicable to energy storage systems due to excessive mass.
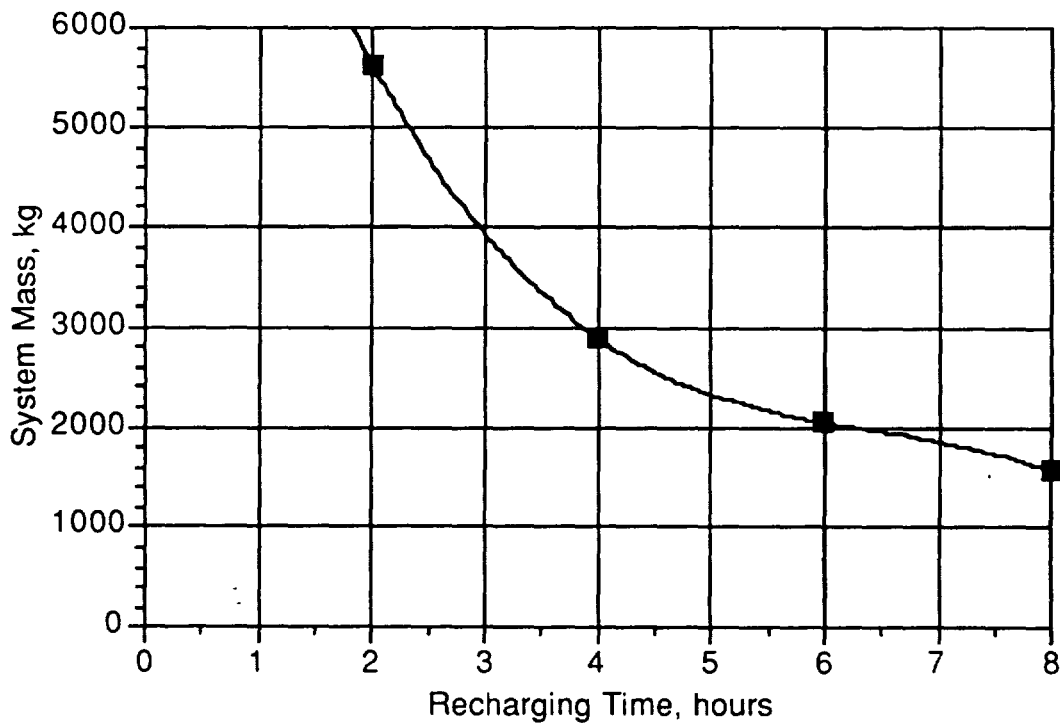
Figure 1. - Effect of recharging time on pressurized rover system mass.

3.3 CONCEPT SELECTION

Potential planetary surface power system concepts were previously identified in the Commonality Study (Ref. 1). This was not an all inclusive study of the possible technologies available. For example, there are many other types of PV cells and nuclear reactors which could be utilized. However, to limit the scope of the current study, example systems for each major type were selected. These concepts and their major subsystems are listed in Table 10. The subsystem types included PEM RFCs, batteries (sodium sulfur and nickel hydrogen), tandem cell PV arrays (GaAs-Ge/CIS), plutonium isotope heat sources, liquid metal cooled reactor (LMCR) or Driver Fuel In-core TFE reactors, thermoelectrics, Brayton cycle power conversion units (PCUs), Stirling Cycle (SC) PCUs, and radiators (conduction, heat pipe, and tube-and-fin).

TABLE 10. - POTENTIAL PLANETARY SURFACE POWER SYSTEM CONCEPTS

Source	Power Converter	Energy Storage Unit	Radiator
Sun	Ga As-Ge/CIS PV	PEM RFC	Heat pipe
Sun	Ga As-Ge/CIS PV	NiH$_2$ Battery	Heat pipe
Sun	Ga As-Ge/CIS PV	NaS Battery	Heat pipe
Sun	Ga As-Ge/CIS PV	Flywheel/PMG	Heat pipe
Concentrator/Receiver	CBC	PEM RFC	Heat pipe
Concentrator/Receiver	Stirling	PEM RFC	Heat pipe
Isotope	CBC		Tube-and-fin
Isotope	Stirling		Heat pipe
Isotope	AMTEC		Heat pipe
LMCR	Thermoelectric		Heat pipe
LMCR	Stirling		Heat pipe
LMCR	CBC		Heat pipe
LMCR	AMTEC		Heat pipe
Thermionic Reactor	Thermionics		Heat pipe
		PEM RFC	Heat pipe
		NiH$_2$ Battery	Heat pipe
		NaS Battery	Heat pipe
		Flywheel/PMG	Heat pipe
Isotope	Thermoelectric		Conduction

However, not all of the systems identified in Table 10 are suitable or desirable for use on Mars. Various screening criteria (both quantitative and qualitative) were applied in the Commonality Study (Ref. 1) to select systems specifically for Mars applications. Screening criteria included applicability (to the environment and mission requirements), commonality, and mass (for storage subsystem comparisons). Table 11 shows the screened Mars power system concepts.

TABLE 11. - SCREENED MARS POWER SYSTEM CONCEPTS

Mobile/Portable:
    PEM RFC
    NaS battery
    CBC DIPS
Fixed:
    CBC DIPS
    GaAs-Ge/CIS PV array/PEM RFC
    GaAs-Ge/CIS PV array/NaS battery
    SP-100 reactor/TE PCU
    SP-100 reactor/CBC PCU
    Driver Fuel In-Core TFE reactor

The AMTEC power systems are currently the least developed and thus are not expected to be available for early or midterm lunar applications. This resulted in a low commonality rating for these systems. These systems also have a high development risk. AMTEC systems generally would apply to low power levels and most likely would be a replacement for RTG systems. The only applicable SEI system identified for AMTEC would be the teleoperated Mars rover.

The best developed, lowest risk systems are the PV/NiH$_2$ battery, NiH$_2$ battery (alone), PEM RFC (alone), and CBC DIPS power systems. Thus, these systems have good availability and commonality ratings (Ref. 1). The NiH$_2$ battery systems were screened out because of excessive mass compared to NaS battery (4 times higher mass) and RFC systems (8 times higher mass).

Flywheel energy storage systems were screened out because of higher mass than NaS batteries or RFCs.

SC DIPS (1050 °K system) also had a high commonality rating (somewhat lower than the CBC DIPS system). However, the DIPS program has already selected a CBC PCU based on earlier availability and lower risk.

Solar dynamic systems which collect and concentrate light energy, will not work very well on Mars since the solar energy is scattered rather than direct. During global dust storms, the solar energy becomes totally scattered light. Thus, solar dynamic systems are not practical for Mars applications. Concentrators for photovoltaic systems offer no benefit on Mars for the same reason.

The refractory metal, LMCR system (SP-100 TE) is tentatively assumed to be applicable, but only if protected from the Mars environment. Additional reactor studies are needed to determine what type of enclosure or protection method is practical. General Electric (GE) will be performing a major study to determine what modifications are required to operate the SP-100 TE on Mars.

The lower temperature LMCR-CBC system (Rocketdyne SNAPDYNE) is applicable to Mars, but has a significantly higher mass and larger radiator area than the SP-100 TE or thermionic systems.

Practical power ranges for the screened Mars power systems are listed in Table 12. The nuclear reactor and PV/PEM RFC systems have a wide module power range. However, the PV systems are much more massive and have a larger deployed area requirement than nuclear systems, as will be seen in Section 3.5. The photovoltaic system upper power limits are based on mass and surface area considerations (i.e., transportation cost, and installation time and practicality).

TABLE 12. - SCREENED MARS POWER SYSTEM POWER RANGES

Description	System Power Range* (kWe)	Tentative Module Power (kWe)
GaAs-Ge/CIS PV array/PEM PEM RFC	≤50	2/25**
GaAs-Ge/CIS PV array/NaS Battery	≤50	2/25**
CBC DIPS	≤25	2.5
SP-100 Reactor/TE PCU	≥25	100
SP-100 Reactor/CBC PCU	≥25	100***
Driver Fuel In-Core TFE Reactor	≥25	100
PEM RFC	≤25	2.5
NaS Battery	≤25	2.5

*Approximate values given; the upper limits depend on environment and application (fixed or mobile).
**PV array module (minimum day insolation)/energy storage module sizes.
***Sized for 550 kWe but run at reduced power for longer life.

Each planetary activity was assigned an availability requirement based on the earliest IOC date. A Mars power system applicability matrix, Figure 2, was then defined by comparing power system requirements with power system capabilities. Applicable power systems are indicated by a √ mark.

It was assumed that there would be no reactors on vehicles or near manned areas (habitat, lander, science, in-situ resource utilization). Non-reactor power sources or distribution of power from a remote reactor power system were assumed for these applications.

Only remote or portable power systems were assigned to the communications and lander areas. This meant the use of PV or isotope systems for these areas.

It was assumed that PV arrays would not be used on the portable applications (≥ 0.5 kWe) due to the large area required (energy storage assumed to be recharged by fixed power systems or portable isotope systems). It is assumed that all portable vehicles either will be used near the base, will return to the base for recharging, or will use an isotope system. Only isotope power systems are suitable for the rovers which have very long ranges.

Power System	Fixed Applications					Mobile Applications					
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11
Power (kWe) - - >	0.9	25	5	10	75	2	5	0.15	7, 12	3	22
GaAs-Ge/CIS PV array/PEM RFC	√	√	√	√	√						
GaAs-Ge/CIS PV array/NaS battery	√	√	√	√	√						
Isotope/CBC	√	√	√	√		√	√	√	√	√	√
SP-100 reactor/TE PCU		√			√						
SP-100 reactor/CBC PCU		√			√						
Driver Fuel In-Core TFE reactor		√			√						
PEM RFC							√		√	√	√
NaS battery							√		√	√	√

Figure 2. Screened Mars power system applicability matrix.

3.4 INFLUENCING FACTORS

A preliminary study of environmental and other system design impacts was completed. The purposes of this study were the following:

- determine the compatibility of power systems to the Mars environment; and

- determine the environmental impacts on power system design criteria.

Key influencing factors on power system design included atmospheric conditions (composition, dust storms), available daytime for recharging energy storage systems), and the type of system (deployment time, recharging requirements, commonality).

3.4.1 Reactor System Influencing Factors

The Martian atmosphere is composed primarily of carbon dioxide. Carbon dioxide will cause corrosion of exposed components made of refractory metals. Refractory metals are required for high temperature power systems (SP-100 reactors and isotope heat sources). Two options were briefly examined for resolving this environmental impact: (1)protection of the materials from the atmosphere; or (2)operation at a lower temperature and use of stainless steel which is compatible with carbon dioxide. Material protection options include coatings and a vacuum enclosure. Coatings may not remain totally protective for long duration high temperature operation. The vacuum enclosure is a viable solution, but issues of increased mass to meet fail safe/fail operational requirements must be considered.

There will be mass penalties for the reduced temperature option (for example, using the 922 °K SNAPDYNE systems) as seen in Figure 3. The stainless steel power conversion system efficiency is reduced and the radiator size is increased due to the lower temperatures. This factor significantly increases power system mass for lower temperature systems compared to the 1300 °K or higher power systems. The Driver Fuel In-core TFE reactor system does not have any refractory metals which are exposed to the environment by its inherent design, and thus rejects heat at a high temperature. The radiator mass is much less than for the other low

temperature radiator systems. Thus, the mass of the Driver Fuel In-core TFE reactor system is lower than other nuclear power system concepts.
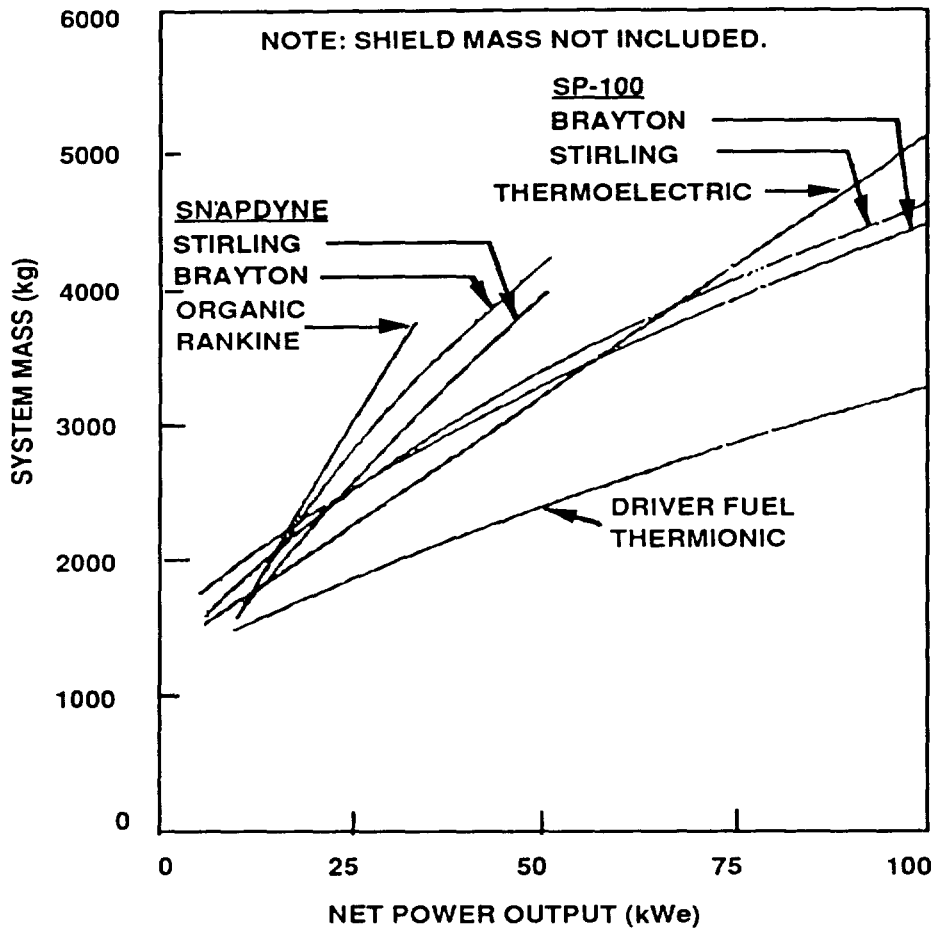
Figure 3. - Mars reactor power system mass comparison.

3.4.2 Isotope System Influencing Factors

Isotope power systems can be easily adapted for the Martian environment. The approaches are either to (1)run at reduced temperature so that super alloys can be used or (2)use an extra enclosure for the fluid loop from the heat source heat exchanger to the engine. The first approach is likely to be developed anyway for nearterm and midterm applications. However, the mass and radiator size of the higher temperature systems would be less. Again, there is the potential for single point failure with the second approach with no redundancy.

3.4.3 PV System Influences

The major impacts on the PV system design are listed in Table 13. These factors reduce the system efficiency and increase the array size required. The input energy to the cell depends on the amount of obscuration presented by the atmosphere. The system losses and wiring mass are dependent on the size of the installation.

TABLE 13. - PHOTOVOLTAIC ARRAY DESIGN IMPACTS

Parameter	Design Values
•System Impacts	
•Wiring & Harness Efficiency	0.97*
•Cell Circuit Efficiency-	
Isc, Imp	0.98*
Voc, Vmp	0.98*
•Packing factor	0.80*
•Environmental Impacts	
•Thermal Cycling	0.97*
•UV	0.98*
•Dust Obscuration	0.90*
•Wind and Gravity Loading	0.1 kg/m^2 (structure)
•Charge/Discharge Time (hrs)	8/16

* Efficiency fractions which are multiplied times the surface insolation to determine effective energy input to the array.

Two important impacts on PV systems are the relatively short night time and the reduced solar insolation compared to the Moon, and Mar's atmospheric conditions: dust and wind. This results in smaller energy storage requirements and larger array sizes for Mars applications than for lunar applications. The impact of global dust storms is also very important since they can last for several months. During a global dust storm the opacity of the dust cloud may reach an optical depth of 5 (Ref. 17). Global dust storms occur on an almost annual basis (Ref. 18). In addition, there are numerous local and regional dust storms that affect some areas. During these local storms the opacity of the atmosphere can increase to an optical depth of greater than 3, cutting off more than 85% of the light to the surface. The ambient atmospheric dust particles also have a major impact on the direct solar energy available to the PV array (average optical depth of 2) even when there are no wind storms.

Dust is pervasive in the Martian environment. An equilibrium concentration of dust will form on surfaces which varies with wind velocity, suspended dust, and surface angle (Ref. 24). Collection of dust on arrays will cause reduced power production due to reduced transmittance of the coverslip. Reduction in the transmittance is due to abrasion and occlusion. The amount of degradation depends on the wind velocity, angle of attack, and whether the arrays are initially coated with dust or not. It has been found that a thin layer of dust will provide effective dust erosion protection. In testing by NASA Lewis, initially clear samples of SiO_2 coverslips had less than 5% degradation for zero angle of attack (horizontal) and 8-12% degradation for an angle of 22.5 degrees. Degradation in transmittance was increasingly worse with increasing angle of attack for initially clear samples. On the other hand, samples that were initially coated with a thin layer of dust had the lowest degradation in transmittance at about 22.5 degrees (3-18%). The degradation for an initially coated sample at 0 degrees ranged from 6 to 30%. The arrays were assumed to be horizontal and non-tracking in the current study. A coverslip transmittance efficiency of 90% (dust obscuration factor in Table 13) was assumed in the PV sizing studies.

The minimum day insolation (including global storm obscuration) was used to size the PV power systems. This results in very large PV arrays but minimizes system mass (compared to the approach of using a larger energy storage subsystem and smaller arrays).

Another impact of the low insolation (from 50% to 100% diffuse light) on Mars is that the arrays probably do not have to track the sun (a longer charge time is seen with tracking arrays particularly at an optical depth $\leq$ 2). This simplifies the array design, reduces array mass, and improves reliability (no moving parts). If a mission is short and planned during times that global and regional storms are not expected to occur, then either a tracking array or a tent type array with an angle of 60 degrees to horizontal (Ref. 23) would be optimum (i.e., constant power profile based on only direct solar input).

3.4.4 General Influencing Factors

The Martian atmosphere has a high degree of particulates (dust) due to almost continual local storms. Dust will collect on horizontal radiators and will reduce component performance unless removed. In order to minimize dust collection and effective heat sink temperature (or radiator area), all the radiators were assumed to be vertical (edge on to prevailing wind direction out of the west). Dust movement may also cause contamination of piping systems during assembly. Thus, the atmospheric factors will require seals and/or housings to shield against corrosion and dust (loose piping before assembly or during servicing). In addition, the high velocity winds (50 m/s or 112 mph) that sometimes occur will cause particle abrasion on exposed materials as noted in the previous section. This abrasion will have to be considered in the power system design.

The Martian winds and gravity increase structure mass required over that for lunar systems. In addition, the winds reduce the stability of mobile vehicles with large surfaces (i.e., radiators).

The distance of Mars from the Earth causes a major delay in electrical signal transmission (10 to 20 minutes each way). Power systems will be deployed and tested prior to arrival of human crews to insure proper operation. This approach requires staggering of cargo and crew flights, probably sent on the next opportunity, to insure sufficient time to deploy systems prior to the piloted launches.

Reactor systems which must be buried (to minimize shield mass transported from the Earth) and large PV systems (much larger than lunar systems due to reduced energy input) will take significant time for deployment, especially using robotic equipment. However, it may be of value to employ a shield from Earth, particularly on the first reactor systems sent.

Idle time after deployment may require significant restart time and checkout once the crew has landed. A standby operating mode may be preferred. The idle time may also result in maintenance being required as a result of dust contamination (i.e., horizontal radiators, arrays, or sensors).

Both the amount of day time and the duty cycle affect the required charging times for energy storage systems. Charging time has a significant impact on the base power requirements as was discussed in Section 3.2.

3.5 CONCEPT CHARACTERISTICS

The next phase of the study involved characterization of all the screened power systems for each applicable power level. This included studies of CBC DIPS, PEM RFC, and NaS battery power systems for mobile/portable applications. Fixed systems included CBC DIPS, GaAs-Ge/CIS PV array/PEM RFC, PV/NaS battery, SP-100 TE reactor, and Driver Fuel In-core TFE reactor concepts. The concepts are described in detail in the technology roadmaps included as appendices. The results of the preliminary design study will be discussed in the following sections.

3.5.1 CBC-DIPS Characteristics

The DIPS, as seen in Appendix A, uses the decay of radioactive plutonium 238 as the source of heat (General Purpose Heat Source or GPHS) and a CBC PCU to convert this heat to electrical power. The DIPS cycle diagram is illustrated in Figure 4. The CBC uses an inert gas working fluid (helium-xenon mixture) which is heated by the radioactive heat source and then expanded through a turbine to convert heat energy to mechanical energy. From the turbine, the working fluid passes through a recuperator to recover heat and improve cycle efficiency. The waste heat from the cycle is then rejected through a gas tube and fin (or pumped loop) radiator assembly. From the radiator, the working fluid is compressed to the peak cycle pressure and then used to cool the alternator. The working fluid again passes through the recuperator before returning to the heat source.

This system uses a relatively low temperature heat engine for converting thermal to mechanical energy. The peak cycle temperature is limited to 1133 °K to insure that the gas containment boundary is totally constructed of nonrefractory materials. A 2.5 kWe module size

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was chosen as the optimum module size on the basis of trade studies done during the DIPS program (DOE Contract DE-AC03-88NE32129) based on a review of potential planetary surface applications. This trade study evaluated various cycle design options, turbine inlet temperature effects, technology readiness levels, development time, as well as overall power system costs, including delivery and support on the Moon and Mars. The 2.5 kWe power module approach had overall cost, schedule and technical advantages over application specific designs.
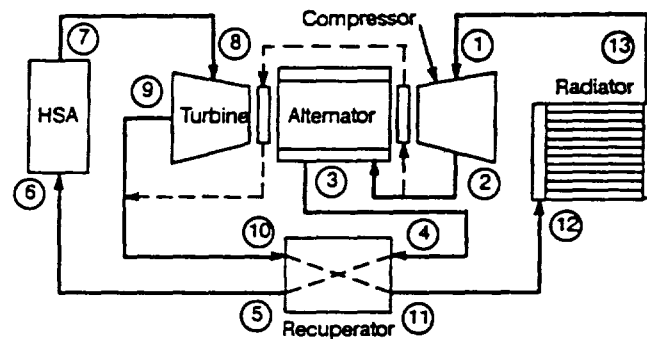
No.	Stream	Temperature (K)	Pressure (kPa)	Flow (kg/s)
1	Compressor inlet	360.83	321.50	0.2007
2	Compressor discharge	469.23	538.55	0.2007
3	Alternator discharge	475.39	538.55	0.1987
4	HP recuperator inlet	475.39	536.69	0.1987
5	HP recuperator outlet	929.87	534.97	0.1987
6	HSA inlet	926.52	533.86	0.1987
7	HSA outlet	1136.67	531.59	0.1987
8	Turbine inlet	1133.31	530.49	0.1987
9	Turbine outlet	960.97	327.78	0.1987
10	LP recuperator inlet	953.79	327.16	0.2008
11	LP recuperator outlet	503.90	325.57	0.2008
12	Radiator inlet	503.90	324.88	0.2008
13	Radiator outlet	360.83	322.81	0.2008

6496-8

Figure 4. - CBC DIPS cycle diagram.

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Pertinent performance characteristics for a 2.5 kWe DIPS power module are presented in Table 14. It can be noted that the peak cycle pressure is only 5.38×10^7 N/m^2 (78 psia).

TABLE 14. - 2.5 kWe CBC DIPS MODULE CHARACTERISTICS

Net power (kWe)	2.5
Thermal power* (kWt)	11.6
Number of Heat Source Units (HSU)	3
Number of GPHS modules per HSU	17
Turbine inlet temperature (°K)	1,133
Compressor inlet temperature (°K)	361
Peak cycle pressure (N/m^2) (psia)	5.38×10^5 (78)
Mass flowrate* (kg/s)	0.20
Net efficiency* (%)	21.6
Net battery energy storage**, kW-h	3
Main radiator area (m^2)	7.14
Electronics radiator area (m^2)	0.9

*End-of-mission (EOM).
**Minimum value required for startup. Additional energy storage was added to meet peak power requirements for mobile systems.

Figure 5 shows a conceptual layout of the system. The heat source units (HSUs) are located under the radiators and include fuel handling canisters that contain multiple General Purpose Heat Source (GPHS) modules. The HSUs contain a reversible heat removal system (RHRS) that allows the radioisotope heat to be dissipated to space in the event the power conversion cycle is not operating.

Table 15 gives a subsystem mass breakdown for the 2.5 kWe power module. Table 16 presents system mass estimates for each applicable mission levels using 2.5 kWe modules. A sodium sulfur battery is used to supply startup and peaking power. The system efficiency (EOM) is 21.6% for a turbine inlet temperature of 1133 °K.
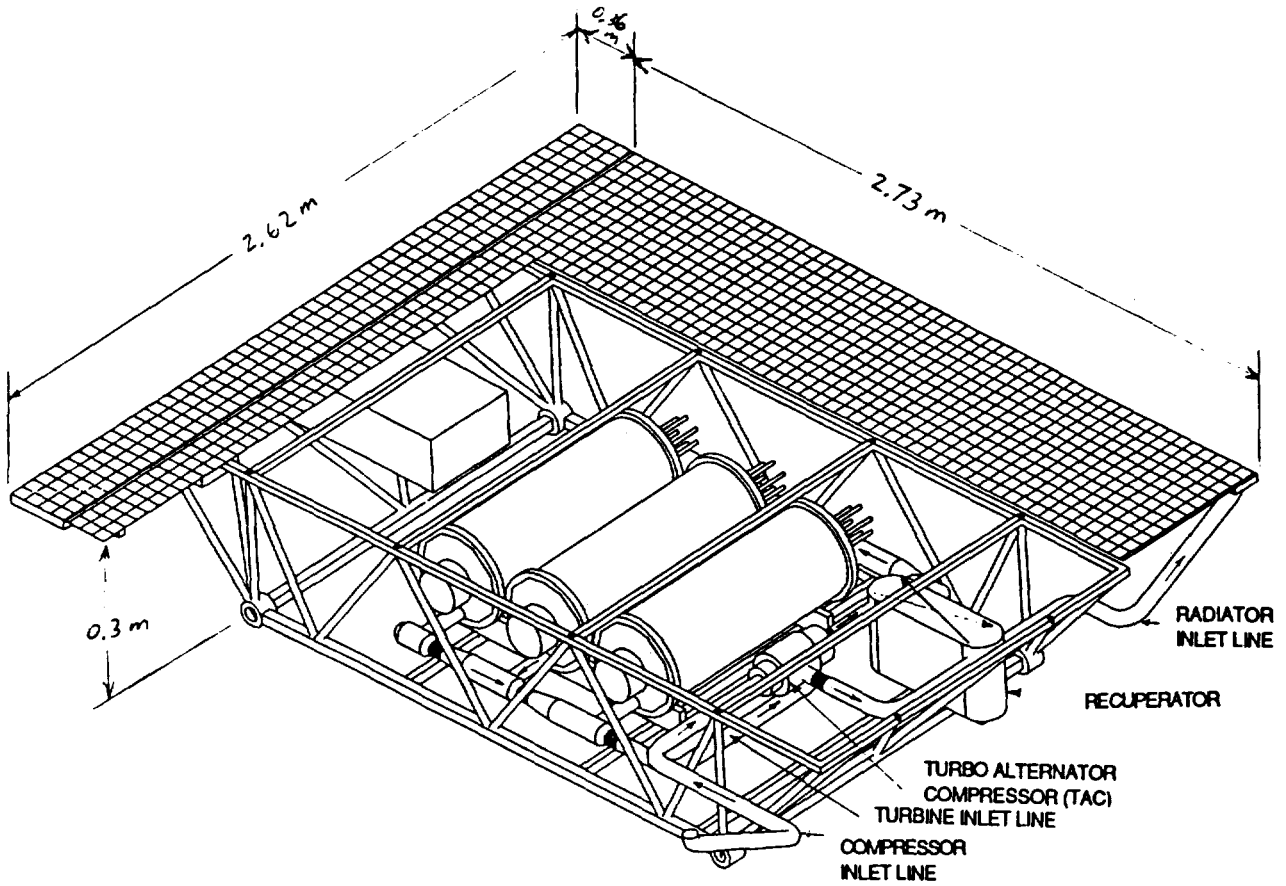
Figure 5. - Conceptual layout of 2.5 kWe CBC DIPS.

TABLE 15. - 2.5 kWe CBC DIPS SUBSYSTEM MASS BREAKDOWN

Subsystem or Assembly	Mass (kg)
HSA	144
TAC	16
Recuperator	47
Radiator	59
Ducting & Bellows	13
PP&C	72
Total	352

Table 16. - CHARACTERISTICS FOR 2.5 KWE MODULAR CBC DIPS SYSTEMS

Application Number	Required Power Level (kWe)*	Total Radiator Area (m^2)**	Mass (kg)
M1	0.9/ 0.9	8	352
M2	25.0/25.0	80	3,520
M3	12.0/12.0	40	1,760
M4	10.0/10.0	32	1,408
M6	5.0/ 5.0	16	704
M7	3.0/10.0	16	779***
M8	0.15/1.5	8	352
M9 (onboard)	7.0/ 7.0	24	1,056
M9 (cart)	5.0/ 5.0	16	704
M10	3.0/15.0/1.5	16.2	967***
M11	22.0/40.0/10	72.0	3,711***

*Nominal/peak.
**Main radiator and electronics radiator.
***Includes additional energy storage above nominal for peaking power.

3.5.2   PEM RFC Power System Characteristics

The Proton Exchange Membrane (PEM) RFC system converts electrical energy into chemical energy and stores the energy for future use. An RFC is an energy storage device similar to a battery. The RFC system can be divided into six major subsystems for development purposes: (1) a fuel cell stack, which electrochemically combines hydrogen and oxygen to create electricity and water; (2) an electrolyzer cell stack, which electrolyzes the fuel cell product water into gaseous hydrogen and oxygen reactants using externally provided power; (3) water management which removes moisture from the electrolysis cell product gases and humidifies fuel cell reactants to maintain proper cell membrane moisture content; (4) thermal management, which removes waste heat from the system, maintains the proper membrane temperature, prevents boiling or freezing in critical flow paths; (5) reactant storage (hydrogen, oxygen, and water); and (6) PP&C. The PP&C must be designed to allow for recharging from either photovoltaic arrays, a nuclear reactor, or a DIPS.
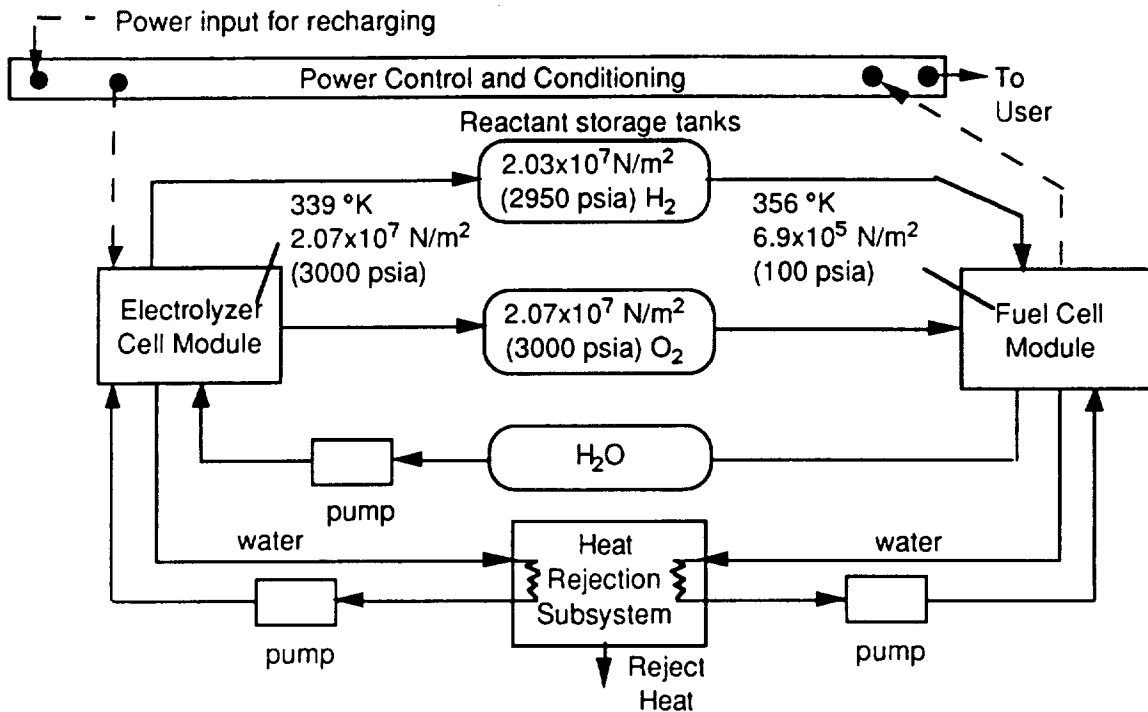
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Figure 6. - PEM RFC power system schematic.

A simplified schematic of a potential PEM RFC system is shown in Figure 6. Figure 6 does not show the details of the design such as electrical controls, fluid controls, trace heating, phase separation, gas humidification, gas drying, or redundant components. These items will be discussed in detail in Appendix B.

In the baseline PEM RFC concept, high pressure oxygen and hydrogen gas were assumed for gaseous reactant storage tanks of relatively low volume. High pressure gas storage reduces the size of the storage tanks. Cryogenic storage of oxygen and hydrogen may be desirable for large fixed systems, but was byond the scope of this study.

Design goals for a PEM RFC power system are summarized in Table 17. Two types of fuel and electrolysis cell technologies are available: alkaline and PEM. PEM fuel cells and electrolysis cells were selected for this study since these technologies have inherent longer life capabilities than alkaline systems.

TABLE 17. - PEM RFC POWER SYSTEM GOALS

Parameter	Value
Life, hrs (10,000 hrs for fuel cell and electrolysis cell stacks)	20,000
End-of-Life roundtrip cycle efficiency, %	40*
Net nominal power output for module, kWe	3-25**
Peak power output, kWe	10-40
Specific energy, MJ/kg	0.72***

*Includes fuel cell stack, electrolysis cell stack, gas cooling, pumping, and PP&C losses included.
**Different module sizes.
***NASA Office of Exploration technology goal.

The mobile PEM RFC power system characteristics are summarized in Tables 18 and 19. Table 18 includes system performance, size, and volume. The base PV array size penalty is also shown. Table 19 shows the mass breakdown for each PEM RFC system plus the base mass growth required. Recharging times were 8 hours for all applications except for the M9 (pressurized rover) power cart (96 hours recharge).

TABLE 18. - MOBILE PEM RFC POWER SYSTEM CHARACTERISTICS

Application No.	Power* (kWe)	Bus Power To Elect. Stack (kWe)	PEM RFC Roundtrip Cycle Efficiency (%)**	Array Area *** (m²)	Radiator Area (m²)	Volume **** (m³)	Energy Density **** (MJ/m³)
M7	3/10	9.8	39.5	866	12.6	0.36	310
M9	7/ 7	17.5	40.1	1,534	10.0	0.59	342
M9	12/12	28.0	42.9	2,477	13.9	7.92	524
M10	3/15/1.5	10.2	41.4	900	5.6	0.31	394
M11	22/40/10	55.5	39.9	4,902	38.9	1.53	417

*Nominal/peak/standby.
**Includes fuel cell, electrolysis cell, PP&C, pumping, and gas cooling losses.
***Increase in base power system array.
****RFC and tanks, only.

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TABLE 19. - MOBILE PEM RFC POWER SYSTEM MASS BREAKDOWN

Application No.	Power * (kWe)	Array Subsystem Mass** (kg)	PEM RFC Mass (kg)	Tank Mass (kg)	PP&C Mass (kg)	Radiator Mass (kg)	Total Mass *** (kg)	Specific Energy **** (MJ/kg)
M7	3/10	630	266	42	76	52	1,076	0.25
M9	7/ 7	1,116	197	73	134	33	1,560	0.45
M9	12/12	1,803	366	1,430	217	52	3,882	2.01
M10	3/15/1.5	655	209	44	79	19	1,009	0.34
M11	22/40/10	3569	530	229	429	155	4,912	0.47

*Nominal/peak/standby power.
**Additional mass required for base power system.
***Includes heat exchanger mass and growth in base PV system.
****Does not include growth in base PV system.

The masses of the required PV array were quite large due to the requirement to size for the minimum day insulation and the low overall efficiency of the PEM RFC systems. One approach to reducing system mass would be to increase the PEM RFC recharging time (reduces array and electrolysis module size) with the penalty of reduced availability of these systems. Another approach (load leveling) would be to recharge mobile units at night when other base power requirements are reduced. Alternatively, these mobile systems could be recharged by a nuclear reactor base power system with less of a mass penalty.

3.5.3 NaS Battery Power System Characteristics

A typical mobile NaS battery power system schematic is shown in Figure 7. Energy is supplied to the user by the batteries. The battery subsystem includes the cells and related structure to tie the cells together.

After each mission, the batteries are recharged. The flow of energy to/from the batteries is controlled by the PP&C subsystem. Power conditioning is included to process power for charging the batteries (down regulator) and processing output power (boost regulator).

Since the batteries must operate at high temperature, thermal management is required to maintain the proper cell temperature and reject waste heat. In addition, the batteries need to be heated prior to startup (for thawing of frozen sodium). The electronic components in the

PP&C also require cooling to remove waste heat. The thermal management subsystem includes (Ref. 26) battery insulation, isolation plates (between battery and structure), battery radiator/interface heat exchanger, PP&C cold plates, and the PP&C radiator.

The NaS battery system is described in more detail in Appendix C.
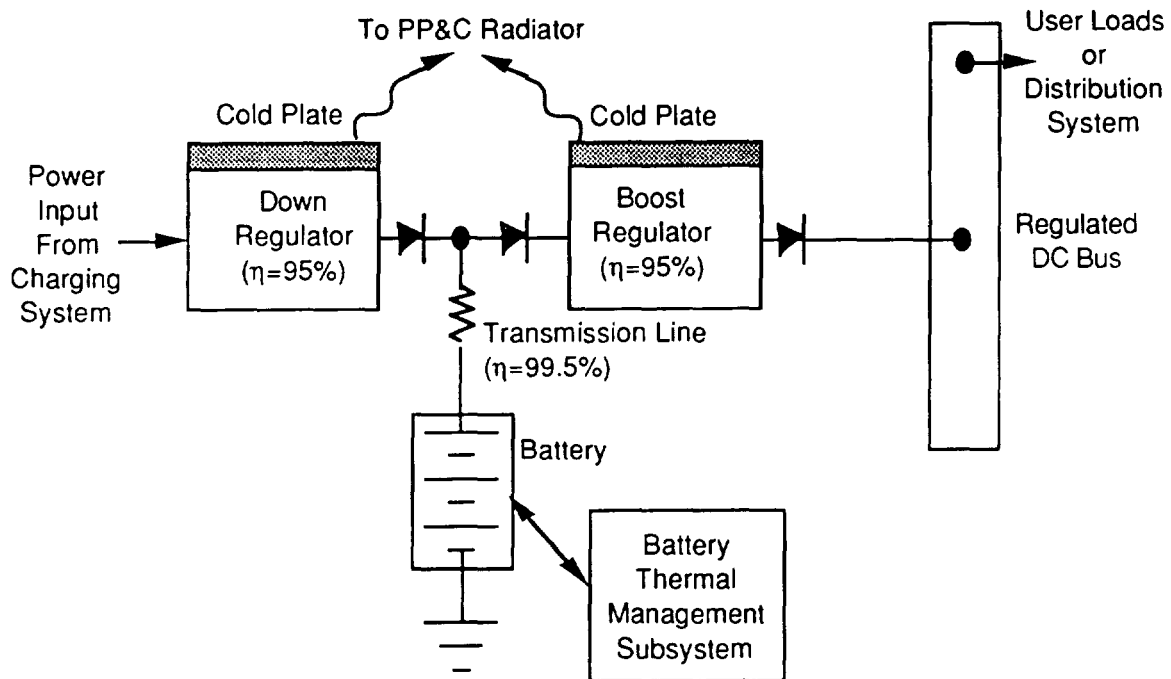
Figure 7. - Battery power system schematic.

Characteristics of NaS battery systems for mobile applications are summarized in Tables 20 and 21. Table 20 includes electrical characteristics (power input and output, voltage input and output, discharge efficiency), waste heat, and battery volume. Table 21 gives a breakdown and the total mass of each battery system including the battery cells, battery structure, thermal management subsystem, and PP&C. The total mass includes a mass penalty for base PV power system growth due to battery recharging given the charging times of Table 9.

TABLE 20. - MOBILE NaS BATTERY POWER SYSTEM CHARACTERISTICS

Application No.	Net Output Power* (kWe)	Charging Power (kWe)	Battery Charging Efficiency	Battery Discharge Efficiency	Waste Heat (kWt)	Battery Volume (m³)	Battery Energy Density** (MJ/m³)
M7	3/10	5.8	0.78	0.90	0.82	0.38	294
M9	7	10.5	0.79	0.89	1.82	0.69	292
M9	12	18.0	0.77	0.92	2.71	13.8	301
M10	3/15/1.5	6.0	0.78	0.90	0.85	0.42	290
M11	22/40/10	33.3	0.79	0.89	5.73	2.19	291

*Peak/nominal/standby power.
**Based on net output to user and the battery volume.

TABLE 21. - MOBILE NaS BATTERY POWER SYSTEM MASS BREAKDOWN

Application No.	Net Output Power* (kWe)	Array Power** (kWe)	Base Mass Growth*** (kg)	Battery Mass (kg)	PP&C Mass (kg)	Thermal Management Subsystem Mass (kg)	Total Mass**** (kg)	Battery System Specific Energy***** (MJ/kg)
M7	3/10	6.3	396	389	75	26	886	0.23
M9	7/7	11.5	716	747	86	50	1,599	0.23
M9	12/12	19.7	1,227	9,719	147	447	11,540	0.40
M10	3/15/1.5	6.9	433	417	113	28	991	0.22
M11	22/40/10	36.3	2,265	2,358	300	158	5,081	0.23

*Peak/nominal/standby.
**Assumes no power to user during recharging.
***Additional mass required for base power system.
****Includes the base growth penalty (additional array plus structure mass).
*****Does not include base growth penalty.

3.5.4 PV/PEM RFC Power System Characteristics.

A typical PV/PEM RFC power system schematic is shown in Figure 8. The power system may be divided into the following subsystems for development purposes:

- Photovoltaic (PV) Array;

- PEM RFC;

- Electronics Thermal Management; and

- PP&C.
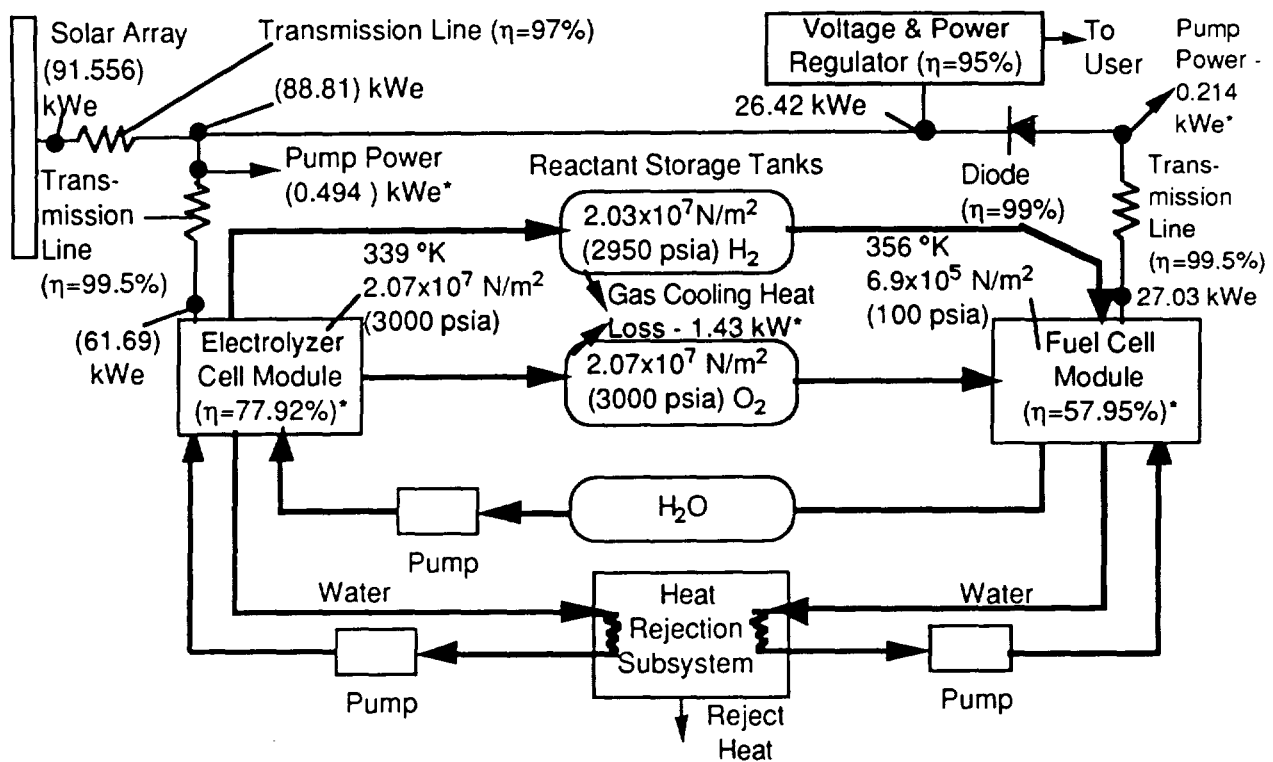
Figure 8. - 25 kWe PV/PEM RFC power system schematic.

The PV subsystem includes the array panels, support structure, deployment mechanism, and wiring harness. This power system concept utilizes high efficiency multijunction tandem photovoltaic cells to minimize array area. A large array area is required for Mars applications due to the low insolation (due to dust from local and global dust storms). Since the PV subsystem is the largest component of system mass for Mars systems, it is important to minimize array area and specific mass (kg/m^2).

The PEM RFC subsystem includes fuel cells, electrolysis cells, water control (humidifiers, dehumidifiers, fluid controls), storage tanks (hydrogen, oxygen, water), thermal control (radiator, thermal control loops), and support structure.

Power conditioning is included to process power for running the electrolysis unit and to process the fuel cell output power. A shunt regular dissipates excess power from the array.

The characteristics of PV/PEM RFC power systems for each fixed application are summarized in Tables 22 and 23. Table 22 includes power (net and array), efficiencies (fuel and electrolysis cell), areas (array and radiator), and energy storage volume. Table 23 includes a mass breakdown for each system. The largest component of system mass by far is the array mass (about two thirds of total). Figure 9 shows design details and sizing data for a 25 kWe PV/PEM RFC power system. The roundtrip efficiency given in Figure 9 for the RFC subsystem includes fuel cell, electrolysis cell, gas cooling, pump, PP&C, and internal power transmission losses. This efficiency varies for each different power system.

TABLE 22. - PV/PEM RFC POWER SYSTEM CHARACTERISTICS

Application No.	Output Power (kWe)	Array Power (kWe)*	Electrolysis Cell Efficiency* (%)	Fuel Cell Efficiency* (%)	Array Area* (m^2)	Radiator Area (m^2)	Volume** (m^3)
M1	0.9	3.0	72.3	63.2	258	0.7	0.07
M2	25	91.6	77.9	58.0	7,795	23.7	2.06
M3	12	45.4	76.1	56.8	3,861	11.3	0.76
M4	10	38.6	76.6	55.9	3,286	9.9	0.64
M5	75	290.2	80.4	52.9	24,705	83.2	6.86

*End-of-life values.
**PEM fuel cell stack, PEM electrolysis cell stack, reactants, and tanks.

TABLE 23. - PV/PEM RFC POWER SYSTEM MASS BREAKDOWN

Application No.	Output Power (kWe)	Array +Struc. Mass (kg)	PEM RFC Mass (kg)	Tank + Reactant Mass (kg)	PP&C Mass (kg)	Radiator Mass (kg)	Total Mass (kg)
M1	0.9	187	79	12	23	2	303
M2	25	5,716	532	380	687	86	7,401
M3	12	2,833	278	187	340	41	3,679
M4	10	2,409	224	161	290	35	3,119
M5	75	18,108	1,317	1,266	2,177	360	23,228

RFC Module

Solar Cell Module

—3.1 m—

7.8 m

Radiator

11.1 m

2 m

Waste Heat Exchangers
Water Tank
Oxygen Tanks

Power
Condi-
tioning

Electrolysis
Module

Fuel Cell
Module

Hydrogen Tanks

Side View of RFC Subsystem
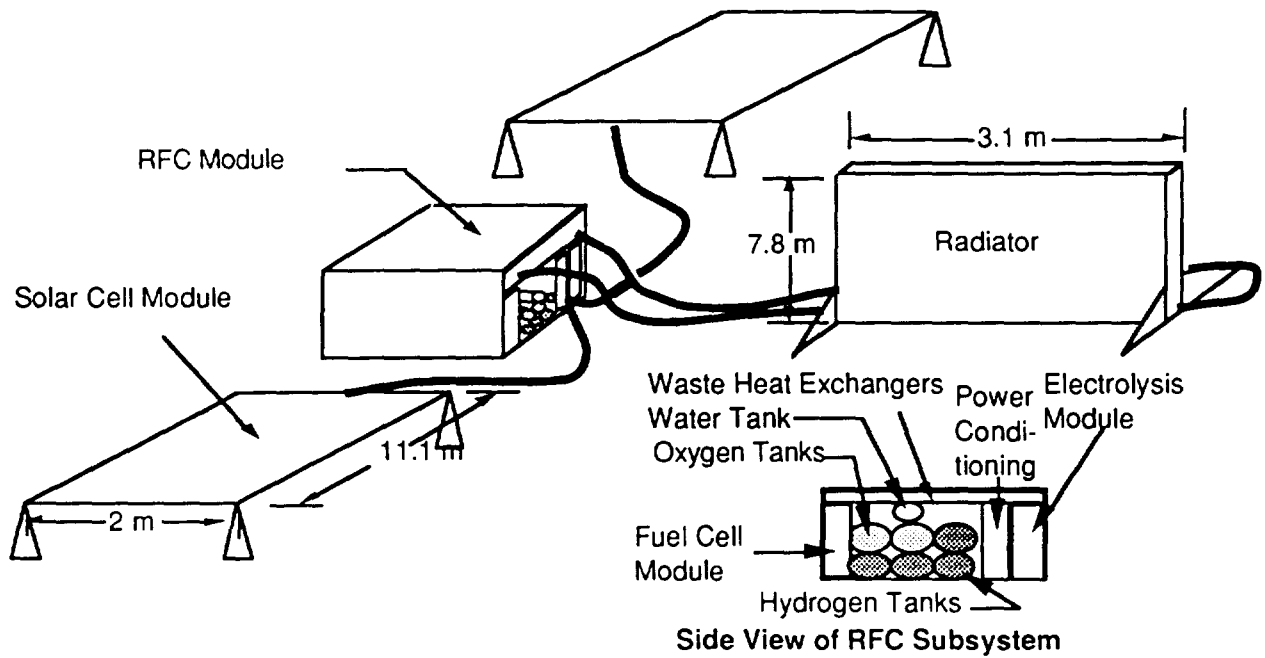
•Rated Power to User, kWe	25
•Voltage, Vdc	160
•Array Power (EOL), kWe	92
•Array Temperature, °K	301
•Cell Size, 8x8 cm Tandem GaAs/CIS	
•1 mil Cover glass	
•Nominal Efficiency (cell/array), %	20.6/16.5
•Total Array Area, m²	7,795
•Number of Modules	350
•Power per Module (EOL), kWe	0.26
•Radiator	
•Total Area, m²	24
•C-C Heat Pipe Type With Water Working Fluid	
•Emissivity (clean)	0.88
•PEM Electrolyzer Module	
•Power Input (EOL), kWe	88.8
•Max. Pressure, N/m² (psia)	2.07x10⁷ (3,000)
•PEM Fuel Cell Module	
•Power Output, kWe	27
•Max. Pressure, N/m² (psia)	6.9x10⁵ (100)
•Operating Temperature, °K	356
•Regenerative Fuel Cell Subsystem	
•Round Trip Efficiency, %	40.5
•Gas Storage Tanks	
•Max. Pressure, N/m² (psia)	2.07x10⁷ (3,000)
•Graphite Epoxy Composite Safety Factor	2
•System Mass, kg	7,401

Figure 9. - Design details for 25 kWe PV/PEM RFC power system.

3.5.5 PV/NaS Battery Power System Characteristics

A typical power system schematic is shown in Figure 10. The overall power system may be divided into the following subsystems for development purposes:

- PV array (GaAs-Ge/CIS cells);

- NaS batteries;

- Thermal management (radiators for cooling battery and electronics, battery insulation and isolation plate); and

- PP&C (controller, down regulator, boost regulator, and shunt regulator).

The solar array converts sun light directly into DC electricity. The energy from the array flows to the batteries, for later use, and to the user. When the system enters a period of darkness, the energy to the user is supplied by the batteries. The batteries are recharged on the next sun cycle by the solar array. The flow of energy from the array and to and from the batteries is controlled by the PP&C subsystem. A shunt regular dissipates excess power from the array.

The PV/NaS battery system is described in detail in Appendix E.
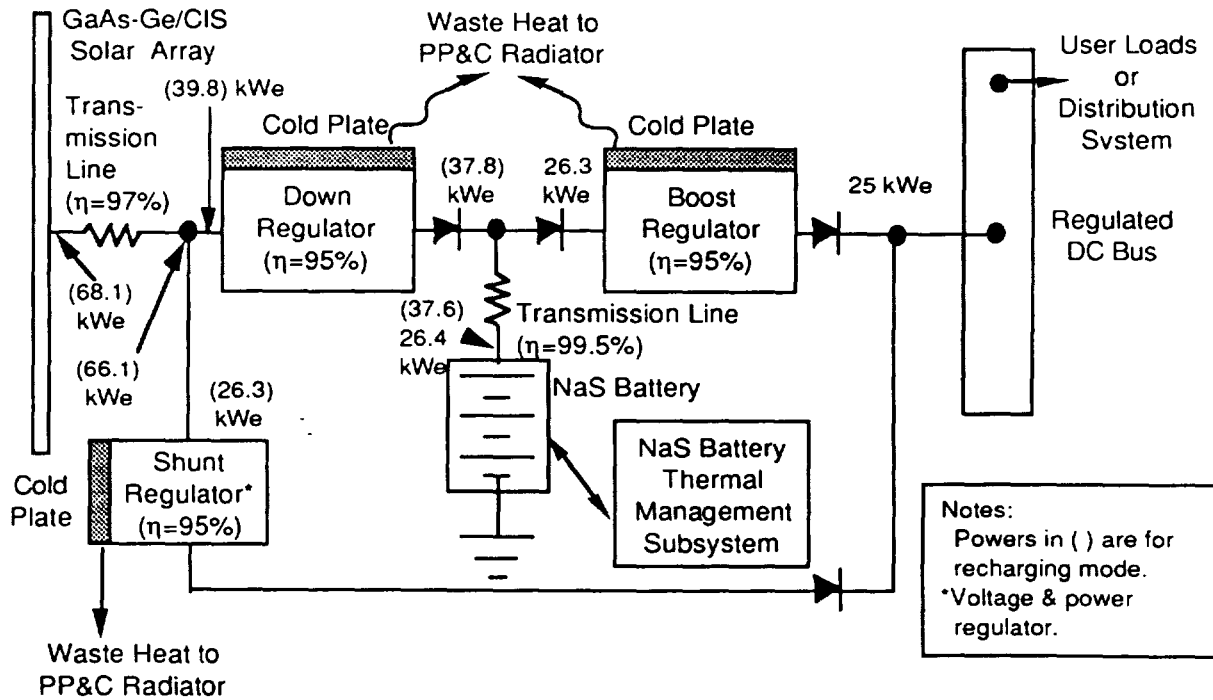
Figure 10. - PV/NaS battery power system schematic.

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Characteristics of the PV/NaS battery power system for each fixed application are summarized in Tables 24 and 25. The output battery voltage was assumed to be 120 V. The battery charging voltage was assumed to be 170 V. The battery discharge efficiency was 90% for all cases. Similarly, the battery charging efficiency was 78.1% in all cases. PP&C efficiencies were previously given in Table 5 and Figure 10. Table 25 gives the mass breakdown for each application. For this system, the array mass is the largest component of the total mass (about 50%).

TABLE 24. - FIXED PV/NaS BATTERY POWER SYSTEM CHARACTERISTICS

Application	Net Output Power* (kWe)	Charging Power ** (kWe)	Array Power (kWe)	Waste Heat (kWt)	Battery Volume (m^3)
M1	0.9	1.35	2.45	0.2	0.13
M2	25	37.6	68.1	6.2	3.67
M3	12	18.0	32.7	3.0	1.76
M4	10	15.0	27.2	2.5	1.47
M5	75	113	204	18.5	11.0

*Net power to user from system (neglects any base power distribution system).
**Input power to battery to recharge (does not include PP&C or transmission losses).

TABLE 25. - FIXED PV/NaS BATTERY POWER SYSTEM MASS BREAKDOWN

Application No.	Net Output Power (kWe)	Array + Structure Mass (kWe)	Battery Mass (kg)	PP&C Mass (kg)	Thermal Management Subsystem Mass (kg)	Total Mass (kg)
M1	0.9	153	131	18	8	310
M2	25	4,246	3,639	511	221	8,617
M3	12	2,040	1,747	245	106	4,138
M4	10	1,700	1,456	204	88	3,448
M5	75	12,750	10,920	1,532	662	25,864

3.5.6 Thermionic Reactor Power System Characteristics

Four distinct systems have emerged as prime candidates for reactor thermionic applications. These four candidates are described in the following paragraphs.

The TOPAZ derivative design uses in-core thermionic fuel elements (TFEs) and a zirconium hydride moderator in a monolithic stainless steel calandria. A few SNAP reactor type fuel elements may be used as driver elements. Enriched tungsten (W-184) is used as the emitter material to minimize the critical mass and number of driver elements. Heat rejection is by circulation of NaK coolant to a potassium/stainless steel heat pipe radiator. Rotating drums are utilized with in-core safety rods providing backup shutdown function. The former Soviet Union has ground tested seven TOPAZ I (5 kWe) systems and successfully flight tested two systems within the last ten years. The U.S. recently agreed to purchase a TOPAZ reactor for research purposes.

STAR-C is an out of core concept using a conduction cooled uranium carbide/graphite core similar to the Soviet Romashka reactor. The reactor heat is converted to electrical energy with planar converters at the core-reflector interface. Waste heat is removed from the back of the collector by a short heat pipe which extends through the reflector and is attached to the radiator heat pipe panels. The radiator heat pipe panels are located circumferentially and comprise the radiator assembly, which can be either cylindrical or conical. There is no coolant loop. Control segments located in the reflector region perform the primary shutdown function while in-core safety rods are provided for backup shutdown.

The Driver Fuel In-core TFE concept couples in-core TFEs with UO_2 driver fuel pins (where required) for criticality purposes. A pumped liquid metal heat transport loop removes waste heat from the reactor core. The waste heat is rejected to space by a heat pipe radiator. Rotating radial reflector drums are used for both control and primary reactor shutdown. In-core safety rods provide the backup shutdown function. The driver fuel is fully enriched.

The In-Core TFE Heat Pipe Cooled Reactor concept exists in two versions; namely moderated and unmoderated. In the moderated version, the reactor is moderated by a

combination of beryllium and zirconium hydride. The zirconium hydride is the primary moderator. The beryllium is used to conduct heat from the TFE to the in-core heat rejection heat pipes. The in-core heat pipes transfer their heat to an external heat pipe radiator. In the unmoderated version, each in-core TFE is surrounded by six trapezoidal shaped heat pipes to form a hexagonal shaped heat transfer module. The hexcan module is, in turn, joined to a single radiator heat pipe. The modules are brazed together so that adjacent modules share the heat rejection load, should a radiator heat pipe fail. Fast driver fuel elements, surrounded by similar heat pipe modules, are included where required for criticality purposes. Sliding radial reflector segments provide both the control and primary shutdown functions. In-core safety rods perform the backup shutdown function.

The relative masses of the different power systems are compared in Figure 11. Figure 11 includes data for unhardened system, systems hardened to meet the Survivable Power Subsystem Demonstration (SUPER) requirements, for photovoltaic systems hardened to meet SUPER requirements, and both hardened and unhardened SP-100 TE systems.

The following conclusions were drawn from the mass estimates:

- all TFE concepts have a mass within +/- 500 kg of the average over the entire range;

- the STAR-C mass is generally lower at 10 kWe, but the scalability rules for this concept are not understood and further study of this aspect will be pursued;

- moderated concepts, especially TOPAZ, have a low mass at 10 kWe; however, presumably, above 50 kWe, they become very much like the Driver Fuel In-Core TFE concept;

- although the system efficiency of the driver fuel concepts at low power tends to be low, system mass is still attractive because the radiator is small and relatively few (heavy) TFEs are used; and

- all designs appear to be at least a factor of 4 less in mass than comparable photovoltaic concepts at 40 kWe.

Based on its superior mass characteristics, scalability aspects, and the possibility that it can be operated at a sufficiently low temperature to permit the use of an all stainless steel external structure, the Driver Fuel In-core TFE power system was selected as the most likely

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thermionic reactor candidate for an extraterrestrial planetary based power system of less than 100 kWe output.
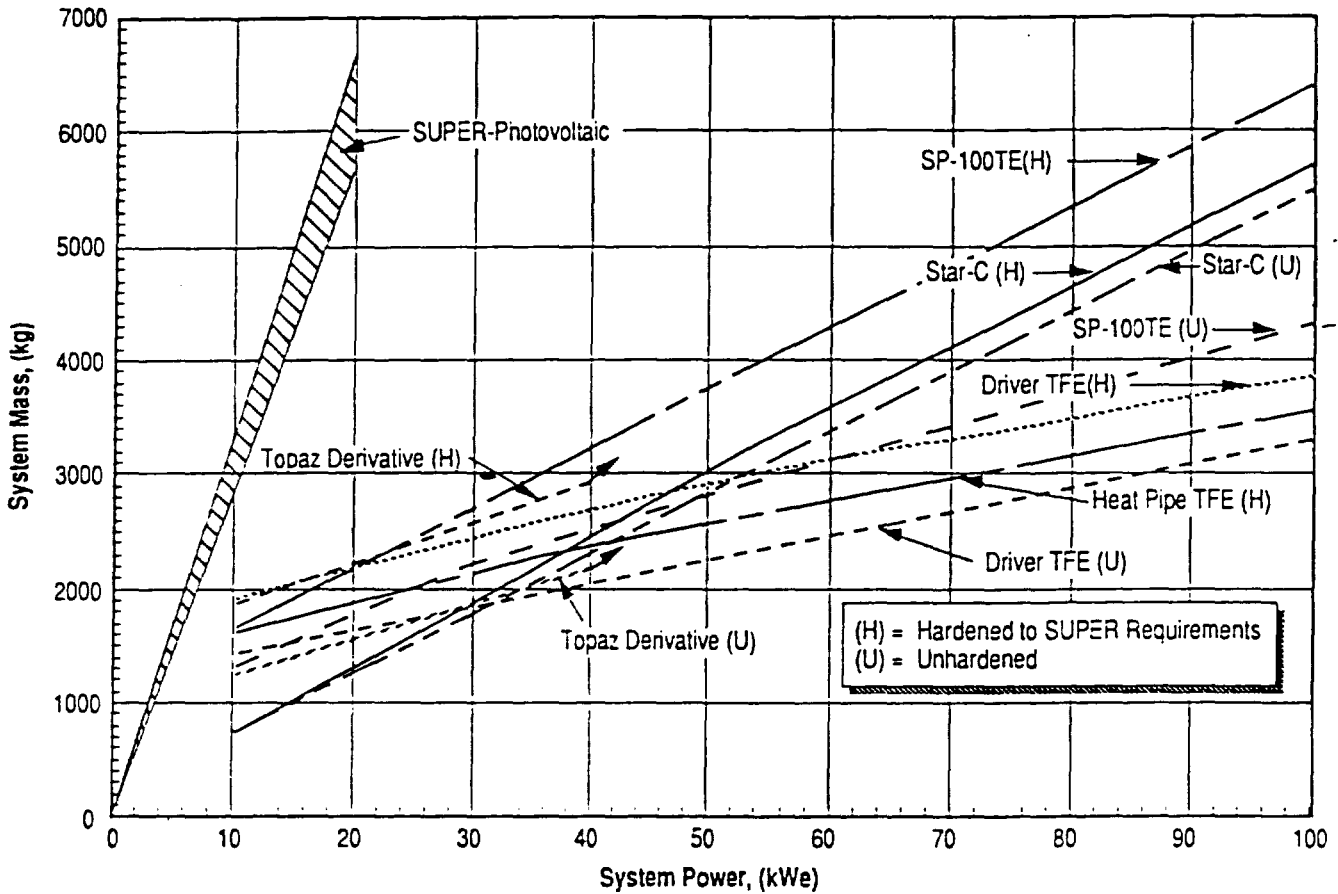
Figure 11. - Candidate TI reactor power system mass comparison.

Figure 12 illustrates the key features and operating conditions for a fast driver fuel in-core TFE power system concept, which is based on existing or presently emerging technology. The system is easily scalable over the range of 10 to 100 kWe.

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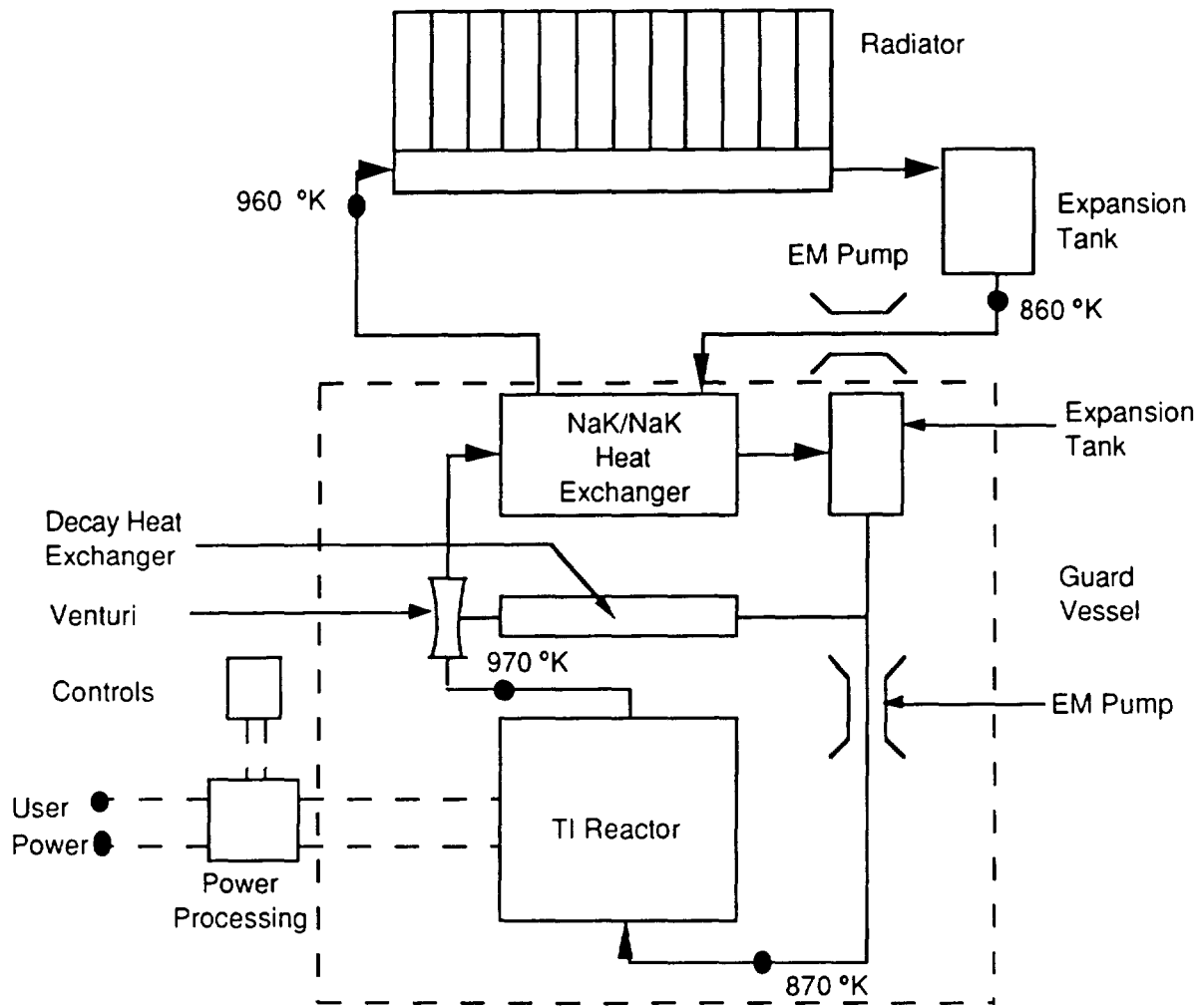
Figure 12. - Driver Fuel In-core TFE reactor power system schematic.

The system contains an in-core thermionic reactor coupled to a fixed radiator by a single pumped, liquid metal cooling loop. NaK at a maximum temperature of 970 °K is circulated through the core by one of two redundant electromagnetic (EM) pumps similar in design to those developed for SNAP 8. An EM pump similar to the one used in SNAP 10A provides passive decay heat removal. A sodium heat pipe radiator was designed to reject waste heat to space. A redundant power processing and control system based on Space Station Freedom technology completes the major subsystems in the concept.

The ability to use the same basic reactor concept over a full range of power outputs reduces the amount of development required and the amount of qualification testing required. In

the case of the fast driver concept scaling is accomplished by using the same TFE and driver pin design and adjusting their quantities within the reactor vessel to meet the required power output. Figure 13 shows the dimensions for 25 and 75 kWe power systems (applications M2 and M5). Table 26 compares the relative performance of unhardened systems designed in this manner.

Dimensions (m)		
	25 kWe	75 kWe
A	3.2	3.2
B	1.4	2.1
C	7.2	7.2
D	6.6	7.6
E	1.6	1.6
F	0.8	0.8

Figure 13. - Driver Fuel In-core TFE reactor power system layout.

TABLE 26. - DRIVER FUEL IN-CORE TFE REACTOR POWER SYSTEM CHARACTERISTICS

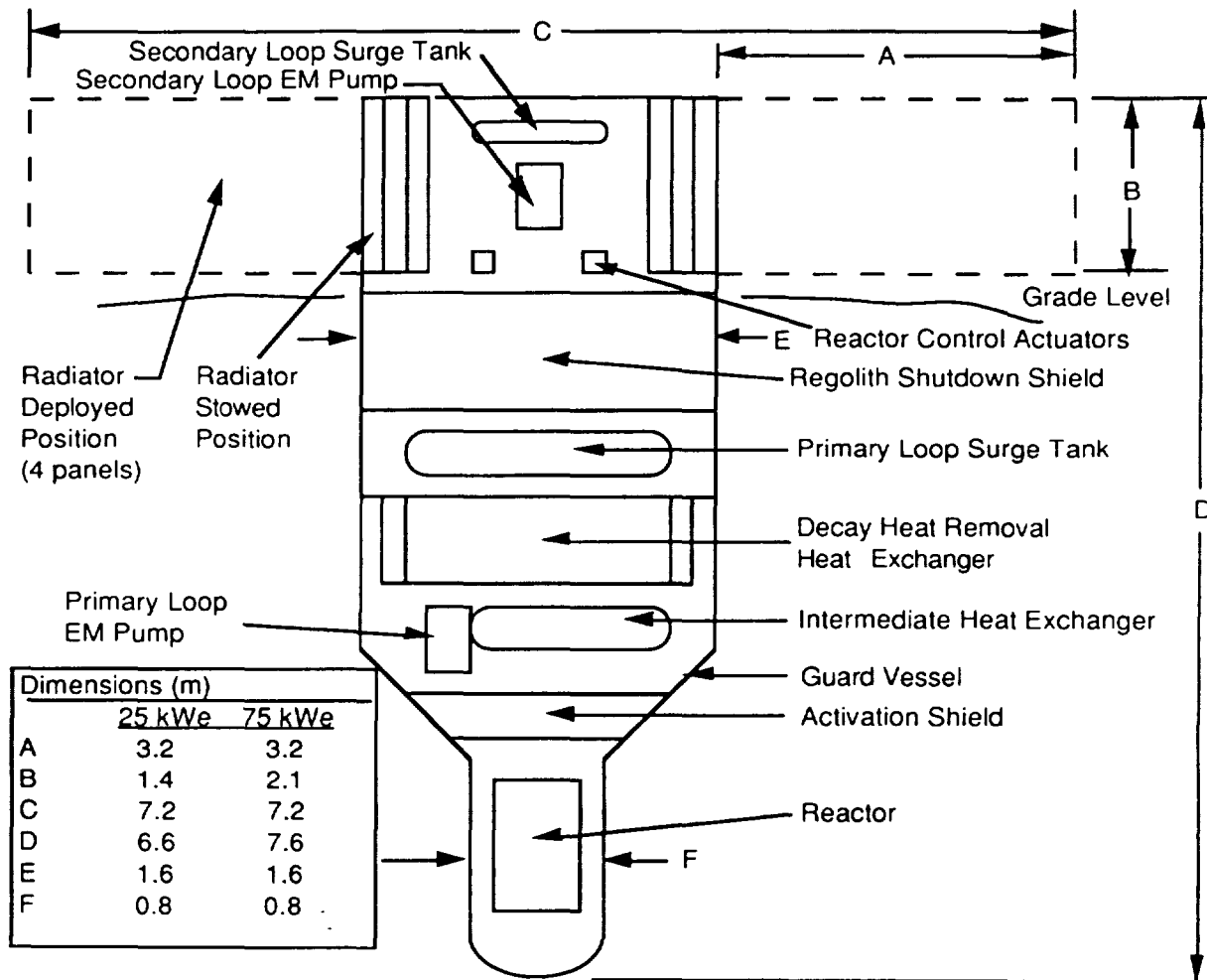| Net EOM Power (kWe)	25	75	Net EOM Power (kWe)	25	75
Net BOL Power (kWe)	27.5	82.5	Net BOL Power (kWe)	27.5	82.5
Number of TFEs	48	132	Radiator Area (sq m)	30	44
Thermal Power (kWt)			Auxiliary Power (kWe)	2.9	6.6
Reactor	600	1,040			
TFE	310	910			
Driver	290	490			
Radiator	569	956	System Mass (kg)		
Efficiency (%)			Reactor	510	920
TFE	9.1	9.1	Reactor I & C	260	260
Net System EOM	4.2	7.2	Activation Shield	395	625
Temperature (°K)			Heat Transport	430	675
Emitter	1,775	1,775	Heat Rejection	520	900
Inlet NaK	870	870	Power Pr. & Cont.	145	270
Outlet NaK	970	970	Cont. & Structure	420	475
Radiator Fin	855	855	Total	2,680	4,125

3.5.7 SP-100 Reactor Systems Characteristics.

SP-100 is a joint DOD/DOE/NASA program to develop, qualify and flight demonstrate a space power reactor system. The SP-100 reactor can be integrated with dynamic or static power conversion systems to provide electric power. The SP-100 program is currently developing a high temperature power reactor coupled to a thermoelectric (TE) generating system. The nominal system power level has been selected as 100 kWe. The basic configuration of the system currently being developed by the SP-100 program is shown in Figure 14. The reactor provides thermal energy to a lithium coolant that is pumped by 12 thermoelectromagnetic (TEM) pump assemblies to an equal number of TE converter assemblies. The TE converter assemblies, located at the rear of the conical structure, convert thermal energy to electrical energy. Waste heat from each Thermoelectric Converter Assembly (TCA) is rejected to a secondary lithium loop which transports the waste heat to heat pipe space radiator panels. The radiator panels are deployable by use of flexible bellows in the secondary lithium lines. Generated power is conditioned for the user in the power processing module, which establishes the primary mechanical and electrical interfaces with the mission payload.

It was assumed that an advanced SP-100 systems using a dynamic power conversion system would be developed following development of the SP-100 TE power system (some time after the completion of testing of the Ground Engineering System). The electrical power output of the basic reactor can be significantly enhanced by the use of dynamic power conversion technologies. Dynamic power systems concepts include Closed Brayton Cycles (CBC), Stirling Cycles (SC), and Potassium Rankine Cycles (PRC) integrated in various ways with the nuclear power source. Recent studies have shown that electrical power outputs of over 550 kWe can be obtained by the use of CBC, SC or PRC power conversion equipment with the SP-100 reactor.
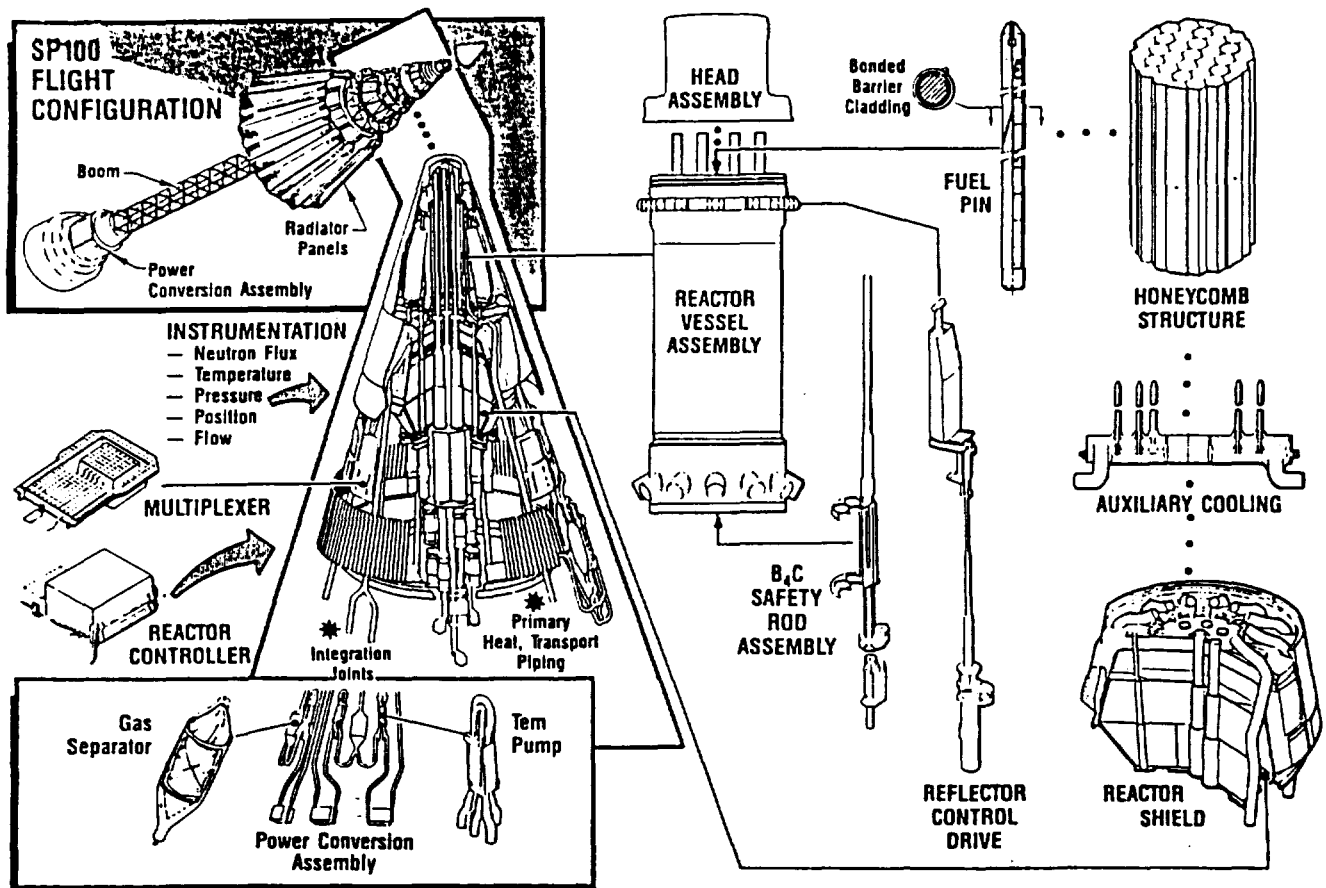
Figure 14. SP-100 TE generic flight system configuration.

This system makes extensive use of refractory materials and could not be used on the Mars surface without protection from the environment. The configuration will require modification for surface applications to provide containment of the refractory alloy components, provide additional shielding consistent with the emplacement geometry, and reconfigure the radiator geometry for packaging. SP-100 TE system masses for 25 and 75 kWe systems without shields were estimated to be 2400 kg and 4150 kg, respectively (as shown in Figure 3). A shield mass of 810 kg was added to bring the total system masses to 3,210 kg and 4,960 for the 25 and 75 kWe systems (assumes reactors are buried).

The reactor designed for the SP-100 system is a fast spectrum design with sealed uranium nitride (UN) fuel pins contained in a single vessel with liquid lithium circulated as the coolant. The reactor is approximately 0.55 meters in diameter by 0.75 meters high. Twelve sliding block reflector control segments provide reactivity control through neutron leakage. PWC-11 refractory metal is used for the reactor fuel pin cladding and for the reactor structure. Three large safety rods are inserted into the reactor core during launch and ascent and are extracted only after a nuclear safe orbit or surface site is achieved. The reactor is nominally rated at 2.4 MWt and delivers its thermal energy to liquid lithium at 1350 °K. SP-100 design goals, requirements, and design features for the generic flight system are shown in Table 27.

TABLE 27. SP-100 GENERIC FLIGHT SYSTEM DESIGN GOALS, REQUIREMENTS AND FEATURES

Parameter	Requirement	Design Feature (s)
Design lifetime	7 years	•Fuel inventory •Fission gas accommodation
Reliability	0.95	•TE conversion flight proven •Established reactor data base
Main bus power	100 kWe	•Modular design provides scalability
Main bus voltage	200 Vdc	•Option range (28 to 400) readily provided
Load following	Rapid, continuous	•Full shunt
Shielded diameter at user interface	15.5 m (50 ft)	•Larger areas provided at minimum penalty
Radiation at user interface	1.0×10^{13} n/cm^2 5×10^5 Rad	•Reactor shield assembly
Thermal flux at user interface	0.07 W/cm^2	•Meets specified requirement (0.14 W/cm^2) •Easily moderated by boom length
Solar orientation	No restrictions	•Full sun design for radiator
Natural radiation and meteoroids/debris	Mass allowance in baseline for worst case envelope	•Meteoroid armor radiator shields

3.6 OPERATIONS CONCEPTS - EMPLACEMENT/DEPLOYMENT REQUIREMENTS

The influencing factors study previously mentioned in Section 3.4 showed the need for autonomous equipment to deploy power systems prior to the arrival of astronauts. Telerobotic means cannot be used in its purist sense as on the moon due to the significant time delay for transmissions to/from Mars. Thus, there must be significant advancements in artificial intelligence, sensor technology, and manipulators to allow reliable "supervised" (not real time) telerobotic emplacement and startup of power systems. The same type of equipment will be needed to maintain and service power systems due to the cost of replacing systems. In addition, astronaut EVA time will be severely limited and costly, and should be devoted to scientific endeavors rather than base maintenance.

Rocketdyne completed a study for NASA of deployment approaches for lunar power systems (Ref. 10). Rocketdyne has continued this work under IR&D in order to address the technology needs for autonomous robotic maintenance (Ref. 11). NASA has also performed inhouse studies to examine nuclear power plant construction and operations (Refs. 12 and 13). The results of these studies were reviewed and applicable information was used for deployment of Mars power systems. More detailed deployment procedures will be found in Ref. 10.

The precise details of the power system design and deployment procedures will depend on the form of the Mars transportation system. The cargo vehicle packaging and mass limitations will greatly determine the configuration and allowable size of the power system, as well as methods of deployment. The two power systems which will require the most deployment effort are the reactor systems and the photovoltaic systems.

3.6.1 Deployment Methods

There are four basic deployment methods available for Mars power systems; Earth Telerobotic, Mars Telerobotic, Extravehicular Activity (EVA), and Autonomous Robotic. Each has its advantages and disadvantages (see Table 28). The deployment method used will depend on the power system design and installation site conditions.

TABLE 28. - DEPLOYMENT METHODS

Deployment Methods	Advantages	Disadvantages
•Earth Telerobotic	•Low cost	•Long signal transmission times
•Mars Telerobotic	•Medium cost	•Mars crew member time
•Autonomous Robotic	•Low cost	•High technical risk
•EVA	•Low technical risk	•High cost •High safety risk •Mars crew member time

3.6.1.1 Earth Telerobotic. The Earth Telerobotic method would involve an earth bound operator to remotely control the installation of the power system. This would include the operation of installation equipment such as excavators for site preparation. Due to the long transmission time this method is not feasible for operations requiring real-time control. Earth control systems will most likely be limited to command/verification/recommand sequences since it could take up to 40 minutes for each step. This method of supervisory control seems to favor the task of deploying a reactor/cart some distance from the base as compared to the installation of many PV array panels over a large surface area.

3.6.1.2 Mars Telerobotic. This method involves an operator remotely controlling the equipment from the Mars habitat. But unlike the earth telerobotics, the delay time will be on the order on milliseconds which allows for real-time control. The big advantage to this method is that it provides on-site real-time control with out exposing astronauts to EVA safety hazards. The disadvantage to this method is that systems could only be installed after the Mars crew has arrived. This method is limited to systems not critical for the first crew arrival.

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3.6.1.3 Extravehicular Activity.   This is the basic of all the methods. This will require an astronaut to either physically install equipment or escort and control installation equipment. This has the lowest technical risk, but the highest safety risk. Humans have a built-in capacity for problem solving and visual imaging, but are very sensitive to the environment. A controlled environment is required (Extravehicular Mobility Unit or EMU). There is danger of an accident at all construction sites where heavy equipment is involved . The combination of construction hazards and the inhospitable environment of Mars makes EVA construction a high risk endeavor. In addition, EVA time is limited for each crew member. Limited EVA means an increased duration for each job.

3.6.1.4 Autonomous Robotic.   This method requires the least amount of human interfacing. The robotic equipment would be programmed to perform a given task from start to finish. This equipment would rely heavily on artificial intelligence to overcome obstacles and abnormalities. The technical success of this method will be dependent upon significant advancements in artificial intelligence, sensor technology, and manipulators to allow reliable autonomous construction. The next generation of robots will most likely have to meet the following requirements:

- mobile;

- highly versatile in the movements they perform and the accuracy/precision with which they perform these movements;

- capable of performing a myriad of non-repetitive tasks;

- equipped with reasonable optical/touch sensory perception;

- capable of coordinating their movements with those of other machines and humans; and

- equipped with some form of on-board artificial intelligence (AI) for adapting to constantly changing environments.

The use of robotic methods will be discussed in more detail in Sections 3.8 and 3.9.

3.6.2 Impacts of Site Architecture on Power System Deployment

There may be up to three different landing sites for 90 day Mars exploration expeditions. Each exploration site will require a 25 kWe power system. This power could be supplied by a PV system (battery or PEM RFC energy storage), DIPS modules, or by a reactor power system. Only the PV system and buried reactor system have significant deployment efforts which will be described in following sections.

Figures 15 and 16 show potential base power distribution architectures for the exploration sites and the permanent base, respectively. To reduce the size of the array required for PV systems, the missions could be scheduled during times when there are no global dust storms (assuming that these occurrences can be well predicted).

3.6.3 Small Nuclear Power System Deployment

Reactor systems require considerable radiation shielding to protect base personnel. This shielding can be provided by Martian materials, by transported shields (Ref. 10 mentions a 5,000 kg lithium hydride and tungsten shield), or by a combination of the two approaches. There are several tradeoffs which must be considered when selecting the deployment approach for reactor systems. Buried reactors (with or without additional berm shielding) minimize the mass of the reactor system. However, buried reactors are more difficult to service (all serviceable components must be above the ground level) and more difficult to deploy. Reactor power systems with only transported shielding (four pi shielding) minimizes the deployment effort, but at the expense of the reactor mass (doubles mass of SP-100 system). The power system characterization done in the current study assumed buried reactors in order to minimize system mass and transportation cost. NASA opted for a full 4Π shield mass for easy deployment.

Communications

Crew Habitation

Photovoltaic Power System

Science

Lander Power System

500 m

a)PV power system architecture.

Communications

Power Production

Reactor Power Plant

1-2 km

Crew Habitation

Science

Lander Power System

500 m

b)Nuclear power system architecture.

Key:

P   Remote Power System

S   Switchgear

C   Converter

     Load
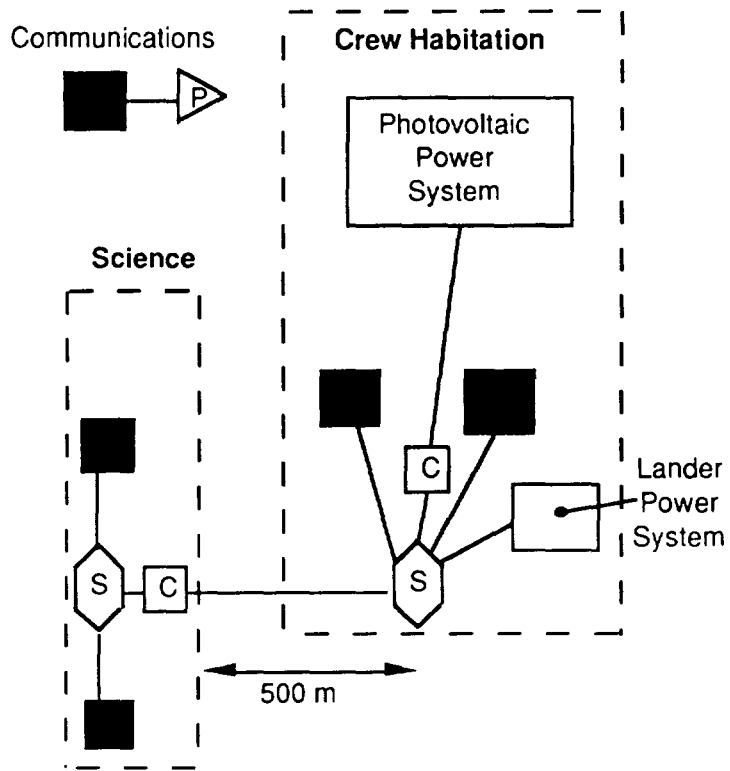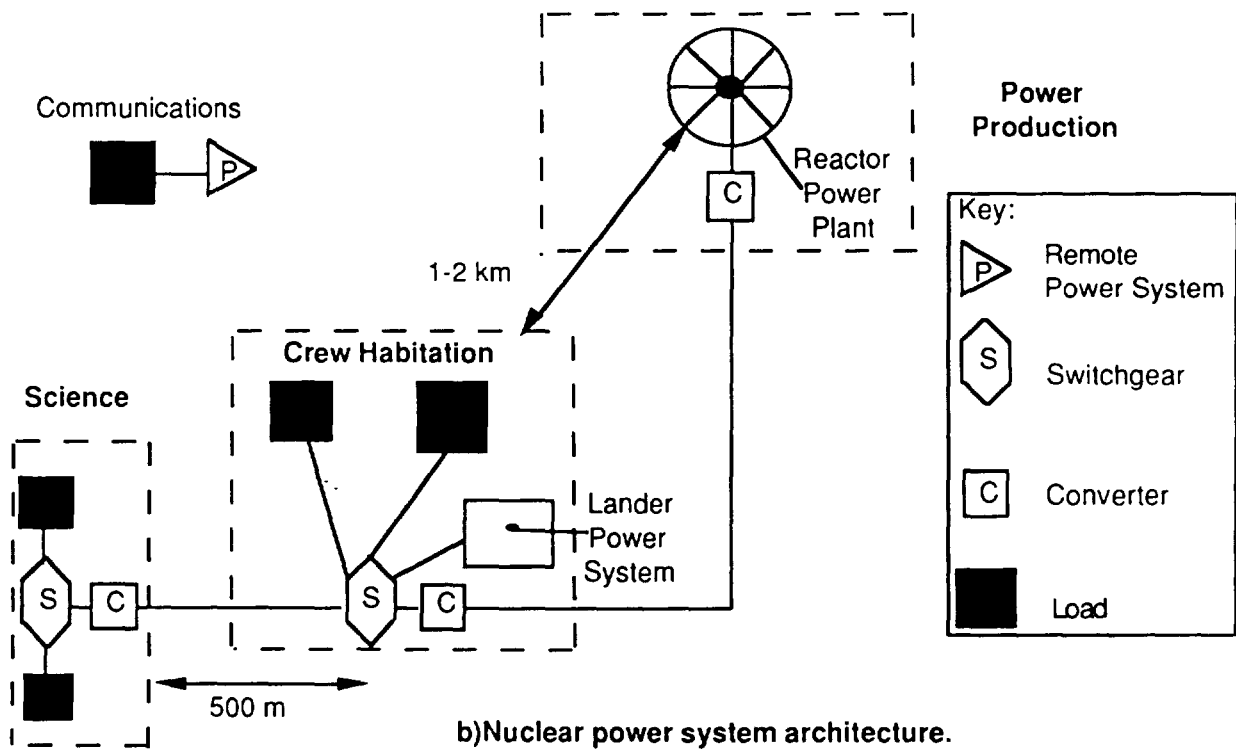
Figure 15. - Exploration site power distribution architecture.
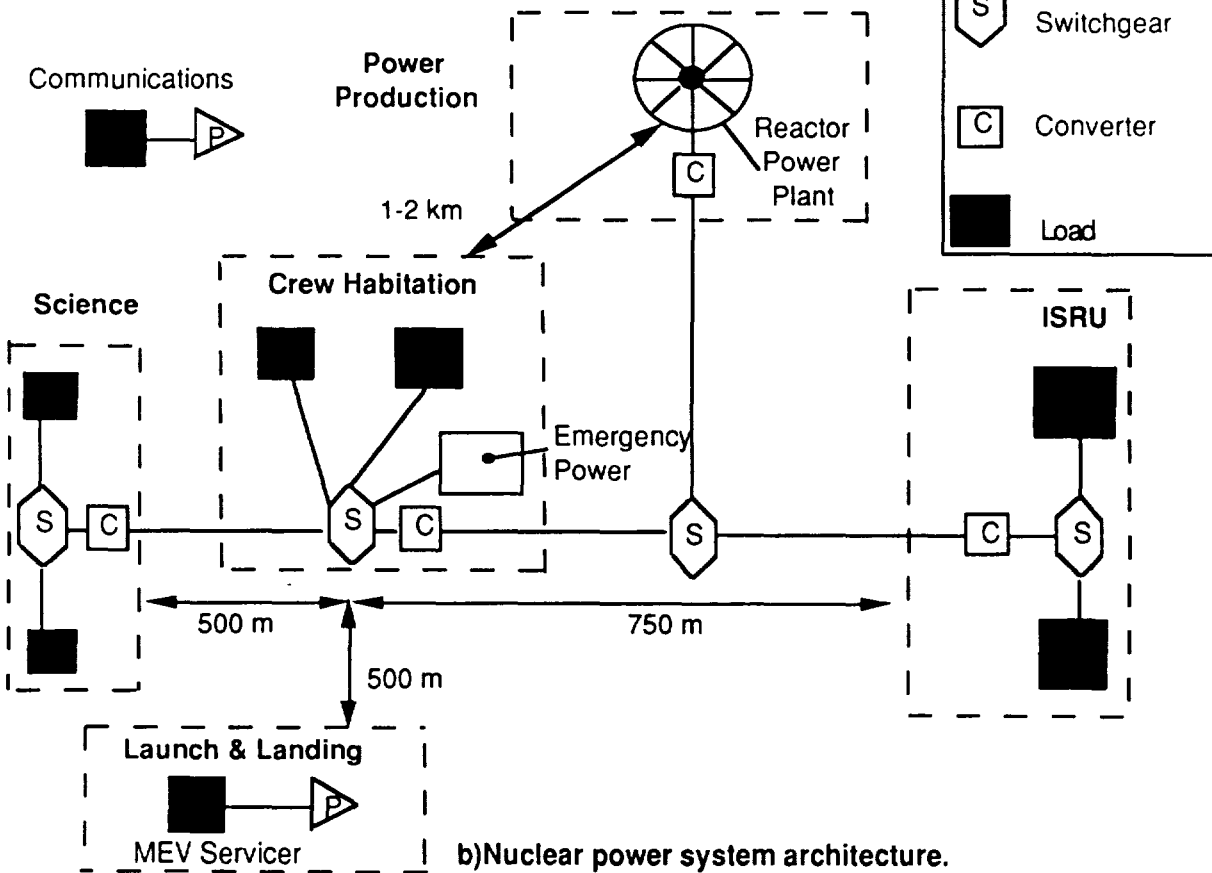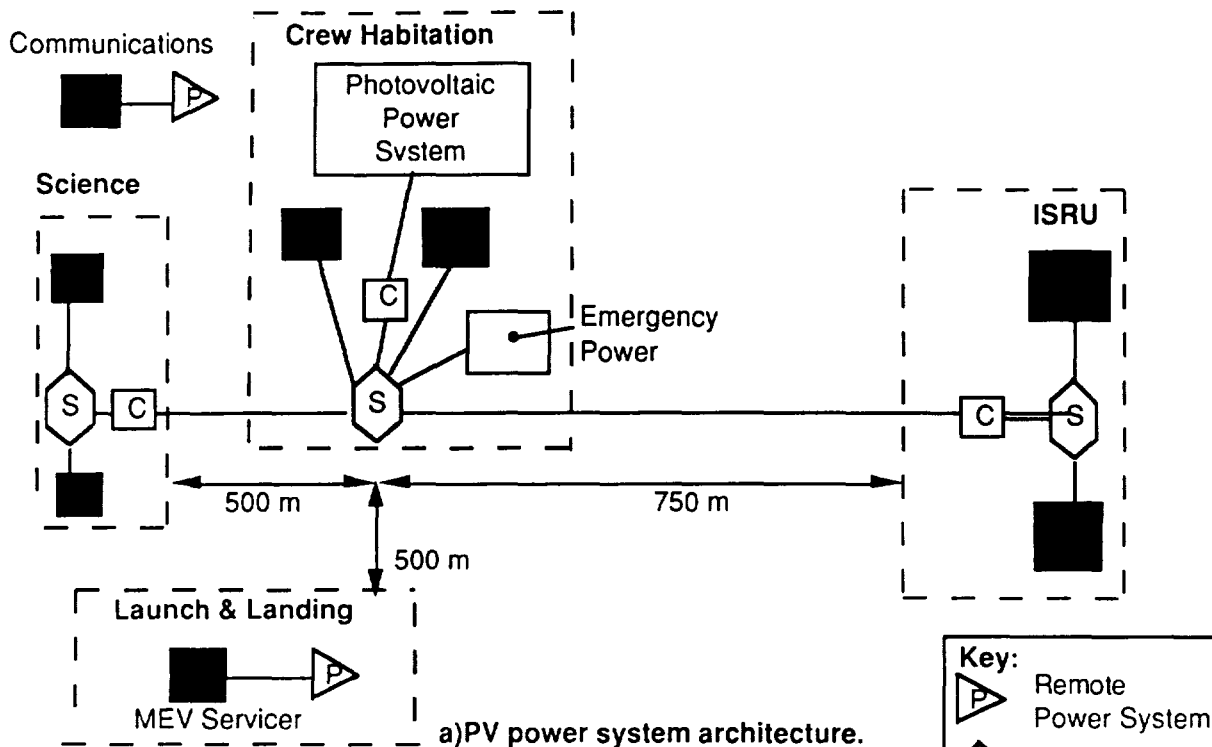
Figure 16. - Permanent base site power distribution architecture.

The deployment approach used is to place the entire reactor, its power conversion units, and control assemblies into the Mars excavation (Ref. 10) as was shown in Figure 13. This approach assumes that most uncertainties and contingencies associated with the Martian soil characteristics have been identified. The amount of regolith being handled during construction is minimized while maximizing the radiation attenuation from regolith material.

The only transported shield for this concept is the shell of the regolith shutdown shield. This shell is filled with regolith to protect astronauts during the shutdown period. This concept of placing the previously mentioned reactor components below grade effectively provides substantial Mars regolith shielding for the beam component of the radiation and effectively attenuates the radiation's scattered component from the control assemblies and power conversion units. Operating doses well below 5 rem/year at a distance from the reactor of 1000 m should be feasible. In fact, this option could probably enable the reactor to be placed much closer to the habitat due to the significantly reduced scattered component of radiation from above grade hardware.

The MEVPU and unpressurized rover may be used for installing the reactor power system. These systems would be DIPS powered if deployment time is to be minimized (no recharging required). If this portable equipment is powered by energy storage systems, then a DIPS powered 12 kWe emergency power system could be used for recharging. Recharging of the construction equipment energy storage systems would increase the deployment time. DIPS powered equipment was assumed for task duration estimates. The total deployment was estimated to take 48 days (after the site has been surveyed). The following tasks must be accomplished in the emplacement of this power system option (Ref. 10):

1)   Survey site - orbiter or rover.

2)   Prepare site using MEVPU or rover with attachments (task duration - estimate 10.9 days per Refs. 12 and 13).

    a)   Transfer the MEVPU or rover to power plant site.

2)   Site preparation (continued):

    b)   Excavate the hole using the MEVPU or rover.
        i.Drill 6 holes and set fracturing charges.
        ii.Remove rubble left after firing charges.

    c)   Grade the site using the MEVPU or rover - clear debris, level, collect soil for later backfill operation.

3)   Emplace the power plant (task duration - estimate 24 days).

    a)   Return the MEVPU to the landing sites.

    b)   Remove the power system from lander using the MEVPU and transport to plant site.

    c)   Orient the power system in the vertical position and unfold the reactor's radiator panels to the horizontal position. Ensure that the panels are locked in place.

    d)   With the MEVPU bridge and crane assembly, pick the reactor up and place the entire assembly over the excavation.

    e)   Lower the assembly into the excavation and attach radiator supports at grade level.

    f)   Backfill the hole and fill the regolith shield using the MEVPU or rover.
    g)   Deploy the control, instrumentation, and power cables. Place local reactor controllers and power conditioning, control, and distribution equipment in position. Use the MEVPU or rover.

4)   Install utility lines (to switching station and to loads; estimated task duration of 11.7 days per Refs. 12 and 13).

    a)   Prepare trenches for the lines using the MEVPU or rover.

    b)   Lays lines using MEVPU or rover.

    c)   Fills trenches using MEVPU or rover.

5)   Initiate automatic reactor thaw and startup (task duration estimated to be 1 day).

    a)   Thaw the liquid metal or other frozen coolants - use battery, isotope, or ground heating.

    b)   Startup power system.

    c)   Run at full power for TBD time and check performance; use dummy load (resistance).

    d)   Transmit data to Earth for review - reactor must operate successfully before piloted launch.

6)   Place reactor in standby mode prior to piloted landing.

3.6.4 PV Power System Deployment

PV systems, especially those with PEM RFC energy storage, require very large arrays (7,795 m^2 for 25 kWe net output). This is because the systems were sized for minimum day insolation (includes the effect of global dust storms) to minimize energy storage mass and system mass. The large number of array modules and their size (350 modules for 25 kWe power system; each about 2 m by 11 m) greatly increases the deployment effort over that required for lunar systems. Figure 17 shows a potential site layout for a 25 kWe PV/PEM RFC power system.

The PV modules are assembled into sub-arrays on site. The sub-arrays are then connected to the PEM RFCs or NaS batteries. The energy storage subsystem housing is a separate unit which includes the PP&C subsystem. The energy storage subsystem/PP&C unit is connected to the arrays after array deployment. The RFC subsystem also includes a vertical radiator for heat rejection.
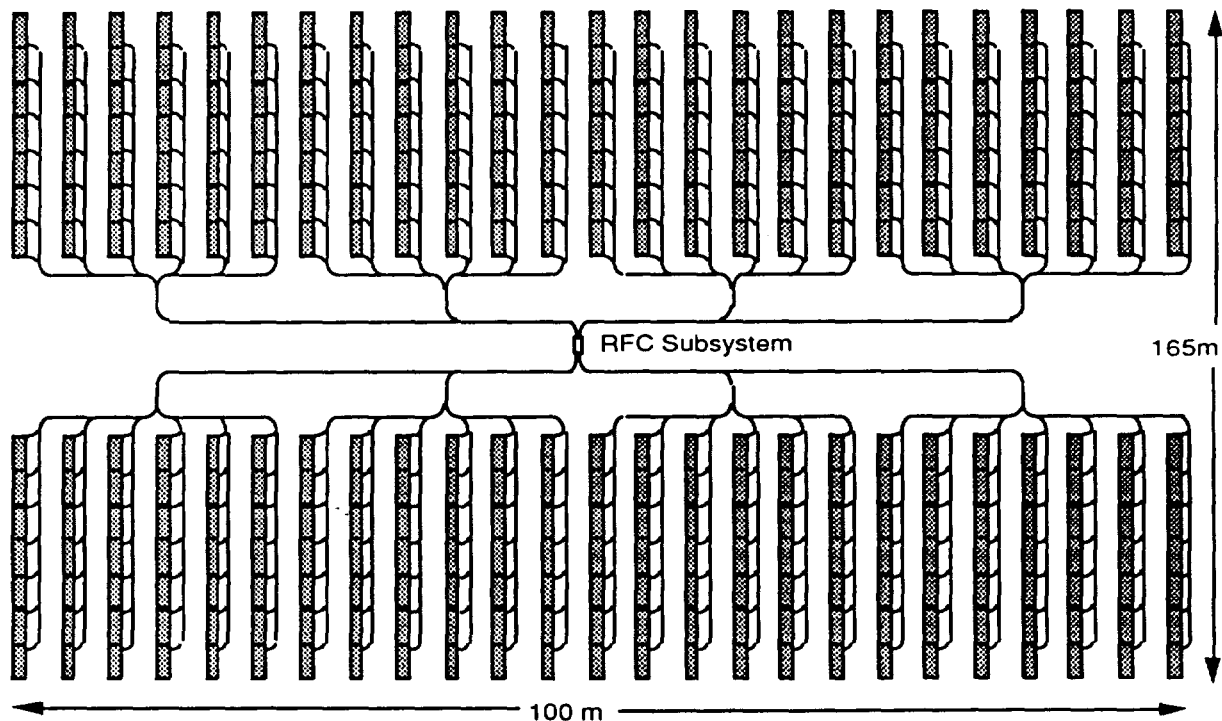
Figure 17. - 25 kWe PV/PEM RFC site layout (not-to-scale).

Robotic construction equipment will be needed for installing the PV power system. This equipment could be DIPS powered if it was necessary to minimize deployment time (no recharging required). If this portable equipment is powered by energy storage systems, then a DIPS powered 12 kWe emergency power system could be used for recharging. Recharging of the construction equipment energy storage systems would increase the deployment time.

The following tasks must be accomplished in the emplacement of this power system option:

1)   Survey the site - orbiter, then rover.

2)   Prepare the site.

    a)   Transfer the construction equipment to the site.

    b)   Grade the site. This allows the PV arrays to be set on the surface rather than being supported above the surface by additional structures which add mass to the system. This preparation is also required to allow the radiator reflective ground sheets to be laid flat on the surface. This part of the deployment process could be the most lengthy depending upon the condition of the selected site. A site that is relatively smooth may need nothing more than a simple grading. A site covered with boulders will require more preparation. In either case, earth moving construction equipment will be needed. Because of the amount of time it takes to do earth moving, this equipment will need to be at least partially autonomous. The site preparation equipment would be programmed to prepare a section of the site without any human supervision. Periodic checks could be made on the progress of the site preparation. If an error or abnormality occurs during the process, then corrective action can be taken.

3)   Emplace the power plant.

    a)   Remove the power system components from the lander. Transport the power system components from landing area to the site. This would involve the use of a payload unloader and a rover.

    b)   Deposit PV panels and radiator panels at appropriate locations on site.

    c)   Activate self-deployment mechanism for PV modules. Assemble modules into a sub-array (hook modules electrical cables to sub-array electrical cable).

    d)   Lay electrical cabling from module to centrally located energy storage/PMAD system (may include excavation and burying of cables).

    e)   Assemble remaining PV modules in a similar fashion.

3)   Emplace the power plant (continued).

f)   Deploy radiator for RFC/PMAD subsystem. Roll out the reflective ground covers on each side of the radiator.

g)   Connect radiator to energy storage module (fluid lines).

h)   Connect RFC/PMAD to base electrical distribution systems.

Steps b through f will require a piece of construction equipment that has enough dexterity for connecting cables and setting down small packages in a given orientation. This equipment could be a simple robotic arm mounted on the rover.

4)   Install power distribution lines (same procedure as for reactor).

5)   Startup power system and test. This task can be done using Earth telemetry.

6)   Standby prior to need.

The following sections discuss design options for self-deploying mechanisms for PV arrays and RFC heat rejection radiators.

3.6.4.1 PV Array Deployment.   The largest elements to be deployed are the PV arrays. Issues which affect the deployment of the PV modules include site preparation (i.e., has the surface been graded to remove large obstructions?), orientation (tracking or non-tracking), geometry (flat, tent, tilting panels), shading (self-shading or shading of other modules; large separation required for tracking arrays - about 7 m for 1.5 m panels), array blanket flexibility (i.e., can it be stowed in a rolled or folded condition?), dust collection and removal, and any required elevation of the modules above the surface. The effects of array orientation on the power profile (due to direct solar energy input) and cover slip transmittance (due to dust obscuration and abrasion) were discussed previously in Section 3.4.3.

Various array designs were identified as a result of a literature review. These included rolled or folded arrays (during storage), tent arrays, and tracking arrays. Table 29 list three of the most likely designs for the Mars array.

TABLE 29. - ARRAY DESIGN COMPARISON

	Advantages	Disadvantages
Tent	•Lightweight (0.65 kg/sq m)	•Semi Auto Deployment •Requires more active area •Non-rigid design may have problems with wind loading
Single Axis Tracker	•Lightweight (1.15 kg/sq m)	•Semi Auto Deployment •Non-rigid design may have problems with wind loading •Increased complexity
First Lunar Outpost (FLO) Based Design	•Auto Deployment •Rigid design can better withstand "real" wind loading	•Heavy (3.79 kg/sq m) •Increased complexity

The First Lunar Outpost power system is a lander mounted design with rigid array panels much like a conventional satellite design. If left on the lander, this design needs no site preparation and is deployed automatically by a signal sent from Earth. The FLO design can also be designed for ground mounting which would require site preparation. The lightweight tent and single axis tracker designs are ground mounted and will require some degree of site preparation.

A PV tent array has been investigated by Sverdrup Technology, Inc. for use on the Moon and Mars (Ref. 23). A 60 degree tent shape was chosen by Sverdrup to produce a nearly constant power profile during the day period. A constant power profile would minimize the mass of the power management and distribution system and any storage device which may be used with the array. One concern with the tent type array is that the curve of the blanket will produce a partial shading on the back side of the array. This can be a problem since partial illumination of a string of PV cells can short out the string. This problem can be alleviated by designing the cell/cover slip stack to make good use of the diffuse light as well as the direct solar input and by aligning the strings such that they run parallel to the shading line. Sverdrup did not include the effects of diffuse light, reflected light from the surface, or the thermal variation of the PV blanket. Diffuse light and reflected light would improve the output of the blanket while the thermal variation of the blanket would tend to reduce the PV cell efficiency.

As previously stated, the PV arrays were assumed to be horizontal in this study. This was due to the large amount of diffuse energy input to the array (50% - 100%) based on the assumption that both regional and global dust storms would occur during the mission. Thus, there seemed to be little advantage to using tracking or oriented arrays to level out the power profile due to direct solar energy input. There may be a slight disadvantage in flat arrays over arrays angled at 22.5 degrees from horizontal due to dust abrasion and obscuration (assuming that the arrays are initially coated with dust prior to the impact of winds on the arrays; Ref. 25). However, there is the advantage of increased reliability of a non-tracking system over a tracking system. In addition, the structural mass of a flat array is also less than for an oriented or tracking array (due to effect of wind loading). For short missions during times when there are no global dust storms, then a tent or tracking array may be desirable to minimize the variation in power output from the arrays (reduces the mass of the power management and distribution system).

A self-deployment system was used in the Sverdrup tent array design. The deployment sequence for this array is shown in Figure 18. The array is stowed with the blanket either folded or rolled, depending on the particular blanket's flexibility. The array structure includes a combination of cables, beams, and columns to support and deploy the PV blanket. The columns are a series of hollow telescoping cylinders which lock into place after being extended. Deployment of the array is done by releasing compressed gas into the columns from a storage tank in the base of the array. As the gas pressure increases in the columns, they extend and deploy the blanket. A similar approach could also be utilized to deploy a flat array.

(a) Stowed configuration.
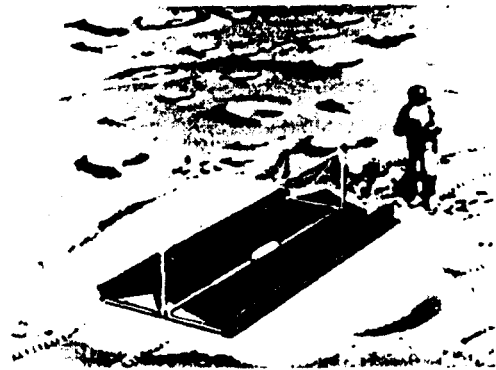
(b) Semi-deployed configuration.
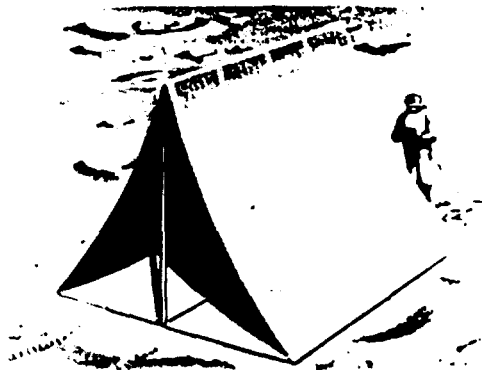
(c) Deployed configuration.

Figure 18. - Deployable tent PV array (Ref. 23).

3.6.4.2 RFC Radiator Deployment. A folding accordion panel design was identified in an earlier Rocketdyne Study (Ref. 10) as a potential concept for deploying vertical radiator panels. They are fashioned to be readily storable in the cargo bays of the various space transportation vehicles while being as near automatically self-deployable as possible on the Mars surface.

These panels are shown in Figure 19 for thermal heat rejection radiator applications. They are basically contained as a collapsible box with a top and bottom 2-track system for ease of deployment. The radiator panels are hung within these two tracks. The top and bottom tracks are in-turn connected to two expandable A-frames on each end as shown. Hence, these panels are set up by: first opening the A-frames to their fully extended position; expanding the top and bottom tracks by pulling the two A-frames apart; and sliding the radiator panels across the tracks in a "shower curtain" fashion until they fully enclose the tracks from both ends of the A-frame.
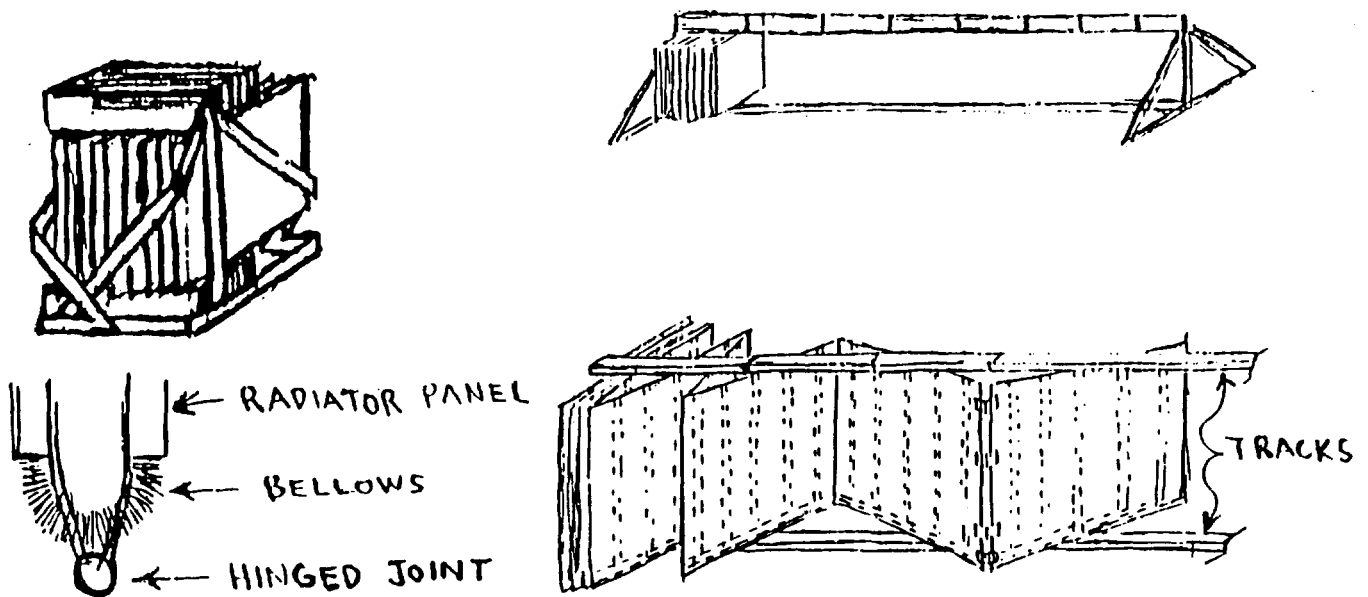
Figure 19. - Detached radiator panel deployment (Ref. 10).

The flexibility between any two adjacent radiator panels is provided by hinged-bellow joints. These joints have two pipe bellows for transporting heat transfer coolant fluid from the energy storage unit to each radiator panel and back again in a pumped loop. Heat is distributed over each individual radiator panel surface by a number of parallel vertically oriented heat pipes.

In all cases, the folding accordion radiator panel system would be made as self-deployable as possible. These will probably be internal motors and pulleys for spreading panels and tracks so as to minimize robotic requirements.

3.7 OPERATIONS - MAINTENANCE/SERVICING

It is expected that all electrical power generation systems will be designed to operate in a completely self-autonomous manner with little or no human involvement. Controllers will be designed with significant levels of "artificial intelligence" in order to properly sense the "health" of these systems and make all necessary adjustments and corrections for successful long term operation. However, vital power system health data will be continuously sent to various terrestrial and planetary mission control centers for continuous monitoring by human personnel if desired. The power system's controllers will also be provided with human over-ride (i.e., manual) capability should mission control subsequently require a more hands-on approach.

Occasionally, either routine maintenance or servicing to repair a power system failure may be required. As part of this study, potential maintenance and servicing needs were identified for potential Mars power systems. Approaches and equipment required for servicing these systems were also defined.

The Martian environment presents unique problems to the design of electrical power generation systems over and above those encountered for the design of lunar based equipment. The main problem appears to be the Martian atmosphere which contains significant quantities of oxidizing gases -- mostly carbon dioxide with some water vapor. For relatively high temperature direct and in-direct electrical power conversion systems which rely on refractory metals as the construction material of choice within many critical components, these gases can cause severe corrosion problems which will significantly shorten the useful life of these devices. Furthermore, additional insulation of high temperature components is required to maintain parasitic heat losses to reasonable levels due to increased environmental heat transfer from thermal convection which is not found in the lunar atmosphere.

The electrical power conversion systems currently being proposed for Mars are typically more complex than their lunar counterparts. This complexity resides in the incorporation of vacuum (or gas tight) vessel enclosures around individual components or

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complete subsystems. These enclosures will insure that oxidizing gases will not come into contact with critical high temperature refractory metal surfaces and that parasitic heat transfer losses from these surfaces to the Martian environment will be minimal.

The increased mechanical complexity of these power conversion systems will also increase the difficulty in maintaining and servicing these devices. Many subsystems and components will no longer be accessible for on-site repair or replacement due to their location within a gas tight vessel or enclosure. Other components made from double wall construction methods (with vacuum cavities) present new problems for the maintenance design engineer. Furthermore, the basic operating concepts of these Martian power systems will be different from those earlier systems designed only for lunar applications.

In addition to increased mechanical complexity for corrosion prevention, power systems for Mars surface missions must rely even less extensively on human involvement than for lunar applications. This is because of the radio-transmission delay times between earth and Mars. These communication delays make it nearly impossible for a human operator on earth to control power system operations and servicing by telerobotic methods. Catastrophic power system failures or unacceptably long servicing times would most likely result if control delays (from sensor stimulus to actuator response) are on the order of many minutes or longer. Because of these unacceptable control delays using earth bound operators --- together with the fact that astronaut activity on Mars is not best served for support of electrical power systems (except on a limited as needed basis) --- these power plants will probably have to be maintained and operated by artificial intelligence (AI) methods. The uncertainty, regarding the maturity of AI methods in the next century, makes the establishment of "specific" design requirements for power system compatibility with AI maintenance and operating interfaces somewhat difficult at this time. Nevertheless, early strawman design concepts must be identified to rapidly facilitate workable Martian power plants.

Logistic studies at NASA's Goddard Space Flight Center have shown that electrical power generation systems should be maintainable at the subsystem and component level (i.e., a

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complete power system should not have to be discarded simply because one component within that system fails). These subsystem and component maintainability goals were identified based upon studies using the Goddard SDU (System Design Utility) and EDCAS (Equipment Designer's Cost Analysis System). These studies show the prohibitive costs associated with launching new complete power replacement systems to the moon and Mars in order to restore electrical power production capability in the event of unforeseen outages.

Electrical power generation systems were investigated (Ref. 16) in terms of their ability to be fully operated and maintained by completely autonomous methods without the need of human involvement. Based upon the rapidly progressing state of micro-sensors, micro-actuators, and artificial intelligent processors; it is expected that (sometime in the 21st Century) Martian planetary surface power systems can be designed for fully autonomous start-up, shut-down, load following, and maintenance/repair operations. However, some intricate repairs to complex subsystems (such as internal reactor control-rod drive components and nuclear refueling operations) are so dangerous and of such difficulty that it is not expected they should ever be performed --- whether by robot or EVA methods.

Servicing equipment for these electrical power systems will probably include a Jet Propulsion Laboratory (JPL) type "Robie" rover which supports a manipulating device such as the Spar Aerospace Ltd.'s Special Purpose Dexterous Manipulator (SPDM). Figure 20 shows a conceptual schematic of this device. It is expected that in the 21st Century the SPDM will be highly versatile and capable of anthropomorphic (i.e., human like) operation. Its end effectors will include not only "special tools" (e.g., screw drivers, pliers, etc.) but also highly anthropomorphic "hands" for grasping, feeling, seeing etc. These end effector tools and hands will probably be removeable for quick change out and rapid versatility depending upon the servicing task to be performed.

The SPDM will more than likely carry its own on-board computer for sensor controlled operation. This very large scale sensor based control scheme (using camera vision sensors, tactile sensors, accelerometers, etc.) will probably be a hybrid "neural net" with some

"programmable" central processing unit (CPU) type computer. This scheme will probably allow the rover/SPDM assembly to function in a nearly autonomous manner while performing its servicing (R&R --- remove and replace) tasks without the aid of human involvement or supervision.
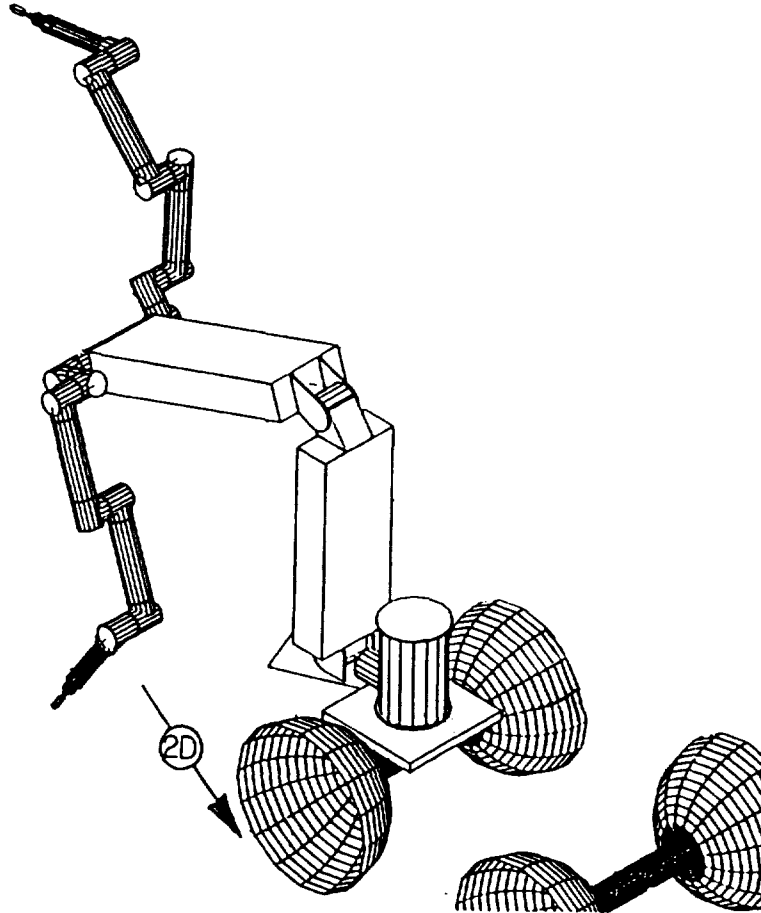
Figure 20. - The Robie/SPDM robotic servicer.

Probably the easiest servicing tasks to be performed will the replacement and repair (R&R) of electrical processing equipment whereby the only functional connections are electrical contact points. However, performing R&R on mechanical components and subsystems will require a special arc welding/cutting device for breaking and reconnecting fluid transport lines. Such a device is currently being developed by Rocketdyne. This device is composed of an arc welding/cutting head containing a three stage rotor which rotates a hollow electrode 360 degrees around a pipe while the handle remains stationary. The handle contains the quick

disconnect fittings for attaching the electrical power supply and blanket gases for welding. It is expected that this device will allow for the R&R of various pumps, radiators, and other mechanical components which can be attached to process piping at single wall locations.

Examples of feasible servicing tasks are listed in Table 30. These tasks are mostly concerned with the removal and replacement (R&R) of failed components. It is expected that these power systems are being designed so that routine maintenance will not be required. The only maintenance envisioned will be to replace unexpected broken or severely damaged equipment. The precision and capacity of the JPL rover and Spar SPDM robotic servicer should be capable of handling these R&R tasks.

TABLE 30. - POWER SYSTEM SERVICING TASKS

Servicing Task
Radiator Panel Tube Leak Repair
Complete Radiator Panel Replacement
Electronics Radiator Replacement
Parasitic Load Radiator Replacement
PP&C Unit Replacement

All servicing tasks should be capable of being performed both by autonomous robots (without the aid of any human involvement) and by direct astronautic intervention methods. It is expected that by the time the first launches to Mars take place, any maintenance servicing task which could possibly be performed by an astronaut will be capable of also being performed autonomously by robotic methods. However, all servicing tasks should be backed up by human intervention methods for added safety margins during specific SEI missions.

It should be further noted that all R&R activities listed in Table 30 will probably be performed only after a Martian outpost has developed to a reasonable high level of maturity. This is because it is doubtful that during the first stages of establishing a human presence on the

Martian surface resources will be allocated to: building warehouse facilities for spare parts, or sending extra equipment for possible replacements.

3.8 OPERATIONS CONCEPTS - STARTUP AND SHUTDOWN

Operations concepts were evaluated for both nuclear reactor and PV systems. Transient operating conditions are often of most concern, especially for autonomous operation. Thus, general startup and shutdown procedures were defined for each type of system to insure proper operation. The Driver Fuel TFE reactor system is used in this section to provide an example of operating procedures for reactor systems. Both PV/RFC and PV/NaS battery system startup and shutdown procedures were examined. These procedures are discussed in the following sections.

3.8.1 Reactor Startup and Shutdown

Initial checkout of the Driver Fuel TFE reactor power system -- after transport to its permanent site location and radiator panel deployment (as described in Section 3.6.4) -- begins by thawing the frozen NaK primary and secondary coolants in their two separate storage vessels. The voltage current data (along with temperature measurements of the electrical trace heating system) are compared with expected values to assure the thaw system is working properly. Electrical power for this coolant thaw system is provided by on-board batteries. Once the NaK storage vessels have been brought up to temperature, the primary and secondary coolant recirculation pumps are turned on to about 25% of their rated flow rate. Pressure drop data throughout the two recirculation loops are obtained and compared to expected values before continuing to the next series of start-up events.

Once the NaK recirculation loops are operating at their predetermined state points, reactivity (from the control segments) is then inserted until just before criticality is reached. At this point, data from neutron flux sensors and control rod drum position sensors are compared with expected values prior to proceeding. Once it is concluded that all subsystems are operating as expected, the reactivity insertion is continued.

Prior to reaching criticality, the electrical bus is short-circuited. This will provide some added dampening in thermal power pulsing by allowing rapid electron boiling. By monitoring the neutron flux (with fission chambers) along with electrical current, reactivity

will be slowly added to the reactor. Once ignition has been reached at a low thermal power, the short circuited electrical bus will be given a predetermined resistive load and control will be passed over to a primary voltage-current (V-I) controller. The V-I approach is a convenient, fast, indirect method of measuring emitter temperature that can be readily correlated to experimental data. This control method is used throughout the remainder of the start-up sequence until full rated electrical power is being generated at expected reactor coolant and emitter conditions. During start-up, this electrical power is being dissipated by the parasitic load radiator.

Once the Driver Fuel TFE reactor power system is shown to operate at full power with all systems functioning within expected limits, the PP&C unit will begin increasing the electrical load resistance (while holding bus voltage constant) until a low power steady-state stand-by condition is reached. This low power stand-by set point will be held by the PP&C controller until external user power demands are initiated by subsequent mission activities. Complete shut-down of the reactor system is simply the reverse of the start-up scenario described above with reactivity withdrawal until the reactor is no longer critical.

It is expected that the PP&C controller will be capable of operating the Driver Fuel TFE reactor power system without the aid of human involvement even during the start-up and shut-down sequences. However, some event trapping points along these transient sequences may be provided in order to allow human monitoring and intervention to occur. In all cases there will be fail-safe trips in the control sequence to prevent reactor melt-down.

3.8.2 PV/RFC Power System Startup and Shutdown

It was assumed that there are no specific requirements or problems for startup of the PV arrays. The arrays were assumed to be the flat, non-tracking type. Thus, the arrays do not have to be positioned prior to startup or repositioned during operation to track the sun.

The PEM RFC system would be delivered to Mars with the tankage fully purged with the appropriate gas (oxygen, hydrogen) in the tank at low pressure (Ref. 19). Having a positive

pressure will prevent inward leaks of atmospheric carbon dioxide. However, leakage of carbon dioxide into a PEM system would not be particularly bad and is not a critical concern.

The RFC system must be thermally conditioned during transit to Mars and prior to startup to prevent critical components from freezing. In particular, the stored water must be insulated and heated to prevent freezing which could damage the tanks and prevent flow in the outlet line during startup. In addition, the water in the cell membranes should be prevented from freezing (although current cyclic temperature testing by Hamilton Standard from ambient down to 244 °K shows no change in performance) to prevent any reduction in performance or life. One approach would be to maintain the electrolyzer in an idling mode prior to Mars operation. This would require a small amount of power from another system to drive the electrolyzer (perhaps a current of 5 Amps) and to power the coolant water recirculation pumps. The valves between the electrolyzer and storage tanks would remain closed during idling. The electrolyzer pressure would be allowed to slowly build up until equilibrium is reached (gas production equals diffusion losses). All current then goes into heating the electrolyzer (i.e., operating at about 311 °K). The water used to cool the electrolyzer could be used to provide heat to the fuel cell for thermal conditioning (through a heat exchanger). Another approach would be to insulate the RFC system and use electrical heaters to maintain the components above freezing.

After deployment of the system, startup is achieved by applying 300 Amps or more of current from the PV array to the electrolyzer stack. The electrolyzer will rapidly come up to full load due to internal resistance heating in the stack. The valves to the gas storage tanks are then opened to allow the produced oxygen and hydrogen to go into storage.

The fuel cell is started by opening the valves from the reactant storage tanks. The power plant starts rapidly and will achieve full power in less than 30 seconds after the reactant gases enter the cell stack (Ref. 21). The power plant responds to load variations and requires no active operator control. The fuel cell can be run in an idle mode for a relatively long period (tests run by Siemens at 3% rated load; Ref. 22), if necessary.

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The electrolyzer system is either shutoff (power system is disconnected or shut off) or put into the idle mode during shutdown. Prior to complete shutdown of the system for maintenance, any water in the lines should be drained out (assuming the lines are allowed to reach water freezing temperature).

3.8.3 PV/NaS Battery Power System Startup and Shutdown

Initial checkout of the PV/battery power system -- after transport to its permanent site location and radiator panel deployment (as described in Section 3.7) -- begins by thawing the frozen NaS batteries. This could be done in stages using a bootstrap approach (Ref. 20). An auxiliary power source (primary battery or PV array) could be used to provide power to a heating coil wrapped around a group of batteries. The voltage current data (along with temperature measurements of the electrical trace heating system) are compared with expected values to assure the thaw system is working properly. Once the initial cells come up to temperature (about 673 °K), then the batteries will begin to function and produce power. The power from the first batteries can be used to heat up another bank of batteries. This process will continue until all of the batteries are at operating temperature. Once at operating conditions, the batteries must be well insulated to prevent loss of heat.

To shut down the system, the batteries would be cooled. Hughes has proposed the use of louvered doors to allow the batteries to radiate heat directly to space. These doors could be opened during shutdown to allow the battery to cool off and freeze.

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3.9 ADVANCED TECHNOLOGY DEVELOPMENT NEEDS

This section of the study was devoted to the definition of technology roadmaps or preliminary development plans. These roadmaps are intended as an aid for NASA in planning technology development for Mars surface power applications. A technology roadmap provides an estimate of the time needed to develop flight qualified hardware given the current state-of-the-art, the required major development tasks, and the schedule for hardware development.

Potential development programs for both fixed power systems (GaAs-Ge/CIS PV array/PEM RFC, GaAs-Ge/CIS PV array/NaS battery, SP-100 TE, SP-100 Dynamic, and Driver Fuel In-core TFE reactor) and mobile/portable power system modules (PEM RFC, NaS battery, and CBC DIPS) are described in Appendices A to H.

The development plans lay out the required tasks to take the power system and components from their current technology levels through flight status. Integration of mobile power system modules with the user load (i.e., vehicle or mobile equipment) was not included. Instead, a generic module approach was taken for power system development. Each power system development plan was treated independent of the others during this portion of the study since it is not known which power systems will be developed. Thus, each development plan is a standalone document. Thus, the effects of prior or parallel development of other power systems were not considered during definition of the development plans. These impacts will be discussed in Section 3.10 for an example power system architecture.

The development plans were divided into component development, Ground Engineering System (GES) development, Qualification Unit development (QU), and Flight Unit (FU) Development. Due to the limited nature of this effort, only major development tasks were identified. Power systems were broken down into major elements or subsystems for ease of description. Both component and system development tasks were identified and described.

Power system technology roadmaps were developed based on the current technology status. Technology status was first assessed for the component technologies and then for the systems. Obviously, the component technology selected affects the technology readiness rating.

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The final component definition has not yet been completed for all subsystems and thus the component technologies actually developed may vary from that assumed during this study. The component technologies ultimately selected may be driven by the mission needs (i.e., launch timeframe, level of funding, acceptable risk level, power level, etc.). In addition, the exact technology readiness of a given system is difficult to assess since the major subsystems may be at different technology levels. The system technology ratings were selected to be close to the rating for the least developed subsystem to be conservative. The impact of on-going development efforts on technology status was included, where applicable. Thus, the start time of the power system development will affect the system development time (due to prior component and ground system development). The start time for each development effort will depend on future mission requirements and the available funding.

It was assumed that power systems will be designed such that flight testing and verification is not required. Ground testing will be done on the component, subsystem, and system level. Qualification testing was included for both components and flight systems. Component qualification testing could be eliminated to reduce costs. Due to the need to reduce development costs for SEI, it is assumed that power systems will be designed to meet both lunar and Mars environments and applications. This forces the technologies to be ready earlier than required for Mars applications. However, this approach improves the likelihood of success for Mars applications which have critical reliability, life, and safety requirements.

Each roadmap includes discussion of the system concept, how the concept differs from current development efforts, and what the impacts of the changes might be. Major components in the system which differ significantly from previously proposed configurations are addressed separately in more detail. In particular, performance enhancement, challenges to fabrication, and long term operability are discussed.

Major development (technical, cost, and operational) issues which remain to be addressed for each power system are addressed here. Both component and system level issues

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are included. The negative system impacts of these issues are identified as well as potential development areas.

The current state-of-the-art was assessed for each power system and major subsystem using the NASA Technical Maturity scale as seen in Table 31. In assessing the technology base for each power system, the key considerations were as follows:

- the degree to which the technology data base is directly applicable to the power system configuration and operating conditions;

- the extent of the applicable data base in terms of number of tests and operating hours and number of units tested and operated;

- the number of items requiring developmental testing; and

- the design basis for the technologies

Overall program plans for each power system were developed which address all major technology issues involved with component development, testing, fabrication, and launching. Additional development time is reserved for system integration to insure satisfactory system performance will be obtained.

A successful SEI power system program will need to focus on developing these technologies, designing and testing actual flight components, and integrating them into complete power systems that will be tested in a representative environment. This will include: demonstrating system level capabilities such as fully autonomous operation in space environments, modularity to support a wide range of power levels, new component design approaches to ensure long life integrity, and testing a complete flight prototypic system from energy source to radiator.

The results of the technology assessment and development plan study are summarized in Tables 32 and 33 for portable and fixed systems, respectively. This table includes estimated development time, technology readiness levels, and technology development needs for both components and systems.

TABLE 31. - TECHNOLOGY READINESS LEVEL

Level	Evaluation
1	**Basic principles observed and reported** The earliest stages of basic research, where physical principals are established
2	**Technology concept and/or application formulated** Basic concepts are incorporated into concepts for hardware or software, and research begins to determine the feasibility of the applications.
3	**Analytical and experimental critical function and/or characteristic proof-of-concept** Critical functions are proven for hardware and software either by analysis or experiment.
4	**Component and/or breadboard validation in the laboratory** Breadboard hardware and software concepts are fabricated and validated in a laboratory environment against predetermined performance objectives.
5	**Component and/or breadboard demonstration in a relevant environment** Breadboard hardware and software are tested in an environment that is relevant to proving the technologies will operate in the operational environment of the projected mission application. This may include, if required, flight research and validation.
6	**System validation model demonstrated in a simulated environment** The breadboard hardware and software are integrated into a system validation model and tested in a simulated operational environment to study the interactions between the different components.
7	**System validation model demonstrated in space** A system validation model, incorporating various technology components and breadboard subsystems, is demonstrated in space.
8	**Flight-qualified system** System has been reconfigured for flight conditions. Performance and life testing have been satisfactorily completed.
9	**Flight-proven system** Safety and acceptance testing of flight systems has been completed. Flight system has been successfully utilized in space for a complete mission.

TABLE 32. - SUMMARY OF TECHNOLOGY ASSESSMENT RESULTS - PORTABLE SYSTEMS

Technology	TRL	Development Time* (yrs)	Key Technology Development Needs
PEM RFC		6.75	•Passive or simplified system
Fuel Cell Stack	3.5	3.25	•Demonstrate long life multicell stack of appropriate size •Integrate gas humidifiers and water deoxygenator
Electrolysis Cell Stack	4	3.0	
Tanks	5	2.25	•Corrosion resistant tank liner for composite gas tanks
Water Management	4	3	•Regenerative gas dryers
Thermal Management	3	3.5	•Long life thermal control components •Low mass radiator (carbon-carbon heat pipe) •Thermal control loops •Tank and outlet line thermal management
PP&C	5	2.25	
NaS Batteries		7.00	•Demonstrate long cycle life and flight
Batteries	4	3.0	•Physical and chemical stability of alpha alumina seal •Physical and chemical stability of electrolyte •Sealing technology for tubesheet to cell case •Battery casing design
Thermal Management	3	3.5	•Heat pipe radiator (low mass carbon-carbon; biphenyl working fluid)
PP&C	5	2.25	
DIPS		6	Full penetration inspectable welded boundaries
GPHS Module	9		•Fuel handling canister and tools •Launch and transport container
HSU; RHSR HSU; MFI HSU; Gas Containment	4	2.75	•RHRS heat pipes •Vacuum liners •Meltable Multifoil Insulation (MFI) •Long life high temperature high emissivity coating
PCU	4.5	2.75	•Alternator stator high temperature electrical insulation •High performance laminar flow recuperator
Thermal Management	8	1.25	
PP&C	5	2.25	

*To launch for systems; to TRL 5 for components.

TABLE 33. - SUMMARY OF TECHNOLOGY ASSESSMENT RESULTS - FIXED SYSTEMS

Technology	TRL	Development Time* (yrs)	Key Technology Development Needs
DIPS		6	•See Table 32.
PV/PEM RFC		6.75	•See PEM RFC system comments in Table 32
PV Array	5	2.25	•Thin film arrays •Higher efficiency top cell (AlGaAs) •Larger size cell •Deployment mechanism •Lightweight structure •Dust removal system •Low cost production techniques •Design and test for thermal extremes
PEM RFC	3.5	3.5	•See PEM RFC system
PP&C	5	2.25	
PV/NaS Battery	3.5	7.00	
PV Array	5	2.25	•See PV/RFC system
NaS Battery	3.5	3.5	•See NaS battery system
PP&C	5	2.25	
Driver Fuel In-core TFE Reactor		7.5	
Reactor and Heat Transport	3	2	•Reactor design
Thermionic Fuel Element (TFE)	4	2	•In-reactor TFE and cell tests (life testing) •High strength emitter materials
Heat Rejection	4	2	•High temperature C-C metal lined heat pipe development (liquid metal working fluid)
PP&C	4	2	•Radiation hardened components
SP-100 TE		13.5	
Reactor and Heat Transport	3	3.5	•Reactor design •Vacuum containment or protective coatings, getters, liners, and dust protection
TE Converters	3	3.5	
Heat Rejection	3	2.5	•High temperature C-C metal lined heat pipe development (liquid metal working fluid)
PP&C	4	1	•Radiation hardened components
SP-100 Dynamic Systems		9.5**	•Depends on amount of prior development of subsystems

*To launch for systems; to TRL 5 for components.
**Assumes SP-100 TE system, high temperature PCUs, C-C heat pipe radiator, and PP&C previously developed. Includes system integration, system testing, and qualification for new system. Additional 2-3 years would be required if PCU (Stirling or liquid metal Rankine) needs additional development.

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3.10 POWER SYSTEM ARCHITECTURE STUDIES

Three power system architecture examples were defined as seen in Table 34 based on the highest commonality power systems (Ref. 1). Other power system architectures are possible, but generally with a lower commonality or higher mass. The purpose of this study, as stated previously, was not to determine the optimum architecture or power systems.

Architecture 1 is a predominantly GaAs-Ge/CIS PV array/PEM RFC approach to meeting the power system requirements. Isotope systems are used only for portable systems where continuous power is required (not practical to use energy storage alone due to mass).

Architecture 2 is a predominantly GaAs-Ge/CIS PV array/NaS battery approach which is similar to Architecture A. Batteries are substituted for RFC storage systems.

Architecture 3 is a CBC DIPS and SP-100 TE reactor approach. SP-100 TE reactor systems are used for the base 25 and 75 kWe power systems.

Architecture 4 is a CBC DIPS and Driver Fuel In-core TFE reactor approach. Thermionic reactors are used for the base 25 and 75 kWe power systems.

A power system mass study was completed for each architecture. The mass results for each architecture and power system are shown respectively in Tables 35-38. The total mass of each architecture included all power systems (including multiple systems for each application), but no replacement systems or redundancy. The DIPS and reactor system architectures (Architectures 3 and 4) had the lowest mass by a factor of two.

TABLE 34. - HIGH COMMONALITY POWER SYSTEM ARCHITECTURE DEFINITIONS

Applic-ation	Description	Architecture 1 (GaAs-Ge/ CIS PV array/ NaS battery + DIPS)	Architecture 2 (GaAs-Ge/ CIS PV array/ PEM RFC + DIPS)	Architecture 3 (CBC DIPS + SP-100 TE reactor)	Architecture 4 (CBC DIPS + Driver Fuel In-core TFE reactor)
FIXED POWER:					
M1	Communications (0.9 kWe)	PV*/NaS Batt.	PV/PEM RFC	DIPS	DIPS
M2	Base Power (25 kWe)	PV/NaS Batt.	PV/PEM RFC	SP-100 TE	Driver Fuel TFE In-core reactor
M3	Emergency Power(12 kWe)	PV/NaS Batt.	PV/PEM RFC	DIPS	DIPS
M4	MEV Servicer (10 kWe)	PV/NaS Batt.	PV/PEM RFC	DIPS	DIPS
M5	Base Power (75 kWe)	PV/NaS Batt.	PV/PEM RFC	SP-100 TE	Driver Fuel TFE In-core reactor
MOBILE POWER:					
M6	Unpressurized Rover with Power Cart (5 kWe)	DIPS**	DIPS	DIPS	DIPS
M7	Payload Unloader (3 kWe)	NaS Battery	PEM RFC	DIPS	DIPS
M8	Teleoperated Rover (0.15 kWe)	CBC DIPS	CBC DIPS	DIPS	DIPS
M9	Pressurized Rover, Power Cart for Rover	NaS (7 kWe) NaS (12 kWe)	RFC (7 kWe) RFC (12 kWe)	DIPS (7 kWe) DIPS (5 kWe)	DIPS (7 kWe) DIPS (5 kWe)
M10	Regolith Hauler (3 kWe)	NaS Battery	PEM RFC	DIPS	DIPS
M11	Mining Excavator (22 kWe)	NaS Battery	PEM RFC	DIPS	DIPS

*All PV systems use GaAs-Ge/CIS arrays.
**All DIPS use CBC PCUs.

TABLE 35. - POWER SYSTEM ARCHITECTURE 1 MASS ESTIMATE

Appli-cation	Description	Power Systems	Power (D/N kWe)	Power Systems	Total Mass (kg)
M1	Communications	PV*/NaS battery	0.9/0.9	3	930
M2	Base Power	PV*/NaS battery	25/25	3	25,851
M3	Emergency Power	PV*/NaS battery	12/12	1	4,138
M4	MEV Servicer	PV*/NaS battery	10/10	1	3,448
M5	Base Power	PV*/NaS battery	75/75	1	25,864
M6	Unpress.Rover with Power Cart	CBC DIPS	5/5	5	3,520
M7	Payload Unloader	NaS battery	3/0.0	3	2,658
M8	Teleoperated Rover	CBC DIPS	0.15/0.15	1	352
M9	Pressurized Rover, Power Cart for Rover	NaS battery, NaS battery	7/7 12/12	1 1	1,599 11,540
M10	Regolith Hauler	NaS battery	3/0	1	991
M11	Mining Excavator	NaS battery	22/0	1	5,081
TOTAL					85,972

*GaAs-Ge/CIS.

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TABLE 36. - POWER SYSTEM ARCHITECTURE 2 MASS RESULTS

Appli-cations	Description	Power Systems	Power (D/N kWe)	Power Systems	Total Mass (kg)
M1	Communications	PV/PEM RFC	0.9/0.9	3	909
M2	Base Power	PV/PEM RFC	25/25	3	22,203
M3	Emergency Power	PV/PEM RFC	12/12	1	3,679
M4	MEV Servicer	PV/PEM RFC	10/10	1	3,119
M5	Base Power	PV/PEM RFC	75/75	1	23,228
M6	Unpress.Rover with Power Cart	DIPS	5/5	5	3,520
M7	Payload Unloader	PEM RFC	3/0.0	3	1,076
M8	Teleoperated Rover	DIPS	0.15/0.15	1	352
M9	Pressurized Rover,	PEM RFC,	7/7	1	1,560
	Power Cart for Rover	PEM RFC	12/12	1	3,882
M10	Regolith Hauler	PEM RFC	3/0	1	1,009
M11	Mining Excavator	PEM RFC	22/0	1	4,912
Subtotal - Mars Missions					69,449

TABLE 37. - POWER SYSTEM ARCHITECTURE 3 MASS ESTIMATE

Appli-cation	Description	Power Systems	Power (D/N kWe)	Power Systems	Total Mass (kg)
M1	Communications	CBC DIPS	0.9/0.9	3	1,056
M2	Base Power	SP-100 TE	25/25	3	9,630
M3	Emergency Power	CBC DIPS	12/12	1	1,760
M4	MEV Servicer	CBC DIPS	10/10	1	1,408
M5	Base Power	SP-100 TE	75/75	1	4,960
M6	Unpress.Rover with Power Cart	CBC DIPS	5/5	5	3,520
M7	Payload Unloader	CBC DIPS	3/0.0	3	2,337
M8	Teleoperated Rover	CBC DIPS	0.15/0.15	1	352
M9	Pressurized Rover,	CBC DIPS	7/7	1	1,056
	Power Cart for Rover	CBC DIPS	5/5	1	704
M10	Regolith Hauler	CBC DIPS	3/0	1	967
M11	Mining Excavator	CBC DIPS	22/0	1	3,711
Total -Mars Missions					31,461

TABLE 38. - POWER SYSTEM ARCHITECTURE 4 MASS ESTIMATE

Appli-cation	Description	Power Systems	Power (D/N kWe)	Power Systems	Total Mass (kg)
M1	Communications	CBC DIPS	0.9/0.9	3	1,056
M2	Base Power	Driver Fuel In-core reactor	25/25	3	8,040
M3	Emergency Power	CBC DIPS	12/12	1	1,760
M4	MEV Servicer	CBC DIPS	10/10	1	1,408
M5	Base Power	Driver Fuel In-core reactor	75/75	1	4,125
M6	Unpress.Rover with Power Cart	CBC DIPS	5/5	5	3,520
M7	Payload Unloader	CBC DIPS	3/0.0	3	2,337
M8	Teleoperated Rover	CBC DIPS	0.15/0.15	1	352
M9	Pressurized Rover,	CBC DIPS	7/7	1	1,056
	Power Cart for Rover	CBC DIPS	5/5	1	704
M10	Regolith Hauler	CBC DIPS	3/0	1	967
M11	Mining Excavator	CBC DIPS	22/0	1	3,711
Total -Mars Missions					29,036

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3.11 INTEGRATED DEVELOPMENT PLAN AND TIME PHASING STRATEGIES

Definition of an integrated development plan for Mars power systems depends on the power system architecture selected. Other considerations include the power system deployment approach (i.e., buried reactor or 4 pi shield), life requirements (number of replacement units and when needed), reliability requirements (amount of redundancy require; partial or complete redundancy), and serviceability requirements (autonomous, human and robotic, human). All of these considerations impact the power system technology or design and the resulting development time.

For this study, an example of an integrated development plan was synthesized for Power System Architecture 4 or the CBC DIPS and Fuel Driver In-core TFE reactor power system architecture. The reactors are assumed to be buried to minimize mass. It was assumed that these power systems will be used as soon as possible for lunar missions which will serve to flight prove these systems. To minimize development costs and time, power systems will be designed to operate on either the Moon or Mars. In addition, a limited number of power system module sizes will be selected to minimize development costs. Advanced versions of the lunar modules could be developed for Mars applications. However, a cost benefit analysis would be required to determine if the cost benefits of the new modules outweigh the increased development costs of the power system architecture. For this study, it was assumed that the benefits of advanced modules do not outweigh the additional costs.

Mission schedules and manifests were obtained from the NASA 90 Day Study (Refs. 3 and 4) for both the Moon and Mars. These manifests were modified for the current study. An emergency power system was added to at least provide habitat power. This power system was assumed to be robotically or telerobotically deployed prior to crew arrival. In addition, the arrival of the pressurized rover was moved back to provide a backup to the habitat. For lunar missions, the pressurized rover was moved back to arrive before the start of the long duration (6 month) missions. For Mars missions, the pressurized rover was moved back to the first piloted flight to the permanent site.

The lunar missions, major manifest items (power systems and deployment equipment), and launch schedule are summarized in Table 39 . Some of the missions not pertaining to power system deployment are not shown in Table 39. Prerequisites to deploying the reactor power systems include deployment of the LEVPU and unpressurized rover. It should be noted for Flight A that a 75 kWe reactor is used rather than three 25 kWe power systems deployed over several missions. This approach was taken in order to minimize the deployment effort.

The Mars missions, manifest items, and launch schedule are summarized in Table 40. Mars missions are staggered due to the long trip time (2 years) assumed for cargo missions. It is assumed that the base reactor power systems are launched and deployed prior to launch of the next piloted mission. The launch dates for the early Mars missions were selected to minimize trip time.

Architecture 4 was chosen to illustrate a representative integrated development schedule, as seen in Figure 21. The latest possible development start dates are shown to meet the lunar mission requirements. A development program for a 2.5 kWe DIPS module and integration into various portable equipment is included. Development of a 100 kWe Driver Fuel TFE power system is shown (100 kWe selected to meet lunar base power requirement). The reactor system could also be used for 25 and 75 kWe Mars applications by removing some of the fuel. Not shown in Figure 21 are the development schedules for the vehicles, portable equipment, and other base equipment. Optional qualification life testing and the necessary development of autonomous robotic equipment are also not shown in Figure 21. More detailed task breakdowns and schedules are included in the appendices.

TABLE 39. - LUNAR MISSIONS, MANIFEST ITEMS, AND LAUNCH DATES

Flight No./ Launch Date	Flight Description	Manifest and Major Deployment Tasks
Flight A - July 1999	unmanned	•Deploy unpressurized rover (2 kWe DIPS) •Deploy communications (0.9 kWe DIPS) •Deploy payload unloader (LEVPU) (3 kWe DIPS) •Use LEVPU to begin excavation for 75 kWe reactor power system
Flight B - January 2000	unmanned	•Deploy 12 kWe DIPS system (emergency power system installed telerobotically; use LEVPU to move to habitation area)
Flight 1 - July 2000	unmanned	•Deploy 75 kWe reactor power system using LEVPU and rover (all done telerobotically from earth) •Move LEVPU back to lander and install habitat
Flight 2 - January 2001	piloted, 30 day	
Flight 3 - July 2001	unmanned	
Flight 4 - January 2002	piloted, 30 days	•Deploy LEV servicer (10 kWe DIPS; telerobotic control from base and EVA) •Deploy unpressurized rover (2 kWe DIPS)
Flight 5 - July 2002	piloted, 6 months	•Deploy pressurized rover (7 kWe DIPS onboard, 5 kWe DIPS cart) •Excavate site for 100 kWe reactor using LEVPU (telerobotic control from base)
Flight 6 - January 2003	unmanned	•Deploy LEV servicer (10 kWe DIPS; telerobotic control from Earth) •Deploy 100 kWe reactor power system (telerobotic control from Earth)
Flight 7 - July 2003	piloted, 6 months	
Flight 8 - January 2004	unmanned	•Deploy LEV servicer (10 kWe DIPS; telerobotic control from Earth)
Flight 9 - July 2004	piloted, 6 months	
Flight 10 - October 2004	unmanned	•Deploy second LEVPU (3 kWe DIPS)
Flight 14 - July 2006	piloted, first crew of 8, 1 year, continuous presence begins	
Flight 18 - March 2008	unmanned	•Excavate site for 550 kWe reactor using LEVPU (telerobotic control from base/test autonomous robotic control) •Deploy 550 kWe reactor power system (telerobotic control from base/test autonomous robotic control)
Flight 20 - October 2008	unmanned	•Deploy regolith hauler (3 kWe DIPS) •Deploy mining excavator (22 kWe DIPS)

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TABLE 40. - MARS MISSIONS, MANIFEST ITEMS, AND LAUNCH SCHEDULE

Flight No./ Launch Date	Flight Description	Manifest and Major Deployment Tasks
Flights S1 and S2 - 1998	site reconnai-ssance	•Deploy orbiters
Flights S3 to S5 - 2003, 2005, 2007	site survey - exploration sites	•Land and deploy rovers
Flight 1 - 2012	unmanned, cargo - exploration site #1	•Deploy communications (0.9 kWe DIPS) •Deploy 25 kWe power system (reactor) (robotically) •Deploy unpressurized rover (2 kWe DIPS) •Deploy MEVPU (3 kWe DIPS)
Flight 2 - 2014	piloted, 50 days - exploration site #1	
Flight 3 - 2014	unmanned, cargo - exploration site #2	•Deploy communications (0.9 kWe DIPS) •Deploy 25 kWe power system (reactor) (robotically) •Deploy unpressurized rover (2 kWe DIPS) •Deploy MEVPU (3 kWe DIPS)
Flight 4 - 2016	piloted, 50 days - exploration site #2	
Flight 5 - 2016	unmanned, cargo) - exploration site #3	•Deploy communications (0.9 kWe DIPS) •Deploy 25 kWe power system (reactor) (robotically) •Deploy unpressurized rover (2 kWe DIPS) •Deploy MEVPU (3 kWe DIPS)
Flight 6 - 2018	piloted, 50 day - exploration site #3	
Flight 7 - 2018	unmanned, cargo) - permanent site	•Deploy 75 kWe reactor power system (45 days) •Deploy MEV servicer (10 kWe DIPS)
Flight 8 - June 2020	manned, 600 days	•Deploy teleoperated rover (0.15 kWe DIPS) •Deploy pressurized rover (7 kWe DIPS, 5 kWe DIPS cart) •Deploy emergency power system (12 kWe DIPS)
Flight 9 - 2026	manned, -- 600 days	•Deploy unpressurized rover (2 kWe DIPS)
Flight 10 - 2030	manned, 600 days	•Deploy hauler (3 kWe DIPS) •Deploy mining excavator (22 kWe DIPS)

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TASKS	1992	1993	1994	1995	1996	1997	1998	1999	2000

DIPS (2.5 kWe modules)

- Component Development
- System Development
- Qualification Program
- Flight Program

Driver Fuel TFE Reactor (100 kWe)

- Component Development
- System Development
- Qualification Program
- Flight Program

Notes: Numbers indicate NASA Technology Readiness Level for systems. PDR=Preliminary Design Review; CDR=Critical Design Review; QU=Qualification Unit; FU=Flight Unit; PSAR=Preliminary Safety Review; USAR=Updated Safety Review; FSAR=Final Safety Review.
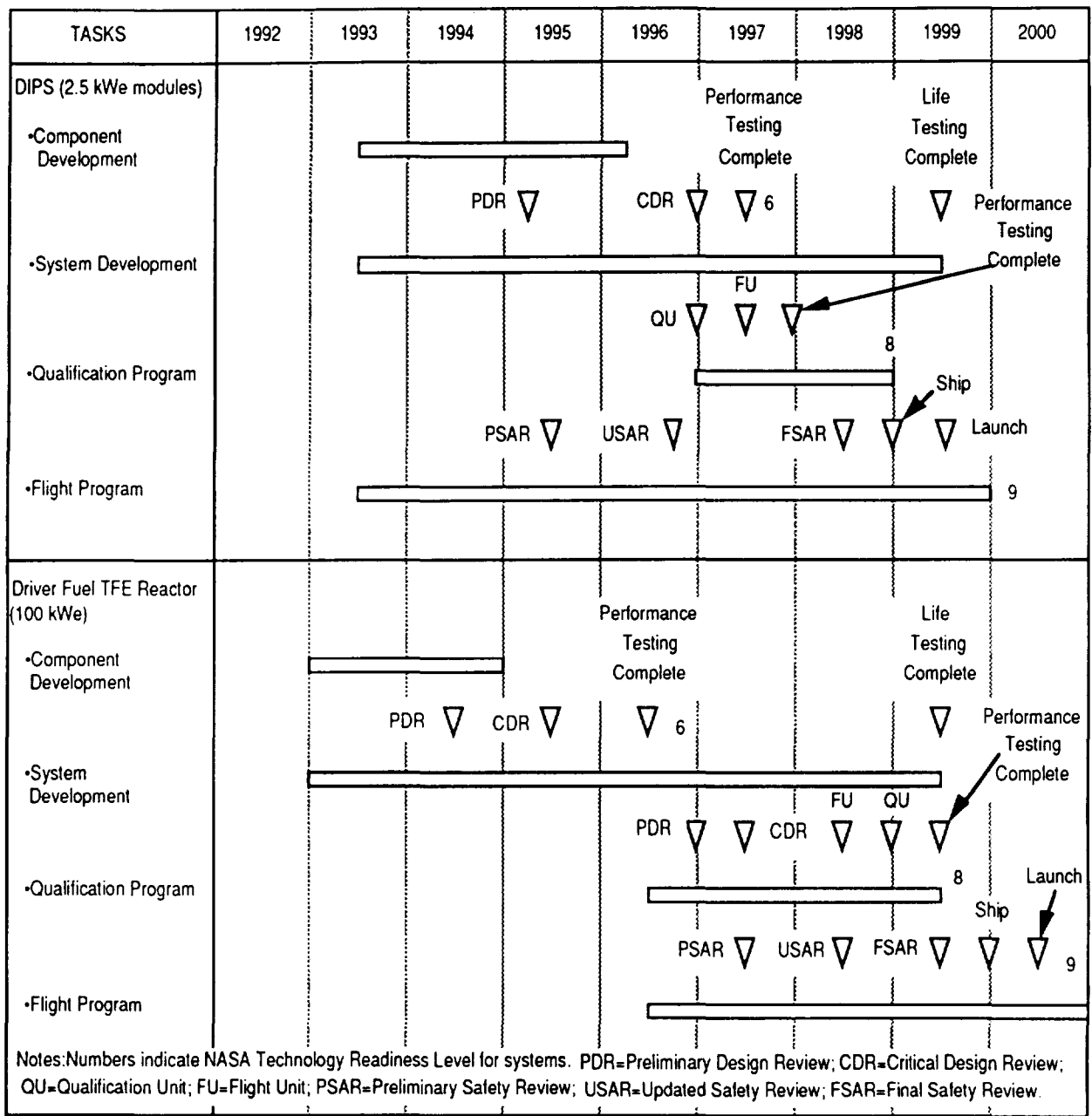
Figure 21. - Integrated development plan for Architecture 4.

4.0 CONCLUSIONS/RECOMMENDATIONS

4.1 CONCEPT CONCLUSIONS/RECOMMENDATIONS

The CBC DIPS concept has the lowest system mass for all mobile applications (even without considering redundancy or lifetime requirements for RFC systems) except the regolith hauler. The DIPS is probably the only power system suitable for long range, long duration applications such as the unpressurized rover (M6) and the teleoperated rover (M8).

Reactor power systems offer the lowest mass and area approach for large fixed power systems (> 25 kWe). Some development effort would be required to adapt the SP-100 system to survive in the Martian carbon dioxide environment. A vacuum enclosed SP-100 system is a viable approach. The Driver Fuel In-core TFE reactor power system is suitable for Mars applications because it has no exposed refractory metals. However, there are significant development issues for the thermionic reactor (lifetime, serviceability, and flexibility to alternate power conversion systems). Additional studies (life cycle cost, safety, and operability) are needed to determine the optimum reactor power system and deployment approach for Mars applications.

PV systems were the most massive of the systems compared except for the 0.9 kWe communications system application. In addition, large fields of arrays are required for most PV systems due to the low solar insolation during local and global dust storms. The large array size would complicate deployment and increase installation time. PV arrays also have potential problems with dust collection on surfaces and abrasion from dust particles.

4.2 OPERATIONS CONCEPTS CONCLUSIONS/RECOMMENDATIONS

High reliability and easy of servicing are key power system design criteria. All Mars electrical power generation systems can probably be designed to operate as stand-alone hardware without the aid of human health monitoring and control. It is expected that the state of AI controllers in the 21st Century will be developed to the point that they will be capable of safely operating these devices over a wide range of foreseen and unforeseen mission

contingencies. Hence, it is expected that all power systems will be fully functional and in a low power generation stand-by mode at the time the first astronauts arrive on Mars. The only human involvement should be to plug in equipment into the electrical outlets and turn-on switches.

In addition to fully autonomous operation, these power systems should be designed to allow for servicing and maintenance of some components when unforeseen failures occur. Although these electrical power systems are being designed with high overall system reliability so that they should be capable of completing their service life without breakdown, this report identifies numerous R&R maintenance task which could be performed on the Martian surface in the highly unlikely event of system failure. All of these maintenance tasks should be capable of being performed by autonomous robots without the aid of human supervision. Depending upon the results of future logistic studies, replacement components could be either: warehoused on the Martian surface, sent to Mars from earth on an as-needed basis, or (probably the most likely option) scavenged from other duplicative power systems which have themselves previously failed. The state of AI robotic maintenance, sometime in the 21st Century, has been assumed to be capable of performing any maintenance task which could have otherwise been performed by an astronaut based upon current university and research laboratory efforts.

4.3 POWER SYSTEM TECHNOLOGY DEVELOPMENT CONCLUSIONS

It appears that all of the power systems investigated except the SP-100 TE system are near term systems and can be developed through flight qualification within 10 years. It appears that a CBC SP-100 system could be developed within a nearterm timeframe as an alternative to the SP-100 TE system since CBC PCUs have had extensive prior development.

The development risk also appears relatively low for each of the nearterm power systems since there has been significant work done on each (at least on the subsystem level). The performance and life goals for these early systems are also relatively modest which reduces the risk. The addition of life testing at the component/subsystem level would increase the

required development times but would improve confidence that the power systems will meet the desired life requirements. This approach may be desirable for more complex systems such as those using PEM RFCs.

4.4 POWER SYSTEM ARCHITECTURE CONCLUSIONS/RECOMMENDATIONS

Four high commonality power system architecture examples were defined in this study. There was a factor of over 2 difference in total delivered mass between the predominantly PV architectures and the predominantly DIPS architectures. Thus, high commonality does not necessarily mean low mass. Since transportation cost to Mars generally outweighs development cost, low mass will tend to be a more important criteria than commonality for selecting the optimum power system architecture. However, there are many additional criteria which must be considered in selecting the optimum power system architecture (i.e., life cycle cost, safety, and operability).

4.5 RECOMMENDATIONS FOR FURTHER STUDY

An additional, more detailed, ranking study is recommended to determine the optimum power system architecture using a more complete set of evaluation criteria (i.e., life cycle cost, risk, reliability/maintainability, and safety). The life cycle cost should include the transportation cost (mass driven), development, installation, decommissioning, and operating costs. The effect of different mission scenarios (i.e., aggressive vs less aggressive) on the optimum power system architecture should be determined. The interactions between power system selection and the base architecture (i.e., mobile system duty cycle tradeoffs and startup/deployment power requirements) should be evaluated and optimized. Key mass drivers should be optimized in follow-on studies (i.e., PV arrays and energy storage). This will require a more in-depth study of system/component masses, costs, etc. Results of these recommended studies would allow selection of a development roadmap for planetary power systems which minimizes life cycle cost. It may turn out that some other combination of power systems with

lower commonality may provide the lowest life cycle cost approach to Mars exploration. Additional issues which should be investigated include power system reliability/life (redundancy and replacement systems), the availability/cost of isotope material, the political acceptibility of using isotope/nuclear power systems, and the total cost of each power system architecture.

(1-2

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13. ABSTRACT (Maximum 200 words)

A preliminary top level study was completed to define power system concepts applicable to Mars surface applications. This effort included definition of power system requirements and selection of power systems with the potential for high commonality. These power systems included dynamic isotope, Proton Exchange Membrane (PEM) regenerative fuel cell, sodium sulfur battery, photovoltaic, and reactor concepts. Design influencing factors were identified. Characterization studies were then done for each concept to determine system performance, size/volume, and mass. Operations studies were done to detemine emplacement/deployment maintenance/servicing, and startup/shutdown requirements. Technology development roadmaps were written for each candidate power system (included in Volume 2). Example power system architectures were defined and compared on a mass basis. The dymamic isotope power system and nuclear reactor power system architectures had significantly lower total masses than the photovoltaic system architectures. Integrated development and deployment time phasing plans were completed for an example DIPS and reactor architecture option to determine the development strategies required to meet the mission scenario requirements.

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