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ISSUES CONCERNING CENTRALIZED VS. DECENTRALIZED POWER DEPLOYMENT

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1.0 SUMMARY

This section presents a summary of the work performed in this study. The assumptions and limitations used during the study are discussed in the next section (Introduction).

The objective of this study was to provide a comparison of a decentralized power generation system against a centralized system to provide power on the lunar surface. As specified in the SOW for this task order, the specific mission option addressed was Option 5a reference architecture (Ref. I-1). The time phased power requirements unique to this mission option will be discussed in Section 3 of this report. However, the nominal power level is approximately 450 kWe. It is important to emphasize here that the power system architectural considerations refer to <u>prime</u> power distribution. However, all power sources, e.g., emergency habitat power were also addressed for completeness.

To examine the key features, advantages, disadvantages and critical issues associated with centralized vs. decentralized power distribution, a number of key technical areas were addressed: namely, (1) power system requirements, (2) power system architecture configurations, (3) power source options, (4) power management and distribution (PMAD) options and, (5) comparison studies leading to observations and recommendations. Figure 1-1 shows the basic logic flow used in this study. The Option 5a reference architecture and power system requirements used as the initial data base were obtained from the NASA program office. Since PMAD issues make up the heart of the centralized vs. decentralized power distribution problem, emphasis was given to the PMAD trade studies and analysis. To cover the family of possible power distribution options three power system architecture configurations were addressed in this study. These configurations were (1) fully centralized, (2) fully decentralized, and (3) a hybrid configuration that contained both centralized and decentralized features. The primary PMAD trade studies that were carried out included:

- ac vs. dc Distribution
- High vs. Low Voltage Transmission
- Buried vs. Suspended Cables
- Bare vs. Insulated Cables

In addition to these PMAD issues, the total power system mass was quantitatively examined. The total power system mass includes the power source, power conditioning and transmission cables. Substantial effort was given to estimating not only the total power system mass for each of the three candidate architectures but the individual contributions (power source, power conditioning, and transmission cables). This allowed the identification of the principal mass drivers.

A summary of the PMAD analysis and total power system mass are shown in Table 1-1 and Figure 1-2, respectively. A breakdown of the total power system mass is presented in Figure 1-3. For all three architecture configurations the largest mass contributor was the power source (~70-80%) with the

Centralized vs Decentralized Task Elements

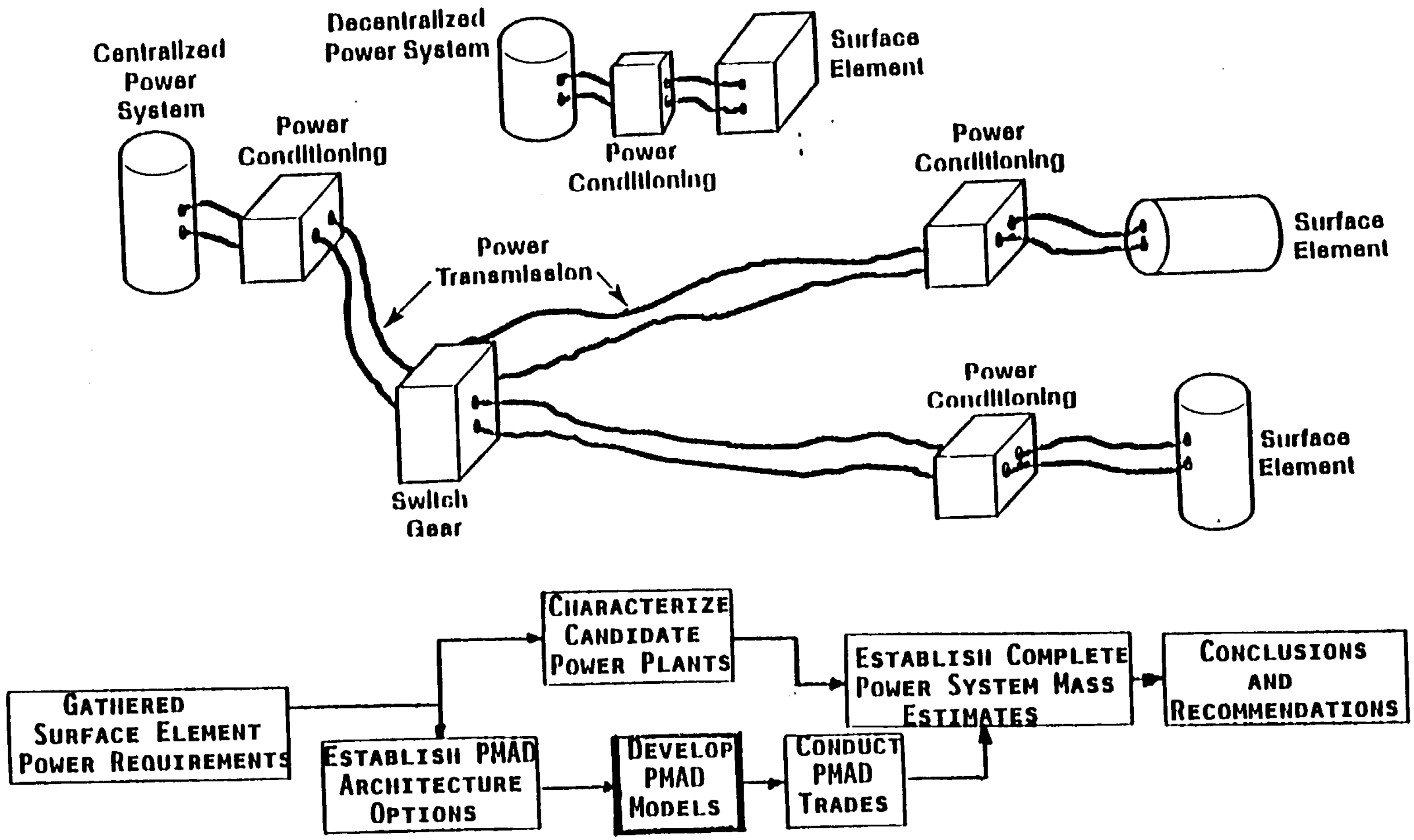

Figure 1-1 Methodology Flow Logic

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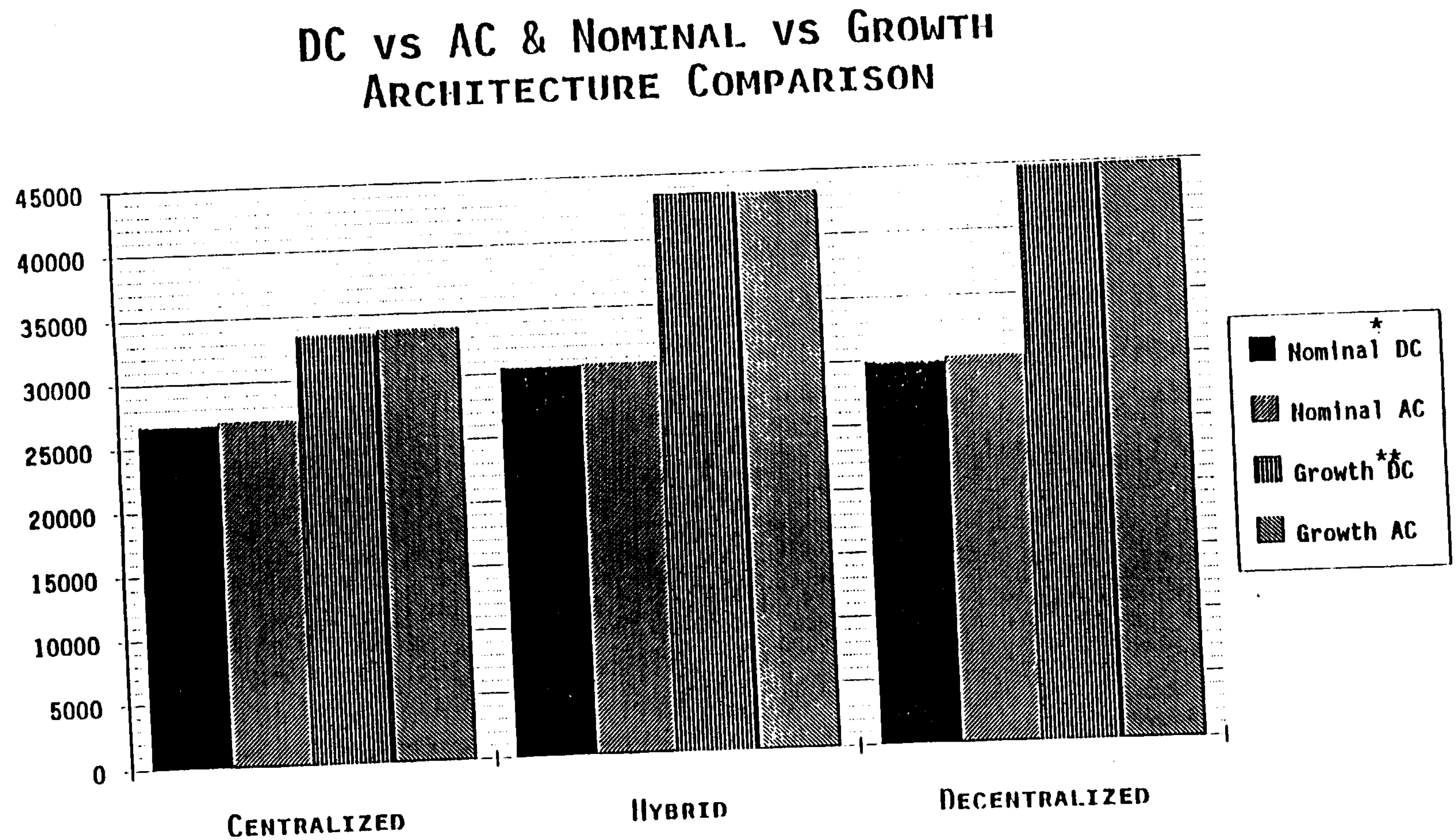

* Nominal = 450 kWe
** Growth = Nominal + 200 kWe to accommodate uncertainties and base evolution

Figure 1-2 DC vs. AC & Nominal vs. Growth Architecture Comparison

COMPARISON OF DC AND AC MASS BREAKDOWN

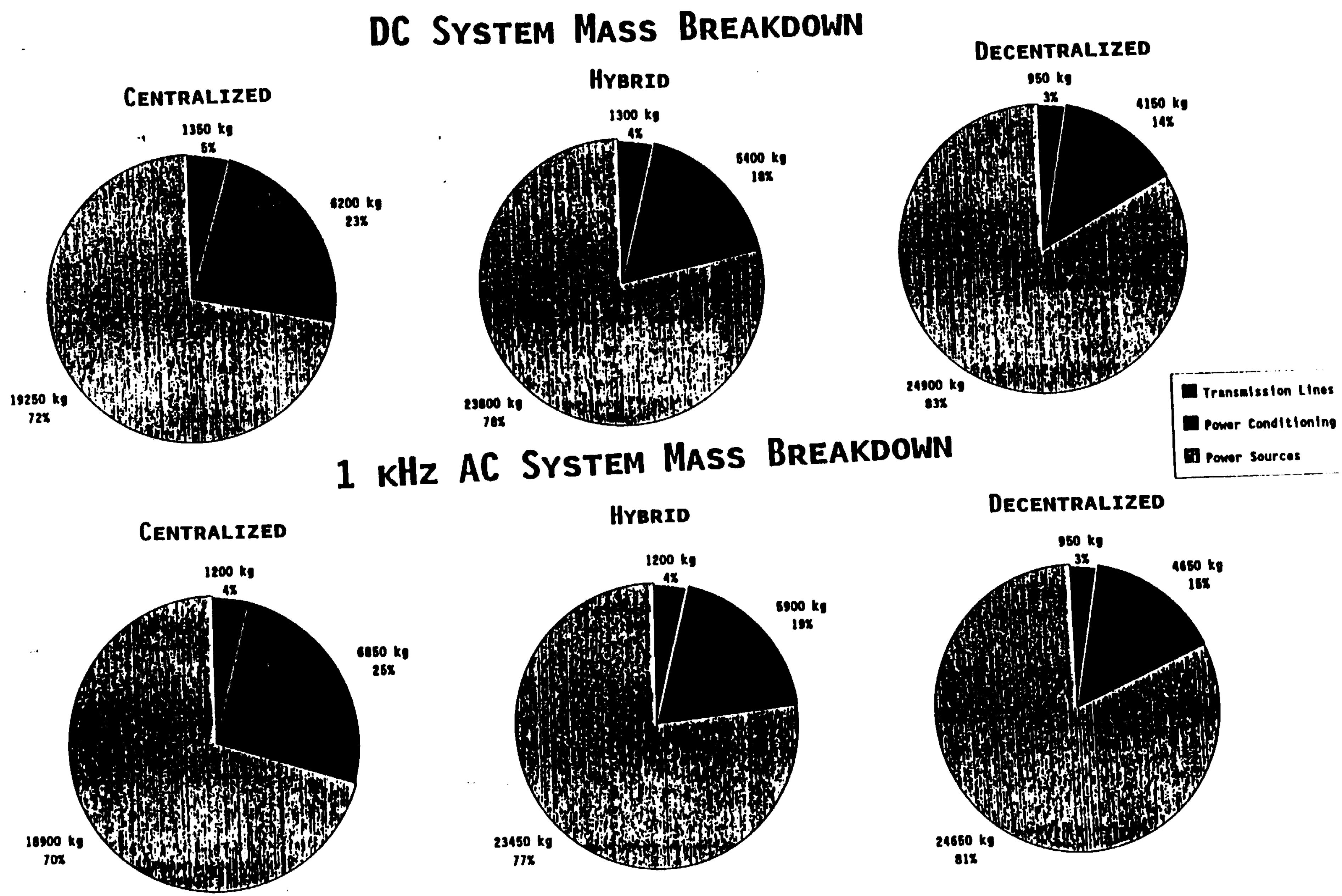

TABLE 1-1

PMAD Summary Results

- Total power system mass comparable for ac and dc distribution
- Ac distribution preferred due to lower risk:
    - 1 kHz
    - 3ø, 3 conductor litz wire
- Long transmission lengths (> few 100 meters):
    - High voltage (5 KVrms)
    - Buried cable (bare aluminum)
- Short transmission length (few 10's meters):
    - Low voltage (120 Vdc & 500 Vrms)
    - Suspended cable (flat bare aluminum)

transmission lines being the smallest (~3-4%) and the remainder coming from the power conditioning. A selection of ac vs. dc distribution cannot be based on mass alone since each approach was shown to be equal within the fidelity of the analysis. However, at present, the ac approach is preferred since it is based on lower risk and more reliable technology. Given that an ac distribution approach is selected, the recommended operating frequency is about 1 kHz. For the longer transmission lengths (i.e., > few hundred meters) high voltage (5 KVrms) buried aluminum cables are recommended. For the shorter transmission lengths (i.e. 10's of meters) the recommendation is flat aluminum suspended cables at low voltage (i.e 120 Vdc & 500 Vrms). Also, all cables either suspended or buried require no insulation (i.e. bare cables). Cables on the lunar surface were not considered because of potential hazards to the astronauts and rover vehicles.

If the base power requirements were to increase or decrease, it is not expected that the conclusions for the PMAD would change. This results since the mass of the power generating equipment dominates, representing 70-80% of the total power system mass. The transmission lines represent only about 5% of the total power system mass, the remainder being the power conditioning equipment.

Based on the results of this study, the preferred selection of a centralized or decentralized architecture is not clear cut. Each approach has unique advantages and disadvantages, as listed in Table 1-2. In Figure 1-1, for example, the centralized architecture has the lowest mass whether ac or dc distribution is utilized. On the other hand, a decentralized architecture has more flexibility to accommodate changes in lunar base configuration and/or evolving requirements. For example, if it is found that the landing area needs to be farther from the habitat because of regolith ejecta, a

TABLE 1-2

ADVANTAGES/DISADVANTAGES OF CENTRALIZED VS. DECENTRALIZED POWER

	ADVANTAGES	DISADVANTAGES
CENTRALIZED POWER SYSTEM	• SINGLE POWER SYSTEM DEVELOPMENT & DEPLOYMENT • LOWER WEIGHT/COST • ECONOMY OF SCALE	• REQUIRES LONG CABLE RUNS • MULTIPLE UNITS REQUIRED FOR RELIABILITY
DECENTRALIZED POWER SYSTEMS	• PROVIDES FLEXIBILITY OF BASE CHANGES • PROVIDES REDUNDANCY AND BACKUP POWER SUPPLIES	• MULTIPLE POWER SYSTEM DEVELOPMENT AND DEPLOYMENT • INCREASED WEIGHT/COST • LOWER OVERALL POWER PLANT EFFICIENCY

decentralized architecture would be more flexible to such a change. A final selection as to the preferred power distribution architecture is complex and will require combined consideration of many factors, e.g., mass, cost, safety, complexity, reliability, availability, growth potential, implementation and spares/maintenance.

A representative centralized ac power distribution architecture for the nominal Option 5a power requirement is shown in Figure 1-4. The origin and details surrounding this architecture is discussed in detail within the body of this report in addition to a dc equivalent.

Based on the results of this task order study, there were several items identified that are recommended for future task order work. These recommendations are as follows:

- Update transmission line model to include new Auburn University ac transmission model.
- Evaluate alternate ac distribution wire configurations.
- Develop models for alternate power conditioning equipment.
- Update results to include any new site architecture options.
- Update models to include life cycle costs, reliability, and commonality.
- Identify key technical issues and prepare development plans for resolving issues.
- Evaluate surface located conductors.
- Evaluate different centralized power system architectures.

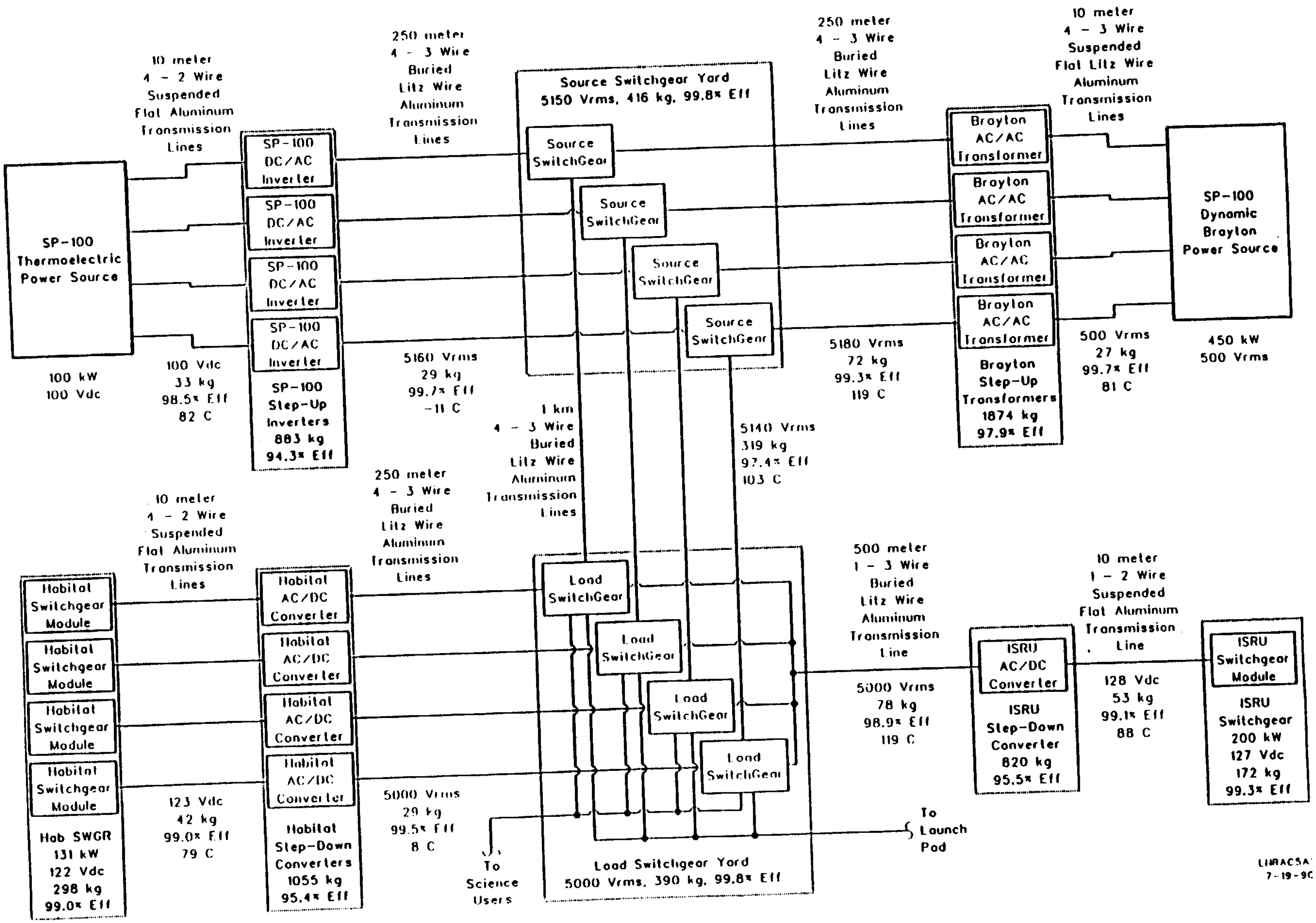

Figure 1-4 Revised Option 5a - 1 kHz AC Centralized Power Distribution
Nominal Power PMAD Values
Include Thermal Management and Radiator Subsystems)

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2.0 INTRODUCTION

This study was performed under NASA Lewis Research Center Task Order Contract NAS3-25808, "Lunar/Mars Mission Energy/Power System Assessment Studies." This is one of many task order studies used to evaluate or compare power systems for Space Exploration Initiative (SEI).

The purpose of this study was to provide comparisons of the use of a distributed (decentralized) power generation system versus a centralized system for providing power on the lunar surface. The comparisons were made using the option 5a architecture (Ref. I-1). This option is a modification of Option 5 defined in the NASA 90-day study with enhanced ISRU production.

The power generation system was divided into three major categories: 1) the power source, 2) power conditioning, and 3) power transmission. The power source is the device that generates the electrical energy. Various types were considered, including photovoltaic with regenerative fuel cells, reactors with static (thermoelectric) and dynamic (Stirling and Brayton) power conversion and radioisotopes with static (thermoelectric) and dynamic (Brayton) power conversion. Power conditioning is the equipment required to condition the power from the source for transmission and to condition the power from the transmission lines to the surface elements. Various types were considered, such as ac to dc, dc to dc, ac to ac, and dc to dc, depending on the power source and transmission conditions. Power transmission considered from the power source to the power conditioning equipment, between power conditioning equipment, and to the surface elements. This was shown schematically in Figure 1-1.

In the study, mass was considered as the primary comparison parameter, however, other qualitative factors such as technical risk were considered. Using mass as the primary comparison had some significant impacts on the study. For example, a reactor Brayton was selected over a reactor-Stirling because of its lower mass. Since the Brayton generates about 1000 Hz, this impacted the selection of the transmission frequency. The scope of the study did not permit considering other important factors such as cost, safety, complexity, reliability, availability, growth potential, implementation, and spares/maintenance. Some of the more significant assumptions and limitations used are as follows:

- Lunar architecture and power levels based on Option 5a.
- Distribution internal to surface elements not considered.
- Support equipment not included.
- Surface element voltage assumed to be 120 V-dc.
- Critical loads supplied by 3+1 power conditioning and transmission channels.

Support equipment would include all the equipment required to install and maintain the power generation system. A surface element voltage of 120 V-dc was selected since that is what currently is being used on the Space Station Freedom (SSF); consequently, there would be much commonality.

3.0 POWER REQUIREMENTS AND ARCHITECTURE OPTIONS

3.1 POWER REQUIREMENTS

Power requirements were gathered for surface element stationary power for the Option 5a (Option 5 with ISRU emphasis) SEI architecture. These power requirements were derived from NASA documents prepared during the 90-day study and updated to reflect the Option 5a SEI architecture (Ref. I-1). In some cases personal communications were used for clarification (Ref. III-1). A summary of these power requirements is presented in Table 3-1 for each of the surface elements. The general science experiments were not well defined at the time of this study. Consequently, an estimated value of 0.75 kWe (continuous power) was used for each defined experiment. Table 3-1 shows the average day and night power levels and an estimate for the peak power requirements which were based on previous commercial experience.

A graphical representation of these power requirements plotted as a function of emplacement year is shown in Figure 3.1. The large jump in the year 2012 is due to the installation of the ISRU mining equipment. Note that the total daytime power requirement beyond year 2012 approaches approximately 400 kWe.

3.2 POWER DISTRIBUTION ARCHITECTURE OPTIONS

To insure all relevant aspects of centralized vs. decentralized power distribution issues were addressed, three diverse power distribution architectures (i.e., centralized, decentralized, hybrid) were defined. The basic layout was based on the Option 5a SEI architecture. These three architectures are shown schematically in Figures 3-2 through 3-4. Figure 3-2 shows a fully centralized power system architecture in which prime power is supplied to all surface elements from a central power production area. This central station power system consists of an initial nuclear power system supplying up to 100 kWe of power for seven years. At the end of seven years a second nuclear power system is installed with a nominal power level up to 400 kWe. Accommodations for additional reactor power systems are required for either redundancy and/or replacement at the end of useful life. Also included in the architecture is a dedicated emergency power system for crew life support that supplies 12 kWe of power day and night. Figure 3-3 shows a hybrid architecture that combines centralized and decentralized power distribution features. For this option the high power areas (crew habitation and ISRU) are fed power from the centralized reactor power plant. The lower power areas have their own dedicated decentralized power systems. Figure 3-4 presents a completely decentralized power system where all areas have their own dedicated power source.

Note in Figures 3-2 through 3-4 that each distribution line has a letter designation. Pertinent characteristics for each of these distribution lines are given in Table 3-2. For each individual line length both a nominal and, in some cases, an uncertainty range is given. These ranges were defined because of the inherent uncertainties in the emplacement of various surface elements and to assist in determining the impact on mass to be discussed in a

TABLE 3-1 LUNAR SURFACE STATIONARY POWER REQUIREMENTS OPTION 5A

SURFACE ELEMENT	POWER REQUIREMENT DAY/NIGHT/PEAK (kWe)	EMPLACEMENT YEAR
COMMUNICATIONS	0.9/0.9/1.4	2002
CREW HABITAT AREA	128.5/63.5/283.5	
HABITAT MODULE	25/12.5/37.5	2003
AIR LOCK	0.5/0.5/10	2003
AIR LOCK	0.5/0.5/10	2006
LABORATORY MODULE	25/12.5/37.5	2006
AIR LOCK	0.5/0.5/10	2010
CONSTRUCTABLE HABITAT	77/37/115	2010
LEV LANDING AREA		
LEV SERVICER	9/9/15	2007

NOTE: PEAK POWERS ARE ESTIMATES

TABLE 3-1 LUNAR SURFACE STATIONARY POWER REQUIREMENTS OPTION 5A (CONTD)

SURFACE ELEMENT	POWER REQUIREMENT DAY/NIGHT/PEAK (kWe)	EMPLACEMENT YEAR
GENERAL SCIENCE (3)	2.3/2.3/-	2004
GENERAL SCIENCE (3)	2.3/2.3/-	2005
GENERAL SCIENCE (4)	3.0/3.0/-	2006
GENERAL SCIENCE (5)	3.8/3.8/-	2007
GENERAL SCIENCE (4)	3.0/3.0/-	2008
GENERAL SCIENCE (2)	1.5/1.5/-	2010
LOX PLANT (57 T/YR)	150/150/-	2012
LOX FUELING PALET	40/40/-	2012
GENERAL SCIENCE (2)	1.5/1.5/-	2011
GENERAL SCIENCE (2)	1.5/1.5	2014
GENERAL SCIENCE (6)	4.5/4.5	2015
GENERAL SCIENCE (10)	7.5/7.5/-	2016
GENERAL SCIENCE (4)	3.0/3.0	2018
GENERAL SCIENCE (2)	1.5/1.5	2019
GENERAL SCIENCE (1)	0.8/0.8/-	2020
GENERAL SCIENCE (67)	?	2022
GENERAL SCIENCE (4)	3.0/3.0	2017
ISRU DEMONSTRATIONS	2.0/2.0	2018

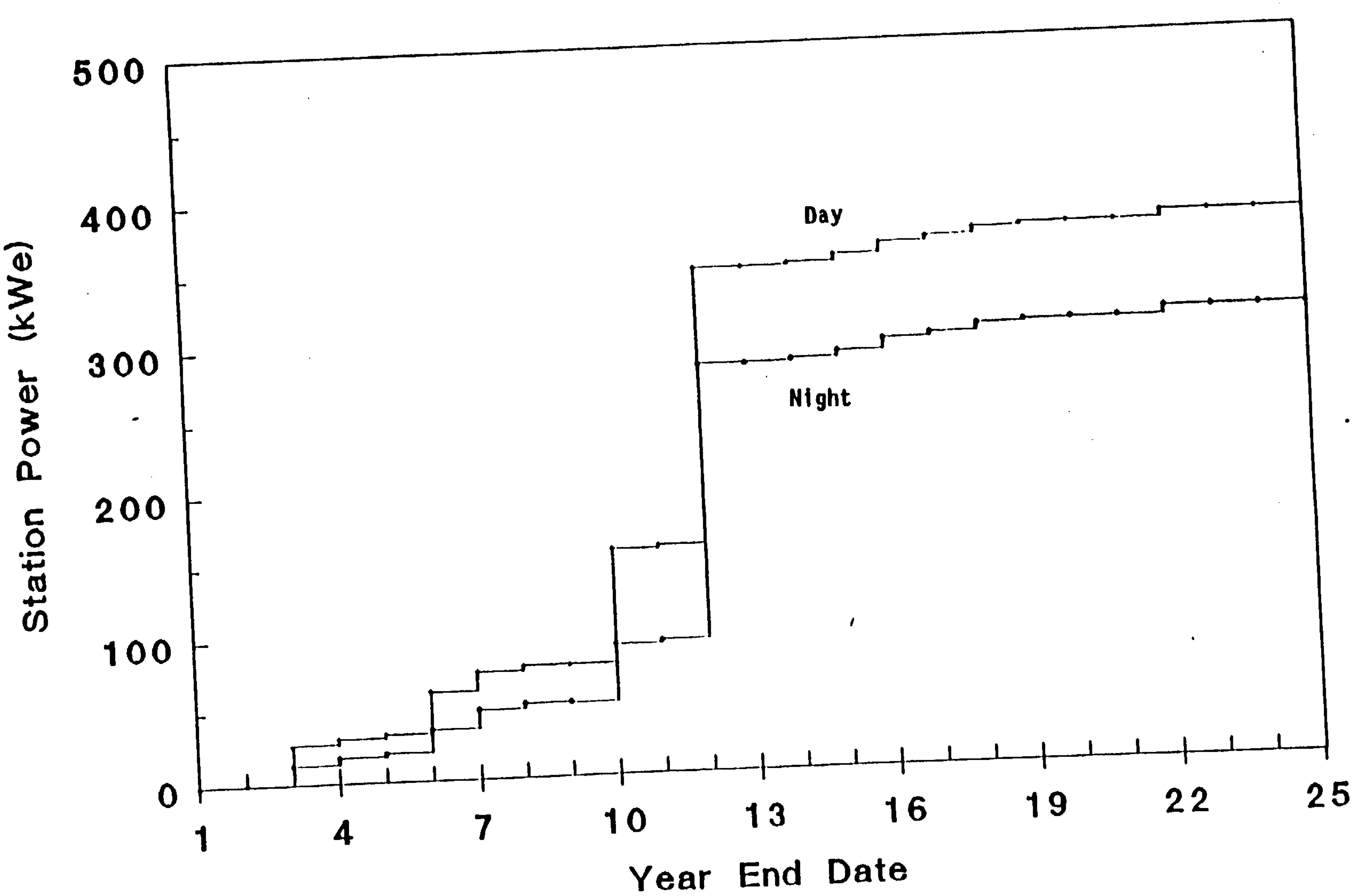


FIGURE 3-1 SURFACE SYSTEMS TIME PHASED POWER REQUIREMENTS
(OPTION 5A)

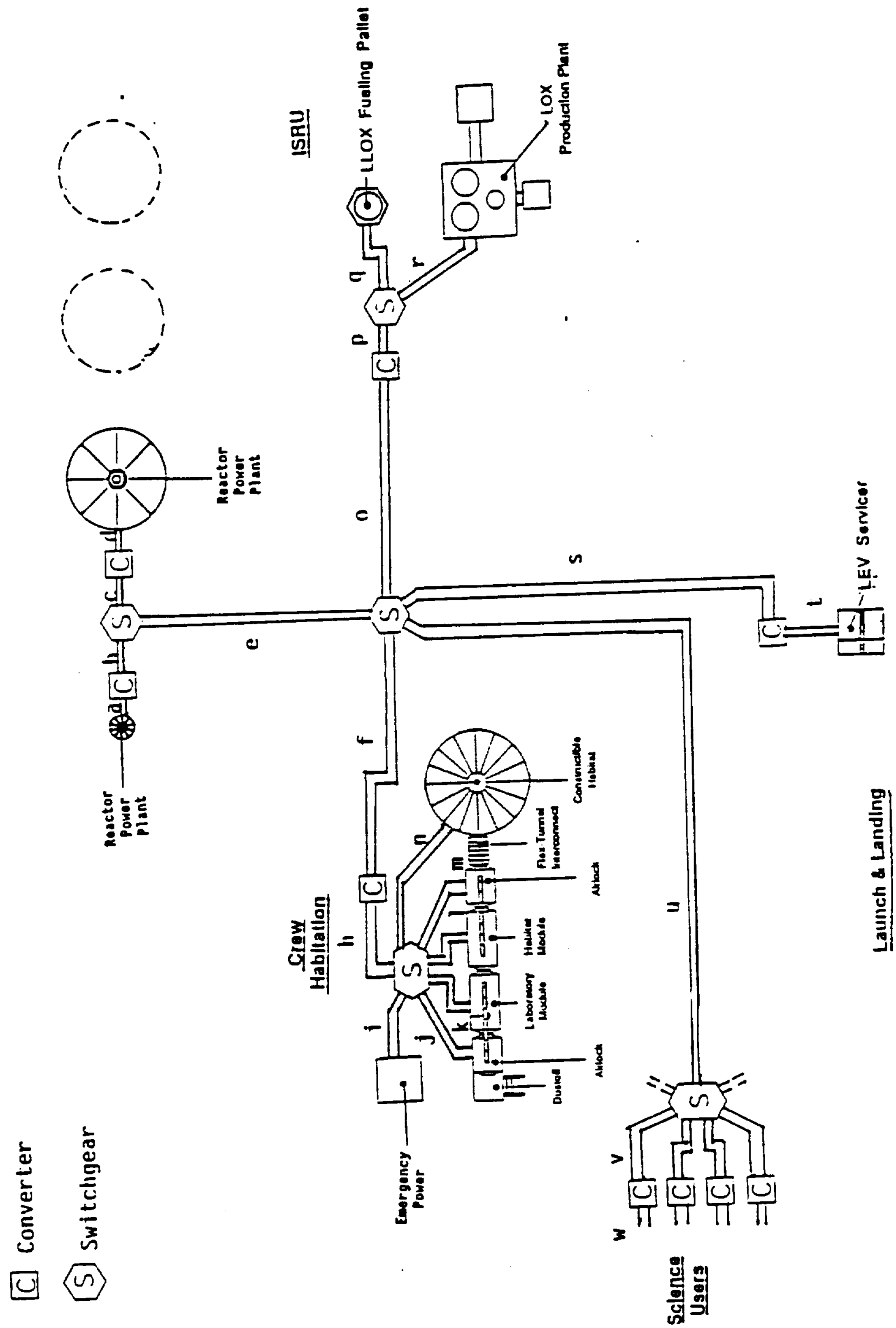


FIGURE 3-2 CENTRALIZED POWER SYSTEM ARCHITECTURE - OPTION 5A

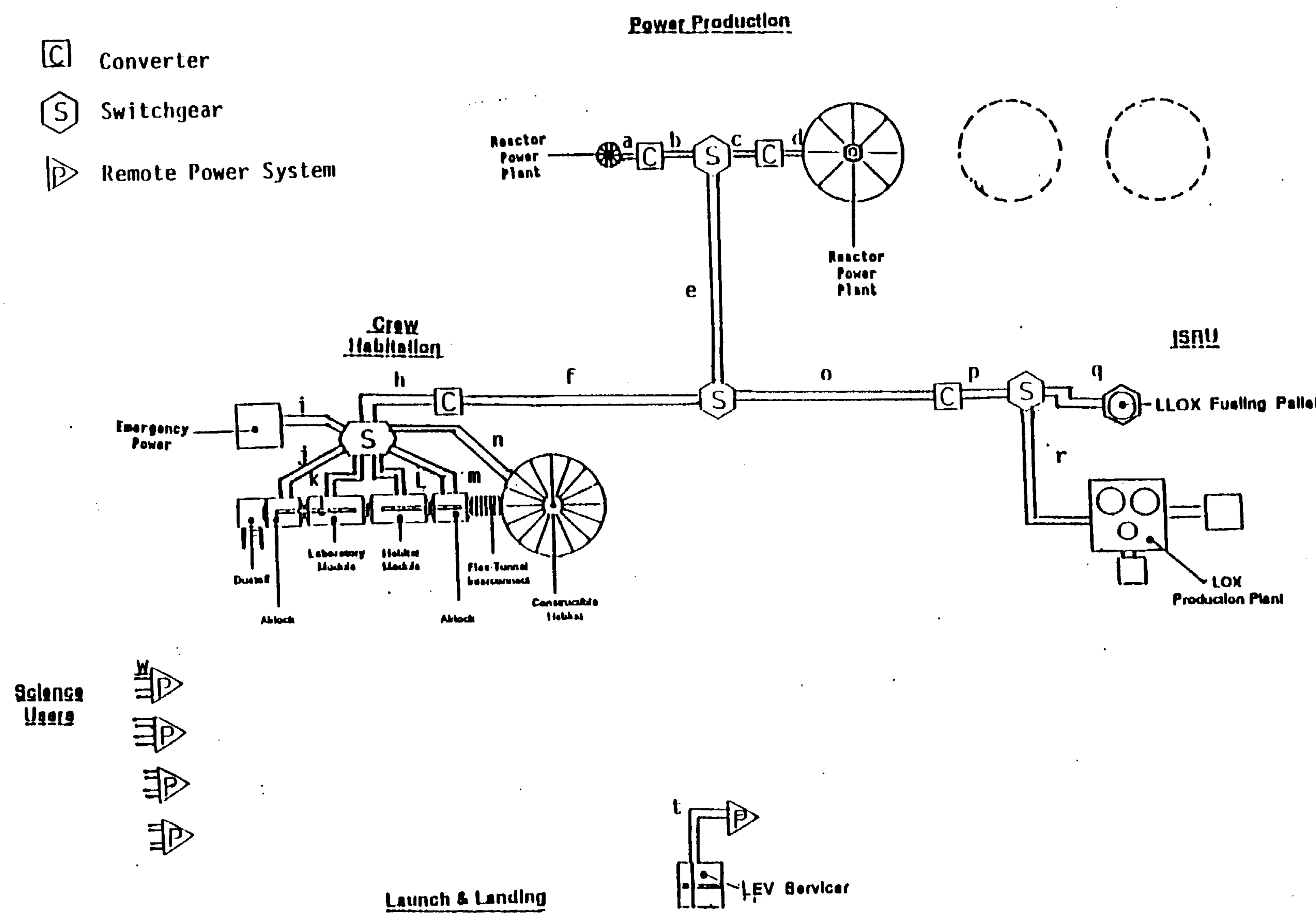


FIGURE 3-3 CENTRALIZED/DECENTRALIZED POWER SYSTEM ARCHITECTURE - OPTION 5A

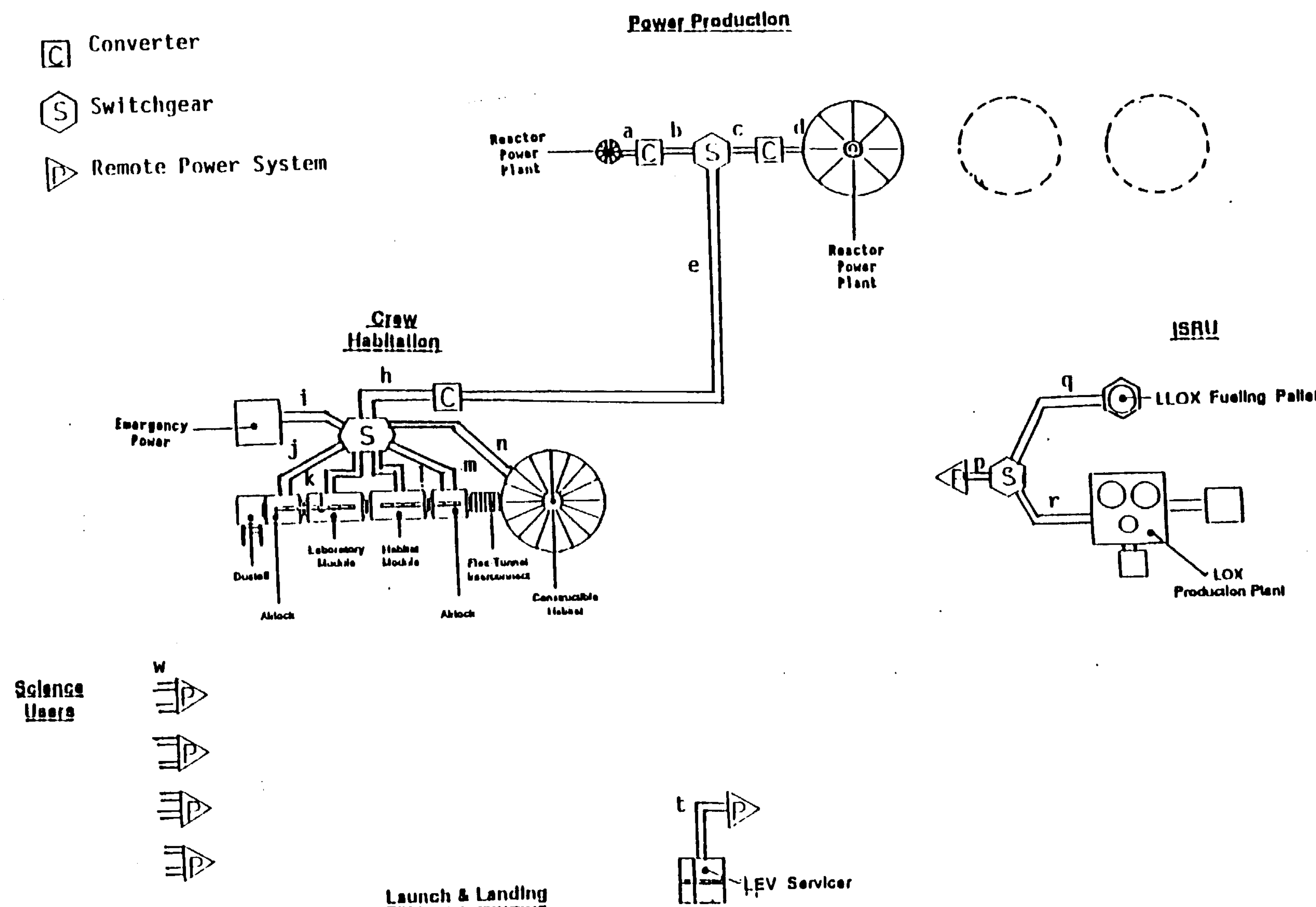


FIGURE 3-4 DECENTRALIZED POWER SYSTEM ARCHITECTURE - OPTION 5A

TABLE 3-2 POWER DISTRIBUTION LINE CHARACTERISTICS

Line No.	Line Length (M) Nominal	Line Length (M) Range	Delivered Power (KW) Nominal	Delivered Power (KW) Growth	Line Placement[3]	Nominal Voltage (VDC)	Need Date
A	10	---			S	100	2003
B	250	100-1000			B	5000AC	2003
C	250	100-1000			B	5000AC	2012
D	10	---			S	500AC	2012
E	1000	100-5000			B	5000AC	2003
F	250	---			B	5000AC	2003
H	10	---			S	120	2003
I	10	---	12	12	S	120	2006
J	10	---	0.5		S	120	2003
K	10	---	25	200	S	120	2006
L	10	---	25		S	120	2003
M	10	---	0.5		S	120	2003
N	10	---	77.5		S	120	2010
O	500	250-1000			B	5000AC	2012
P	10	---			S	120	2012
Q	50	---	40	40	S	120	2012
R	50	---	150	260	S	120	2012
S	500	500-5000			B	5000AC	2007
T	10	---	9	27	B	120	2007
U	500	500-5000			B	5000AC	2004
V	100[1]		100-1000		B	5000AC	2004-2021
W	100[2]	---	150	100	S	120	2004-2021

(1) 10 AT 10 KWE EACH
(2) 100 AT 1 KWE EACH
(3) S - SUSPENDED, B - BURIED

subsequent section. The nominal delivered power is shown for distribution lines that terminate at a surface element. In some cases a growth power was defined based on a judgement of the uncertainty of the nominal power levels. This growth power category was defined to assist in determining the impact on mass if installing extra capacity distribution lines and conditioning equipment are needed.

Also shown in Table 3-2 is the line placement, i.e., suspended or buried. The rational for this selection is presented in Section 5, Power Management and Distribution. The nominal line voltage and the date needed for each distribution line are also listed in Table 3-2. Again, it should be mentioned the method of emplacement and emplacement equipment for the power system were not included in this study. A separate task order addressed emplacement options (Ref. III-2).

4.0 POWER SOURCE OPTION

4.1 INTRODUCTION

A variety of power systems were characterized with respect to mass and other relevant parameters. These power systems include the following:

Reactor
- SP-100 Reactor with Thermoelectric Power Conversion System (PCS)
- SP-100 Reactor with Stirling PCS
- SP-100 Reactor with Brayton PCS

Radioisotope
- Dynamic Isotope Power System (Brayton PCS)

Solar
- Regenerative Fuel Cell/Photovoltaic (Proton Exchange Membrane with GaAs on Ge)

Each of these power systems was first optimized and then mass characteristics were determined over their applicable power range. Power source selection was based primarily on minimum mass. Funding did not permit evaluation of life cycle costs, which most likely would be a better selection criteria.

A summary of specific mass characteristics for each of the power systems considered above is presented in Figure 4-1. The PV/RFC mass was based on sizing the power source to provide 50% of the indicated power during the lunar night. A more detailed mass breakdown and other characteristics are presented in more detail later in this section.

4.2 POWER SYSTEM SELECTION

The initial lunar surface stationary power system for the Option 5a architecture will be used to supply power to the habitat module (2003) and laboratory module (2006). A nominal power of 51 kWe (including air locks) is required for daytime hours and 26 kWe for nighttime. This power level is adequate until the constructable habitat (2010) and lunar mining equipment (2012) are installed. The most mass efficient power system to supply this initial power is a reactor power system. A 60 kWe (slightly higher than required to account for power conditioning and line losses) SP-100 reactor with thermoelectric power conversion would weigh 3800 kg, compared to about 18,000 for a PV/RFC system. Because of life limitations of the RFC, the fuel cells and electrolyzer cells would likely need replacing after five years. Taking account of the reduced reactor power level (compared to a 100 kW SP-100) and lower nighttime power, the reactor life could be up to 16 years. Dynamic power conversion (Brayton or Stirling) could just as well have been selected and would result in even longer operating lifetimes and provide more commonality with the next reactor power system. However, the SP-100 thermoelectric was arbitrarily selected for this study and used to evaluate the mass characteristics of low voltage power conditioning and transmission cables.

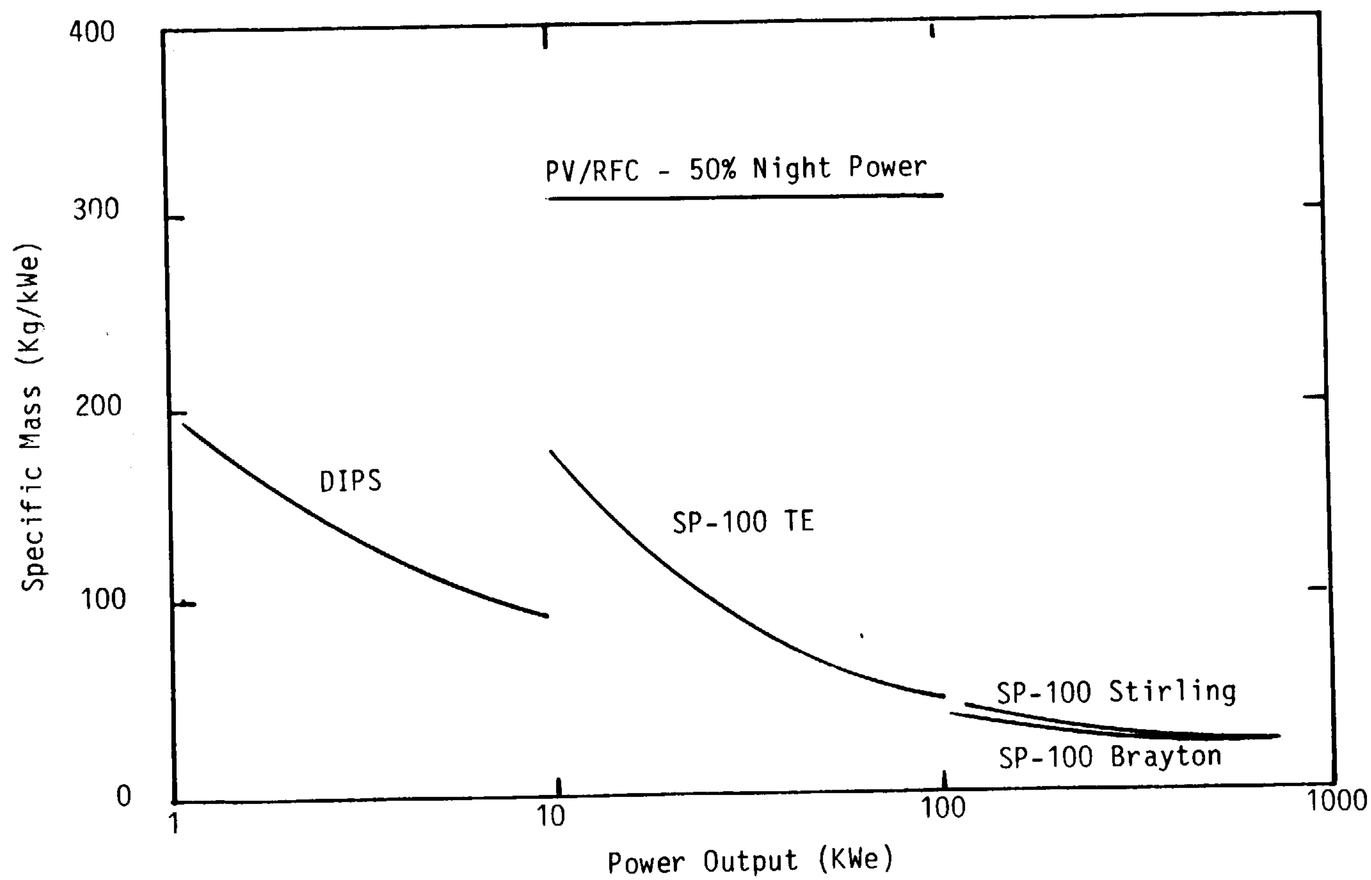


Figure 4-1. Comparison of Power Source Specific Mass

After installation of the constructable habitat and lunar surface mining equipment, the total base power requirement rises to 375 kWe. Taking PMAD losses into account raises the requirement by about another 25 kW, thus requiring a 400 kWe reactor power system. For this study a 400 kWe SP-100 reactor with closed Brayton cycle power conversion was selected. This system would have a mass of about 11,000 kg compared to a significantly higher mass (more than 10 times) for a PV/RFC system. At this power level the full power life of the reactor is about ten years. By reducing power for nighttime use a lifetime of fifteen years should be achievable. The Brayton system was selected over the Stirling because of its slightly lower mass (5%), technical maturity, integration complexity, and less complex power conditioning (Ref. IV-1).

In the centralized architecture, the reactor power systems would supply power for the Lunar Excursion Vehicle (LEV) servicer and scientific experiments. In the decentralized and hybrid architectures, separate power sources are used for the LEV servicer and scientific experiments. For the LEV servicer which requires 9 kWe of continuous power, the DIPS is the most mass efficient system. A DIPS unit would weigh about 850 kg as compared to 2800 kg for a PV/RFC.

Very little is known about the duty cycle of the scientific experiments. It was assumed in this study that they would be continuous, consequently, DIPS was selected as the reference power source for all scientific elements.

A summary of the selected power systems is shown in Table 4-1 for each power system architecture option. For the reactor systems a shadow shield configuration was assumed along with a scaled SP-100 reactor. For DIPS an optimized configuration was assumed at each power level.

4.3 POWER SYSTEM CHARACTERISTICS

4.3.1 SP-100 Thermoelectric

Two different configurations were evaluated for the SP-100 reactor with thermoelectric power conversion, the first with transported 4 Pi shielding and the second with shadow shielding. These two configurations are shown schematically in Figure 4-2. The 4 Pi shield would be used with a lunar lander (combined power plant and lunar excursion vehicle) to minimize setup time and site construction. The shadow shield would be used when additional regolith was used for shielding or when the reactor was installed in a crater, either existing or man made.

The performance characteristics for the SP-100 thermoelectric power system with a transported 4 Pi shield are presented in Table 4-2. The dose criteria for the shield mass presented in this table is 30 rem/yr at 1 km. The shield mass for other separation distances and dose criteria are given in Figure 4-3. It can be noted from Table 4-2 that at 100 kWe the 4 Pi shield mass is 65% of the total system mass.

TABLE 4-1

POWER SYSTEM SELECTION SUMMARY

	CENTRALIZED	HYBRID	DECENTRALIZED
HABITAT AREA			
INITIAL	SP-100 TE(1)	SP-100 TE	SP-100 TE
UPGRADED	SP-100 DYNAMIC(2)	SP-100 DYNAMIC	SP-100 DYNAMIC
ISRU AREA	SAME AS ABOVE	SAME AS ABOVE	SP-100 DYNAMIC
LAUNCH AREA	SAME AS ABOVE	DIPS	DIPS
SCIENCE AREA	SAME AS ABOVE	DIPS(3)	DIPS

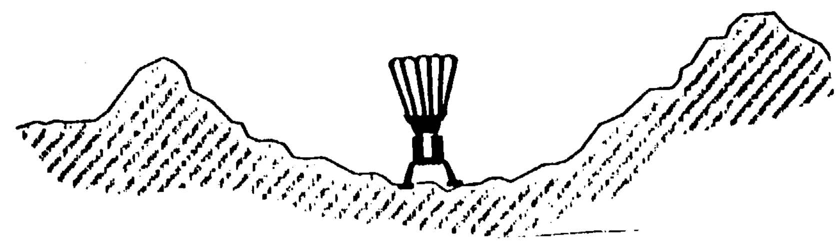
(1) SP-100 TE SELECTED TO PROVIDE CHARACTERIZATION OF DC/AC POWER PROCESSING - DYNAMIC PCS WOULD HAVE BETTER COMMONALITY

(2) BRAYTON SELECTED OVER STIRLING BECAUSE OF LOWER MASS (5%) AND LESS COMPLEX SYSTEM

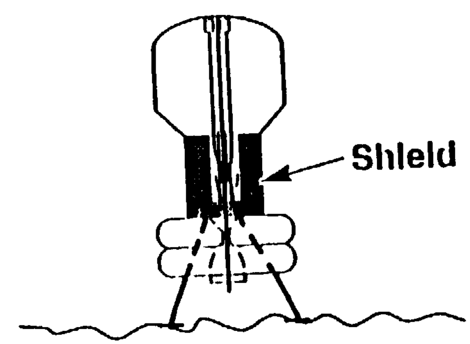
(3) POWER PROFILE OF SCIENCE MODULES NOT DEFINED - ASSUMED TO REQUIRE STEADY-STATE POWER - DIPS LOWEST MASS

Lunar Reactor Shield Options

- Existing crater
  (SELECTED OPTION)



- 4π unit shield
  (transported from earth
  as integral part of
  nuclear system)



- Lunar regolith shield
  (constructed on moon
  as part of reactor
  emplacement)

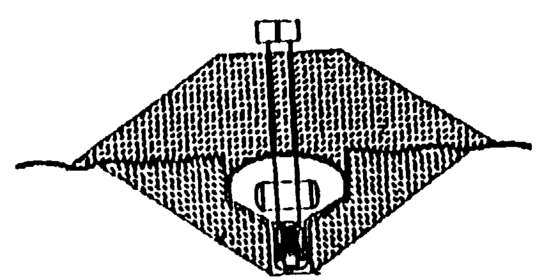


Figure 4.2

TABLE 4-2

System Performance Characteristics

SP-100 Reactor/Thermoelectric (With Transported 4π Shield)

Power output (kWe)	10	30	100
System net efficiency (%)	4.0	4.1	4.3
Reactor outlet temperature (K) (EOM)	1,400	1,400	1,400
Average radiator temperature (K) (EOM)	855	830	791
Radiation area (m^2)	8.4	28.2	104
System mass breakdown (kg)			
Reactor + reentry shield	280	350	760
Shield (4π) (30 rem/yr at 1 km)	1,800	2,390	6,700
Primary heat transport	60	180	480
Power conversion	100	190	340
Heat rejection	240	620	1,290
Power processing & controls	370	420	650
Total system mass (kg)	2,850	4,150	10,220

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Transported (4π) Shield Mass vs Dose Rate & Distance

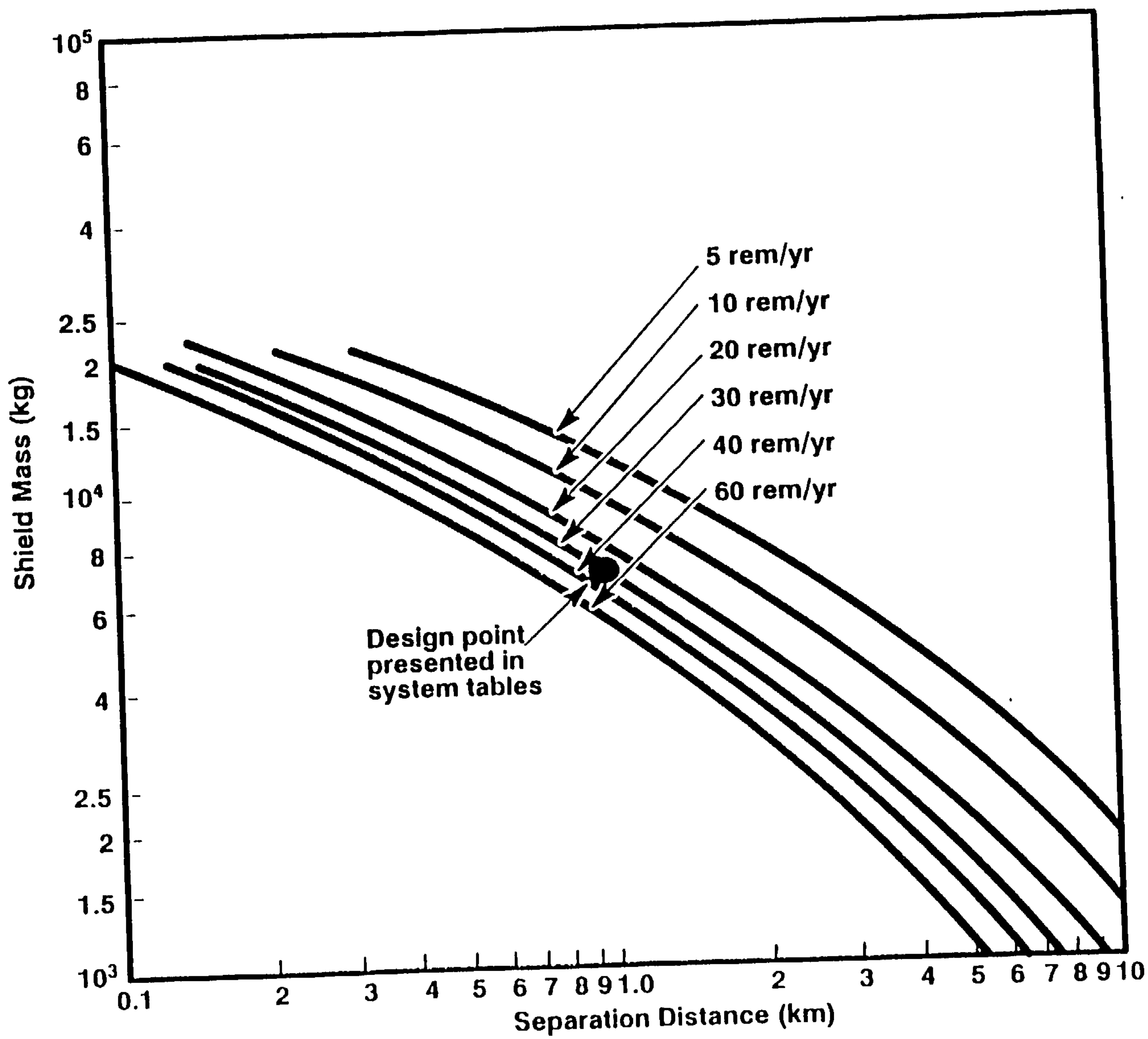

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FIGURE 4-3

The performance characteristics of an SP-100 thermoelectric system with a shadow shield are presented in Table 4-3. With these shield configurations, additional regolith shielding or a buried configuration would be required.

4.3.2 SP-100 Stirling

Stirling engines have been identified by NASA as a growth option for the SP-100 reactor. These systems were characterized over the power range from 200 to 800 kWe. 800 kWe is about the maximum power achievable using the 2.5 MWt SP-100 reactor. Configurations considered a power system with a transportable shadow shield. The power system would be buried and the local regolith would be used for biological shielding. A schematic of this configuration, along with key features, is shown in Figure 4-4.

The performance characteristics for the SP-100 Stirling system at discrete power levels is presented in Table 4-4. The reactor outlet temperature was assumed to be 1350K, resulting in a Stirling hot side temperature of 1265K. The masses presented do not include ancillary equipment (bulkhead, retaining wall, etc.) required for a buried configuration. The mass of such equipment has been estimated to be about 1350 kg.

In Table 4-4 the operating and redundant engines used were based on a recent study performed by NASA (Ref. IV-2) which select six operating and two standby units for a 825 kWe system. A single Stirling engine is limited in size to about 200 kWe (100 kWe per cylinder), consequently, at 600 kWe and below a 3 operating and one standby redundancy can be used.

4.3.3 SP-100 Brayton

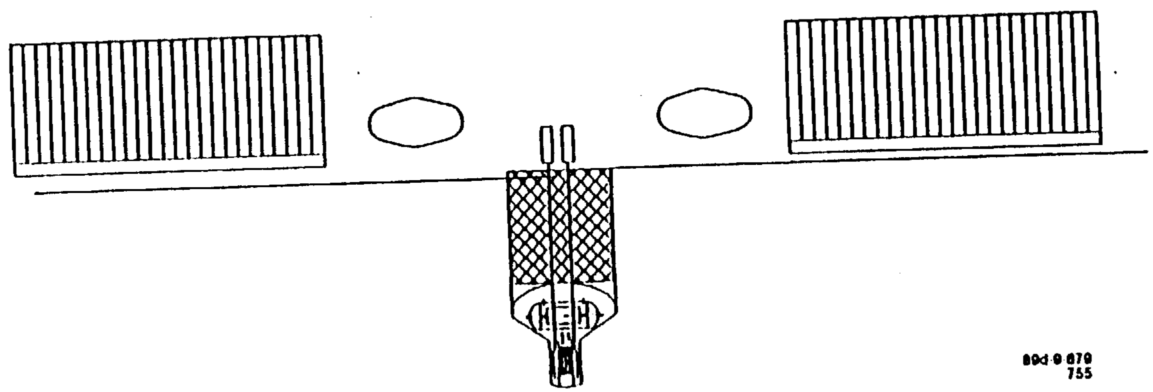
Brayton power conversion is a well-developed technology and was selected for the Space Station Freedom Solar Dynamic Power System and the Dynamic Isotope Power System. Several Brayton engines can be coupled to the 2.5 MWt SP-100 reactor in a manner similar to the Stirling system to provide up to about 600 kWe for a mass optimized system. The achievable power level is lower than that for the Stirling system because the Brayton cycle efficiency is lower. From grade level down, the reactor system is identical to the Stirling system. Above grade, Brayton engines are used in lieu of the Stirling engines, and the radiator panels are somewhat larger. Figure 4-5 presents a sketch of the concept along with key features.

Performance characteristics for the SP-100 Brayton power system are shown in Table 4-5. As with the Stirling system, the mass does not include ancillary equipment required for a buried configuration. The four operating and one standby redundancy used for the Brayton was based on an earlier SP-100 Brayton study (Ref. IV-3). This is somewhat inconsistent with the Stirling redundancy, however, and will only have a small effect on total power source mass.

In comparing the mass breakdown shown in Table 4-5 with that of the Stirling (Table 4-4), it can be noted that the masses of the power conversion and power processing are lower for the Brayton. The mass of the Stirling heat rejection is low for the Stirling because of its much lower radiator area.

Power Sources Key Features

SP-100/Stirling System



- 2.5 MWt SP-100 nuclear reactor, buried
- Lithium primary coolant
- Nonradioactive secondary lithium loops
- Six of eight Stirling engines for full power
- User power up to 800 kWe
- On-site erection of major components
- Radiation level above reactor at ground level 50 rem/hr operating, <10 mrem/hr shutdown
- Radiation level 200 m from operating system 1 mrem/hr

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FIGURE 4-4

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TABLE 4-3

System Performance Characteristics

SP-100 Reactor/Thermoelectric (With Shadow Shield)

Power output (kWe)	10	30	100
System net efficiency (%)	4.0	4.1	4.3
Reactor outlet temperature (K) (EOM)	1,400	1,400	1,400
Average radiator temperature (K) (EOM)	855	830	791
Radiation area (m^2)	8.4	28.2	104
System mass breakdown (kg)			
Reactor + reentry shield	280	350	760
Shield	750	950	1,270
Primary heat transport	60	180	480
Power conversion	100	190	340
Heat rejection	240	620	1,290
Power processing & controls	370	420	650
Total system mass (kg)	1,800	2,710	4,790

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TABLE 4-4

System Performance Characteristics

SP-100 Reactor/Stirling

Power output (kWe)	200	400	600	800
System net efficiency	24.9	27.8	29.4	31.1
Redundancy				
Number operating modules	3	3	3	6
Number redundant modules	1	1	1	2
T_{hot} engine (K)	1,265	1,265	1,265	1,265
T_{cold} engine (K)	666	632	602	575
Temperature ratio	1.9	2.0	2.1	2.2
Radiation area (m^2)	100	214	370	560
System mass breakdown (kg)				
Reactor	380	520	650	760
Shield	450	640	820	960
Primary heat transport	640	970	1,290	1,560
Power conversion	1,970	3,910	5,740	7,440
Heat rejection	1,350	2,690	4,380	6,360
Power processing & controls	1,800	2,720	3,520	4,240
Total system mass	6,590	11,450	16,400	21,320

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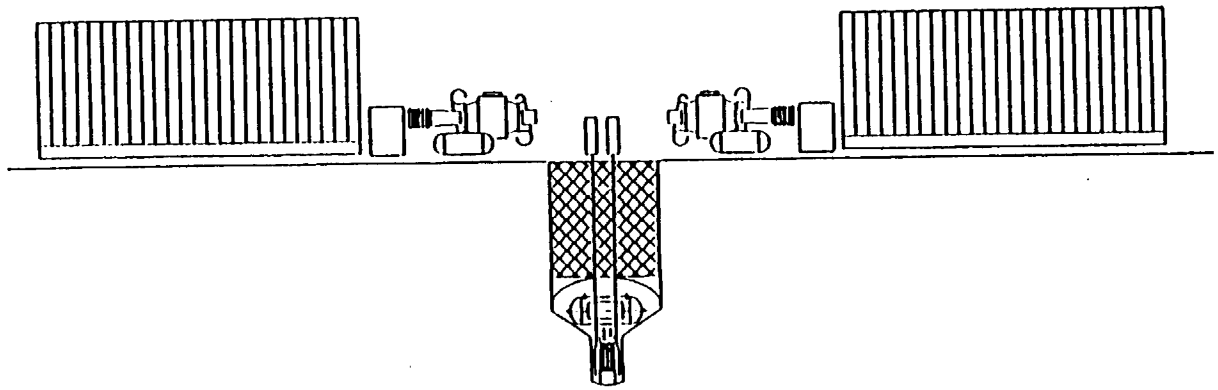
Power Sources Key Features

SP-100/Brayton System



- 2.5 MWt SP-100 nuclear reactor, buried
- Lithium primary coolant
- Nonradioactive secondary He-Xe loops
- Four of five Brayton engines for full power
- User power up to 600 kWe
- On-site erection of major components
- Radiation level above reactor at ground level 50 rem/hr operating, <10 mrem/hr shutdown
- Radiation level 200 m from operating system 1 mrem/hr

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FIGURE 4-5

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TABLE 4-5

System Performance Characteristics

SP-100 Scaled Reactor/Brayton

Power output (kWe)	100	200	400	600
System net efficiency	23.0	22.7	22.7	23.7
Redundancy				
Number operating modules	4	4	4	4
Number redundant modules	1	1	1	1
Turbine inlet temperature	1,300 K	1,300 K	1,300 K	1,300 K
Compressor inlet temperature	425 K	440 K	450 K	450 K
Radiation area (m^2)				
Main radiator	130	230	420	590
Auxiliary radiator	18	33	60	90
System mass breakdown (kg)				
Reactor	300	400	590	760
Shield	340	480	760	960
Primary heat transport	320	560	1,040	1,440
Power conversion	680	1,220	2,200	3,000
Heat rejection	1,380	2,440	4,430	6,150
Power processing & controls	780	1,130	1,830	2,530
Total system mass	3,800	6,230	10,850	14,840

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The mass of Brayton power conversion is less than the Stirling since Brayton engines scale much better with power level. Also, since the Stirling alternator has a low power factor and low frequency the power conditioning is heavier than the Brayton.

4.3.4 Dynamic Isotope Power System

The Dynamic Isotope Power System (DIPS) has applications to both mobile and low power stationary power sources. The DIPS consists of four major assemblies, as shown schematically in Figure 4-6. The heat source assembly includes the plutonium-238 radioisotope. The power conversion assembly consists of closed Brayton cycle components, including the rotating unit (turboalternator compressor) and the recuperator. The heat rejection assembly includes the heat pipe radiator to reject waste heat. The power processing and control assembly includes all the power conditioning and control electronics.

The performance characteristics of the DIPS for powers up to 10 kWe are presented in Figure 4-7. The stair-stepped curves are for the modular 2.5 kWe DIPS, while the smooth curves are for point designs optimized at each power level. For the point design, a low turbine inlet temperature (1144K, 1600°F) line is also shown. Curves for the optimum and alternate 2.5 kWe module designs are also shown. The alternate module has a lower radiator area at the expense of a small mass penalty. In the mass comparisons, the smooth curves with a turbine inlet temperature of 1300K were used.

4.3.5 Regenerative Fuel Cells and Photovoltaics

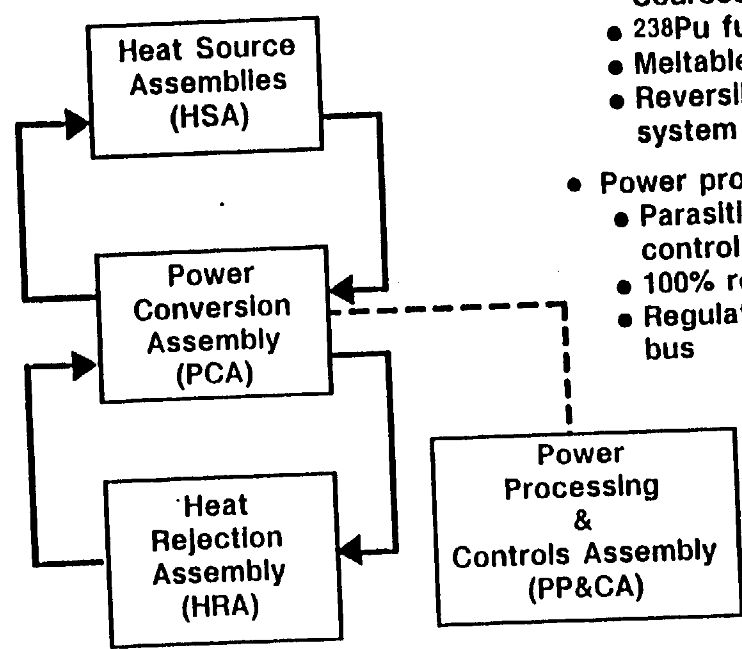
Although there are no photovoltaic/regenerative fuel cell (PV/RFC) options included in lunar Option 5a architecture, this system was characterized for completeness. A PV/RFC system consists of five major components; PV array, gas tanks, reactants, fuel cells, and water tank with radiator. For the PV array, various cell materials were evaluated, including amorphous Si, Si, and GaAs on Ge. In addition, both fixed and tracked arrays were evaluated. A mass comparison of the various cell/array types is presented in Figure 4-8. The array mass comparison is for a 25 kWe day/12.5 kWe night power system. The actual end of mission (EOM) array power is about 60 kWe. As can be noted, the GaAs on Ge is the lightest array for both fixed and tracked orientations. The tracked system was selected because of the lunar dust problem of locating an array on the surface.

For the regenerative fuel cell system, various concepts were evaluated. For the actual fuel cell, both alkaline and acid (proton exchange membrane (PEM) were considered. The alkaline fuel cell is used on the STS and was the prime power source on Apollo. The alkaline fuel cell, however, has shorter life, is somewhat heavier, and has startup problems compared to a PEM cell. The PEM cell was selected as the reference because of its potential for lunar surface application.

The PEM fuel cell uses H_2 and O_2 as the reactants. A trade-off exists as to whether it is best to store these reactants in the gaseous or cryogenic state. A detailed trade study is currently in progress to determine the most

DIPS Features

- Isotope heat source
  - General Purpose Heat Sources (GPHS)
  - 238Pu fuel
  - Meltable multifoil insulation
  - Reversible heat removal system
- Power processing & controls
  - Parasitic load for power control
  - 100% redundant
  - Regulated output to user bus



- Power conversion
  - Closed Brayton Cycle (CBC)
  - Helium-xenon working gas
- Heat Rejection
  - Redundant H_2O/ammonia heat pipes
  - Optical solar reflector (OSR) tiles for enhanced emissivity

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FIGURE 4-6

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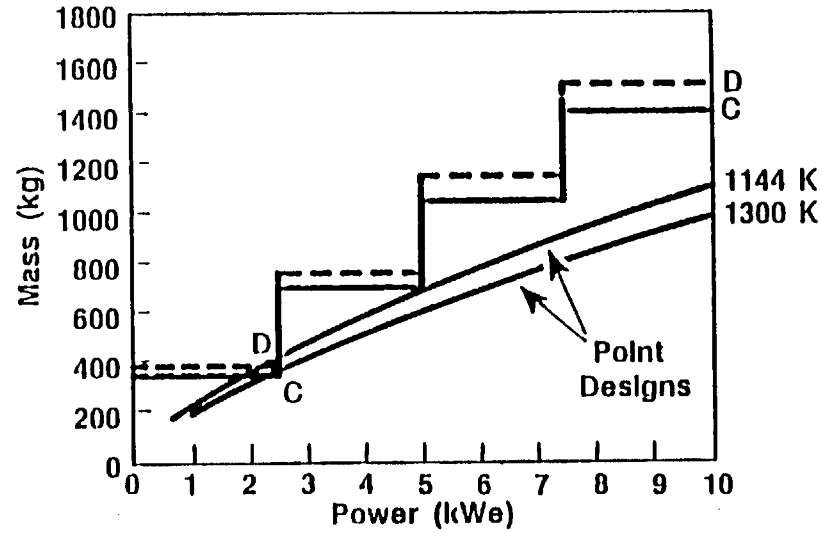
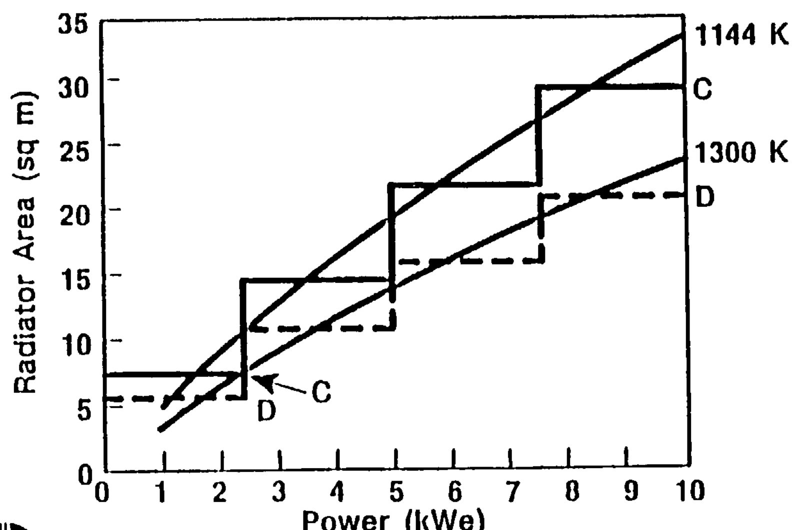
DIPS System Performance Characteristics
Manned Missions



General Features

- Common modules for multiple uses
- Redundancy and availability through spare modules
- Fuel transferable between modules
- Sink temperature = 220K

C	2.5 kWe "optimum module
D	2.5 kWe "alternate" lower area module



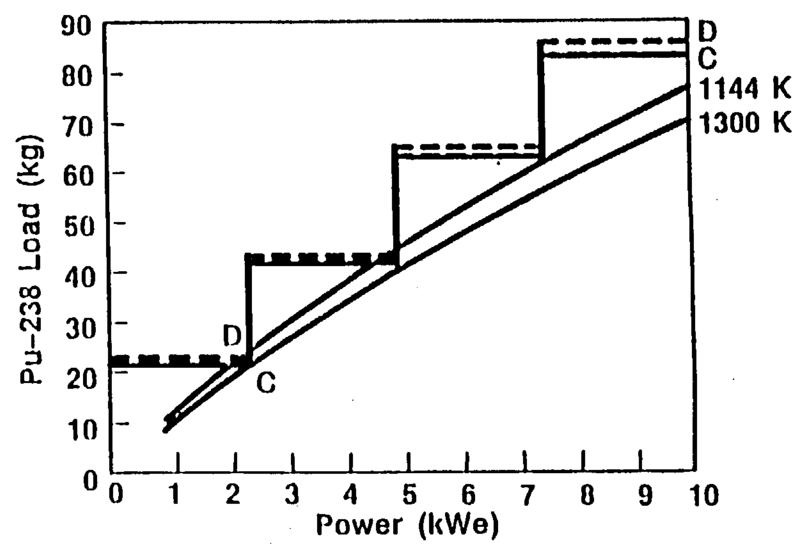


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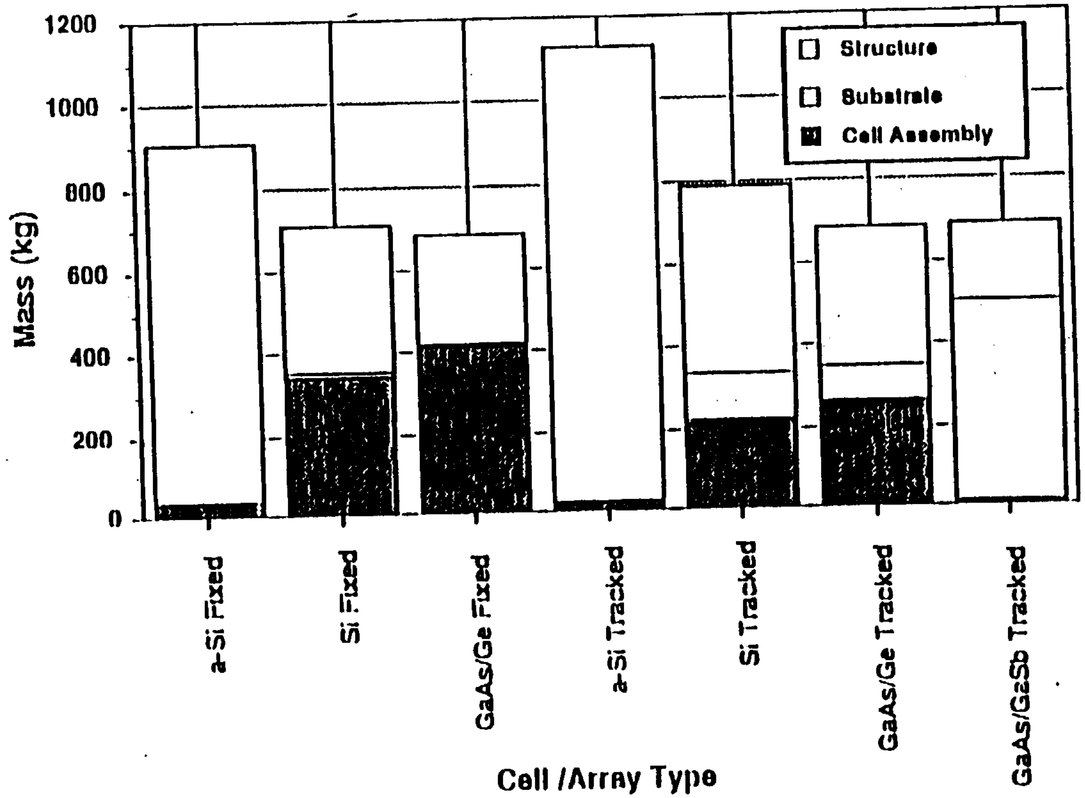
FIGURE 4-7

LUNAR SURFACE POWER SYSTEM ARRAY MASS COMPARISON

25 kWe Day Power output



Assumptions:

1. Fixed array substrate is Kapton
2. Tracked array substrate is a composite sandwich
3. Structure Mass is
   .5 kg/sqm for Fixed
   1.0 kg/sqm for Tracked

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FIGURE 4-8

optimum storage method. Cryogenic storage requires an additional 12 kWe for the liquefaction stage (for a 12.5 kWe nighttime power), resulting in a larger array and added system complexity. For this reason, gaseous storage was initially selected.

A breakdown of the mass for a 25 kWe day/12.5 kWe night power system is shown in Figure 4-9. It can be noted that the PV array represents less than 10% of the total system mass. The major portion of the system mass is the reactants and storage tanks. A sketch of a typical PV RFC configuration, along with performance characteristics for a 25 kWe day/12.5 kWe night power system, is shown in Figure 4-10. It is interesting to note that the electrolyzer power input is 32.6 kWe, resulting in a total RFC round trip efficiency of 43%. A mass summary for a total GaAs/Ge PV/RFC is shown in Figure 4-11 as a function of day and night power level.

LUNAR SURFACE PV / RFC POWER SYSTEM MASS

GaAs/Ge Array, PEM RFC, 25 kWe Day and 12.5 kWe Night Power Levels

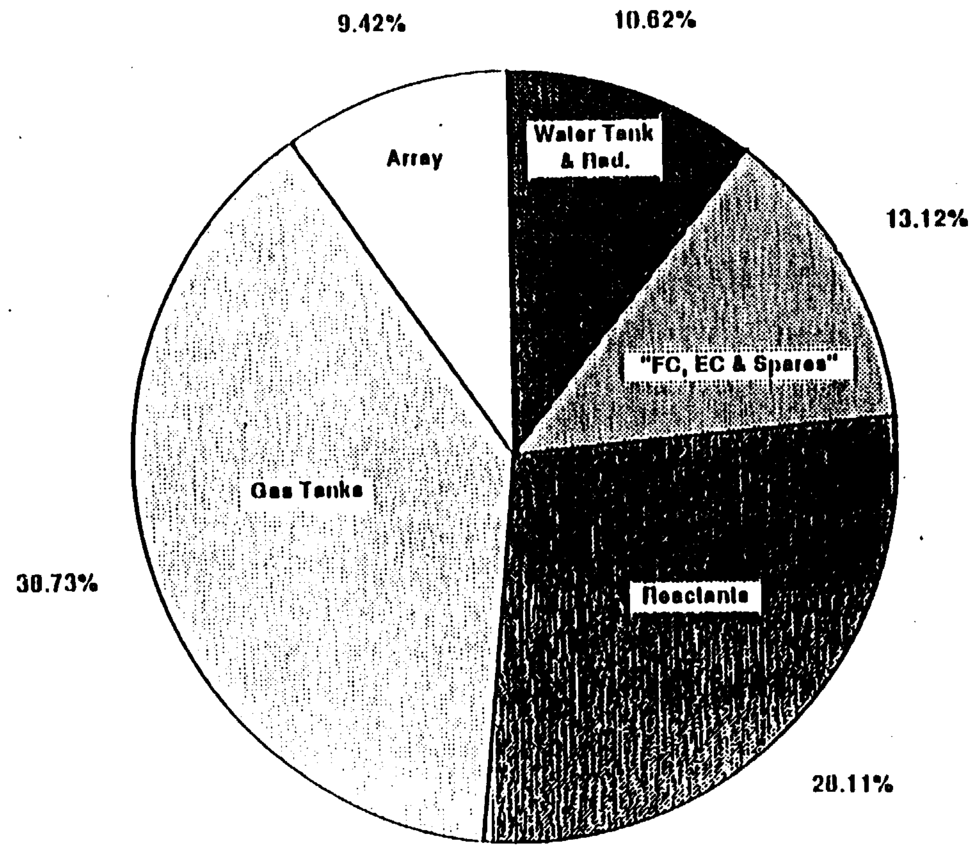

FIGURE 4-9

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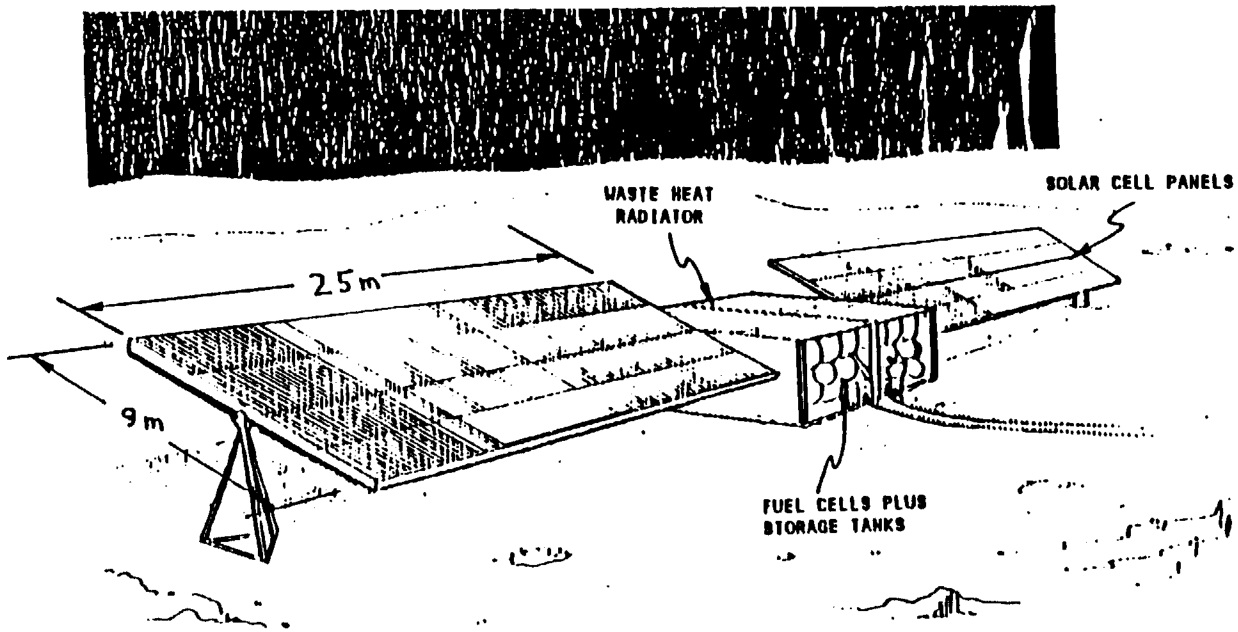
PHOTOVOLTAIC ARRAY/REGENERATIVE FUEL CELL



• RATED POWER, kWe	DAY/NIGHT	25.0/12.5
• VOLTAGE, Vdc		~160
• RATED POWER LIFE (EOM), YR		5
• SERVICEABLE LIFE, YR	UP TO	10
• TRACKING ARRAY POWER (EOM), kWe		61
• ARRAY TEMP, °C		≤100
• CELL SIZE, 8X8 CM BY 4 MIL Ga/As/Ge		
• NOMINAL CELL EFFICIENCY, %		18

• ELECTROLYZER MODULE, PEM OR ALKALINE	
• POWER INPUT (PEM), kWe	32.6
• MAXIMUM PRESSURE, PSIA	3000
• FUEL CELL MODULE, PEM OR ALKALINE	
• POWER OUTPUT (PEM), kWe	13.4
• REGENERATIVE FUEL CELL SUBSYSTEM	
• ROUND TRIP EFFICIENCY (PEM), %	43
• GAS STORAGE TANKS	
• OPERATING PRESSURE, PSIA	3000
• GRAPHITE EPOXY COMPOSITE, SAFETY FACTOR	2
• SYSTEM WEIGHT, Kg	7700

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FIGURE 4-10

LUNAR SURFACE POWER SYSTEM MASS

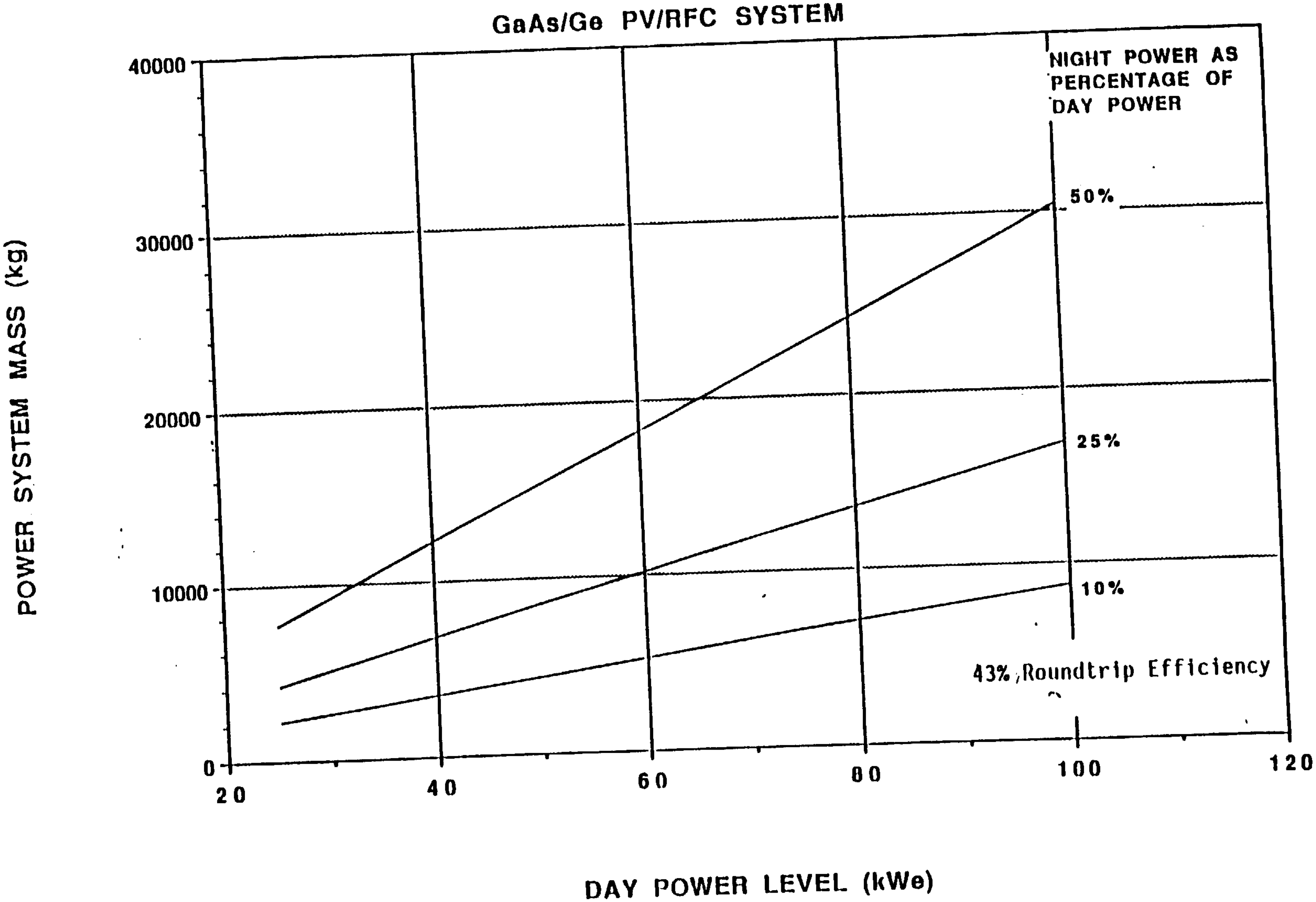

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FIGURE 4-11

5.0 POWER MANAGEMENT AND DISTRIBUTION

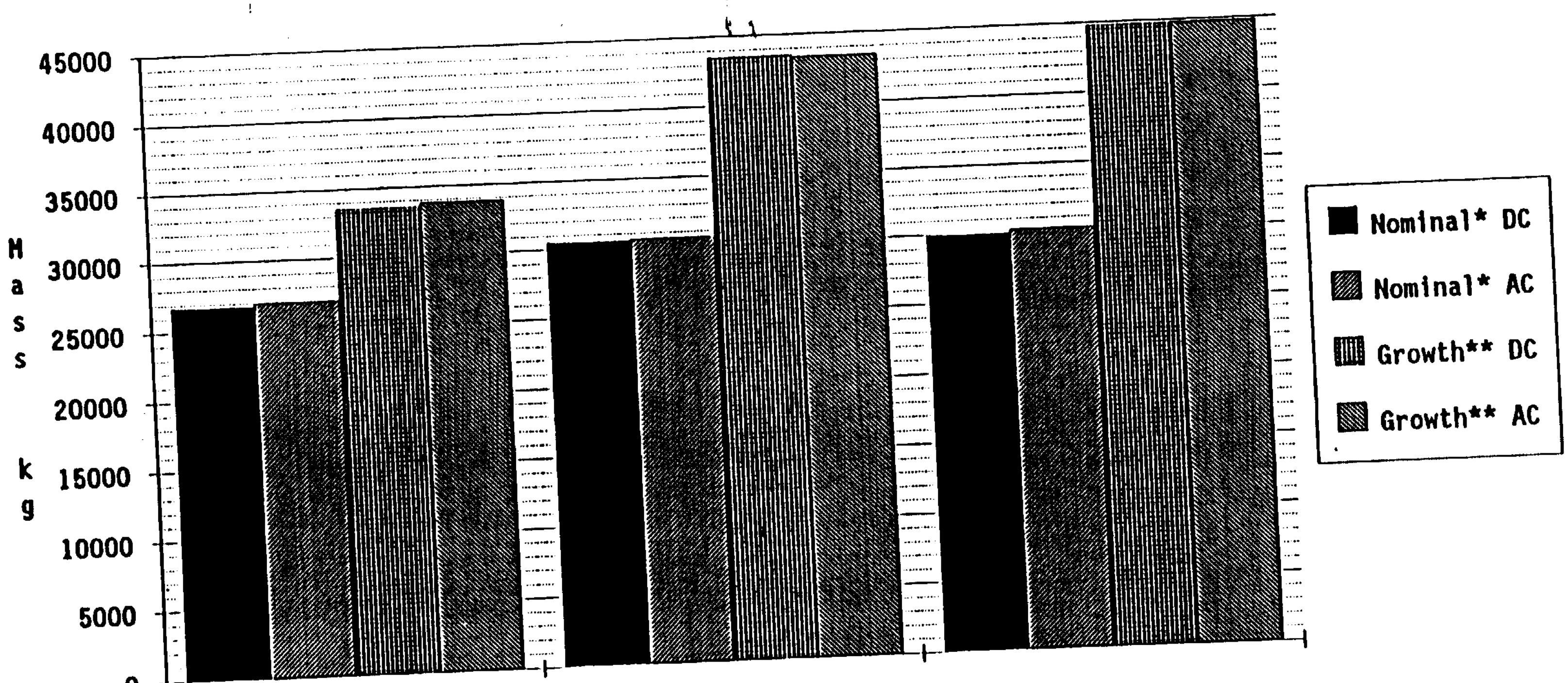
The power management and distribution (PMAD) system consists of the power conditioning components used to convert the generated power to different forms for transmission, or to meet user requirements and the transmission lines that will conduct this power from the power sources to the loads. Three PMAD architecture configurations, centralized, hybrid, and decentralized were evaluated during the course of this study (see Section 3.0 for a detailed discussion of these architectures). Two models were created for each architecture to identify the preferred method of power transmission, dc or ac. Each model permitted the load power demands and the transmission voltage level to be varied to assess the impact on power system mass. The ac power system models also allowed the transmission frequency to be changed. Finally, individual models were developed for different transmission line configurations and placements to determine the best conductor construction and installation location. Key parameters were used to evaluate each PMAD configuration: power conditioning component efficiencies and mass, transmission line mass and operating temperature and total system mass.

The PMAD models have enabled conclusions to be drawn about the architecture configurations, the transmission voltage, the form of power transmission, and various transmission line placements and configurations. The conclusions and supporting rationale are summarized in Table 5.0-1. Based on these studies, the centralized architecture configuration has some distinct advantages. It exhibited the lowest mass at nominal power levels and the smallest mass increases for power system growth. However, the greater deployment flexibility of a decentralized architecture may justify its additional mass. The form of power transmission is difficult to select. The masses of the dc and ac systems are quite close; therefore, they were evaluated using less quantitative criteria. Figure 5.0-1 graphically compares the masses of the architecture options and power transmission methods. Based on the existing technology and required advancements, projected development costs, component reliability and operating characteristics, and a higher overall PMAD system efficiency, an ac transmission approach appears preferable. The ac transmission line models used in this study are preliminary and future analysis may alter this conclusion. The suggested transmission voltage for distances greater than a few hundred meters is 5000 V. This is based on system mass calculations and perceived component technology levels. It was concluded that the small mass reductions obtained at higher voltages did not justify the increase in development costs. In fact, development costs may ultimately drive the selected transmission voltage downward. Finally, it is recommended that high voltage transmission lines be buried, while the short distance, low voltage transmission lines should be flat, suspended cables. Burying the high voltage lines will significantly reduce installation costs and still yield acceptable line masses and operating temperatures. To maintain tolerable line temperatures and mass, the low voltage, short distance transmission lines should be suspended.

TABLE 5.0-1
PMAD STUDY SUMMARY

- COMPLETED CENTRALIZED VS DECENTRALIZED ARCHITECTURE COMPARISON
  - CENTRALIZED HAS THE LOWEST MASS
  - DECENTRALIZED HAS BETTER BASE FLEXIBILITY
- PREFER 5000 VRMS TRANSMISSION VOLTAGE
  - YIELDS BEST VALUES FOR PMAD MASS, DEVELOPMENT COSTS TRADE-OFF
    - PMAD MASS AT 5000 VRMS APPROACHES MINIMUM VALUE
    - HIGHER VOLTAGE DEVELOPMENT COSTS DO NOT JUSTIFY SLIGHT MASS GAINS
- SUGGEST AC POWER TRANSMISSION
  - DC AND AC SYSTEM MASSES COMPARABLE
  - ANTICIPATE LOWER DEVELOPMENT COSTS FOR LOW-FREQUENCY AC SYSTEM
  - AC SYSTEM HAS FEWER COMPONENT STAGES - EXPECT HIGHER RELIABILITY
- BURY HIGH VOLTAGE (5000 VRMS) TRANSMISSION LINES
  - COMPARABLE LINE MASS, DO NOT HAVE ADDITIONAL MASS OF SUPPORT POLES
  - LOWER INSTALLATION COSTS, LAY IN TRENCH AND COVER WITH REGOLITH
  - REDUCED THERMAL CYCLING SHOULD IMPROVE RELIABILITY
- SUSPEND LOW VOLTAGE (120 VDC) TRANSMISSION LINES
  - LINES MUST BE SUSPENDED TO OBTAIN LOW MASS AND TEMPERATURE
  - USE FLAT CONDUCTOR GEOMETRY TO ENHANCE THERMAL RADIATION
  - INSTALLATION COSTS ACCEPTABLE FOR THESE SHORT DISTANCES

DC vs AC & Nominal vs Growth Architecture Comparison



* Nominal Power is 450 kWe
** Growth Power is Nominal Power + 200 kWe to Accomodate Base Evolution

FIGURE 5.0-1

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5.1 PMAD ANALYSIS OBJECTIVES AND EVALUATION CRITERIA

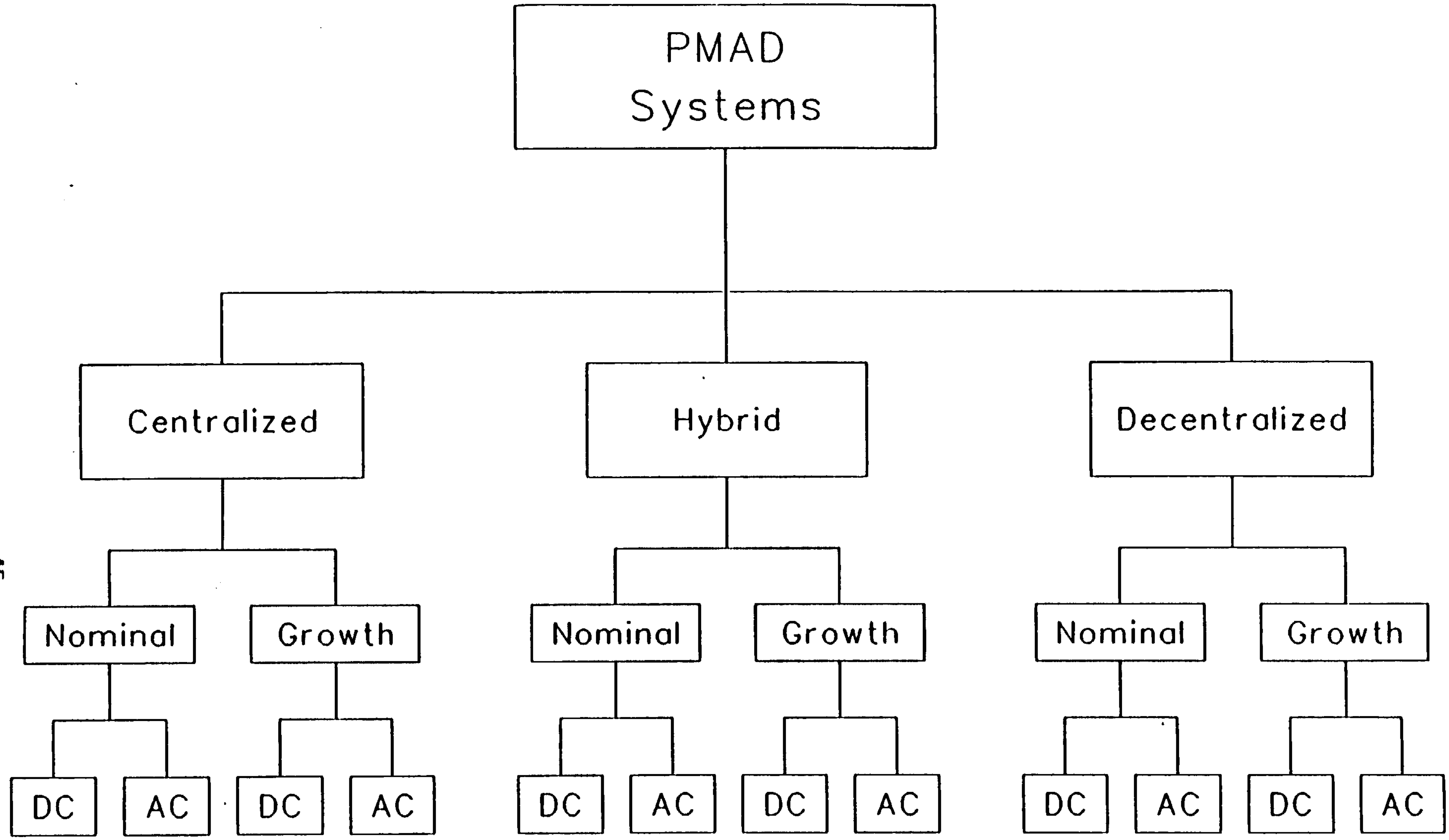
Four basic objectives were identified for this study: (1) characterize centralized, hybrid and decentralized PMAD architectures; (2) recommend transmission voltage levels; (3) compare ac and dc power transmission modes, and (4) recommend a preferred transmission line configuration and placement for each line segment. To define a well-balanced power system, both quantitative and qualitative evaluation criteria were established to assess each of these technical areas. PMAD architectures were evaluated on the basis of total power system mass at nominal power levels and the capability to grow to higher power levels as the lunar base evolves. To define the optimum transmission voltage, the PMAD mass reductions realized at higher transmission voltages were weighed against the increasing technological complexity and escalating development costs. The power system mass was the prime consideration when evaluating the form of power transmission, dc or ac. However, important factors such as technological maturity, development costs, reliability, and expected system performance were also considered. When assessing transmission line options numerous factors were considered. The transmission line configuration is largely determined by the form of power transmission. The transmission line placement, buried or suspended (surface placement not considered), was selected on the basis of line mass, operating temperature, installation demands and relative costs. Information on some of these items was obtained from a separate Task Order that addressed emplacement options (Ref. III-2).

5.2 PMAD MODELING STATUS

Several models were created by Rocketdyne to study variations of the PMAD system, as shown in Figure 5.2-1. First, three basic PMAD architecture configurations, centralized, hybrid, and decentralized, were defined. Each architecture was analyzed at nominal and growth power levels to assess the impact on power system growth as the base evolves. To complete the initial model formulation, two models were created at each power level to compare both dc and ac power transmission methods.

The dc PMAD system models were created first. Numerous runs have been performed to ascertain architecture features, identify voltage trends, and resolve transmission line placements. The mass comparisons shown in Table 5.2-1 summarize the results. These values were obtained at identical transmission voltages and load power requirements utilizing the nominal transmission line lengths and their suggested configurations. Figures 5.2-2, 5.2-3 and 5.2-4 show mass breakdowns for the three architectures. Based on Table 5.2-1 and Figures 5.2-2, 5.2-3 and 5.2-4: the centralized architecture mass is the lowest at the nominal power level and increases the least to reach the growth power level; the power source mass is the dominant item in each power system and its mass percentage increases in going from the centralized to hybrid to decentralized architectures; and for all three architectures, the transmission line mass is a relatively small percentage of the total power system mass.

The centralized, hybrid, and decentralized ac PMAD models that were developed allow preliminary mass comparisons to be made at frequencies varying



PMAD Modeling Tree

FIGURE 5.2-1

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Table 5.2.-1

DC Power System Architecture Mass Comparison

Nominal Line Lengths

Distribution	Power Level	Mass (kg): Power Source	Transmission Lines	Power Conditioning	Total
Centralized	Nominal	19,250 (72%)	1350 (5%)	6200 (23%)	26,800 (100%)
	Growth	21,800 (65%)	2750 (8%)	9000 (27%)	33,550 (114%)
Hybrid	Nominal	23,800 (78%)	1300 (4%)	5400 (18%)	30,500 (100%)
	Growth	33,600 (77%)	2450 (6%)	7500 (17%)	43,550 (143%)
Decentralized	Nominal	24,900 (83%)	950 (3%)	4150 (14%)	30,000 (100%)
	Growth	37,350 (83%)	1600 (4%)	5800 (13%)	44,750 (149%)

CENTRALIZED DC SYSTEM MASS BREAKDOWN (NOMINAL POWER LEVELS)

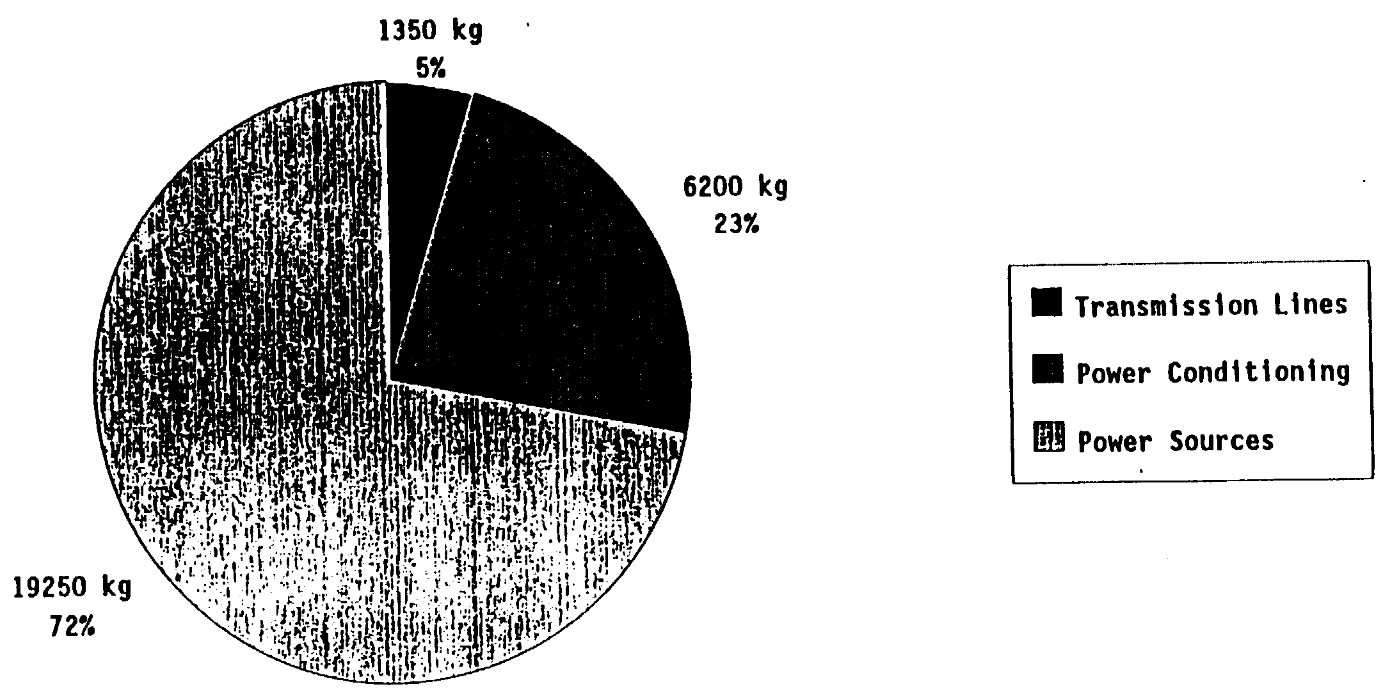

Figure 5.2-2

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Hybrid DC System Mass Breakdown (Nominal Power Levels)

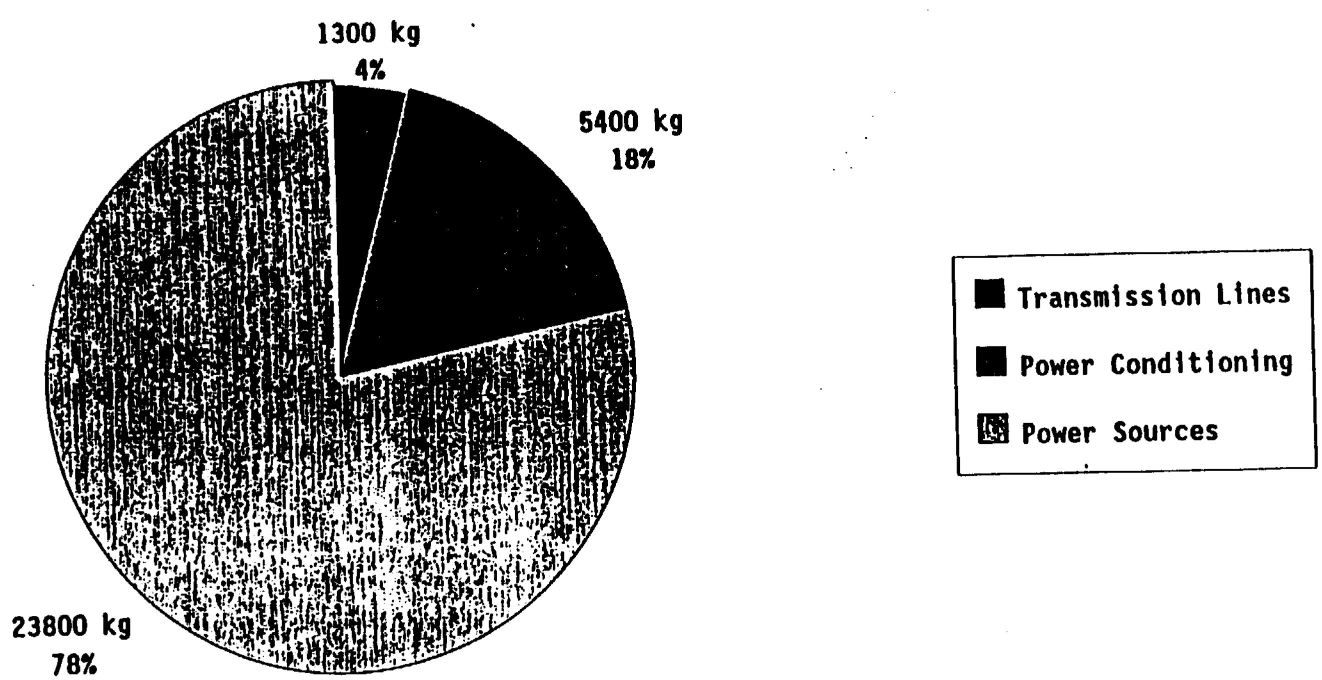

Figure 5.2-3

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DECENTRALIZED DC SYSTEM MASS BREAKDOWN (NOMINAL POWER LEVELS)

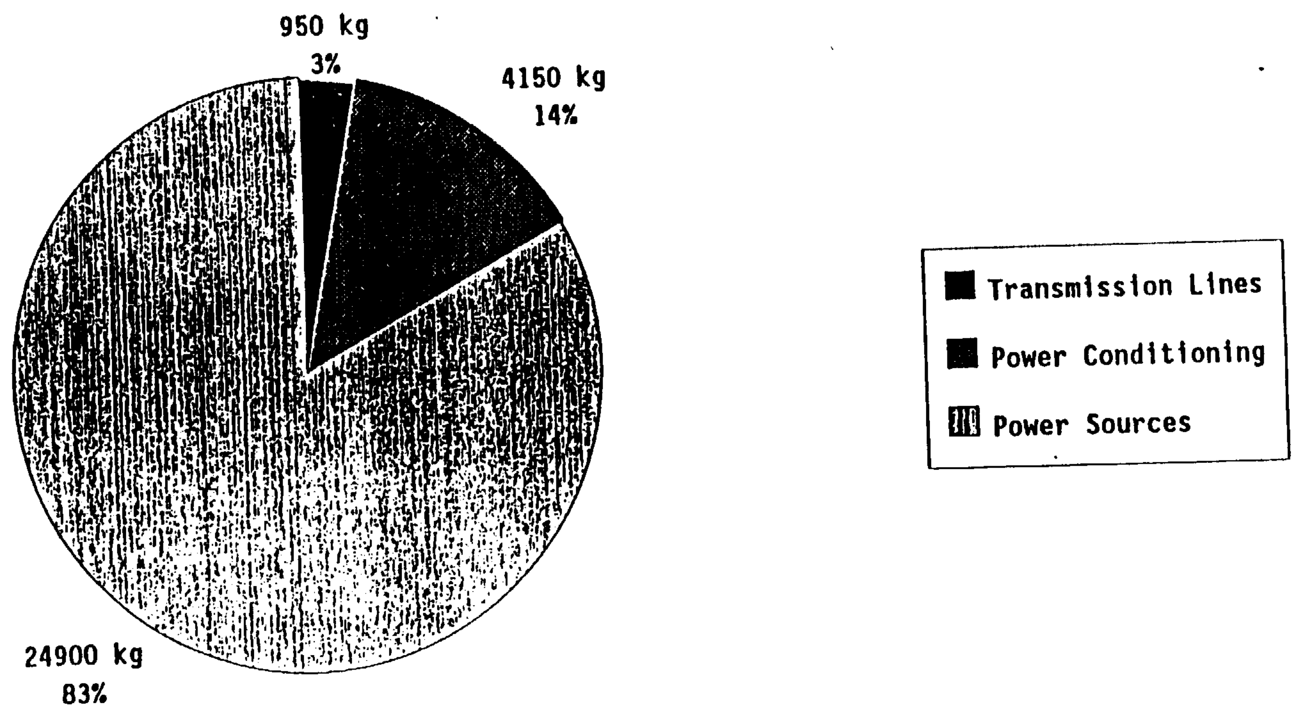

Figure 5.2-4

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from 60 Hz to 5 kHz. However, there is concern about the accuracy of the individual transmission line algorithms contained in these PMAD models. Auburn University is developing models for these lines, but they were not available for this study. In the interim, simplified models were created. It is felt sufficient fidelity exists to yield meaningful results, but it is recommended that comparisons be made with Auburn's models to verify these results.

The transmission frequency of the ac power system modeled in this study was determined by the SP-100 Brayton system alternator frequency (a PMAD system with a Stirling engine source was not considered). The Brayton system was selected because of its slightly lower mass, 5-percent; technical maturity; and less complex power conditioning (see Section 4.2). Alternate frequencies can be obtained if a frequency converter is placed on the output of the alternators; however, the converter will increase the power source mass and reduce its efficiency. Unfortunately, there was not sufficient time to study this option, but it is suggested as a subject for future studies.

The ac PMAD mass prediction results are summarized in Table 5.2-2. These values were calculated at the same transmission voltages, load power requirements, and transmission line lengths utilized in the dc analysis. However, the transmission line configurations were changed to incorporate conductor designs that might be utilized in actual ac transmission lines. The transmission line models represented a 3-phase, 3-wire transmission system that used litz wire[1] construction for the conductors. Earlier analysis indicated this line configuration weighed less than options using single phase power transmission or solid conductors. (This study is discussed in Sections 5.3.2.2 and 5.4.2.) Finally, a 1 kHz transmission frequency was selected since initial projections indicate it will be near the operating frequency of the SP-100 Brayton system alternators. Mass breakdowns of the three architectures are shown in Figures 5.2-5, 5.2-6 and 5.2-7. Looking at Table 5.2-2 and Figures 5.2-5, 5.2-6 and 5.2-7, one draws the same conclusions voiced previously in the dc discussion: the centralized architecture exhibits the lowest mass, the power sources are the heaviest items and transmission line mass is a small percentage of the total system mass.

Comparing dc and ac transmission methods, the first thing noted is the nearly identical mass estimates obtained for each architecture configuration at the two power levels. Usually, the dc system is lighter, but the difference is so small it is considered beyond the accuracy of these models. Since a mass advantage was not evident for either method, (refer back to Figure 5.0-1 for a graphical comparison), the power transmission form must be selected on the basis of other criteria. A subtle distinction can be seen if Figures 5.2-5, 5.2-6 and 5.2-7 are compared with Figures 5.2-2, 5.2-3 and 5.2-4. The power source mass is slightly lower for an ac system, but its power conditioning mass is slightly heavier. This occurs because ac voltage transformations are inherently more efficient, resulting in a higher overall

[1]Litz wire consists of separately insulated strands woven to assume all possible positions within the conductor cross section. See Section 5.3.2.2 for additional details.

Table 5.2-2

AC Power System Architecture Mass Comparison
Nominal Line Lengths

Distribution	Power Level	Mass (kg): Power Source	Transmission Lines	Power Conditioning	Total
Centralized	Nominal	18,900 (70%)	1200 (4%)	6850 (25%)	26,950 (100%)
	Growth	21,750 (64%)	2350 (7%)	9700 (29%)	33,800 (125%)
Hybrid	Nominal	23,450 (77%)	1200 (4%)	5900 (19%)	30,550 (100%)
	Growth	33,350 (77%)	2150 (5%)	7900 (18%)	43,400 (142%)
Decentralized	Nominal	24,650 (81%)	950 (3%)	4650 (15%)	30,250 (100%)
	Growth	37,000 (83%)	1600 (4%)	6200 (14%)	44,800 (148%)

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CENTRALIZED 1 kHz AC SYSTEM MASS BREAKDOWN (NOMINAL POWER LEVELS)

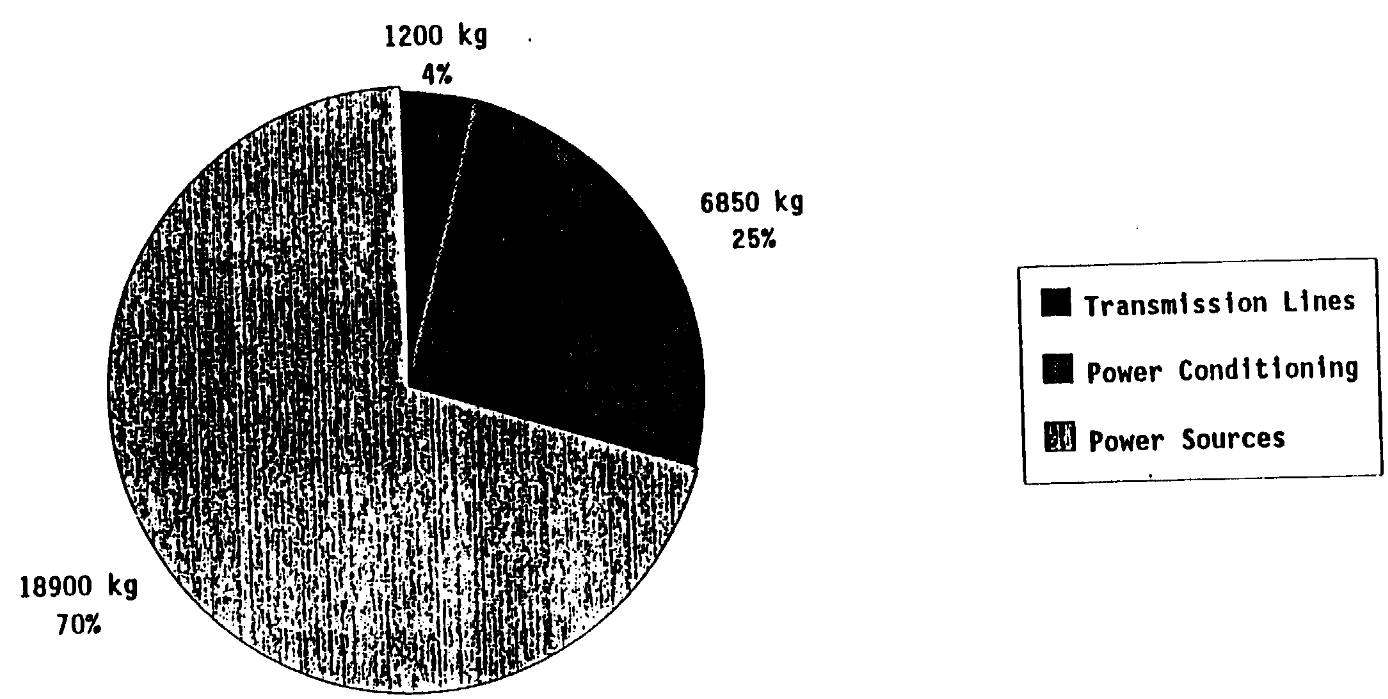

Figure 5.2-5

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HYBRID 1 kHz AC SYSTEM MASS BREAKDOWN (NOMINAL POWER LEVELS)

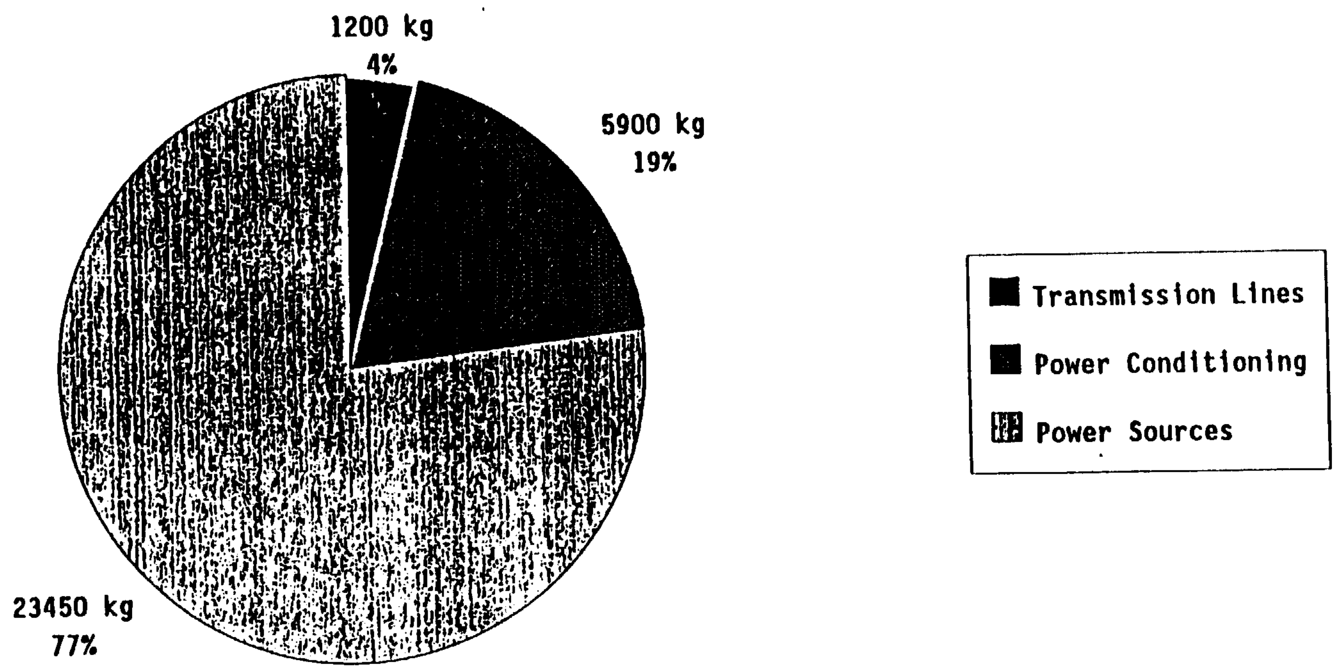

Figure 5.2-6

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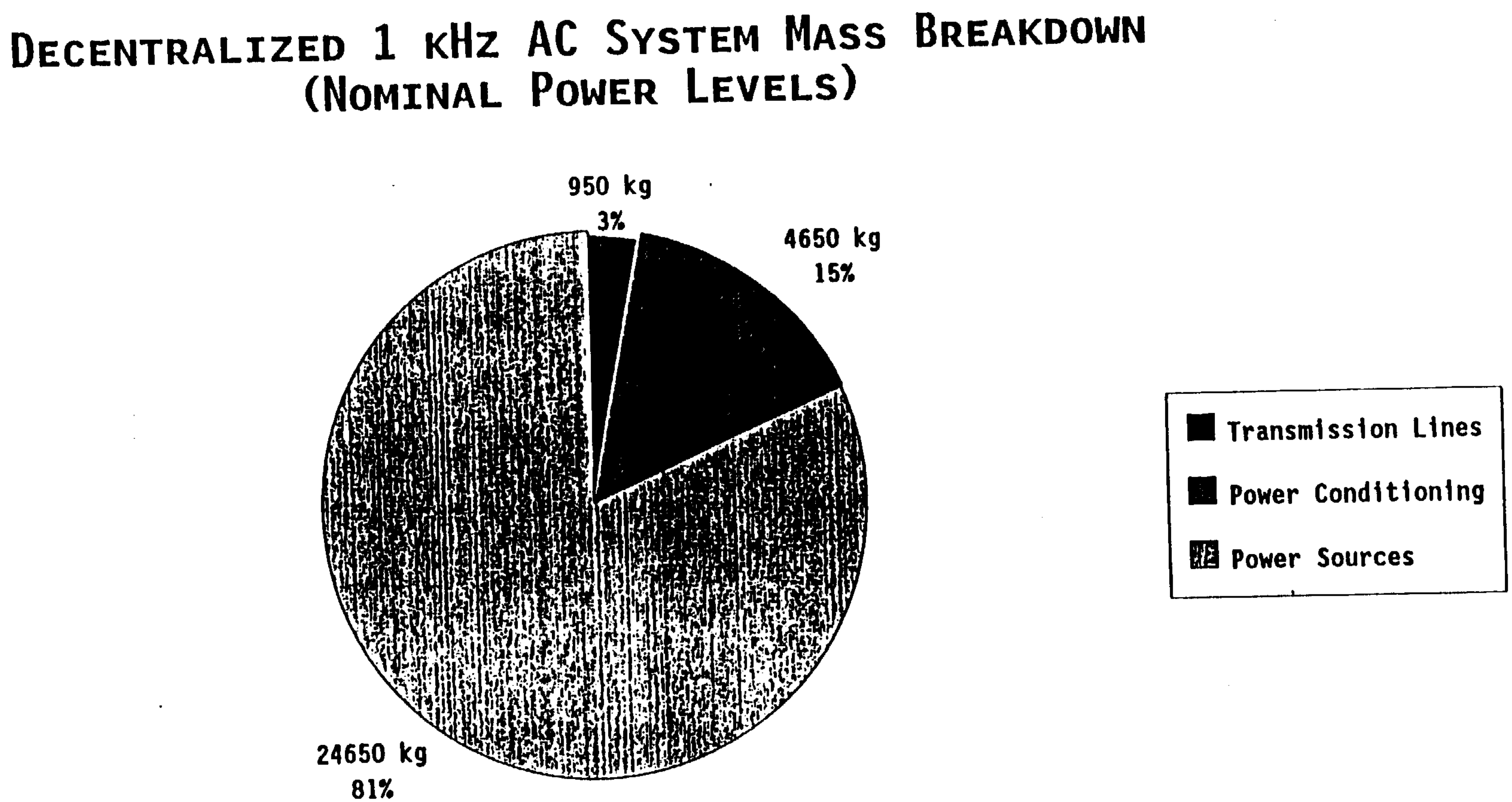

Figure 5.2-7

7/18/90

system efficiency. This improved efficiency reduces the power source requirements and subsequent mass. The ac PMAD system, however, operates at the SP-100 Brayton alternator frequency, which does not result in the minimum mass for ac power conditioning components containing transformers.

In summary, it should be noted that all power conditioning mass estimates include the mass of the accompanying thermal management and radiator subsystem. It is imperative that these masses be included to obtain the complete power conditioning system mass. To assess the impact of different component operating temperatures and radiator sink temperatures, the PMAD models permit the user to change these values. Finally, individual models exist for each of the power conditioning components and transmission lines utilized in the PMAD analysis. This allows the creation and analysis of unique power system configurations by selection of the proper power conditioning and transmission line elements.

5.3 PMAD MODEL DEVELOPMENT METHODOLOGY AND ASSUMPTIONS

The PMAD models consist of two parts, the power conditioning components and the transmission lines. The operating characteristics and functions of these items are substantially different; therefore, the models representing them also differ considerably. Individual models were created for each type of power conditioning component, transmission line configuration and placement. To create a complete PMAD system model, specific component models were selected based on the PMAD architecture and type of power transmission. These component models were then integrated into an overall PMAD model by interlinking the component voltages and powers. Key input and output system values were placed in a summary section to facilitate model parameter changes and display the results in an easy to read, convenient manner.

The algorithms utilized in these models were developed for components that are projected to be available in the 2000 to 2010 timeframe. Numerous improvements are projected for converter components, thermal management subsystems and packaging techniques. It is anticipated that carbon-carbon will be used extensively for enclosures and heat pipes, replacing aluminum in many applications. Component radiators will also utilize carbon-carbon extensively. The use of amorphous metals for transformer cores should reduce their mass and losses, especially at high frequencies. Presently, most individual semiconductor switches are limited to operating voltages below 500 V (Ref. V-1, V-2, V-3, V-4). Silicon controlled rectifiers (SCRs) are available at voltages up to 5000 V; however, their turn-off requirements limit their applications[2] (Ref. V-5). The development of high voltage, high power semiconductor switches should decrease the mass of converters and improve their efficiency. The algorithms incorporate these anticipated technology advances, and they are reflected in the mass estimates.

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[2]An SCR cannot be turned off by simply removing the gate signal; the current flow must either be interrupted or forced to flow in the opposite direction. For ac switching or rectification, these turn-off requirements are acceptable because the current naturally crosses through zero each half cycle. However, in a dc application such as an inverter switch, they usually are not acceptable.

The PMAD system mass is governed by the PMAD architecture, the number and size of the transmission channels or modules included to meet reliability criteria, the output power demands, the power source, output and transmission voltages, the power conditioning component operating frequencies and stage efficiencies, and the transmission line placements, lengths, geometries, materials and efficiencies. The algorithms contained in the models calculate component and line masses based on these factors. Other items, such as filtering requirements and power factor demands, were also considered during the model development.

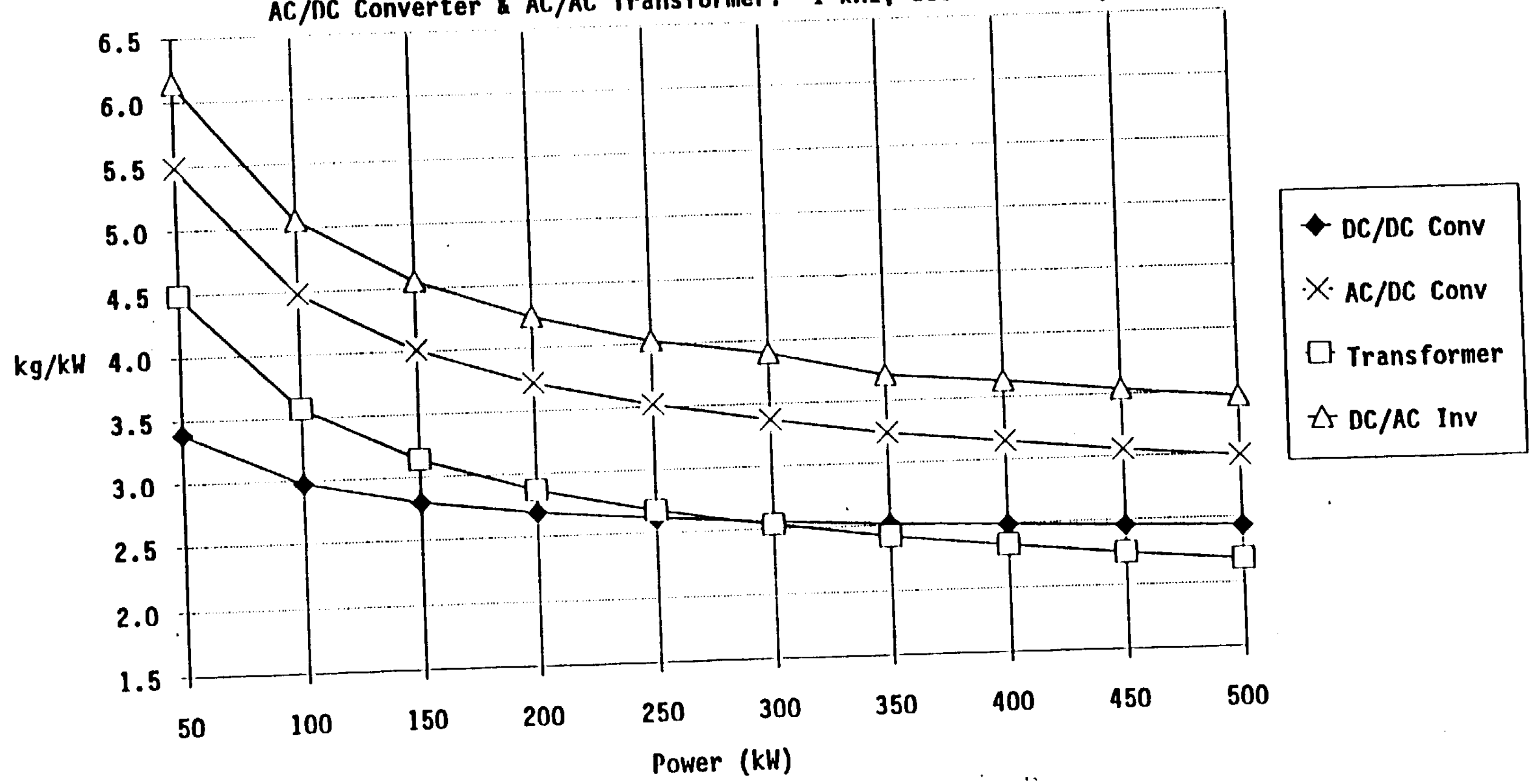
Reliability will be a key consideration as the lunar base power system design evolves. A detailed reliability analysis was not conducted during this study; therefore, some basic assumptions were made. Drawing on experiences obtained from prior programs and Space Station Freedom (SSF) studies, it was decided that four parallel channels would be used for PMAD components feeding the habitat. Each channel would be sized to carry a third of the power. This allows one channel to fail and still provide full power. If two channels failed, power would be reduced by a third. This was considered adequate to continue essential operations. One more failure would force the habitats to adopt emergency power conserving measures, but enough power should be available to maintain life support systems. This approach will also simplify component fabrication and maintenance. A channelized PMAD system reduces the power disruptions that will occur during maintenance since power can continue to be provided through the parallel paths. The power conditioning component sizes are also reduced, making them easier to manufacture and replace. A channelized PMAD system was the only type considered in this study. A ring bus architecture may also be viable, but it was not considered due to time and funding constraints. It is suggested as a subject for future study.

Unfortunately, reliability considerations typically increase power system mass. For the habitat power feed, even without the added fourth channel, the PMAD mass would be increased. Multiple smaller units are almost always heavier than a single unit. The magnitude of this effect can be seen in Figure 5.3-1. A single 300 kW transformer will weigh about 30 percent less than three 100 kW transformers. This occurs because of economies of scale present in transformer design practices and the reduced percentage of mass occupied by ancillary hardware such as the enclosure and the control and monitoring system.

It was assumed that each of the loads (typically module or habitat secondary distribution systems) would be fed a common voltage, 120 Vdc. This voltage was selected to be consistent with the present SSF requirements and reduce the variables under study. If it is ultimately selected for the lunar base, much of the development work invested in low power circuit protection and switching will be directly applicable. It is recognized that some loads will prefer other power forms and voltages. For example, the ISRU will probably contain several motors; therefore, a 480 Vrms, three-phase power feed may be more appropriate. As these load power requirements are defined, the models will be modified to reflect their impact. Finally, inside the habitat or at the ISRU, a PMAD distribution system is necessary to distribute the load power at the chosen voltage and frequency to individual devices. These secondary distribution systems were not considered in this study.

Converter & Transformer SPWT Comparison

(DC/DC Converter: 40 kHz, 100 to 5000 Vdc; DC/AC Inverter: 1 kHz, 100 to 5000 Vrms;
AC/DC Converter & AC/AC Transformer: 1 kHz, 500 to 5000 V)



Note: All values include thermal management & radiator subsystem masses

FIGURE 5.3-1

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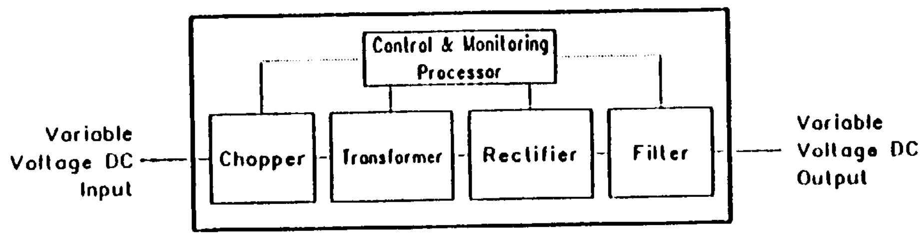
5.3.1 Power Conditioning Modeling and Analysis Approach

The lunar base power system will use several types of converters; however, one can note from the diagrams in Figure 5.3-2 that all converters have common stages. For example, the dc/dc converter, the dc/ac inverter and the ac/ac frequency converter each have a chopper stage. The interconnection and control of these stages determine the function and operation of the total converter. Hence, one can define the stages contained in a specified converter, calculate their individual masses, and then add these values to the control and monitoring hardware mass, the enclosure mass and the thermal management and radiator subsystem mass to determine the total mass of a complete converter.

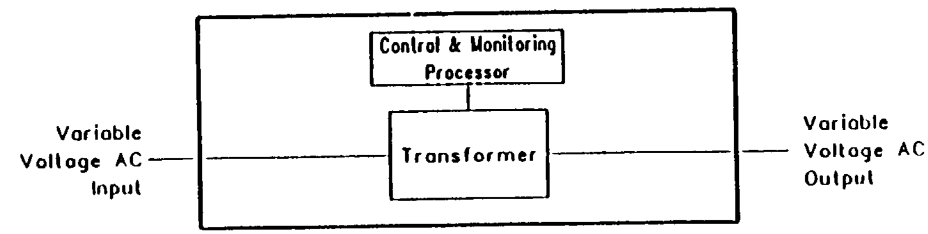
Although power conditioning components differ, their masses were all calculated in a similar manner. First, the composite stages were defined and an algorithm was formulated to estimate the mass of each stage. These algorithms were developed by obtaining information on representative component designs and noting the mass variations occurring with frequency, voltage, power level, etc. The main source of component information was the SSF documentation. These designs best typify proposed lunar base hardware and represent the latest space-based components, operating at the highest steady state power levels. Since the lunar base will be erected about ten years in the future, these designs and their corresponding masses were adjusted to incorporate projected technological advancements. Other individuals have also developed power conditioning mass prediction algorithms (Ref. V-6, V-7, V-8). Their reports were perused to obtain alternate power conditioning component designs and incorporate their observed mass trends if they were deemed relevant and accurate. Algorithms were then developed to determine the mass of ancillary equipment such as controllers, data interface modules and monitoring sensors. The masses of the individual stages and ancillary equipment are summed to determine the mass of the component electronics. Based on this mass and a factor computed for the density of electronics, the mass of the surrounding enclosure, including mounting plate, internal heat pipes, and thermal pad was estimated. These values are then summed to obtain the component mass. Finally, this mass is added to the thermal management and radiator subsystem mass to yield the total power conditioning element mass.

The thermal management and radiator subsystem mass is an important element in the power conditioning system models. To calculate this mass, the efficiency of the converter and its resulting power losses must be estimated. The converter efficiency is determined in a similar manner as the mass. The efficiencies of the individual stages at the selected voltage and power levels are estimated. Multiplying these stage efficiencies together yields the conversion efficiency. Utilizing the output power level, the calculated conversion efficiency, and including the parasitic power demands of the control and monitoring system, the total converter power losses can be determined. The radiator mass algorithm utilizes this power loss value in conjunction with the effective radiator and lunar surface sink temperatures to calculate the radiator mass. The effective radiator temperature value assumes a 16.7° C (30° F) temperature delta exists between the electronics cold plate and the radiator surface. The assumed radiator configuration is a vertical

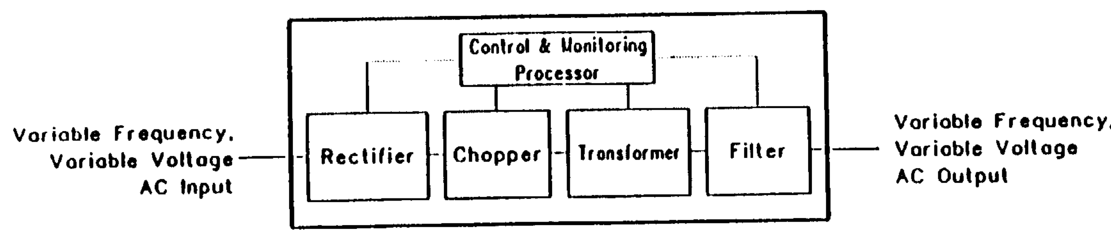
Lunar PMAD Modeling
Converter Block Diagrams



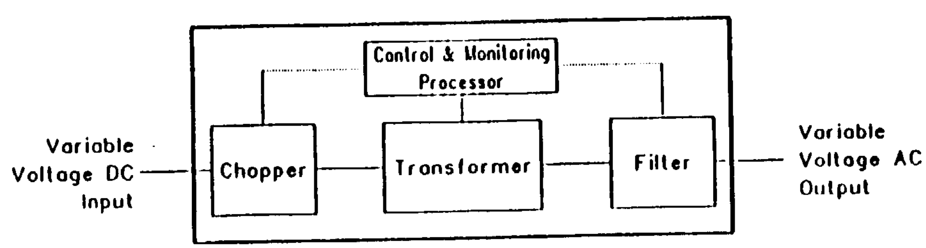
DC/DC Converter Block Diagram



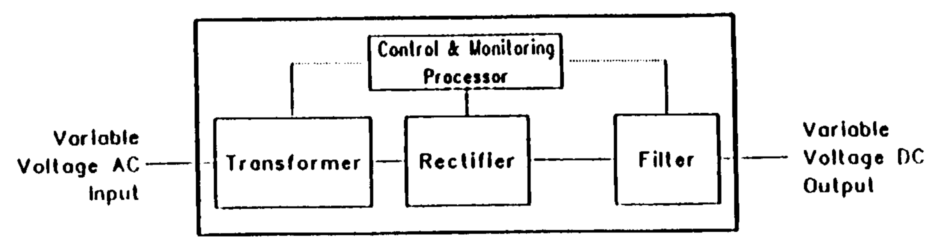
AC/AC Transformer Block Diagram



AC/AC Frequency Converter Block Diagram



DC/AC Inverter Block Diagram



AC/DC Rectifier Block Diagram

CONVDIAG
5 8 90

FIGURE 5.3-2

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Rocketdyne Division

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flat plate under 15 feet in height that utilizes a reflective blanket placed on the lunar surface to reduce the effective sink temperature.

The electronics cold plate temperature of 40° C (104° F) that is utilized in the models is based on present SSF component cold plate temperatures and anticipated technology improvements. A diagram of the thermal management system for a SSF dc to dc converter unit (DDCU) and a lunar base component are compared in Figure 5.3-3. Although the finned heat exchanger concept shown in this diagram was heavier and had a higher temperature drop than other approaches considered, it was used on SSF to allow replaceability of the power conditioning units and other components. The algorithm development utilized this concept since it is relatively well developed and information on it was readily available. It should not be considered a recommendation. An alternate approach may be employed for the lunar base since the requirements and environment differ. A detailed study of this area is necessary to determine the best method of thermal management.

The SSF DDCUs, which are representative of the proposed lunar base converters, experience the highest cold plate temperatures because they are located the furthest from the coolant pumps. The maximum specified DDCU cold plate temperature is 10° C (50° F). Using this value, the latest thermal modeling indicates numerous DDCU devices may experience temperatures in excess of 80° C (176° F). This analysis is based on the finned heat exchanger design that conducts heat from the DDCU thermal pad to the equipment assembly cold plate. Presently, this heat exchanger has a worst case temperature drop of 30° C (54° F) across it. Assuming thermal transfer improvements are made and increases in electronics operating temperatures occur, a value of 40° C (104° F) was selected for the lunar base component cold plates. This represents a cold plate temperature increase of 30° C (54° F), and it may result in some electronic element temperatures exceeding 100° C (212° F). Since the efficiency and reliability of electronics assemblies are adversely affected by increasing temperature, and limited work is being done in the development of high temperature electronics, it is difficult to justify cold plate temperatures higher than 40° C (104° F) (Ref. 9)[3]. In arriving at this cold plate temperature, it was assumed the power conditioning components would be required to operate reliably and efficiently for a minimum of 10 years.

The algorithms used in this study to determine the thermal management subsystem mass yielded a value of about 12.2 kg for each kWe of power loss. This translates into a mass increase of 90.6 kg (30.5 percent of its total mass) for a 100 kWe dc/dc converter operating at 92.3 percent efficiency. For a 100 kWe, 1 kHz transformer that has a 97.9 percent efficiency, the mass

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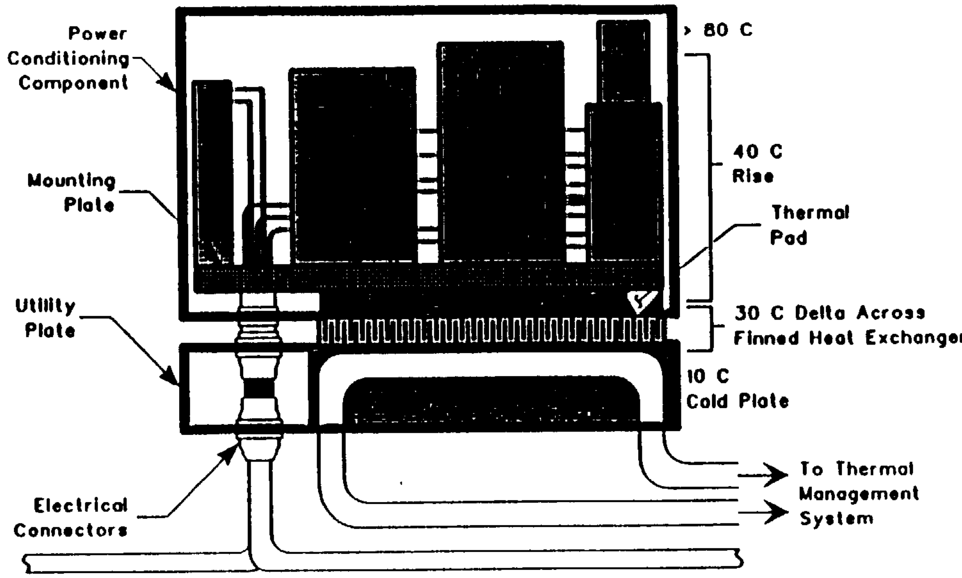
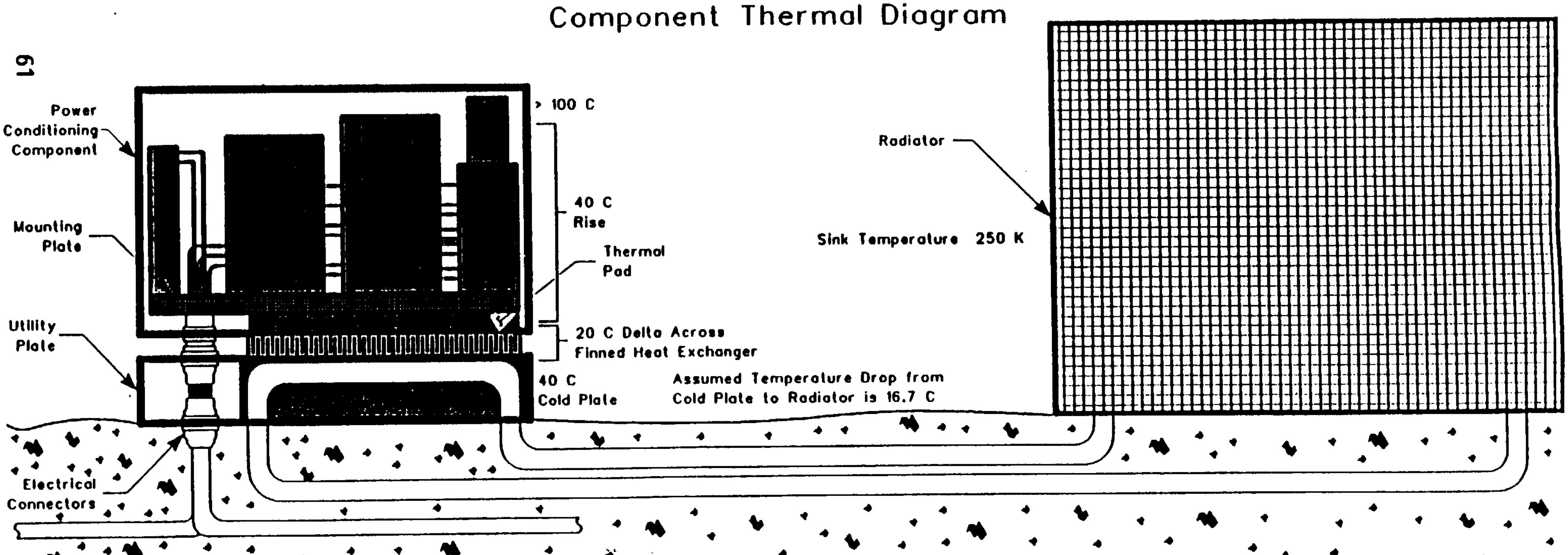
[3]MIL-HDBK-217 indicates the reliability of electronics assemblies will decline with increasing temperature. The reliability of devices such as logic elements, semiconductors, resistors and capacitors declined as their temperature increased from low (0-10° C) to high (125-160° C) values. The maximum allowable operating temperature of a device is determined by summing the ambient temperature and internal temperature rise. As the ambient temperature rises, devices must be derated to maintain an equivalent reliability. This increases component mass.



Space Station Freedom
Component Thermal Diagram



Projected Lunar Base Component Thermal Diagram

Figure 5.3-3

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required for thermal management would be 25.6 kg (7.2 percent of its total mass). In general, the mass of the power conditioning thermal management subsystem was between 7.5 and 16.0 percent of the mass of the total PMAD system or 2.0 to 3.2 percent of the total power system mass.

5.3.1.1 Power Conditioning Component Types

Five basic power conditioning converter types were considered during this study: a dc/dc converter, a dc/ac inverter, an ac/ac transformer, an ac/ac frequency converter, and an ac/dc rectifier. Diagrams of these converters, depicting their internal power conditioning stages and controls, were shown in Figure 5.3-2. A brief explanation of these converter types and their function and role in the PMAD system are addressed below.

Dc power systems generally must use dc/dc converters to change the voltage level for transmission and/or to meet user needs. In the lunar base architectures under study, a dc/dc converter is required for the main power transmission channels to step up the 100 Vdc produced by the thermoelectric power source to high voltage dc in the range of 3000 to 10,000 Vdc. Current analysis indicates the optimum transmission voltage is approximately 5000 Vdc. A step-down dc/dc converter is required at the user end to convert this high voltage dc back to low voltage dc for distribution to the loads.

Hybrid power systems utilize inverters and rectifiers to change the power type from dc to ac or vice versa. Applied to the lunar base PMAD system, a dc/ac inverter would be used to convert low voltage dc to high voltage ac, at an intermediate frequency. The selected voltage and frequency would probably be near 5000 Vrms and between 1 and 5 kHz. At the user end, an ac/dc converter transforms the high voltage ac to low voltage ac and then rectifies it to produce low voltage dc for distribution to the loads.

In an all ac system, an ac/ac transformer or ac/ac frequency converter would be utilized. An ac/ac transformer converts the low voltage ac to high voltage ac for transmission. At the user end, a complementary transformer with a high voltage primary would transform this high voltage ac back to low voltage ac. With a low frequency power source such as a Stirling engine, an ac/ac frequency converter might be used to convert the low frequency ac to high frequency ac to reduce the mass of subsequent transformers. At the user end, ac/ac frequency converters might be used to provide different frequencies for specialized applications. Although an ac/ac frequency converter is mentioned, there was not sufficient funding during this study to develop a model incorporating this element. The use of an ac/ac frequency converter and high frequency distribution system is recommended for later study since the mass of the PMAD transformers will be reduced. The added mass of an ac/ac frequency converter must be traded against the reduced mass of the distribution transformers to determine if the overall power system mass is reduced.

It was stated earlier that each converter type contains common stages. Although differences exist within individual converter stages, basically their number and interconnection defines the converter's function. A brief explanation of these stages and their operation is provided in Appendix A to acquaint the reader with their function. Frequent comparisons are made to existing space station elements to provide a reference technology base. Some of the development issues and testing requirements are also addressed there since they will have a bearing on the final PMAD configuration and they were considered during the model development. An introduction to the individual stages and some of their technology issues will provide a better understanding of the complete PMAD system and the models created to analyze it.

5.3.2 Transmission Line Modeling and Analysis Approach

The transmission line models developed during this study considered the conductor material, the installation location and configuration, the conductor construction and geometry, and the effects of ac or dc power transmission (see Table 5.3-1). Separate models were created for each transmission line option, but only certain ones were actually employed in the final PMAD models. To identify the best transmission line configurations and reduce the PMAD modeling and subsequent trade study to a manageable size, the various line options were first evaluated in expected lunar base applications. By varying the transmission line operating parameters, the effects on mass and operating temperature were assessed. Based on these initial results certain unattractive options were quickly identified and eliminated. The remaining options were included in the overall PMAD models to support system analysis.

TABLE 5.3-1
TRANSMISSION LINE PARAMETERS

Parameter	ac Lines	dc Lines
Cable Placement	Buried, Suspended	Buried, Suspended
Cable Configuration	2-Wire, 3-Wire	2-Wire
Cable Insulation	Uninsulated	Uninsulated
Conductor Material	Aluminum, Copper	Aluminum, Copper
Conductor Geometry	Round, Flat	Round, Flat
Conductor Construction	Solid, Litz Wire	Solid

The individual transmission line models were based on the work produced by Auburn University (Ref. V-10). The initial dc transmission line models were created by simply converting the algorithms in Auburn's report into computerized spreadsheet equations. Later, minor modifications were made to the spreadsheet equations to include a flat conductor geometry. The ac transmission line models used the dc models as a starting point and included the chief effects characteristic of ac transmission. To reduce the losses that occur when solid conductors are used to carry ac, especially high frequency ac, a model utilizing a litz wire conductor construction was created.

Reducing the conductor cross sectional area to cut transmission line mass causes the efficiency to decline and the resistance and temperature to increase. The ensuing temperature rise then further increases the conductor resistance. These simple relationships have major implications and lead to relatively low conductor temperatures. Our studies show the best overall system mass was achieved when the average conductor temperature was about 70° C (158° F). Two conductors of identical length, operating at the same power, voltage, and efficiency, but exhibiting different temperatures, will have different masses. The hottest conductor will be the heaviest; and depending on the temperature difference, this mass difference can be significant. For example, a flat, suspended, aluminum, 5000 Vdc, 1-kilometer transmission line operating at 95 percent efficiency and supplying 500 kWe will have a temperature of 86.4° C and a mass of 140.6 kg. If a round transmission line is used instead, its operating temperature will increase to 131.6° C. This causes the line mass to rise to 152.1 kg, an increase of 8.2 percent.

However, the greatest impact of a reduction in conductor efficiency and the accompanying increase in line resistance and temperature will be the effect they have on the power source mass. The above 95 percent efficient, flat transmission line has a temperature of 86.4° C and a resistance of 2.63 ohms. The mass of the 526.3 kWe power source required to feed this line is 14,166 kg. Reducing the efficiency to 90 percent increases the temperature to 119.5° C and the resistance to 5.56 ohms. The transmission line mass now drops from 152.1 to 70.7 kg; but, the power source mass increases to 14,531 kg because it must now supply 555.6 kWe. This is an overall increase of 284 kg. It pays to have highly efficient transmission lines that will naturally operate at a relatively low temperature and have a low resistance because the power source mass is dominant and quite sensitive to changes in transmission line efficiency.

5.3.2.1 Buried vs Suspended Transmission Lines

Two transmission line locations were considered in this study, suspended and buried (surface placement was not considered). A detailed discussion of the effects identified with buried and suspended transmission lines can be found in Auburn University's report entitled "Electrical Transmission on the Lunar Surface - Part I dc Transmission" (Ref. 10); however, the primary difference is the manner in which heat is removed from the conductors. Due to the absence of an atmosphere, suspended conductors utilize thermal radiation. Buried conductors must rely on the thermal conduction of the lunar soil.

Although thermal management is the main difference between suspended and buried transmission lines--it is the only one specifically addressed by algorithms--other factors were also considered by Auburn University in the model development. Bare, suspended lines are relying on the insulating properties of a vacuum. A vacuum is a superb insulator, but it can be contaminated by gaseous discharges. Other problems that may occur with suspended lines are dielectric surface flashover and electrostatic charging of regolith dust particles. Suspended conductors must be supported. High field stresses may cause a charge to travel between conductors, along the surfaces of the supporting members. Regolith dust particles may also be attracted to transmission lines by electrostatic charging. Dust particle bonding would impede thermal radiation. Buried, uninsulated transmission lines will utilize regolith as an electrical insulator. The electrical resistance of regolith appears quite high, about the same as standard conductor insulations, but variations in regolith composition could result in insulation failures[4]. Although none of these items appears to be a major obstacle, transmission line testing is required to verify the assumptions and characteristics used by Auburn in its model development.

5.3.2.1.1 Suspended Transmission Line Considerations

Terrestrial transmission lines are mainly cooled by convection. Since the Moon does not have an atmosphere, the sole practical means of cooling suspended lines is thermal radiation. The line cooling problem is compounded by solar heating. Any time the sun is above the lunar horizon, it is insolating the conductor surface with 1372 watts/meter^2. An absorptivity coefficient of 0.1 was used for both copper and aluminum conductors; hence, 10 percent of the solar flux incident on the conductor surface will be absorbed. It may be possible to enhance conductor cooling through the use of specialized coatings designed to reduce absorption, but increase emissivity.

Figure 5.3-4 shows some of the transmission line options that were considered to determine the best methods of thermal management. The first option used a single round conductor sized to handle the full circuit current. The second approach utilized three round conductors, each rated to carry a third of the current. The last approach employed a horizontal flat conductor geometry with an aspect ratio of about 50:1. A vertical orientation was also considered, but rejected due to the installation difficulties and the absence of any major improvements in thermal radiation. Because the Moon lacks an atmosphere, the solar radiation striking a vertical conductor when the sun is near the horizon is the same as the solar radiation striking a horizontal conductor when the sun is at high noon. If later studies indicate settling regolith dust may be a problem, this orientation may need to be revisited.

Based on several cases, it was generally determined that the best approach was a flat conductor. The largest amount of conductor surface is exposed, thus enhancing thermal radiation. However, at lower conductor temperatures, Figure 5.3-5 shows a round conductor configuration may be superior. This occurs because thermal radiation increases by the fourth power with conductor temperature. Solar flux remains constant, independent of conductor temperature. Therefore, at lower conductor temperatures, it becomes more important to minimize the absorbed solar energy by reducing the conductor surface area. This favors a round geometry. Although the option utilizing

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[4]The range of resistivities defining an electrical insulator depends on the application and the applied voltage, but it is typically between 10^6 and 10^{20} ohm-cm. The resistivity of lunar rock varies between 10^6 and 10^{10} ohm-cm (Ref.IX.)

Transmission Line Options

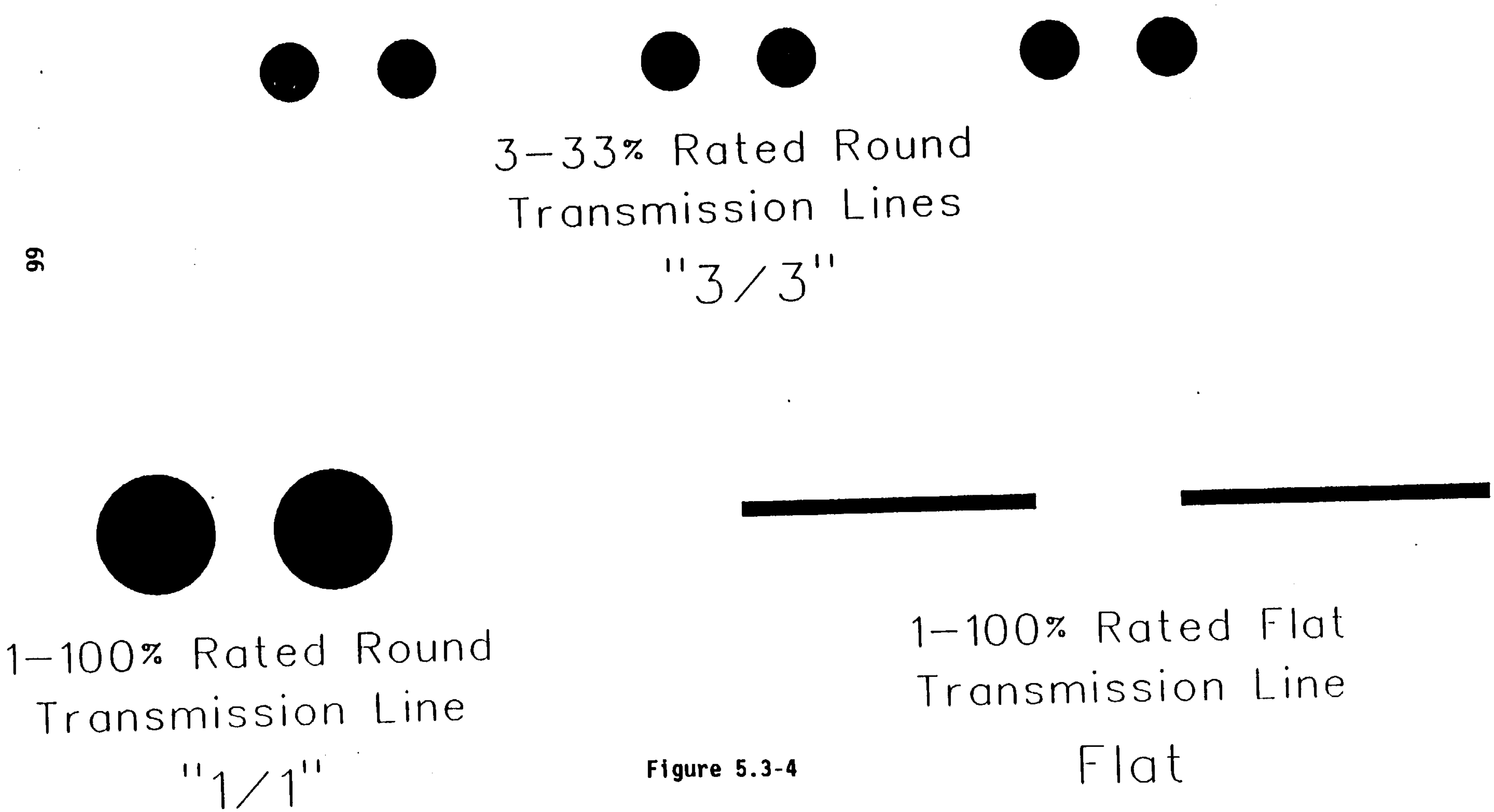


Figure 5.3-4

10 Meter Suspended Transmission Line Temperature vs Efficiency (100 kW, 100 VDC)

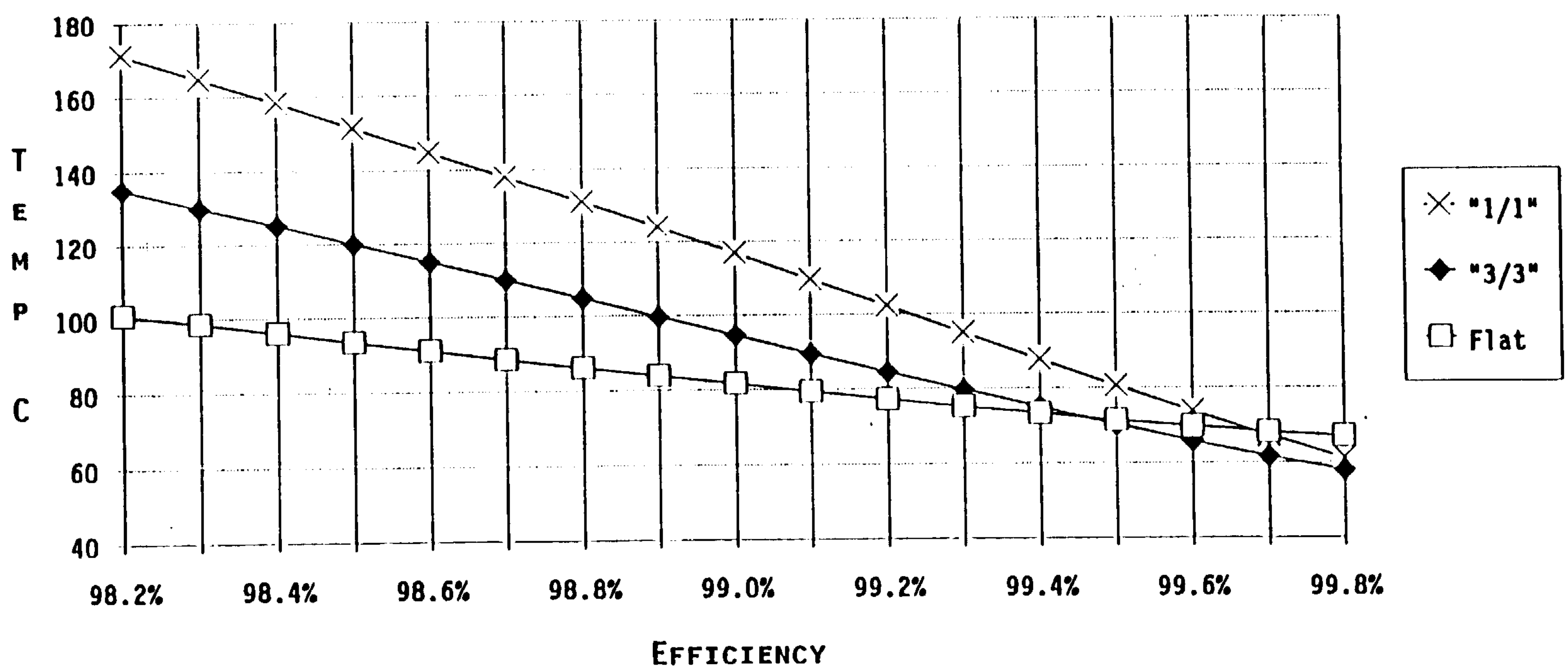


Figure 5.3-5

6/7/90

three 33 percent rated conductors exposes more surface area, this is not the main reason it was initially considered. Dividing a transmission line into smaller lines enhances reliability, since a failure will not result in a total power loss. This approach is one of the few instances where it may be possible to increase reliability and actually reduce mass.

5.3.2.1.2 <u>Buried Transmission Line Considerations</u>

Since buried conductors are cooled through thermal conduction, the lunar soil thermal conductivity is critical. Regolith tests indicate its thermal conductivity is extremely poor, approximately 100 times worse than terrestrial soil. This is partially caused by differences in composition, but mainly due to the absence of moisture. Because of this poor conductivity, a high efficiency design is required to minimize line losses. This reduces the conductor temperature, but at the expense of increased mass. For low voltage, high power transmission applications, buried cables proved to be impractical. To achieve acceptable temperatures, the line mass would become prohibitive.

The only buried conductor geometry considered was a round configuration. The impact of other configurations has not been examined. The algorithm changes required to assess other shapes appear quite involved and they would have taken considerable time to develop. The additional time and resources needed for this task were not available.

5.3.2.2 <u>dc vs ac Transmission Lines</u>

Two basic forms of power transmission were studied for lunar base power transmission, dc and ac. dc power transmission is typically more efficient than ac because dc line losses are primarily due to the conductor resistance. Losses may also occur from corona discharges, but these should be very small in the near-vacuum atmosphere of the Moon. For ac power transmission, the skin effect plus inductive and capacitive reactance terms must be added to the dc conductor resistance to determine the total ac line impedance. The ac resistance is the sum of the line's dc resistance and the resistance resulting from the skin effect. ac characteristics have necessitated the development of alternate cable configurations, especially for high frequency ac power transmission. The transmission line options shown in Figure 5.3-6 (except the parallel plate configuration because of funding limitations) were used during this study to analyze ac effects. Only a few of the potential ac cable types are shown in this figure.

The skin effect is a phenomenon that occurs in ac transmission due to the rapidly changing current intensity. It arises from the fact that the inductance encountered by the current is higher at the center of the wire than at the periphery. This causes an uneven current density over the conductor cross section; the current density is a minimum at the wire center and a maximum at the periphery. The net result is an increase in the effective resistance of the conductor. This effect becomes more pronounced as the conductor size and frequency increase.

A special wire construction, called litz wire, has been developed to reduce the skin effect losses. Litz wire consists of numerous wire filaments,

AC Transmission Line Configurations & Constructions

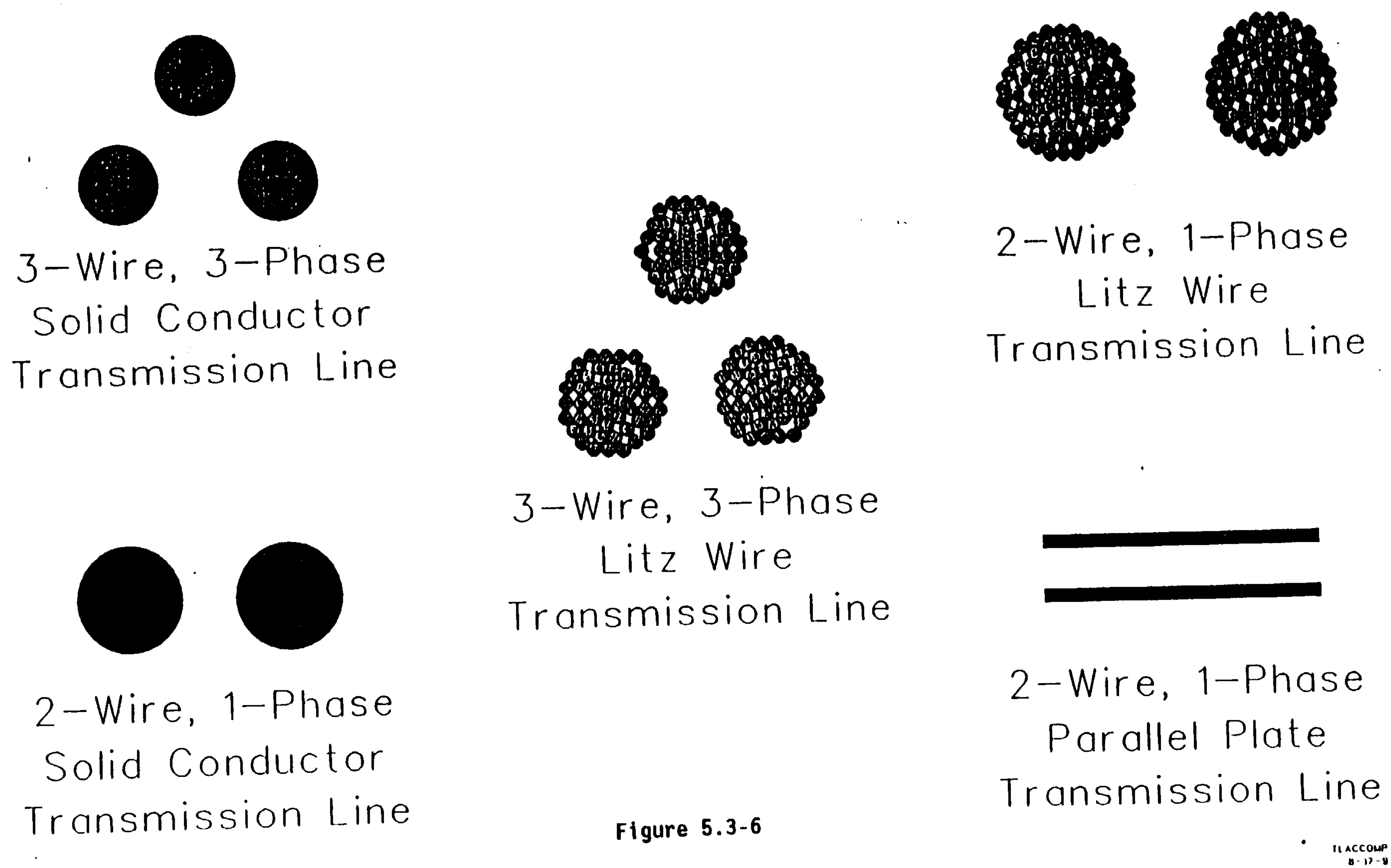


Figure 5.3-6

each individually insulated, within a conductor bundle. Because each strand is insulated, the conductor behaves like many small wires run in parallel. This dramatically reduces the losses resulting from the skin effect because the useful conductor cross section of these individual strands is much larger than that of a single large conductor. However, the cable mass is increased due to the added weight of this wire filament insulation. Other conductor configurations are probably better suited for power transmission at the frequencies considered in this study, 1 to 5 kHz; but the algorithm changes needed to model a simple litz wire construction were the easiest to develop within the study time frame. For transmission at 20 kHz, a special flat cable wire construction was developed for SSF that exhibited lower impedance than litz wire. This cable or a derivative may also be suitable for the 1 to 5 kHz frequency range addressed during this study.

Line inductance is an important factor in ac power transmission, especially at high frequencies. Since inductive reactance is determined by the formula $2\pi fL$, it increases linearly with frequency for a constant value of inductance. A high inductive reactance generates a large reactive power demand and causes a poor power factor. A larger current must now be conducted by the transmission line to supply this reactive power. The net result is an increase in the transmission line diameter and mass.

Line inductance can be divided into two parts: the external portion determined by conductor separation, and the internal portion resulting from the magnetic field within the conductor. For most applications the external portion dominates. As frequency increases, the internal portion declines; the external part remains unchanged. The main determinant of external inductance is the distance separating the conductors. Ideally, to minimize it, a conductor and its return conductor should occupy the same space. Although this is impossible, it demonstrates why it is increasingly important to develop a transmission line configuration that minimizes the conductor separation distance as the operating frequency increases to minimize inductive losses.

Other ac transmission line effects, such as shunt capacitance and standing wave losses, were not included in this study. Auburn University addressed these items during the course of their model development. Discussions with Auburn personnel indicated their models included shunt capacitance terms, but not standing wave loss terms. Standing wave losses were determined to be insignificant. Shunt capacitance did have an effect, but for the frequencies covered in this study, 1 to 5 kHz, they indicated the power loss attributable to it was relatively minor. This certainly does not mean it can be ignored, though, and later algorithms should include its effects. Capacitive losses will increase with frequency unless the line spacing is increased to compensate. Since this approach is in conflict with the method employed to minimize inductive losses, the conductor construction and relative placement becomes much more critical as frequency rises. Longer transmission distances further compound these problems.

The resistive power losses in the transmission lines because of reactive power flow, however, are only part of the impact. The power source must be capable of supplying the higher current levels resulting from the reactive power demand. Preliminary calculations by Rocketdyne personnel indicate the series inductance and shunt capacitance of the lines may have a more pronounced effect then originally assumed. At the frequencies considered in this study, 1 to 5 kHz, it appears the reactive power demands of the system may be sufficient to increase the power source size or alter its design. The impact of reactive power must be addressed in greater detail in later studies to determine its full effects, but it is clear that the operating frequency will have a major influence on the results.

The main points that should be noted from this discussion are: (1) dc lines will be simpler to fabricate than ac lines, and (2) ac conductor construction and relative placement will become increasing critical as the operating frequency is increased. To minimize the inductive reactance of ac lines, solid dielectrics may need to be employed to maintain a minimal distance between the conductors and ensure an adequate insulation resistance. At higher frequencies, specialized constructions such as parallel plate or litz wire will probably be required. These items will lead to increased development costs for ac lines and probably complicate their installation.

5.4 LUNAR BASE PMAD ANALYSIS RESULTS

After the individual models were developed and evaluated, the lunar base power system study assessed the effects of voltage, frequency, and transmission line geometries and placements on the overall power system. It is important to consider the lunar base power system as a complete entity, not a collection of individual components. Discrete model results are suitable for eliminating obvious items, but final power system optimization requires a complete system model addressing all the interactive component effects. However, it is frequently beneficial to present component effects first to identify the underlying causes of an overall system trend. In this section, system influences were primarily assessed on the basis of total system mass. Before a final recommendation can be made, technology requirements, development costs, and system reliability must also be considered.

5.4.1 PMAD Voltage Study

The voltage level ultimately selected for long distance power transmission will have a major impact on virtually every component design. The transmission voltage primarily affects power system elements in two ways. Transmission lines and power conditioning conductors are basically sized on amperage requirements. Increasing the voltage level reduces the amount of current a line must carry and its size. However, a higher voltage level forces power conditioning components, and possibly even transmission lines, to require more insulation. Using specific examples, the impact of these influences can be illustrated with individual components to identify the effects present within a complete power system.

The voltage effects present with most power conditioning components can be addressed by considering a dc/dc converter. To perform its function, four power conditioning operations are included in one component. This chopper, transformer, rectifier, and filter combination exhibits most voltage effects. The impact of voltage on the component mass as shown in Figure 5.4-1 is

DCOUTVLT.XLC

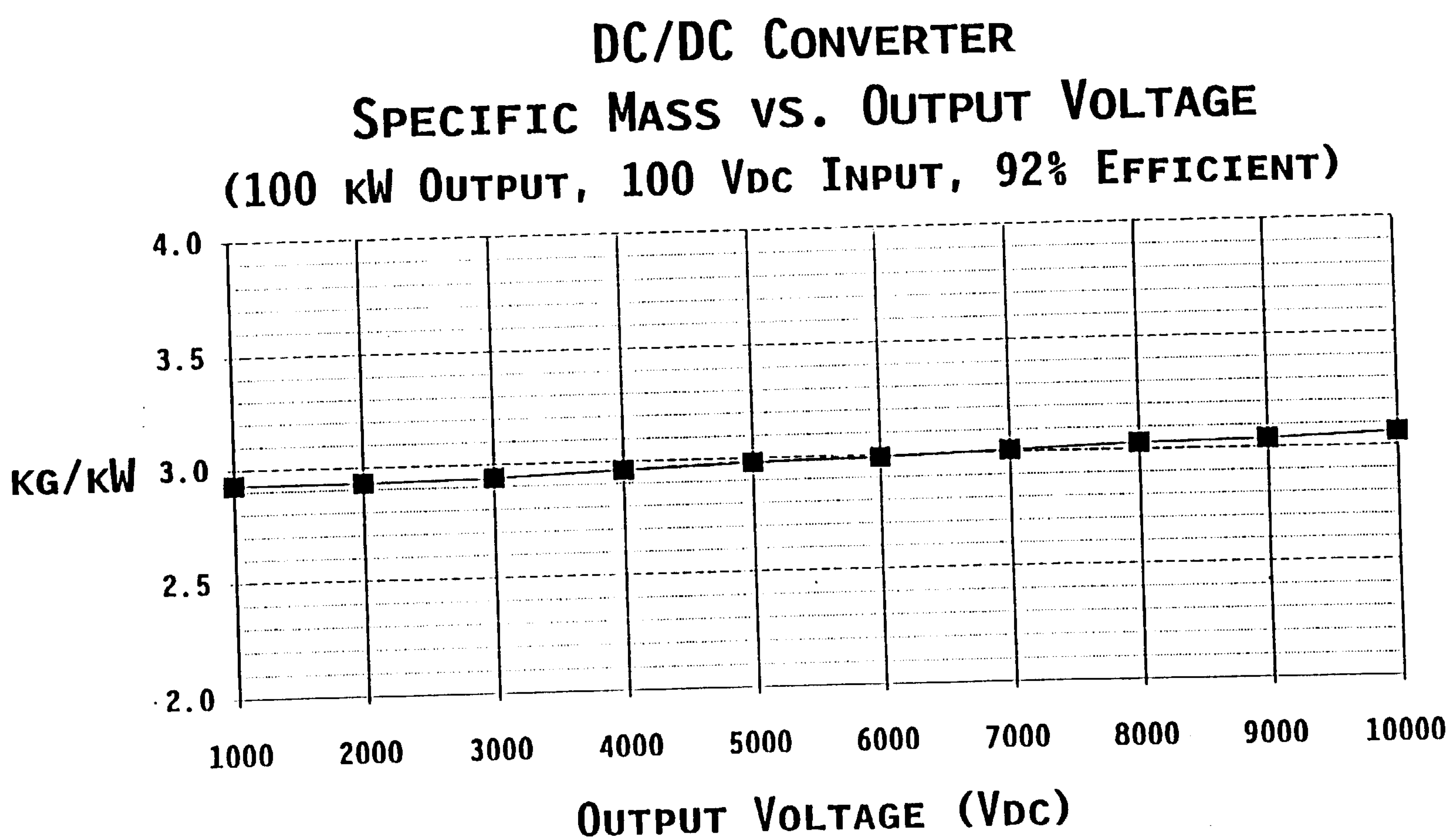


FIGURE 5.4-1

7/19/90

relatively minor over the range shown. Voltage does not have a pronounced affect on component mass until values above 20 kV are required. At extremely high voltage levels, added insulation is required for devices and the distance those devices must be separated to prevent flashover becomes significant. Both factors increase the component volume, and consequently its hardware mounting area and enclosure mass. To further examine power conditioning voltage effects, it is necessary to address the individual stages.

The chopper section is composed of modules, each containing a semiconductor switch and a snubber circuit. These modules are connected in series to switch higher voltages. Theoretically, since the voltage across a single module is not increased, its insulating requirements are unchanged. In practice, this is not always true. The insulation and switch ratings may need to be increased to tolerate uneven or improperly applied voltages.

A high voltage transformer requires additional insulation to electrically isolate the primary and secondary windings and the turns that compose these windings. However, since the insulation mass is a very small percentage of the total transformer mass, it can increase substantially and the transformer mass will only change slightly. The main increase in mass is probably due to a secondary effect. If extra wire insulation is required, the winding cross sectional area is increased. This necessitates a larger window area to accommodate the windings; consequently, the core size and mass increase.

The rationale employed in discussing the chopper stage also applies to the rectifier stage. The rectifier construction may utilize a pancake configuration of stacked diodes or thyristor modules. In this construction, the elements are electrically connected in series. Since the normal voltage across an element is not increased, the only reason to increase an element's rating or its insulation is to withstand higher transient voltages.

The filter section utilizes a network consisting of capacitors and inductors to filter voltage transients. Two factors are typically involved in assessing this stage. If only the component voltages are increased, the ratings of these elements can be increased or they can be connected in series. The effect of this would probably be quite small. The other factor that must be considered is the magnitude of the voltage spikes and the energy that is contained in them. The energy stored in a capacitor is related to the voltage squared; therefore, the mass of a filter capacitor may increase due to the higher energy levels present in the voltage spikes.

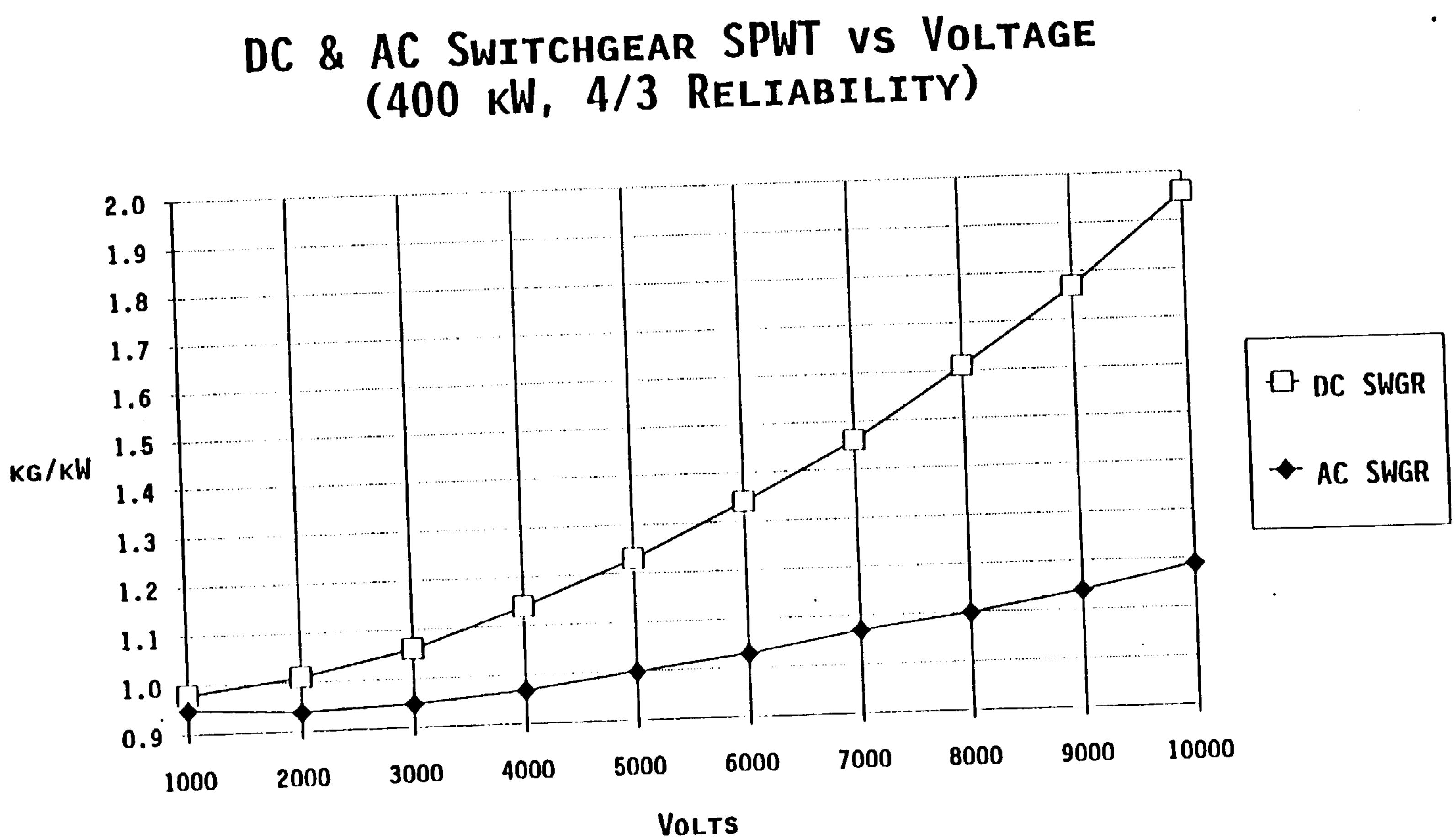
Another voltage effect has a major impact on the design of dc switchgear. A dc remote bus isolator (RBI) must use a mechanical and/or semiconductor switch designed to interrupt the maximum bus voltage. This substantially increases the dc switchgear mass (see Figure 5.4-2) as the voltage level is increased. A mechanical switch interrupting a high voltage normally draws a sizable arc. It is important to extinguish this arc as rapidly as possible and harmlessly dissipate its energy. A semiconductor switch will encounter high electromagnetic forces during opening that will generate high stresses and concentrated heating. These factors force a dc RBI design to be structurally stronger and capable of dissipating higher heat loads. An ac RBI switch design utilizes a technique known as zero current crossing to minimize the stresses present during opening. An ordinary ac waveform will have a zero current level twice each cycle. If the power flow is interrupted at this point, the I^2R heating effects and electromagnetic forces will be minimal. This enables the ac RBI design to be much lighter since the voltage drop across the switch should never reach the full bus voltage level. Referring back to Figure 5.4-2, one can see the pronounced effect this has on switchgear design as the voltage levels are increased.

Increasing voltage has a positive effect on conductor mass, especially if bare conductors are utilized. The reduction in conductor mass as the voltage level is increased is shown in Figure 5.4-3. The curves are nonlinear because a specific efficiency is shown, 98 percent, and conductor losses are calculated by the formula I^2R. As current increases linearly, losses increase exponentially.

One other point should be made about Figure 5.4-3. At an equivalent voltage and efficiency, the mass of an aluminum conductor is almost exactly half the mass of a copper conductor. Since mass is typically the most important yardstick for long distance transmission lines, aluminum conductors were used throughout the PMAD system. The main reason aluminum conductors have not been widely used before is due to concerns about terminations. New termination methods and hardware have largely solved these problems and it is expected aluminum conductors will become commonplace on high power, space based systems. Aluminum conductors and buses are already the norm for most terrestrial switchgear equipment and motor control centers. Because of its smaller volume and better ductility, copper will continue to have a place within the power conditioning components; but for external conductors aluminum appears superior.

These component examples have demonstrated the main voltage effects, now a system view is required to assess the summed magnitude of these individual influences. The power source and transmission mass as a function of transmission voltage is shown in Figure 5.4-4. Based on this figure, power system mass approaches a minimum value at about 5000 V and remains relatively constant. In addition, the ac and dc masses are quite close at each voltage level. To obtain better clarity, these curves are repeated for a smaller voltage range in Figure 5.4-5. This figure shows the minimum dc system mass lies between 6000 and 7000 Vdc, while the ac system mass continues to decline slightly over the entire range. This disparity is attributable to the differing switchgear design requirements.

Since the power system mass does not change notably beyond 5000 V, it is important to determine if a higher voltage level can be substantiated. The advantages and disadvantages of high and low voltage power transmission are summarized in Table 5.4-1. In addition to the earlier discussed results, several other voltage effects are listed here. The selection of 5000 V, as the transmission voltage level, was strongly influenced by the factors identified in this table.



Note: Values include enclosure, control & monitoring, bus & capacitors, thermal management, and radiator

FIGURE 5.4-2

7/19/90

2WBRVOLT.XLC

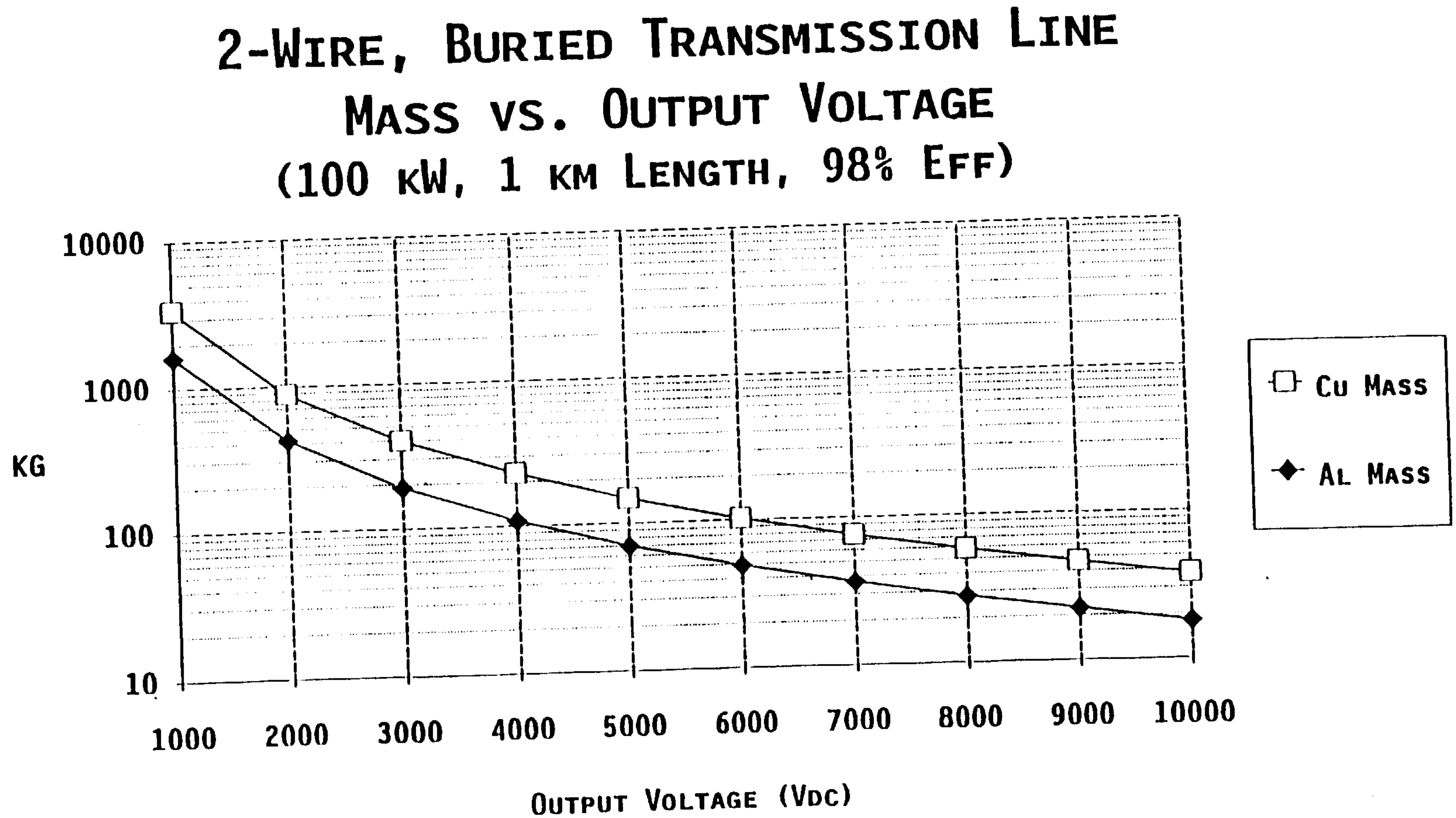


FIGURE 5.4-3

7/19/90

Power Source and Transmission Mass versus Distribution Voltage

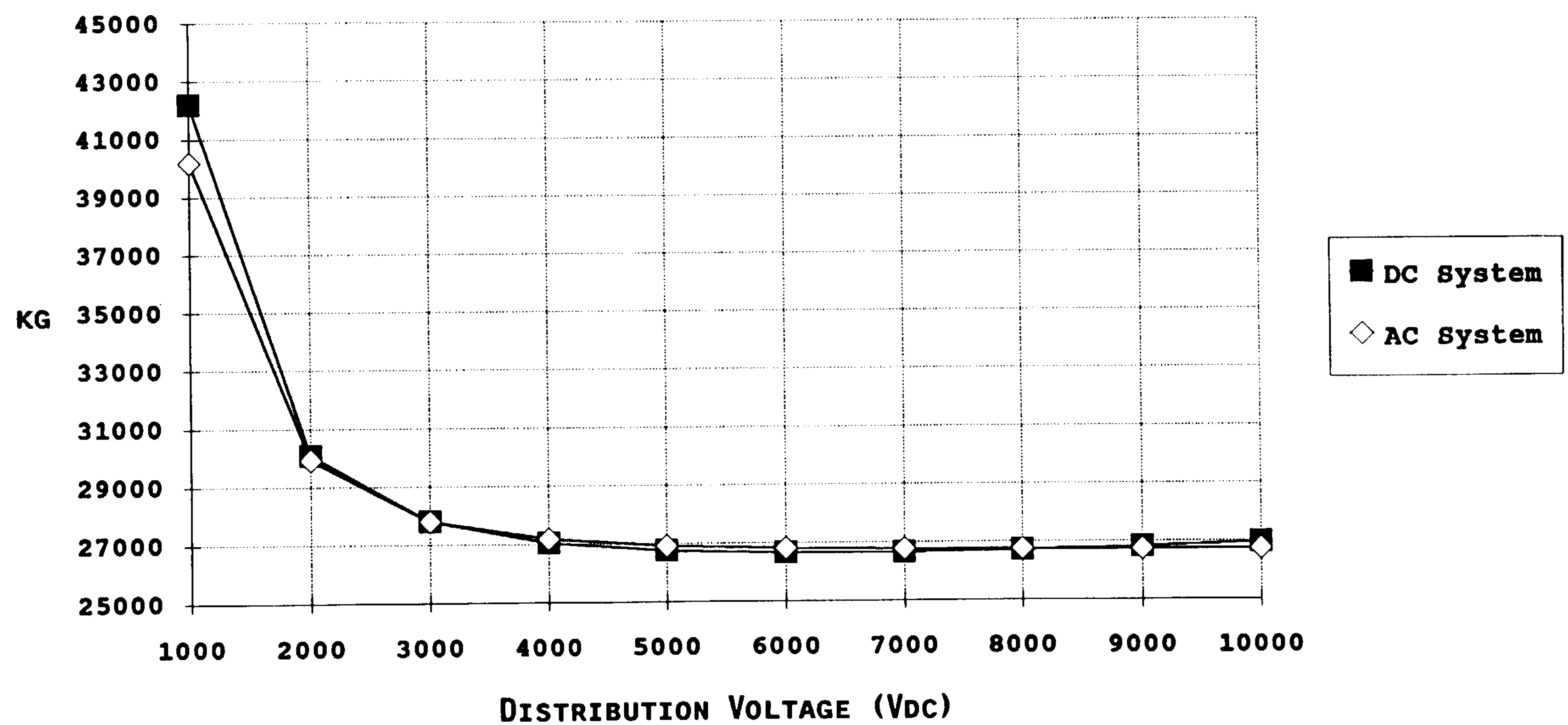


Figure 5.4-4

PSMASVT1.XLC

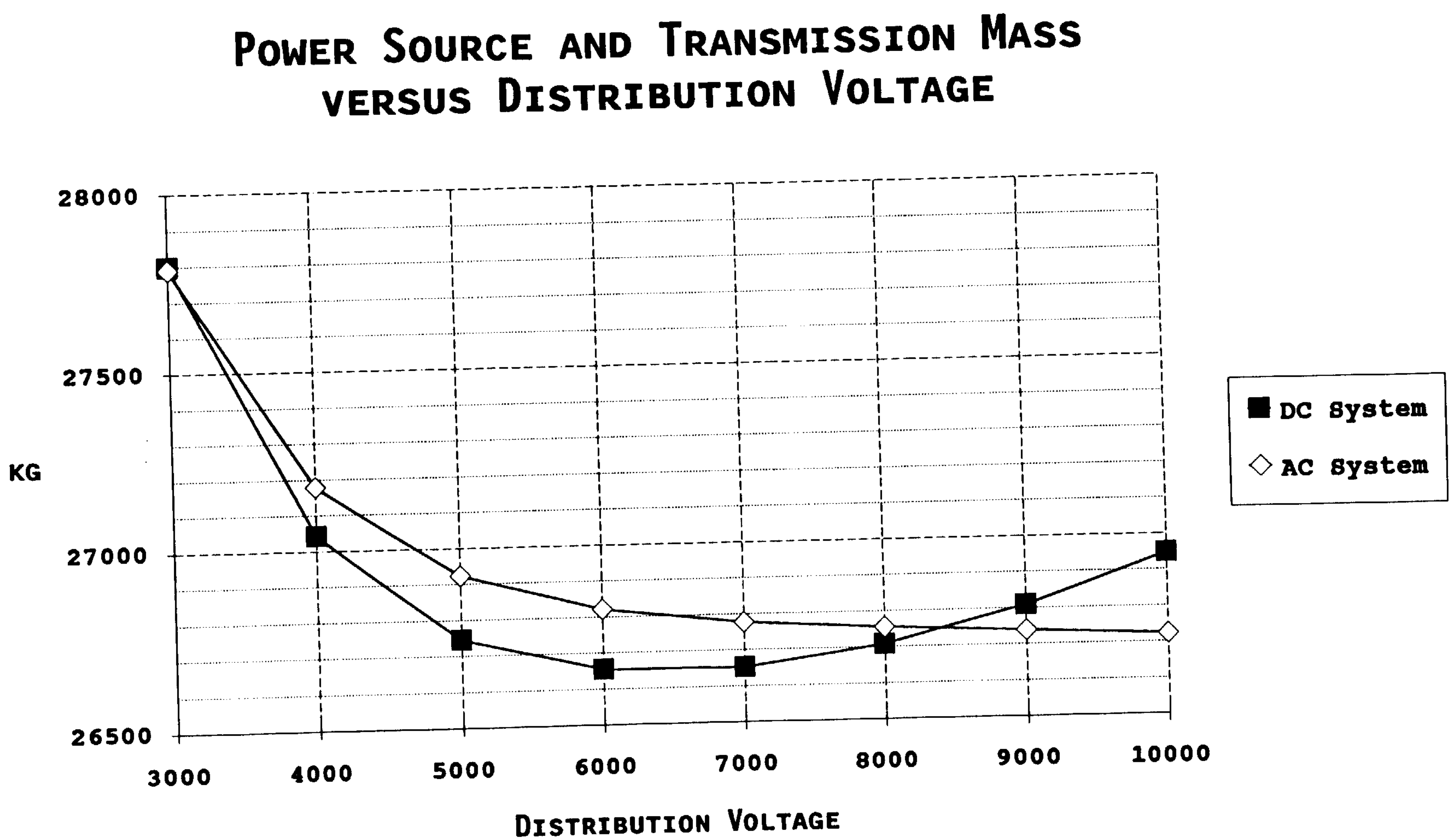


FIGURE 5.4-5

TABLE 5.4-1
POWER TRANSMISSION VOLTAGE COMPARISON

	ADVANTAGES	DISADVANTAGES
HIGH VOLTAGE	• REDUCES TRANSMISSION LINE MASS • INCREASES TRANSMISSION LINE EFFICIENCY, LOWER I^2 LOSSES	• AT EQUIVALENT EFFICIENCIES, TRANSMISSION LINE TEMPERATURES RISE DUE TO DECLINING SURFACE AREA • NECESSITATES MORE INSULATION IN POWER CONDITIONING • REQUIRE DEVELOPMENT & TESTING OF HIGH VOLTAGE SWITCHES FOR DC TO DC CONVERTERS & SWITCHGEAR
LOW VOLTAGE	• TECHNOLOGY BEING DEVELOPED & TESTED FOR SPACE STATION EPS • DC TO DC CONVERTERS EASIER TO MANUFACTURE, PROBABLY MORE RELIABLE • MINIMAL INSULATION IN POWER CONDITIONING COMPONENTS	• DC TO DC CONVERSIONS ARE LESS EFFICIENT • HIGH I^2 LOSSES IN TRANSMISSION LINES & POWER CONDITIONING • HIGH SWITCHING LOSSES IN POWER CONDITIONING

5.4.2 PMAD Frequency Study

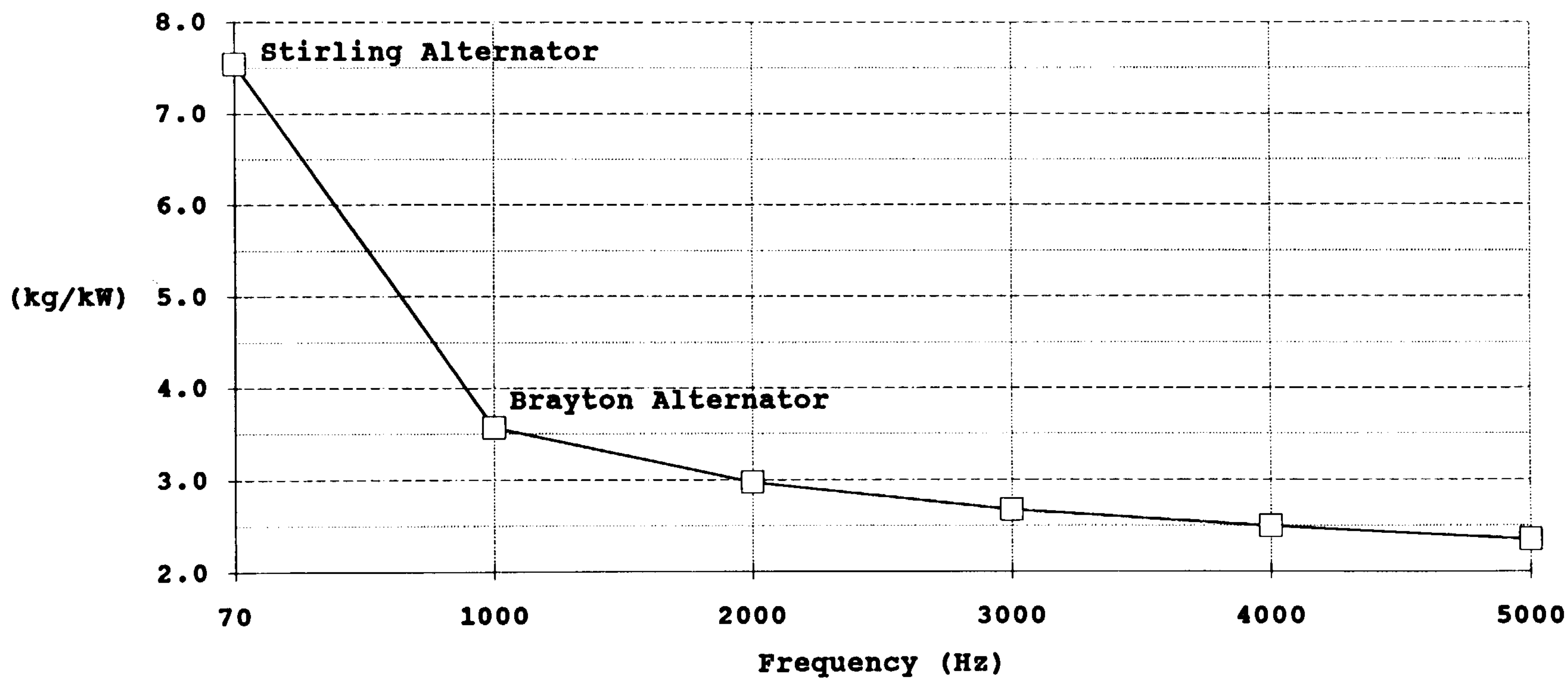
Since an ac system certainly appeared viable from earlier results obtained in this study, several frequency levels were investigated to determine the effects on power system mass. Prior experience indicated two offsetting effects would emerge as frequency was increased, one decreasing the power conditioning mass, the other increasing the transmission line mass. Individual component examples will again be used to illustrate these effects before addressing the complete power system.

To display the effect frequency has on power conditioning mass, a transformer was selected. By referring to a fundamental principle of magnetics, Faraday's Law, it can be established that the voltage induced in a conductor at an equivalent flux density will linearly increase with frequency. Therefore, at higher frequencies the flux density needed for a specified voltage is less, reducing the transformer core volume and mass. The magnitude of this effect on a complete transformer assembly is shown in Figure 5.4-6. The values shown in this figure include the various transformer elements, core, windings, insulation, and mounting hardware plus its ancillary components: enclosure, thermal management and radiator, and control and monitoring. Since the transformer core mass is only a portion of this total value, and alternate core materials must be employed as frequency is increased to minimize losses, the total mass does not decline linearly with frequency, but it is a strong function.

Transmission line mass increases with increasing frequency due to the skin effect and inductive reactance. These effects were addressed during the discussion on transmission line model development, but the main points will be repeated here. The skin effect causes an uneven current density to exist in a conductor. The higher current density at the conductor periphery increases its effective resistance. The conductor diameter and corresponding mass must be increased to compensate. This effect is more pronounced with larger conductors and at higher frequencies. Every conductor possesses some inductance. If the transmission line construction is unchanged, the corresponding inductive reactance will increase with frequency. A circuit's power factor declines with increasing inductive reactance, resulting in a reactive power demand. A larger current must now be conducted by the transmission line to supply this reactive power. The net result is the transmission line diameter and mass must be increased.

Several different transmission line configurations were compared at different frequencies to identify the best types to use for ac power transmission. A comparison of these types is shown in Figure 5.4-7 for a particular set of parameters. Because the skin effect and line inductance are influenced by the conductor size and the proximity of its return line, the shape of these curves will change for different power levels, efficiency requirements, and transmission line distances. However, these general trends will still exist. (Note, the dc transmission line is provided for reference purposes only; by definition, dc does not have a frequency attribute.) This figure indicates solid conductor transmission lines will become prohibitively heavy at high frequencies. For this reason, other conductor types should be

TRANSFORMER SPWT VS FREQUENCY (100 KW, 500 TO 5000 VRMS)



Note: Values include enclosure, control & monitoring, thermal management and radiator mass

FIGURE 5.4-6

3/14/91

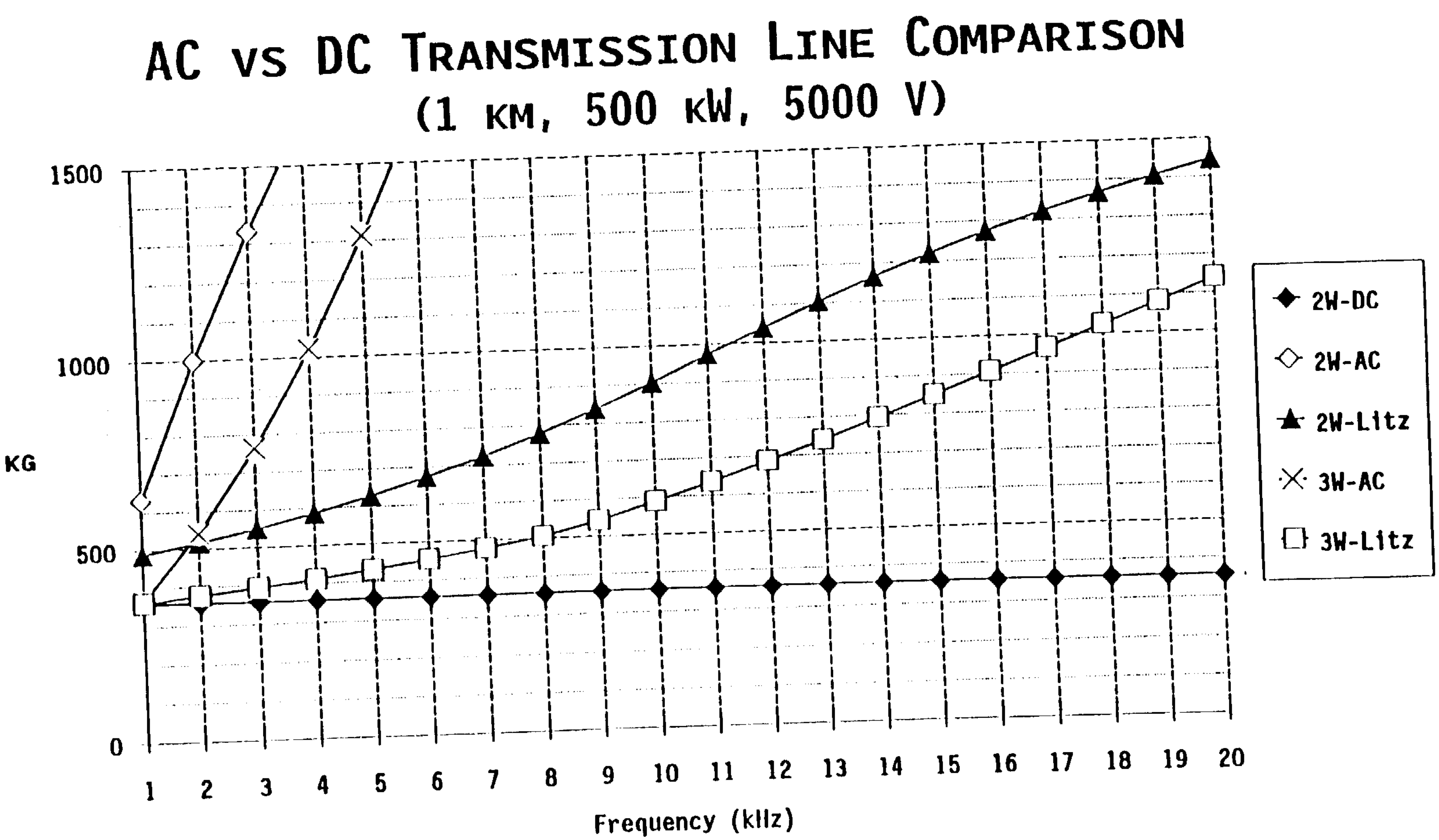


Figure 5.4-7

7/12/90

employed. Although litz wire has the lowest mass of the conductor types shown, it is not necessarily the best type available or being recommended. Alternate constructions such as parallel plate or hollow conductor may be better and should be evaluated in future studies. It also appears from this figure that three-phase power transmission is more weight efficient and, consequently, more economical than single-phase. This agrees with terrestrial conclusions and is one of the reasons three-phase power transmission is used in terrestrial applications. However, three-phase power transmission may be more complicated and difficult to control. Additional sensors will be required to control and monitor a three-phase system; consequently, the data handling requirements will be greater. In fact, the mass of a three-phase system may actually be higher when the component modifications and additional devices necessary for its operation are considered. The pros and cons of single-phase and three-phase systems must be considered in greater detail in later studies to determine the best method of power transmission and distribution.

To display the effect an increasing transmission frequency has on the total system mass, the masses of the transmission lines, the power conditioning, the power sources, and the total power system are shown in Figure 5.4-8. Since the power source mass predominates, the reduction in mass that occurs with an increasing frequency is relatively minor and difficult to see. The mass reduction from 1 kHz to 5 kHz is 1560 kg, a percentage change of six percent. To better display this change, only the PMAD subsystem and its elements are shown in Figure 5.4-9. While this chart clearly shows mass improvements are possible at higher frequencies, the problem will be designing a power source capable of supplying this increased frequency. Frequency converters are one method of obtaining higher frequencies, however, they were not included in this analysis due to funding and time constraints. They should certainly be considered further in later studies.

It was previously stated that the transmission frequency of the power system is defined by the SP-100 Brayton system alternator. While the frequency of this alternator can be changed by modifying its design, limitations exist. An alternator's frequency is defined by the formula:

$$f=Np/120$$

where N is the rotational speed in revolutions/minute (RPM) and p is the number of poles designed into the machine. Referring to this formula, it can be seen that the frequency can be increased by increasing the rotational speed or the number of poles. The rotational speed is limited by rotor dynamics and critical speed considerations. The number of poles can generally be increased, but the design is constrained by the inner circumference of the stator. An excessive number of poles will result in an inefficient machine. Normally the magnetic flux induced in the machine links the rotor and stator to transfer power. In a machine with too many poles, much of the flux will simply travel between rotor poles and will not link with the stator to produce useful work.

The presently envisioned power system architecture utilizes Brayton cycle turbines to drive high speed electrical alternators. Power sources of

Centralized Power System Composite Masses (DC System & AC System vs Frequency)

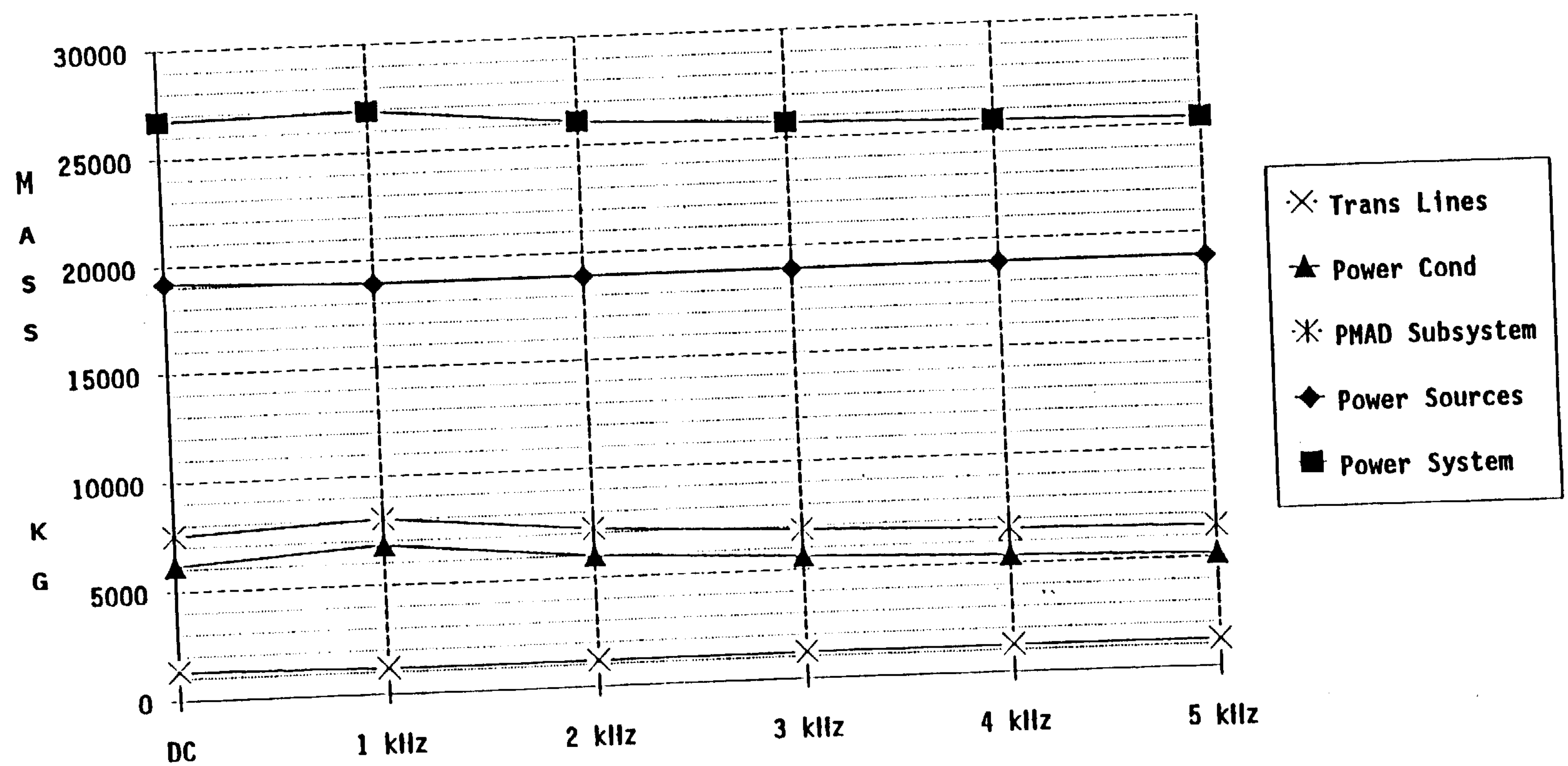


Figure 5.4-8

7/13/90

CENTRALIZED PMAD SUBSYSTEM COMPOSITE MASSES (DC SYSTEM & AC SYSTEM VS FREQUENCY)

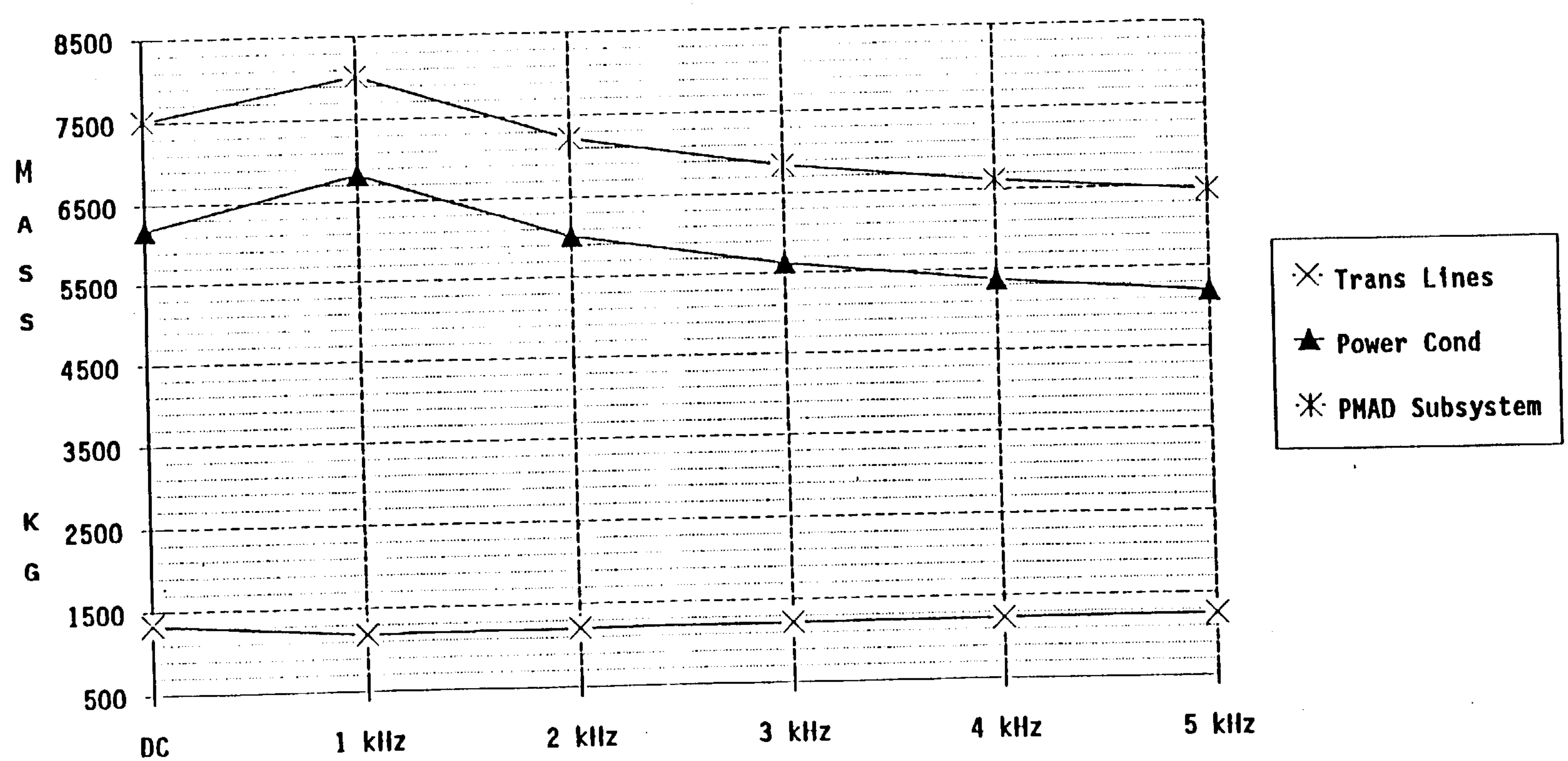


Figure 5.4-9

7/13/90

this type, like any other, require technical analysis and component and control system design features to ensure that they can be successfully paralleled and will operate in parallel under varying load conditions. Typically, alternators produce sinusoidal waveforms with a low harmonic content. In addition, the energy stored in the rotating mass tends to stabilize their dynamic operation. If one alternator slows down, its portion of the load declines and the torque input from the turbine causes it to accelerate. If it starts to go too fast, it assumes more of the load and experiences a braking action. Thus, alternators can generally be paralleled, in a straight forward manner, by matching their output voltages (generator field control) and frequency (shaft speed control). For stable operation, once paralleled, the control system must continue to adjust shaft speeds and field controls to maintain load balance between the alternators and minimize circulating reactive currents. The fundamentals of alternator control are well understood and have been extensively demonstrated in terrestrial systems.

The inverters following the SP-100 thermoelectric power source would need to be paralleled, either at the source or far downstream at the load switchgear unit. Extensive development work in inverters and other electronic power converters is underway for space applications. Typically, inverters are proposed for space applications because of their ability to generate higher frequencies than rotating machinery. At the higher frequencies, electromagnetic components, such as transformers, are lighter in weight and the synthesis of lower frequencies from the higher inverter frequency is facilitated. Additional factors must be considered when operating inverters on a power system either individually or in parallel. The effect of inverter harmonics on the power system and the interference with other components must be considered in the system design. Inverter operation lacks inherent self correcting mechanisms for load sharing; continuous active control is necessary to ensure stability. For this reason, a high speed controller and control circuitry within each inverter are required to ensure real and reactive power sharing between the inverters. The stored energy within the inverter is lower and therefore the stiffness of the source is lower when compared to rotating systems. Load sharing requires continuous adjustment of the individual inverter voltages and respective phase angles to match changing power demands, adapt to varying load impedances, and limit undesirable reactive power flows. Difficulties arise because these parameters are interrelated and adjustments in one may have an undesirable affect on the operation of others. Consequently, greater attention is required in the analysis and design of the inverter and the power control system to assure that successful paralleling and stable system operation is achieved.

Many of the points presented in the above discussion are contained in Table 5.4-2. The main advantages and disadvantages of dc and ac are listed to substantiate the rationale used in selecting ac power transmission. Because the masses of the two systems are quite close, these items heavily influenced this recommendation.

5.4.3 PMAD Transmission Line Location Study

Before beginning the transmission line studies, two basic criteria were established: conductor sizes smaller than a 12 AWG were not allowed, and

TABLE 5.4-2
POWER TRANSMISSION FORM COMPARISON

	ADVANTAGES	DISADVANTAGES
AC	• VOLTAGE TRANSFORMATIONS LESS COMPLEX, MORE EFFICIENT	• INCREASED TRANSMISSION LINE LOSSES DUE TO "SKIN EFFECT"
	• SWITCHING ON ZERO CURRENT CROSSING GREATLY EASES FAULT CURRENT INTERRUPTION	• FURTHER INVESTIGATION REQUIRED TO PARALLEL SOURCES; SOURCES MUST BE IN PHASE, EQUIVALENT VOLTAGE & REACTIVE POWER
	• SWITCHING ON ZERO CURRENT CROSSING REDUCES SWITCHING LOSSES AND TRANSIENTS, AND EMI	• AC TO AC FREQUENCY CONVERSIONS TYPICALLY REQUIRE 2 STEPS
DC	• TRANSMISSION LINES ARE MORE EFFICIENT, LIGHTER IN WEIGHT	• VOLTAGE TRANSFORMATIONS REQUIRE 3 STEPS, MORE COMPLEX, LESS EFFICIENT & RELIABLE
	• EASIER TO PARALLEL & CONNECT DC LINES	• HIGH FAULT CURRENTS ARE DIFFICULT TO INTERRUPT, DAMAGING ARC
	• LOW VOLTAGE DC TECHNOLOGY BEING DEVELOPED FOR SPACE STATION EPS	• CHANNELIZED APPROACH PROBABLY NECESSARY TO HANDLE FAULT CURRENTS, REDUCES POWER UTILIZATION EFFICIENCY

transmission line temperatures were not permitted to exceed 120° C (248° F). The transmission lines will be subjected to pulling tensions during installation. To ensure the lines would have adequate mechanical strength, the minimum permitted transmission line size was 12 AWG. This restriction is fairly common for power conductors and it is frequently a stated requirement in terrestrial power system designs. The 120° C (248° F) temperature limit was defined mainly because of the electronics. The lines could probably tolerate higher temperatures--especially since they will probably be uninsulated--and still maintain adequate mechanical strength. However, the conductors are attached to the power conditioning components with low resistance connectors, which also tend to be good thermal conductors. High conductor temperatures may lead to excessive electronics temperatures. Later studies should consider this point further.

During this study, two transmission line locations were considered for each application, suspended and buried. Early transmission line analyses had indicated suspended transmission lines would be superior in virtually every case because a reasonable line temperature could be maintained over a much wider efficiency range. More heat could be dissipated by radiation to space than by using the soil to conduct the heat. Buried lines would only be competitive when the line efficiency was relatively high. A complete discussion of this initial study and its results is contained in Section 5.3.2.1.

When the two transmission line options were analyzed within the context of the complete PMAD model, some interesting results were noted. The minimum power system mass was obtained when high transmission line efficiencies were used. The increased transmission line mass that resulted from selecting a higher efficiency was more than offset by the reduced power source mass. At these high efficiencies, the masses of the buried conductors were quite competitive for high voltage, long distance power transmission.

These results were pleasing, since another study had indicated long distance suspended transmission lines would have higher installation costs (Ref. III-2). The installation costs associated with suspended and buried transmission lines, however, will be studied in greater detail by the PSS HART team and their recommendations will ultimately determine the locations and methods of installation. The buried lines will require trenching and digging equipment; the poles needed to support the suspended lines will increase their overall mass. These items were not included in this study.

Suspended conductors were still the best at low voltage levels. The installation costs associated with these lines should be tolerable since the distances, typically 10 meters, are so short the lines may be simply supported by the attached equipment. Buried conductors are impractical for low voltage, high power transmission because the line mass is prohibitive at satisfactory line temperatures.

The buried and suspended transmission line masses associated with the four longest runs are shown in Figures 5.4-10, 5.4-11, 5.4-12, and 5.4-13. These lines represent the main power transmission channels. Cable E is the main power system transmission line and it conducts power from the source to

Cable E
Suspended vs Buried
Transmission Line Mass

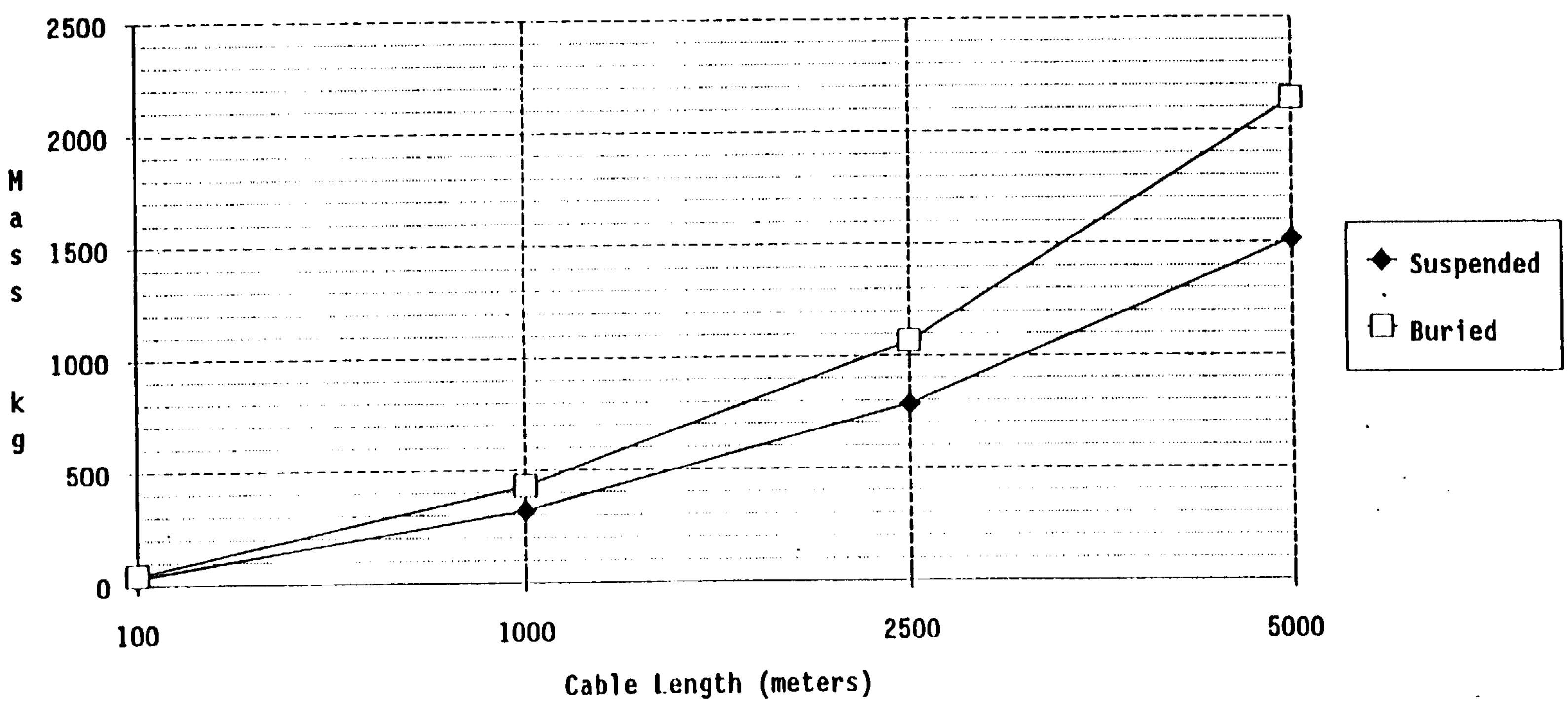


Figure 5.4-10

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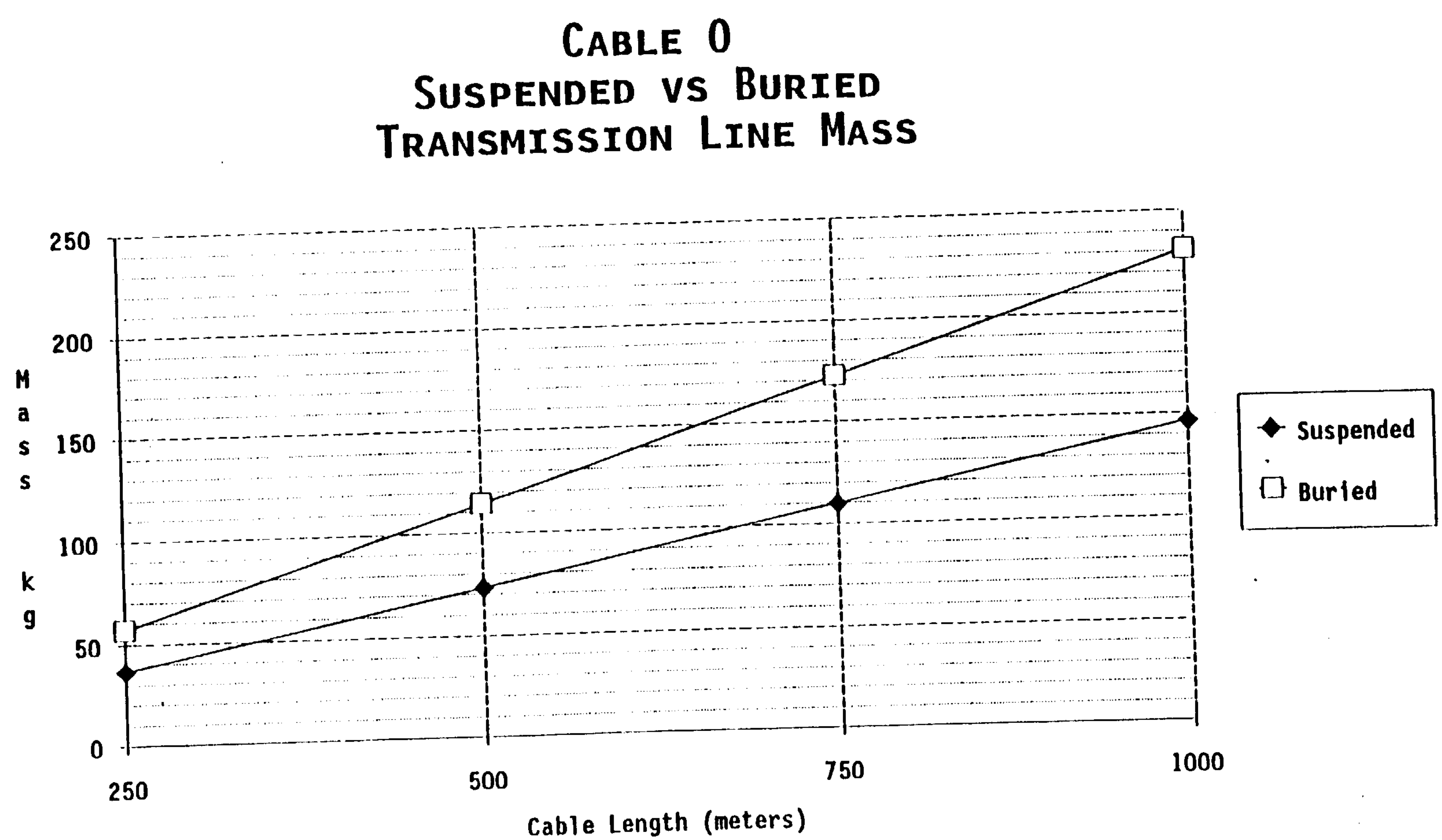

Figure 5.4-11

7/5/90

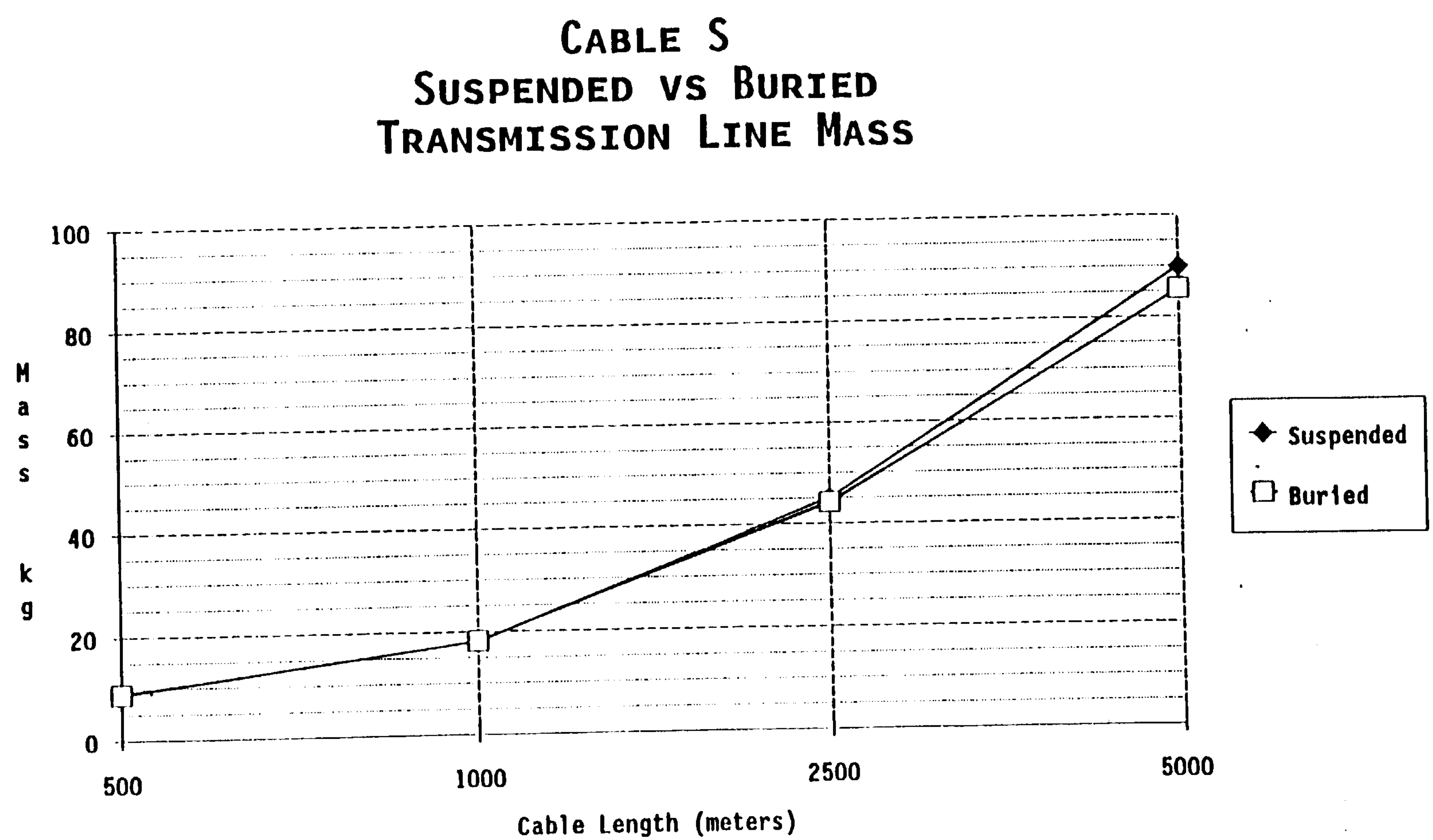

Figure 5.4-12

7/3/90

CABLE-U.XLC

CABLE U
SUSPENDED VS BURIED
TRANSMISSION LINE MASS

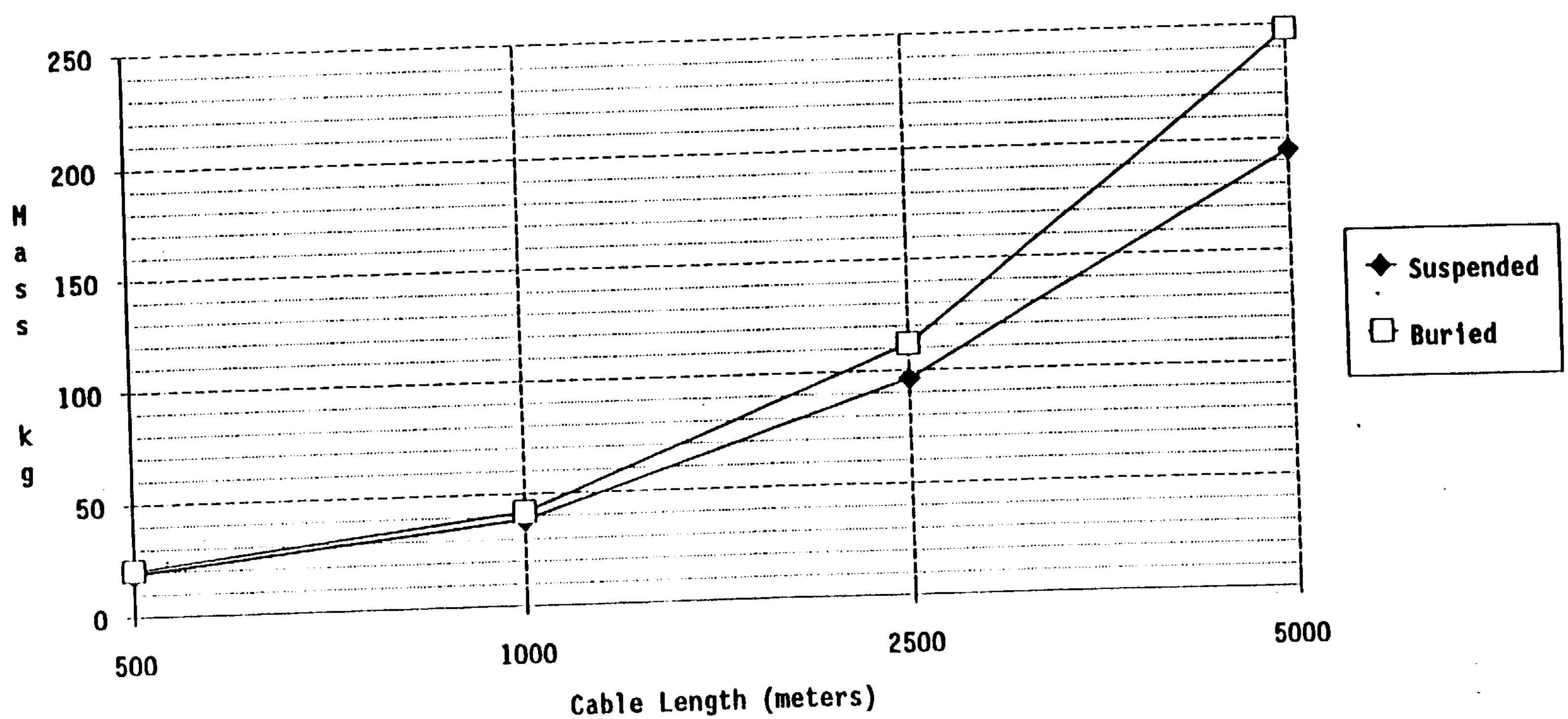

Figure 5.4-13

7/3/90

load switchgear units. The ISRU power is supplied by cable O. Cable S provides power to the landing area. The science user area will receive power via cable U. For cables E, O and U, an earlier study (Ref. III-2) had indicated the increased mass of a buried cable was more than offset by the additional mass of the supporting poles and higher installation costs. The mass of cable S is actually less when it is buried.

6.0 LUNAR BASE PMAD CONCLUSIONS AND RECOMMENDATIONS

This PMAD study has provided sufficient information to draw conclusions about the architecture configuration, the transmission voltage, the form of power transmission, and the various transmission line placements and configurations. Before presenting these conclusions and recommendations, it will be beneficial to show the main portions of the dc and ac PMAD configurations. These two system options are shown in Figures 6.0-1 and 6.0-2. These figures combined with earlier figures depicting the power conditioning component stages and transmission line configurations visually depict the proposed power system architecture and the interaction of its PMAD components.

The study results showed a centralized power system architecture has some advantages. It has the lowest mass at nominal power levels (10 percent lower) and the smallest mass increases for power system growth (25 percent less). The reliability concerns associated with a centralized architecture can be resolved with multiple transmission channels based on a modular design approach. There are qualitative features that favor a decentralized power system architecture: (1) added base flexibility; and (2) the availability of redundant, backup power supplies. A decentralized architecture can more readily accommodate base changes during the design and emplacement phases. During certain periods, mobile power supplies can be obtained from nearby locations to provide critical power. These features may justify the additional mass of a decentralized architecture.

The PMAD voltage study showed the dc and ac power system masses are nearly equal over a voltage range of 1000 to 10,000 V, with both approaching a minimum near 5000 V. It is felt the small mass gains obtained at higher voltages do not justify the increased development costs; therefore, the suggested transmission voltage is 5000 V. This suggested value is based on projected component technologies expected to be available in the lunar base timeframe (Ref. V-1, V-2, V-3, V-4). Since mass penalties appear tolerable for voltage levels as low as 2000 or 3000 V, component development demands may ultimately drive the actual transmission voltage downward.

The best form of power transmission is difficult to select. The masses of the dc and ac systems are quite close, so it is difficult to use mass as a discriminator. In addition, the ac transmission line models are preliminary, and model revisions could change these mass values. Alternate factors must be considered to reach a decision. Based on the existing technology base and the required advancements, projected component reliabilities, simplified fault protection and a higher overall PMAD system efficiency, ac transmission is recommended. The system frequency is determined by the Brayton system alternators, which are currently projected to have an operating frequency of about 1 kHz. Analysis indicated a frequency increase from 1 to 5 kHz will reduce the PMAD system mass, but the impact on these alternators is not known. Until the practicality of a higher frequency alternator design is determined, a system frequency of 1 kHz will continue to be recommended for use with a Brayton source. This recommendation would probably change if another power source, such as a Stirling engine, is used. Also, a system that utilizes frequency converters to increase the transmission frequency must be studied.

Revised Option 5A – DC Centralized Power Distribution
Nominal Power PMAD Values
(Mass Values Include Thermal Management and Radiator Subsystems)

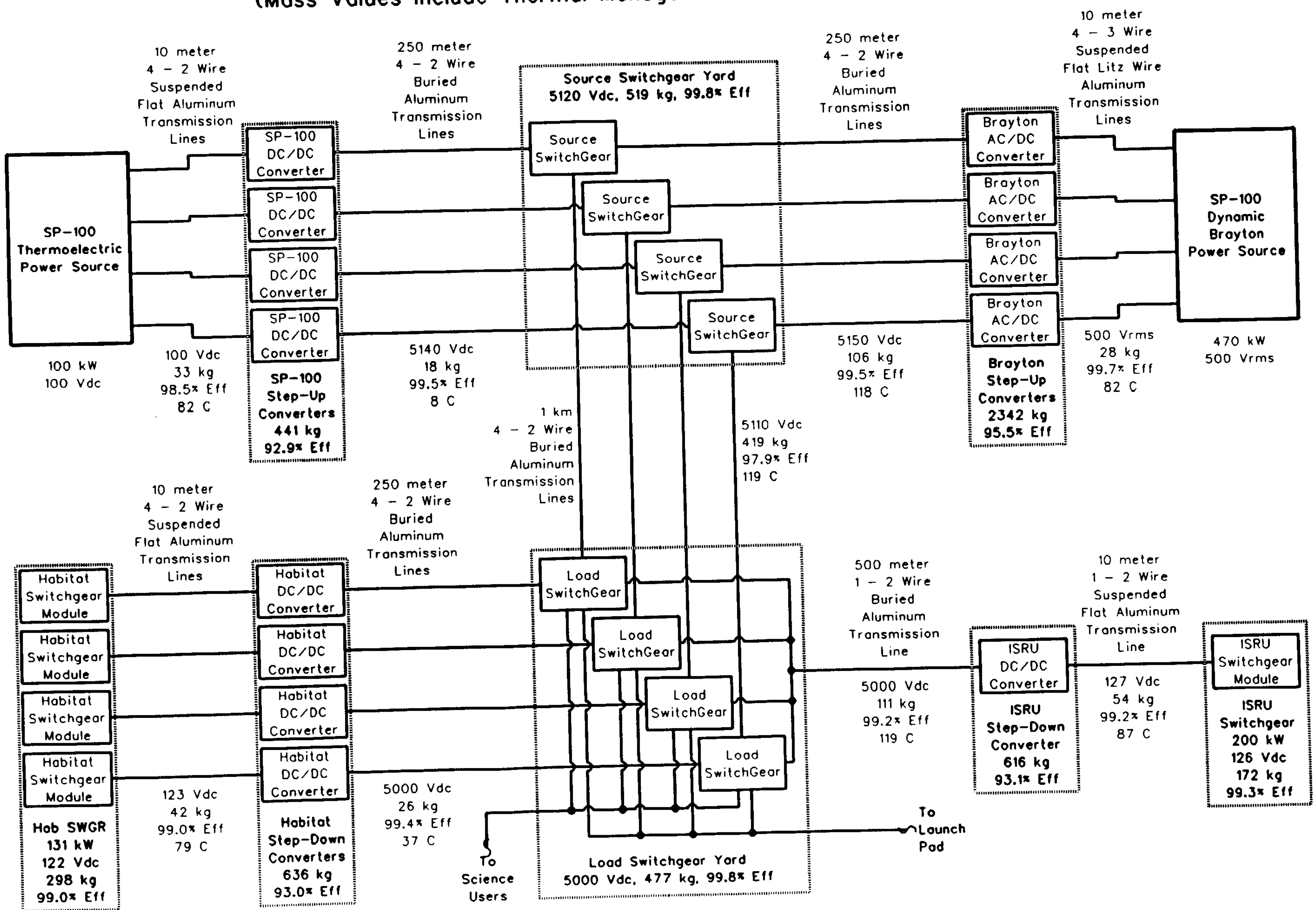

FIGURE 6.0-1

LNRDC5A1
8-25-90

Revised Option 5A – 1 kHz AC Centralized Power Distribution
Nominal Power PMAD Values
(Mass Values Include Thermal Management and Radiator Subsystems)

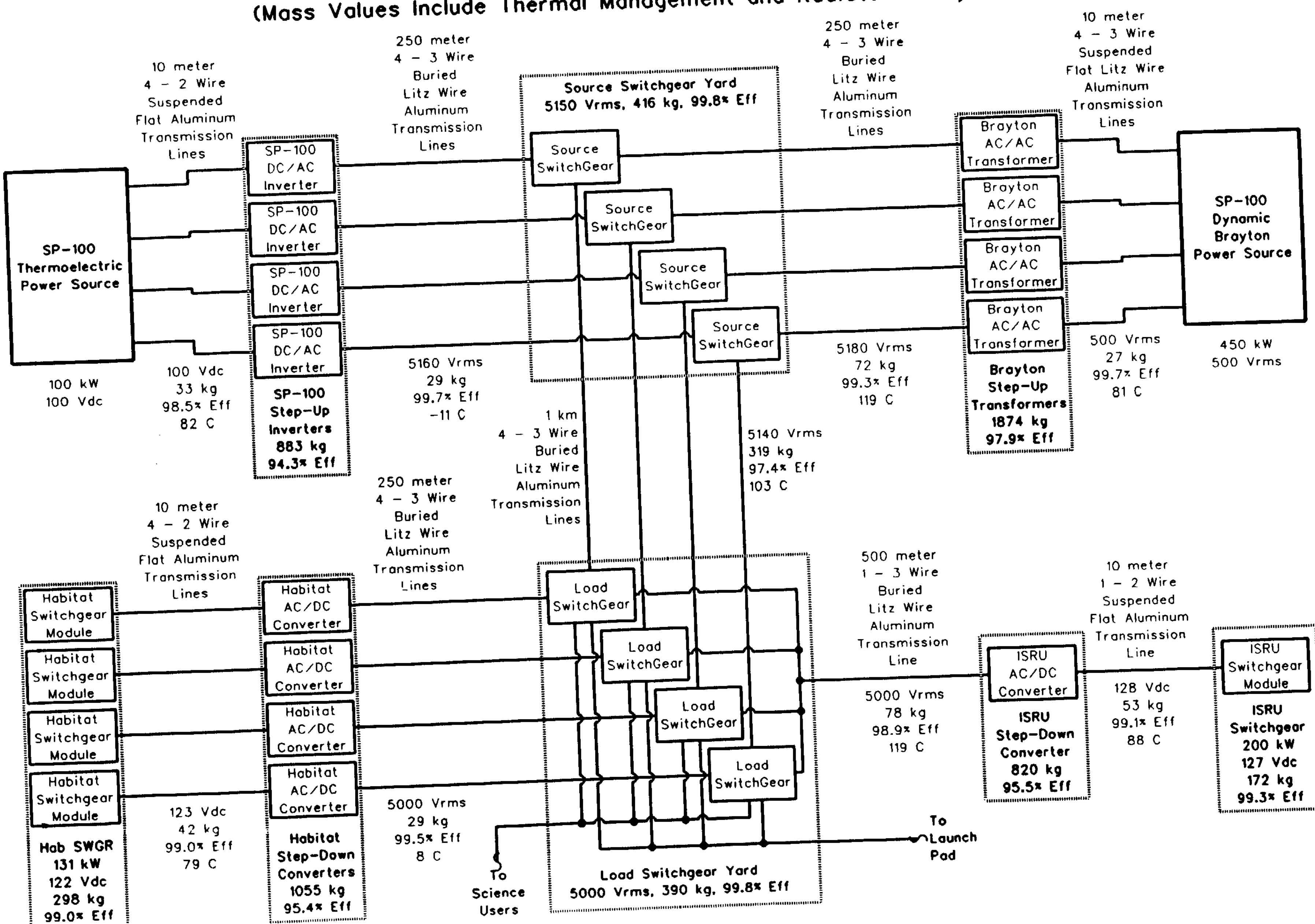

FIGURE 6.0-2

It is beneficial at this point to discuss some development issues associated with the various PMAD system options to better justify the 5000 V and ac power transmission suggestion. Although many of these items are discussed in Appendix A, generally in greater detail, they are mentioned here because they have a direct bearing on the PMAD recommendations. It was only after carefully weighing the development requirements that a low frequency ac power transmission system was selected. It was judged to have the best technology base and fewest development issues; consequently, the development risk and costs should be the lowest.

Indications are that the item with the highest development costs will be the high voltage chopper stage contained in the step-down dc/dc converters. A chopper stage switches a dc voltage at a high rate to generate an alternating voltage. This is fed to the subsequent transformer to be stepped down. Precise, synchronized switching is required to provide a constant frequency and fine voltage regulation. The proposed chopper stage will be required to reliably switch 5000 Vdc, at a 40 kHz rate, for at least 10 years. Switch synchronization problems are exacerbated in a high power, high voltage chopper, since switches must be connected in series to handle these high voltage levels. Component testing must demonstrate that the chopper switch modules can reliably and efficiently provide precise, synchronized switching at the projected lunar base voltage and power levels before a dc power transmission system can be confidently selected.

Another dc power transmission component that will require extensive development is a dc switchgear unit. The dc RBIs contained in the switchgear assembly must use a mechanical and/or semiconductor switch capable of interrupting the maximum projected bus voltage. Depending on the design, these switches will draw an arc or encounter high electromagnetic forces during opening that will generate high stresses and concentrated heating. This forces the dc RBI construction to be heavier. A comparable ac RBI switch can open during the zero current crossing. This dramatically reduces the stresses encountered and consequently its mass.

One of the most difficult tasks for the ac system will be the development of ac transmission lines. Dc lines should be simpler to design and fabricate since three factors associated with ac power transmission, the skin effect, line inductance, and shunt capacitance are not present with dc transmission. At higher frequencies, these effects will become more pronounced, meaning ac conductor construction and relative placement will become increasingly critical. This is one reason high frequency ac power transmission should be carefully examined. The ac transmission lines developed for SSF demonstrated that 20 kHz power can be efficiently transmitted over several hundred feet at voltages up to 440 Vrms; however, the higher voltage levels and longer transmission distances needed for the lunar base will necessitate further cable development. Specialized constructions, such as parallel plate, litz wire, or a derivative of the SSF 20 kHz power cable, will probably be required. Solid dielectrics may need to be used between the conductors to maintain a constant, small separation distance that minimizes the inductive reactance while providing sufficient insulation resistance. Since the effects of shunt capacitance grow as the transmission voltage and frequency are increased, it will also affect the cable design.

All these items will raise the development costs and may complicate the transmission line installations.

Both the dc and ac systems will require power sources to operate in parallel; therefore, it is important to address this method of operation. The dc architectures require the rectified Brayton system alternators and the SP-100 source dc/dc converters to operate in parallel. The present ac architectures require the parallel operation of the Brayton source alternators and SP-100 inverters.

Technical analysis and careful control system design will be required to ensure the Brayton alternators can successfully operate in parallel under varying load conditions; however, the fundamentals of alternator control are well understood and have been extensively demonstrated in terrestrial systems. Alternator operating characteristics facilitate paralleling since the energy stored in their rotating mass stabilizes dynamic operation. Thus, alternators can generally be paralleled, in a straightforward manner, by matching their output voltages (generator field control) and frequency (shaft speed control). To maintain stable operation after alternator paralleling, the control system must continue to adjust shaft speeds and field controls to maintain load balance between the alternators and minimize circulating reactive currents.

The inverters following the SP-100 thermoelectric power source need to be paralleled, either at the source or at a downstream switchgear unit. Extensive development is underway to refine the control techniques needed for inverter paralleling under varying load conditions. Continuous adjustment of the individual inverter voltages and respective phase angles is necessary for balanced load sharing. Difficulties arise because these parameters are interrelated and adjustments in one may interfere with the operation of another. In addition, because the stored energy in an inverter is lower than a comparable rotating machine, it is more difficult for it to maintain a stable output during load changes. The analysis and design of the inverter and the power control system will require greater attention to assure successful paralleling and stable system operation are achieved.

The last items to be addressed are the transmission line configurations and locations. Based on the two line locations analyzed in this study (a surface installation was not addressed), it is recommended that high voltage transmission lines be buried, while low voltage transmission lines should utilize a flat geometry and be suspended. Information obtained from another study (Ref. III-2) indicated burying the long distance, high voltage lines will significantly reduce installation costs. A buried location will yield acceptable line masses and temperatures. However, the costs incurred in burying the transmission lines, trenching, filling, and repair difficulties must be considered further. The mass and installation costs of the power poles used to support a suspended transmission line must also be added to the line's mass and installation costs to provide a complete accounting. The requirements necessary to install the different transmission line configurations in various locations will be provided to the PSS HART team and they will use this information to ultimately decide the best locations and methods of installation for the power system transmission lines.

To maintain tolerable line temperatures and/or masses, the short distance, low voltage transmission lines normally must be suspended. The installation costs of these lines should not be excessive because the distances between equipment are short enough that supporting poles probably are not needed. The only exception to this rule will be the line feeding the launch pad. Due to the particle ejections and settling regolith dust caused by a vehicle launch, a suspended cable might be damaged or become coated with dust. The regolith dust would be a natural thermal insulator, hindering its ability to radiate excess heat.

For ac power transmission with a Brayton source, three-phase transmission appears better than single-phase transmission. This approach fits naturally with the Brayton alternator output and yields better power transfer characteristics for a given transmission line mass. This is one of the main reasons it is the standard for terrestrial power systems. However, three-phase power transmission may be more complicated and difficult to control. Additional sensors are needed to control and monitor a three-phase system; consequently, the data handling requirements are higher. These factors in conjunction with the component modifications and additional devices necessary for operation may actually cause the mass of a three-phase system to be higher. The advantages and disadvantages of single-phase and three-phase systems must be considered in greater detail to make a final recommendation on the best form of power transmission and distribution.

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Appendix A
Power Conditioning Component Issues

The lunar base power system will use several types of converters; however, most converters have common stages. Differences exist within these stages but, basically, their number, interconnection and type of control determines the converter's function and operation. Hence, one can address the development required for a certain combination of stages to assess the development required for a complete converter. In fact, the initial modeling and analysis will probably concentrate on separate sections before a full model is constructed to analyze the complete design. Proving the operation of critical components at applicable power, voltage and frequency levels would resolve certain feasibility issues. Additional funding is then required for further testing to assure the stages interact properly and to ultimately combine these stages into a fully functioning converter. The following paragraphs present some feasibility and development issues identified for the separate stages with a few of the tests required to resolve these issues.

Chopper Stage

A chopper stage switches dc power at a high rate to generate an alternating voltage and current. By varying the switching rate the frequency can be changed. Voltage regulation is normally accomplished in two ways. First, controlling the on duration of the switches, which determines the waveform pulse width, controls the output voltage. The second technique utilizes two separate, independently controlled modules, each designed to supply half the required maximum voltage. Summing these module voltages while varying their relative phase angles enables the combined output voltage to be varied from zero to full value. Using these techniques, fine voltage regulation can be achieved; but, precise, synchronized switching is required. Switch synchronization problems are exacerbated in a high power, high voltage chopper since numerous switches must be paralleled or connected in series to handle the high voltage and/or current levels. Voltage regulation will probably be performed by the chopper section utilizing pulse width modulation, controlled phase angle voltage summation, or a combination of these methods. Regardless of the method ultimately selected, precise, synchronized switching of the chopper switch modules must be verified at the voltage and power levels projected for the lunar base power conditioning system.

The step-up converter chopper section will operate at voltages similar to those encountered in the space station, less than 200 Vdc, although the power level will be significantly higher. The current space station converters are rated at 12.5 kWe. The lunar base converters will probably be designed for powers up to 100 kWe, possibly even more as the base evolves. Currently, metal-oxide semiconductor field effect transistors (MOSFETs) are utilized for the chopper switches, although MOS controlled thyristors (MCTs) are being developed as replacements due to their lower switching losses, and higher voltage and power capabilities. Generally, several MOSFETs are paralleled to handle the switching current levels. Due to their thermal-resistive characteristics, MOSFETs tend to share the current load relatively equally, preventing any one MOSFET from conducting too much current and failing. Early MCT testing results indicate these devices do not share currents as well as MOSFETs. Consequently, more MCTs may need to be paralleled to prevent any one from assuming too much of the load. MCT circuit testing is required to determine methods to enhance current sharing and verify that high power, high frequency, synchronized switching is practical.

The step-down converter chopper section must be rated for similar power levels as the step-up converter chopper section. However, since its input voltage is much higher, probably about 5000 Vdc, the current levels will be much lower. Consequently, MCTs may not need to be paralleled; instead they must be connected in series to withstand the high switching voltage potentials. A survey of high power, high voltage MOSFET manufacturers, conducted in September of 1988, indicates a MOSFET device with a 5000 volt breakdown voltage, a 250 amp current rating, and a 20 kHz switching speed is achievable by 1995-2000 (Ref. V-4). For the lunar base power conditioning mass estimates, it was assumed that MCTs with a 5000 volt breakdown voltage and a 40 kHz switching speed will be available by 2000. The acceptable operating voltage for a semiconductor device is half the breakdown voltage; therefore, two series connected MCTs would be required for each switch module to accept a 5000 Vdc input voltage. Again, MCT testing and development is required to determine if high power, high frequency, high efficiency, synchronized switching is feasible for series connected switch elements.

Transformer Stage

Two types of transformers may be utilized in the lunar base PMAD system depending on the architecture and user needs: stand alone ac transformers and inverter transformers that are an integral part of a converter circuit. These transformer designs will be significantly different because the operating frequencies, waveform harmonic content, and voltage ratios are different for the two applications. A brief discussion of the two types and their applications will clarify these differences.

A stand alone ac transformer would probably be utilized in an ac power transmission system following an alternator output. It would increase the alternators voltage, which may be below 1000 Vrms, to around 5000 Vrms for transmission. Therefore, its voltage ratio should be between five and ten. In a high voltage transformer, it is harder to achieve good coupling between the primary and secondary windings because the windings cannot always be placed in close proximity due to the increased winding insulation. These transformers will be designed for relatively low frequencies, probably less than 5 kHz. Transformer core volume and mass decrease with increasing frequencies until eddy current and hysteresis losses become predominant, generally around 50 kHz. Consequently, a transformer core will be much larger at 5 kHz than at 20 kHz, but core losses can be held low through the use of low-loss silicon-steel core materials. The type of ac waveform it encounters should be a smooth sinusoid with a low harmonic content. A pure sinusoid minimizes transformer core losses because the added eddy current and hysteresis losses resulting from high frequency harmonics aren't present.

The transformer section of the dc/dc converter is a higher risk development item than the stand alone transformer. Testing and analysis is required to select the core material and winding design that optimizes transformer efficiency and mass; however, there do not appear to be any feasibility issues or items requiring extensive development. These transformers will operate at high switching frequencies, possibly as high as 40 kHz, to minimize transformer core volume and mass. This high frequency input is generated by rapidly switching a dc voltage--the function of the earlier discussed chopper section; therefore, the waveform is not a smooth sinusoid. It is normally a square wave, which has a high harmonic content. High frequency, square waves necessitate the use of specialized core materials, such as Permalloy, Supermalloy, or amorphous metals, that have low core loss characteristics. These transformers must also be insulated for approximately 5000 Vrms. At high voltage levels, the thickness of the winding insulation must be increased to prevent insulation breakdown and a resulting arc over between windings. Because the windings must be separated further to allow for this increased insulation, optimum coupling between the primary and secondary windings is difficult to achieve. In addition, the voltage ratio is approaching 50 for this transformer design, about 75 Vrms to 3700 Vrms[5]; therefore, the primary to secondary coupling problem may be further compounded and an interleaved winding design may be required. Consequently, the main design challenge will probably be determining the winding configuration that limits the leakage inductance and winding capacitance at a high inversion frequency such as 40 kHz, while ensuring adequate insulation strength.

Rectifier Stage

The rectification section of the step-up converter must be designed for high voltages, while the step-down converter rectification section will experience high current levels. These voltage and current values are comparable to those encountered by the two chopper section designs. But since the rectification stage probably will not require high frequency switching, its design is simplified and development costs reduced. It may be desirable to utilize thyristors, however, to enable power to be switched off in the event of a fault or provide voltage regulation by means of pulse width modulation. Extremely high voltage rectifiers typically utilize a pancake configuration consisting of diodes or silicon controlled rectifiers (SCRs) stacked in series to withstand the voltage potentials. The low voltage rectification stages will conduct high currents; therefore, diodes or SCRs may have to be placed in parallel. Presently, diodes and SCRs with high voltage and current ratings are available that appear to be adequate for the lunar base power conditioning needs. Although both high and low voltage rectifier designs will require the development of weight efficient methods of removing waste heat, there do not appear to be any feasibility issues associated with either one.

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[5]Based on current information, a dc/dc converter following the SP-100 source will receive an input of 100 Vdc. The assumed converter output voltage is 5000 Vdc. Utilizing a six-pulse full wave rectifier for the dc output to facilitate rectifier filtering necessitates a three-phase transformer. A six-pulse input invertor (the chopper stage) is needed to converter the SP-100 dc input into three-phase ac. The voltage relationship for a full wave conversion from dc to three-phase ac, or vice versa, is $3*\mathrm{SQRT}(2)/\pi$ or about 1.35. Although this number does not include commutation losses, it is reasonably accurate. The values obtained are (100 Vdc/1.35)≈75 Vdc and (5000 Vdc/1.35)≈3700 Vdc.

Filter Stage

The primary purpose of filtering is to prevent interference generated in one component propagating to other elements in the system. Normally the components generating the most interference contain switching devices or chopper stages; for example, dc/ac inverters and dc/dc converters. Generally, the higher the switching frequency, the easier it is to filter. For this reason, high frequency filter designs are often lighter in weight than comparable low frequency designs. In addition, the PMAD system itself can be designed to reduce system harmonic content. For example, in a three-phase system the symmetry of the phase groups precludes any even harmonics and the third harmonic and its multiples are naturally suppressed. Other harmonics can be mitigated through judicious paralleling practices or the inclusion of special components such as zig-zag transformers.

It is difficult to discuss a specific filter design since the power quality requirements have not been defined. However, one can make certain assumptions about the filtering needs. The power quality requirements imposed on the space station dc/dc converters can be utilized for the step-down converters that feed the habitat modules. The loads and internal distribution equipment will probably be similar, since it would be wise to build on existing technology. The power source step-up converters will be feeding long transmission lines. The inherent transmission line inductance will naturally filter the converter output, therefore, the filtering demands should be less stringent. The converter filter stage and the transmission line inductance should be considered together when defining the PMAD system filtering requirements. For ac transmission, the losses resulting from high frequency harmonics must be considered during the development of the ac transmission lines. Component filters will significantly reduce high frequency harmonics, nevertheless, the transmission lines will experience noticeable harmonic distortion if they are fed by inverters. Dc transmission line designs must consider the skin effect and inductive losses resulting from ac ripple and noise superimposed on the dc voltage. If these added losses are overlooked, they could lead to excessive line heating. The filter designs utilized in the space station and lunar base converters will probably use similar topologies; however, the capacitor and inductor power ratings of the lunar base converters must be larger due to the higher voltage and current levels. Since the two designs will be similar, no feasibility issues exist and much of the development expended on the space station filter designs should be applicable to the lunar base filter designs.

Control and Monitoring

Each of the power conditioning components will have some type of control and monitoring subsystem. This subsystem can be quite simple and consist of a few voltage, current, and temperature sensors connected to a data interface card, or be quite complex and utilize a processor capable of conducting a complete built-in component test and assessing its operation before the device is brought on line. A component controller responds to higher level commands and performs the minute steps necessary to implement these commands. Typical commands might inform a unit to change its output voltage setpoint or make the latest device temperatures available to the data bus. The monitoring system provides component operating status information to the internal controller or higher level computers. These data signals require a data interface module, normally composed of numerous analog to digital conversion circuits, to convert the sensor signals into the proper form for data bus transmission.

While the mass of this subsystem is frequently underestimated, it can be considerable, especially in small power conditioning components. This is because its mass remains relatively constant, regardless of the component power level. It increases only slightly as component power levels increase to accommodate the use of sensors designed for the higher voltage and current levels. Because the power conditioning components contained in the lunar base will typically be designed for high power levels, this subsystem will occupy a much smaller percentage of the mass than was the case with the SSF components. There does not appear to be any feasibility issues associated with this subsystem and commercial electronics developments should result in some mass reductions.

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16. Abstract This report presents the results of a study of proposed lunar base architectures to identify issues concerning centralized and decentralized power system deployment options. The power system consists of the energy producing system (power plant), the power conditioning components used to convert the generated power into the form desired for transmission, the transmission lines that conduct this power from the power sources to the loads, and the primary power conditioning hardware located at the user end.

Three power system architectures, centralized, hybrid, and decentralized, were evaluated during the course of this study. Candidate power sources were characterized with respect to mass and radiator area. Two electrical models were created for each architecture to identify the preferred method of power transmission, dc or ac. Each model allowed the transmission voltage level to be varied to assess the impact on power system mass. The ac power system models also permitted the transmission frequency to be changed. Finally, individual models were developed for different transmission line configurations and placements to determine the best conductor construction and installation location. Key parameters used to evaluate each configuration were power source and power conditioning component efficiencies, masses, and radiator areas; transmission line masses and operating temperatures; and total system mass.

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