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SPACE VEHICLE ELECTRICAL POWER PROCESSING, DISTRIBUTION AND CONTROL STUDY

VOLUME I - SUMMARY

1.0 SCOPE AND OBJECTIVES

The primary purpose of this study program is the definition of a practical generalized concept for electrical power processing, distribution and control applicable to manned space vehicles and future aircraft with special emphasis on the needs of the currently envisioned Space Station and Space Shuttle configurations. It is not intended to provide detailed designs or equipment specifications for a specific vehicle.

The utility of present day aircraft electrical power standards (MIL-STD-704A) for future space vehicles is questionable since aircraft use rotating generators to provide on-board power while space vehicles generally rely on static energy sources such as solar cell arrays, batteries, and fuel cells whose inherent output voltage characteristics are different from the characteristics of rotating generators. In order to arrive at rational power quality standards this study program concentrated on the methodology for selecting voltage levels and frequencies for transmission and distribution of electric power applicable to a broad range of aerospace transportation and payload vehicles. Since a major goal of this study is to point the way towards significant cost reductions through standardization, we have concentrated on a small number of candidate configurations and have evaluated their performance aboard widely different vehicles. A systems approach was used which includes the impact of the power processing, distribution and control concept on overall vehicle cost, weight and thermal dissipation requirements. Since the power distribution voltage and frequency which are chosen for the Shuttle and Space Station will strongly influence the electrical system design and performance of all other large aerospace vehicles for many years to come, this choice merits the most careful analysis and review of all factors which influence the resulting overall vehicle cost and performance.

The ultimate objectives of the Space Vehicle Electrical Power Processing, Distribution and Control Study program may be summarized as follows:

- Develop a data base for rational selection and evaluation of electric power processing, distribution and control methods for manned space vehicles.

- Recommend system voltage, frequency, power switching and control standards to be used for manned space vehicles.

- Establish the need for a new power quality specification or recommend changes to MIL-STD-704 applicable to manned spacecraft and future airplanes, as appropriate.

- Identify any significant deficiencies in technology.

- Recommend areas for improvement and suggest methods for early feasibility demonstrations to reduce cost and development risks.

These objectives have been achieved within the present scope of the study program. Additional effort is required for development of detailed power quality and load utilization interface specifications applicable to any specific type of manned aerospace vehicle.

For convenience we shall refer to the complete network of power lines, buses, switchgear, and power conditioning equipment which is required for electric power processing, distribution and control as the processing, distribution and control subsystem (PDCS) of the on-board electrical power system (EPS). The other EPS subsystem is the electric power generation subsystem (EPGS) which contains all generators and generator control equipment. The PDCS must control, monitor and regulate the flow of power to every on-board component or load unit which requires electric power for its operation. It therefore must contain means for supervision and control by the crew or utilize a central control and display subsystem which also serves other vehicle systems. The scope of our study program encompassed the basic PDC subsystem including power processors or power supplies which are part of load units. It did not include detailed analyses of command and display techniques except to the extent that they determine requirements for PDCS equipment and its design. In addition, detailed studies of the basic power requirements of various types of loads were performed and generator configurations were analyzed to establish realistic PDCS design requirements.

2.0 CONCLUSIONS AND RECOMMENDATIONS

This study program has shown that higher voltage dc transmission and distribution (above 100 Vdc) can provide significant reduction in weight, greater design flexibility, reliability, and lower cost when compared to presently used 28 Vdc or 115 volt, 400 Hz, 3 phase ac systems. This conclusion applies to all four types of vehicles which were considered during this study and whose salient characteristics are summarized in Table 1.

Table 1. Vehicle/Mission Characteristics

	Modular Space Station	Shuttle Orbiter	Commercial Aircraft	Military Aircraft
Mission Duration	5-10 Years	168 Hours	2-12 Hours	2-8 Hours
Environment	Space	Atmosphere & Space	Atmosphere	Atmosphere
Main Propulsion Engines	None	H_2/O_2 Rocket	Turbo Jet	Turbo & Ram Jet
Powered Flight Duration	None	3-5 Minutes	Continuous	Continuous
Elec. Power Source	Solar Array or Nuclear/ Brayton PCS	Fuel Cell and APU	Engine Driven Alternator	Engine Driven Alternator
Maximum Electric Power Required	80 KW	15 KW	125 KW	200 KW
Heat Rejection	Radiator	Deployed Radiator	Structure & RAM Air	Fuel Heat Sink

·The basic design features of the recommended power processing, distribution and control concept are listed in Table 2 and compared with the conventional approach which has been used for present-day aircraft and Apollo space vehicles. Although 115 Vdc is recommended for the Space Station and Shuttle, higher voltages would provide correspondingly larger weight reductions but are considered beyond the range of currently available semiconductors when the usual derating factors for space vehicles are applied.

Table 2. Recommended Power Processing, Distribution and Control Subsystem

Function	Conventional Method	Proposed Method	Reason for Change
Distribution Voltage	28 Vdc or 115/200 Vac per MIL-STD-704	115 Vdc	Lower Weight Better dynamic performance and redundancy management
Load Control	Switch controlled remote relays	Mux. digital signals via data bus to solid state relays and electronic power supplies	Better reliability
Bus Control & Protection	Manually reset circuit breakers	Remotely controlled circuit breakers	Shorter power cables
Command & Display	Toggle switches, panel lights and meters	Computer generated, mux. signals via data bus	Better reliability, reduced wiring
Reconfiguration	Manual	Automatic	Better reliability
Checkout	Manual	Computer programmed	Better reliability

High voltage dc distribution provides a major saving in I^2R losses which reduces the weight of wires and cables and permits use of smaller generators and waste heat radiators. Selection of dc over ac provides compatibility with a solar cell array, battery, or fuel cell source as required for space vehicles and allows simple interconnections between redundant power distribution channels by means of isolation diodes. The recommendation to use multiplexing and solid state switchgear represents a significant departure from conventional practice made necessary by the increased complexity of the power distribution and control network. The use of a computer for supervision, reconfiguration, and checkout is in line with modern control techniques and not restricted to the electric power system.

Results of detailed weight, efficiency, reliability, and cost calculations for different power processing, distribution and control subsystem (PDCS) candidate configurations applied to each of the four types of vehicles or missions of Table 1 are presented in Section 5.0 of Volume II and are summarized in Figures 1, 2 and 3. Figure 1 graphically shows the breakdown of the PDCS by equipment category and illustrates the dominant role of the power processing equipment in almost every candidate configuration.
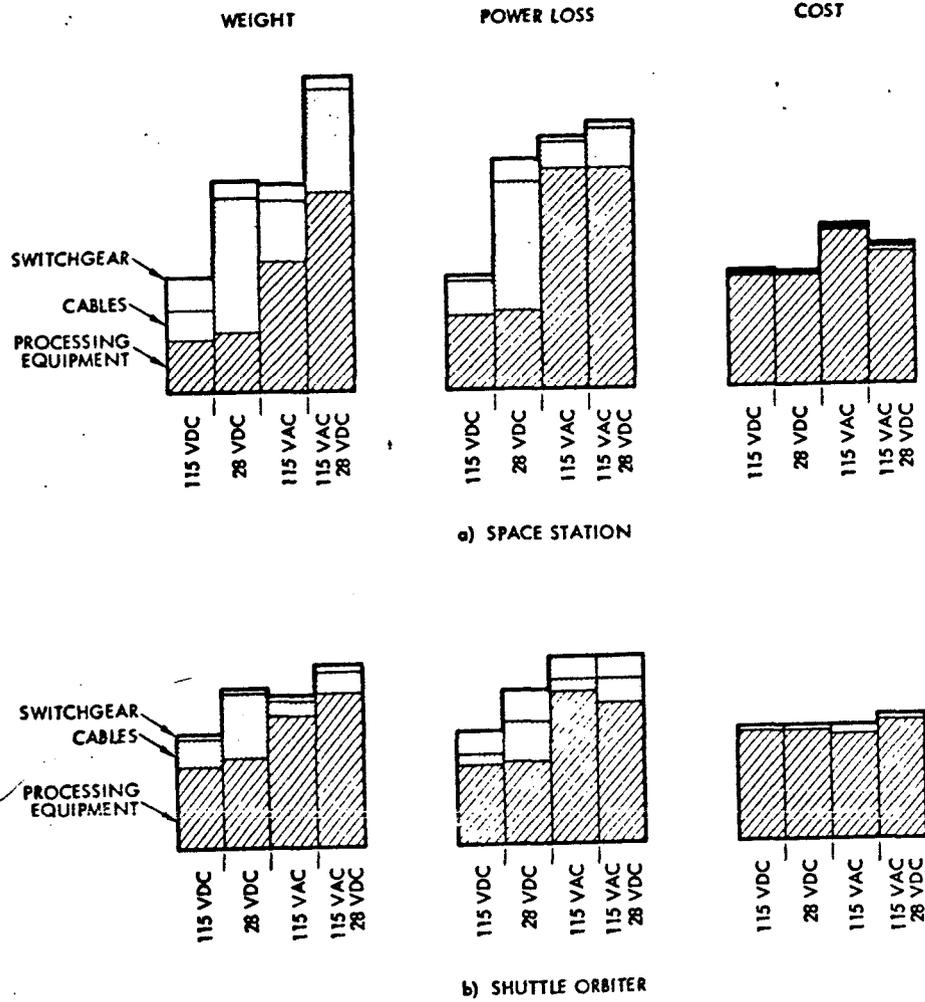
Figure 1. Detailed Breakdown of PDCS Equipment Weight, Power Loss and Cost (Normalized to 115 Vdc Configuration)

Figure 2 shows the relative weight for different system voltages normalized with respect to the PDCS equipment weight of the selected 115 Vdc configuration. The overall weight includes the support weight consisting of the portions of power generation and heat rejection subsystem weights which are required to supply PDCS power losses. Figure 3 compares overall or total effective cost for different voltages. It includes PDCS equipment and supporting EPGS cost per vehicle, life cycle cost for transportation or launch of the overall weight of Figure 2 and non-recurring PDCS development cost. Figure 3 shows that for the Space Station the effective PDCS cost consists almost entirely of equipment development and acquisition costs since the Shuttle can deliver Space Station payloads for only $100 per pound.
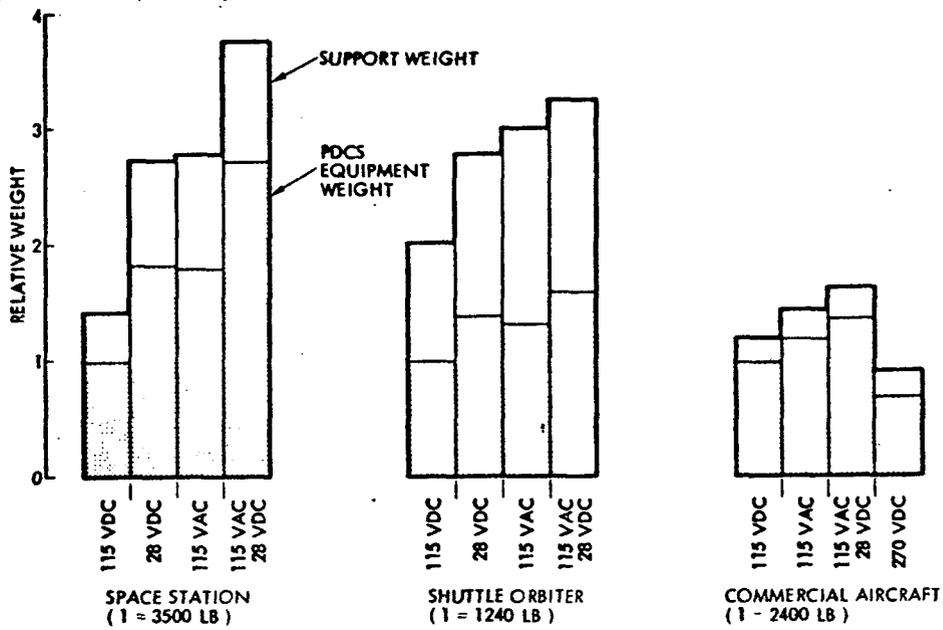
Figure 2. Overall Weight Comparison
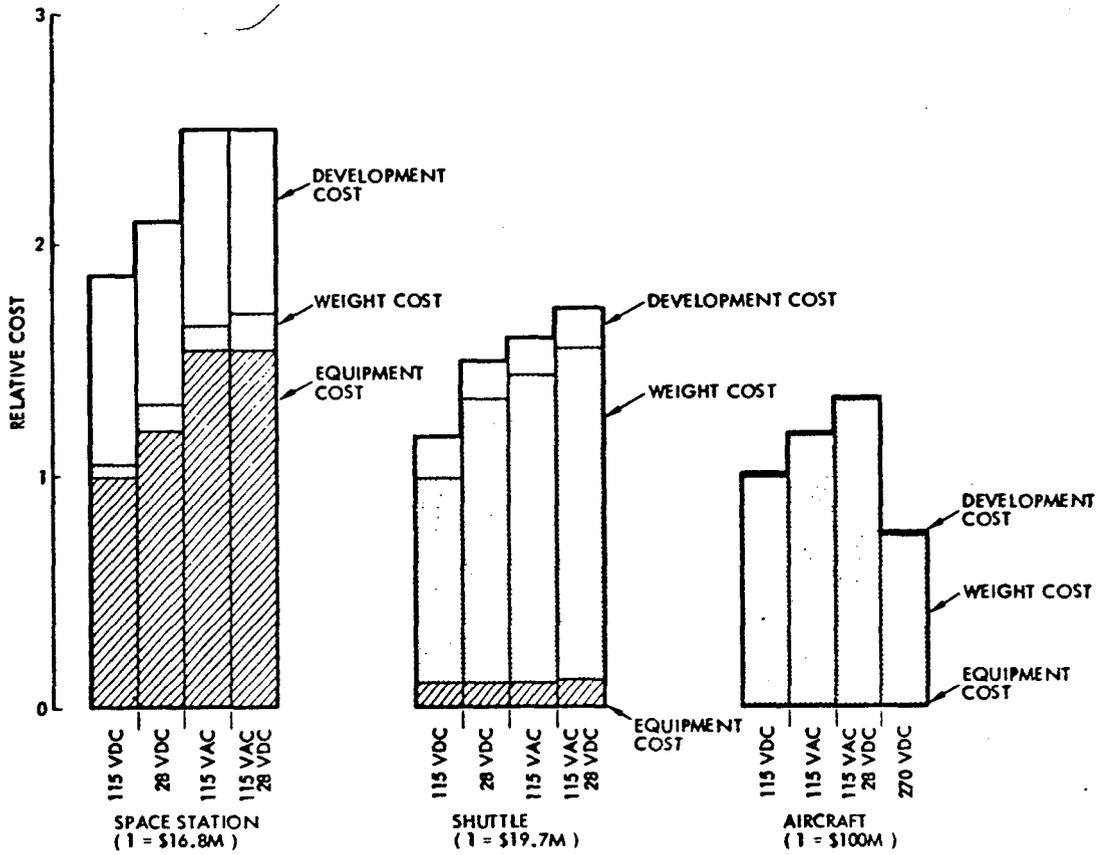
Figure 3. Cost Comparison

For the Shuttle, on the other hand, the effective dollar value of the PDCS consists largely of the transportation cost because 60 flights per vehicle are anticipated which makes the specific weight cost equal to $6,000 per pound for all on-board equipment. For transport aircraft the initial equipment cost is found to be completely negligible when the economic value of payload weight in terms of the revenue earned during the life time of the aircraft is considered. In Figure 3 we used a value of $50,000 per pound which is slightly less than the figure which was used by the Boeing Co. for economic analyses of their supersonic transport. Note that for all three types of vehicles several million dollars per vehicle can be saved by using 115 Vdc instead of 28 Vdc or 115 Vac. For aircraft an additional $20M can be saved if a hybrid system is used which supplies variable frequency ac to motors and 270 Vdc to all other loads.

For applications requiring an early design commitment, the existing background of aircraft experience on ac and 28 Vdc systems may offer advantages of lower cost and development risk. For future high performance vehicles presently under consideration, however, the possible added development risk in the higher voltage dc system is more than offset by relief of exceedingly tight weight and performance margins and the provision of performance growth potential. Even use of conventional 28 Vdc or inversion to 115 Vac is not without risk for space vehicles due to the large dc current transients during load or bus switching and the need for harmonic suppression with ac systems. Each case requires close examination within its own set of vehicle-program constraints since the lowest cost and development risk for the power subsystem will not always result in the lowest cost and development risk for the overall vehicle. Recommendations for a specific vehicle such as Space Shuttle or a particular Space Station configuration are outside the scope of this study.

The principal deterrent to application of high voltage dc systems to near term space vehicles is the need for demonstrated, space rated, power control and protection devices. Solid state devices offer important inherent advantages of life and reliability, but are not yet available in the higher voltage and current ratings, are presently somewhat costly, and represent an undesirably high series loss in the transmission line. If a near term design commitment to a high voltage dc system were made, it is

probable that development of mechanical as well as solid state-mechanical hybrid devices would be needed to offset the above cited limitations in present solid state switchgear.

The heavy use of solid state electronic equipment aboard all aerospace vehicles requires a more complete understanding of dynamic interactions between various loads and electric power system equipment than was necessary in previous systems which were designed to withstand large steady state and transient overloads with the attendant penalties in overall system performance. Much more effort in system analysis, simulation, and computer modeling is required to develop new electromagnetic control standards, power quality specifications, and equipment design procedures (for converter input filters, etc.) to enable rational design of the most cost effective power distribution and control subsystems even assuming use of low voltage dc.

It is recognized that the desire on the part of program managers to use "off-the-shelf" equipment and their confidence in conventional power distribution and control practices which have been used for the last 30 years are difficult to overcome. We have shown, however, that aircraft practices and standards are inadequate to meet the dynamic performance and efficiency requirements of large spacecraft and a change to higher dc voltage distribution can be expected to become mandatory. In order to gain increased confidence in the proposed PDCS configuration and encourage its selection for future aerospace vehicles, we recommend fabrication of a PDCS technology breadboard to demonstrate the static and dynamic performance, fault isolation characteristics, reliability and operability in the laboratory. The breadboard must be a full power mockup containing the same redundancy as the final electric power system. It is composed of prototype or breadboard components and uses full length transmission and distribution cables positioned to approximate the layout in an actual vehicle. Generators may be simulated with storage batteries and must have the same dynamic internal impedance as the actual vehicle electric power souce. Actual loads or dynamic load simulators are required. The basic elements of a flexible test and evaluation program are described in Volume II.

3.0 ANALYTICAL RESULTS

In accordance with the study procedure outlined in Volume II, calculations were performed at the component, subsystem, and system levels to determine the variation in efficiency, weight, failure probability, and cost as a function of selected values of voltage, frequency, and redundancy. Although we have not restricted our investigations arbitrarily we have performed detailed calculations only for the more common voltage values of 28, 56, 115, and 270 volts and frequencies of 0, 400, and 1200 Hz. Results are summarized below.

3.1 Power Processing Equipment

In order to illustrate the type of parametric data which was generated for this study, typical results for power processing units are shown in Figures 4, 5, and 6. Table 3 gives the specific weight, efficiency, and failure rate for typical power levels as a function of the input voltages considered in detail. Descriptions of the circuits which were considered and assumptions made for calculation of weight and efficiency are contained in Sections 3.1 and 3.4 of Volume II. Load Type 1 is typical of electronic
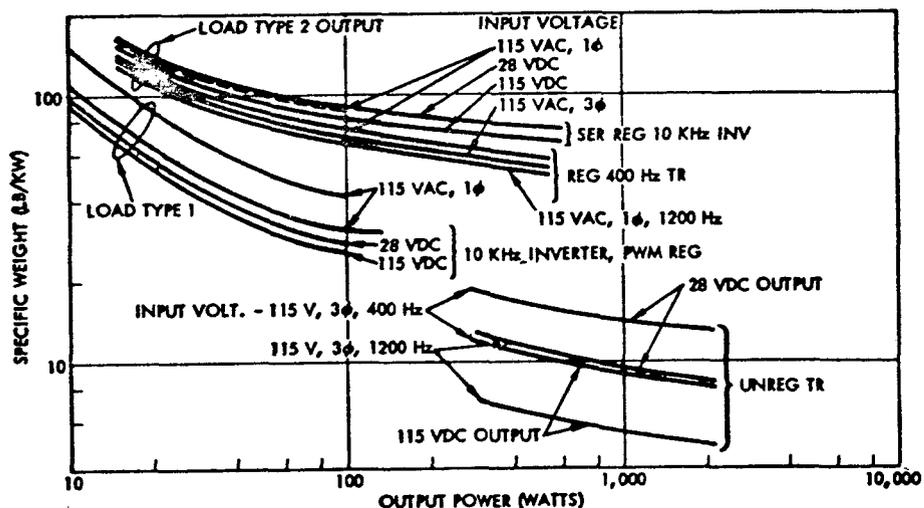
Figure 4. Specific Weight of Secondary dc Power Supplies
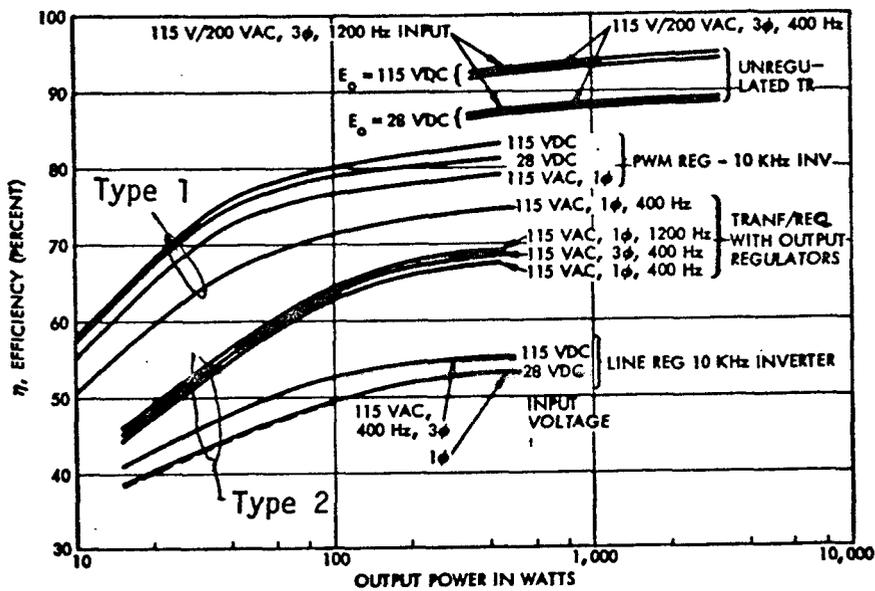
Figure 5. Secondary Power Processing Unit Efficiency

loads which consist primarily of analog circuits and require power at +28 Vdc (80% of total), +15 Vdc (15% of total), and -15 Vdc (5% of total) all regulated to ±3%. Type 2 loads are representative of digital electronic equipment which typically requires power at +5 Vdc, -5 Vdc, +15 Vdc, and -15 Vdc with 70% of the total at 5 volts. The following conclusions may be drawn:
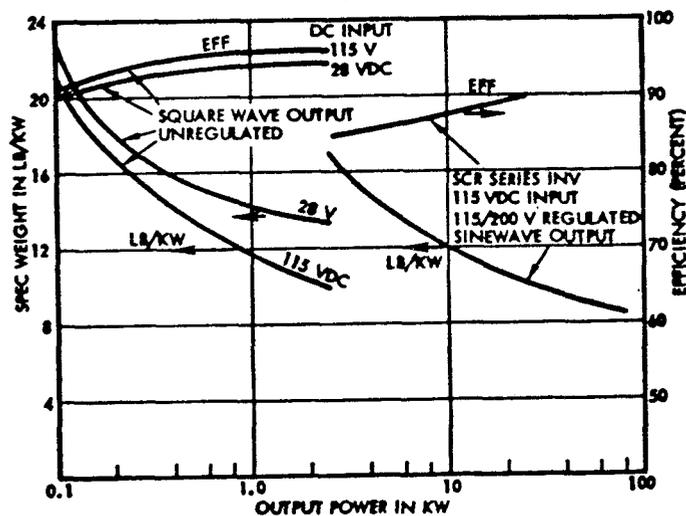
Figure 6. Weight and Efficiency of 400Hz Inverters

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Table 3. Results of Power Processing Study

	Output Voltage/Power					
	28Vdc/800W	28,+15Vdc/300W (Load Type 1)	+15,+5Vdc/300W (Load Type 2)	115/200V,400Hz 2KW SquareWave	115/200V,400Hz 3KW SineWave	115Vdc/300W
Weight (lb/kw)						
28 Vdc	-	26	42	13.5	22	11.5
115 Vdc	10	23	38	9	16	-
115V, 400Hz, 3ø	14	29	45	-	-	10
115V, 1200Hz, 3ø	10.5	26	44	-	-	6
Efficiency (%)						
28 Vdc	-	81	68	93	82	88
115 Vdc	90	83	69	96	85	-
115V, 400Hz, 3ø	88.5	79	65	-	-	94
115V, 1200Hz, 3ø	89	80	65.5	-	-	94.5
Failures (10^6 hrs)						
28 Vdc	-	2.55	2.32	8.0	12	1.7
115 Vdc	1.7	2.55	2.32	8.5	12	-
115V, 400Hz, 3ø	.5	2.72	2.50	-	-	.5
115V, 1200Hz, 3ø	.5	2.6	3.2	-	-	.5

● The weight and efficiency of power processing units (PPU) depends on the number and magnitude of isolated voltages required at the output. The lower the output voltage and the greater the number of different voltages the higher the weight and the lower the efficiency will be.

● Input voltage and frequency within the range of 28 to 300 volts has less influence on PPU weight and efficiency than output voltage requirements, the spread being about 25% with the higher input voltages yielding lower weight.

● The circuit design used to mechanize electronic power supplies strongly affects their performance. In general the lightest and most efficient method for providing multiple isolated output voltages from a single input voltage is to use a high frequency pulse width modulated (PWM) square wave inverter.

● Availability of ac input power provides no advantage over dc at equivalent voltage since voltage transformation and isolation can be obtained more efficiently with high frequency PWM inverters than power frequency transformers.

- About 30% of the weight and volume of typical PPUs is devoted to filter and noise suppression circuits for meeting power quality requirements at both input and output terminals.

- Improved voltage regulation at power supply input terminals does not usually lead to lower power supply weight or increased efficiency.

Further discussion of power processing unit design characteristics are contained in Volume II.

3.2 Cable Design

The weight of the power cables depends on the number of loads, power to be delivered, distribution voltage, allowable voltage drop ΔV and whether structure is used for current return. The cables usually are sized so that the voltage drop ΔV at maximum current does not exceed a specified value and the temperature rise in the cable does not overstress the insulation. For most space vehicles, however, where the weight of the source of electrical energy is significant, a better design procedure is to size the cables so that the sum of cable weight and generator weight penalty, which may be called "transmission weight" is minimized. It can be shown that the minimum transmission weight occurs when the voltage drop is chosen so that the weight penalty imposed on the generator due to the fact that it must be sized to supply the power losses in the cabling is equal to the weight of the cables given by

$$M_c \approx \frac{P}{V} \ell \sqrt{m_G \rho \sigma} \tag{1}$$

This requires a voltage drop given by

$$\Delta V \approx \ell \sqrt{\frac{\rho \sigma}{m_G}} \tag{2}$$

where   P   =   Power to be transmitted

V   =   Transmission voltage

ℓ =   Cable length

ρ =   Specific weight of cable

σ =   Resistivity of cable

m_G =   Specific weight of generator

The effect of this optimization procedure for a typical Space Station and Shuttle Orbiter is illustrated in Figure 7 which shows the transmission weight and voltage drop for a 100 ft. length of cable as a function of transmission voltage.
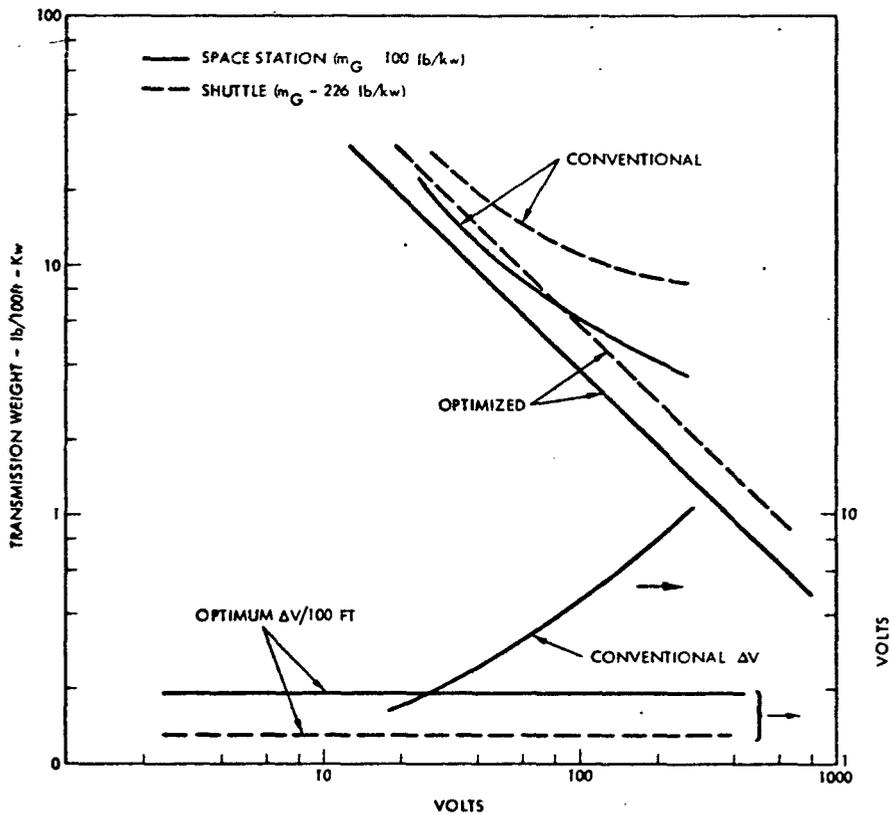

Figure 7. Transmission Weight for Space Station and Shuttle

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3.3 Control, Display and Protection Equipment

The power processing, distribution and control subsystem must contain a variety of switches, sensors, and displays for load and generator on/off control, for connecting redundant equipment, for automatic removal of faulty loads or generators, and for display of system status. Because in the future the number of separate loads which must be commanded and monitored will become very large with an attendant increase in the work load on the crew, various methods for computer control of the EPS and multiplexing of command and status signals have been considered or proposed by several contractors and government agencies. During this study program we did not concern ourselves with the detailed design of a data bus or evaluation of computer control and supervision of the EPS but have concentrated on the technical feasibility and performance of the switchgear as a function of distribution voltage and frequency.

Reconfiguration of the power distribution network may be required when load requirements change during different phases of a given flight or as a consequence of failures. Since the exact reconfiguration switching requirements can only be determined as part of an overall vehicle electrical systems study, we have assumed that reconfiguration is restricted to cross strapping or paralleling of generators and turn on/off of individual loads and power distribution units which contain the local load buses.

Three types of circuit breakers or power controllers were considered, electromechanical circuit breakers with thermal or magnetic overload sensing, solid state power controllers and hybrid circuit breakers which contain mechanical contacts for current interruption and use electronic circuits for overload sensing. All circuit breakers can be remotely controlled and monitored either by means of a toggle switch which supplies power to the operating coil of the electromechanical circuit breaker (RCCB) or a low power bilevel signal in the case of the solid state and hybrid remote power controller (RPC).

In the past high voltage dc power distribution has been avoided because of the belief that dc circuit interruption at voltages much above 28 Vdc is not possible or requires excessively large and complicated circuit breakers. This topic will therefore be covered here in somewhat more detail than other parts of the study. Currently available mechanical circuit breakers and

toggle switches are only suitable for supply voltages up to about 50 volts dc or about 250 Vac. Solid state circuit breakers are under development for 115 and 230 Vac circuits and for dc voltages up to 300 Vdc. Both types have fundamental limitations which must be recognized for proper application. In all mechanical switches an arc will form when the contacts separate provided the initial current exceeds about one ampere and there is sufficient voltage to initiate the arc. The voltage between contacts during arcing depends on the current, contact material, arc environment, and contact separation, and has the general characteristics shown in Figure 8. The limitation on dc voltage for mechanical circuit breakers is due to the fact that the arc may be stable and not interrupt the current if the circuit voltage and impedance are proper for this condition as exemplified by operating point A of Figure 8. In ac circuits the current goes through zero each half cycle so that the arc will interrupt and not restart during the next half cycle if the contact separation is sufficiently wide to sustain the peak voltage supplied by the external circuit.
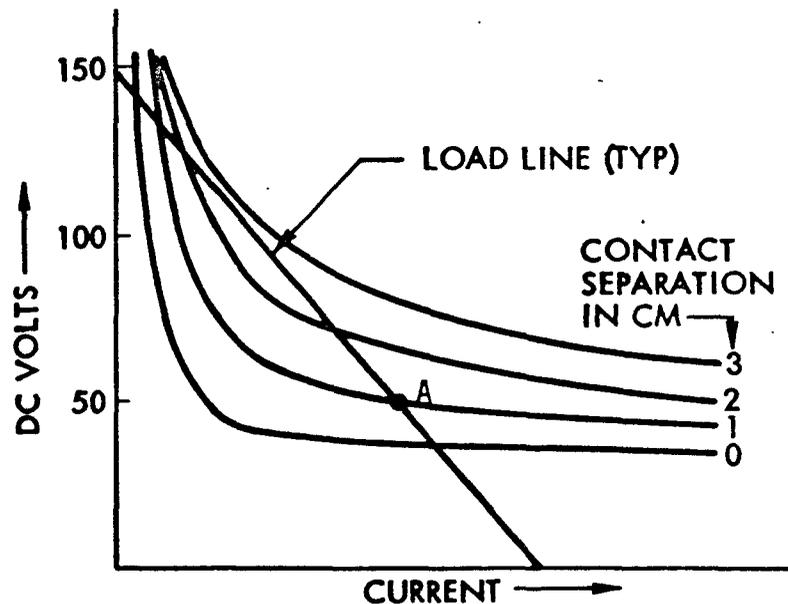
Figure 8. Typical Electric Arc Characteristic

As seen from the oscillograms of Figure 9, arcing will occur even in low voltage circuits. In conventional 30 Vdc breakers arc interruption is insured by using two gaps in series so that the circuit voltage is insufficient to supply the cathode drops for the two series connected arcs. For reliable arc interruption when the dc source voltage exceeds about 50 volts, more than two gaps are required or the arc must be interrupted by reducing its temperature below the value required for ionization of the plasma. This can be accomplished by "magnetic blowout", air blast cooling or other means. Although such breakers are commonplace for sea level use they are not available in sealed configurations for aerospace vehicles. They can be designed to withstand dc voltages in excess of 120 Vdc but will be larger than conventional sealed 28 Vdc breakers.
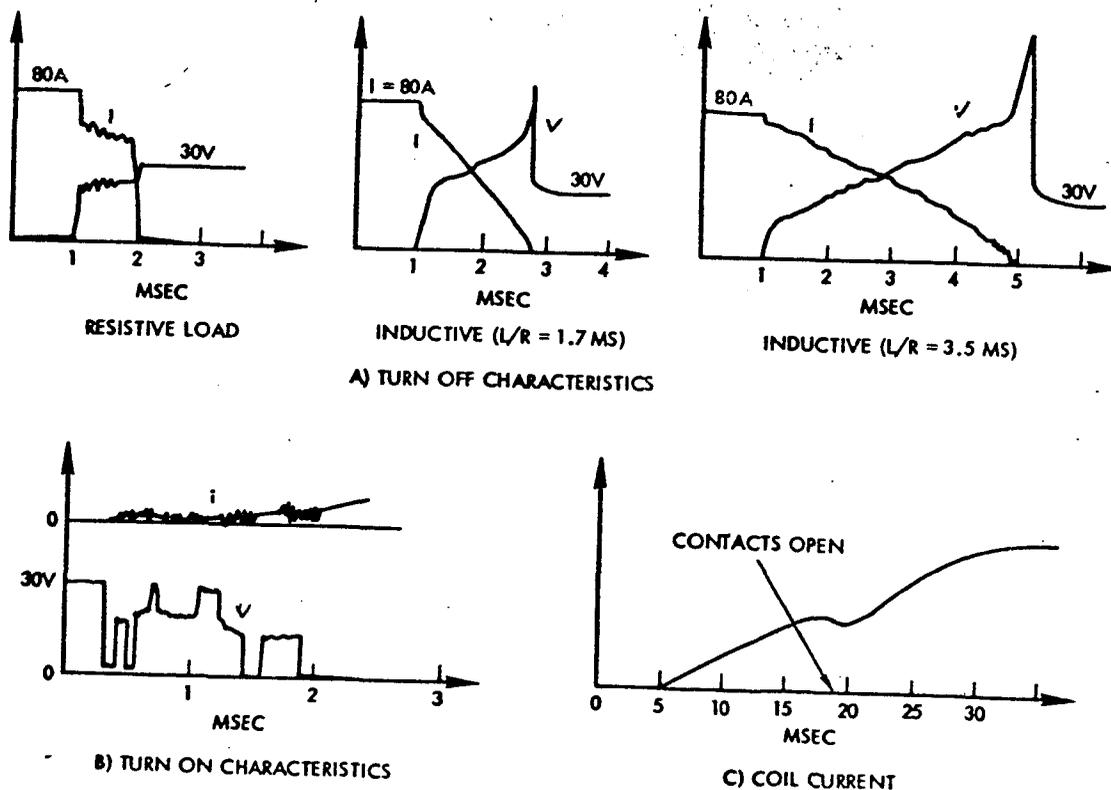
Figure 9. Transient Characteristics of a 30 Volt dc Mechanical Relay

Solid state circuit breakers use transistors or SCRs instead of separable mechanical contacts. They depend on their switching speed and high reverse breakdown voltage to limit fault currents. Currently available high speed switching transistors have current ratings of about 10 amp and V_{CEB} in excess of 350V. Thyristors can be used for current interruption in ac circuits and have current ratings up to 650 amp with $V_{CEB} > 2000$ volts. Their saturated forward voltage drop however is around 1.5 to 2 volts. Solid sate circuit breakers are under development with continuous ratings up to 75 amp, at 120V, 400Hz; 15 amp at 300 Vdc and 35 amp at 80 Vdc. Typical weights of remotely reset mechanical and solid state breakers are plotted in Figure 10. In addition to their higher power handling capability, mechanical switches have lower power loss and are lower in cost. Their major disadvantage is the electrical noise generated during arcing, the relatively high failure probability due to contact erosion, and their large coil operating current.
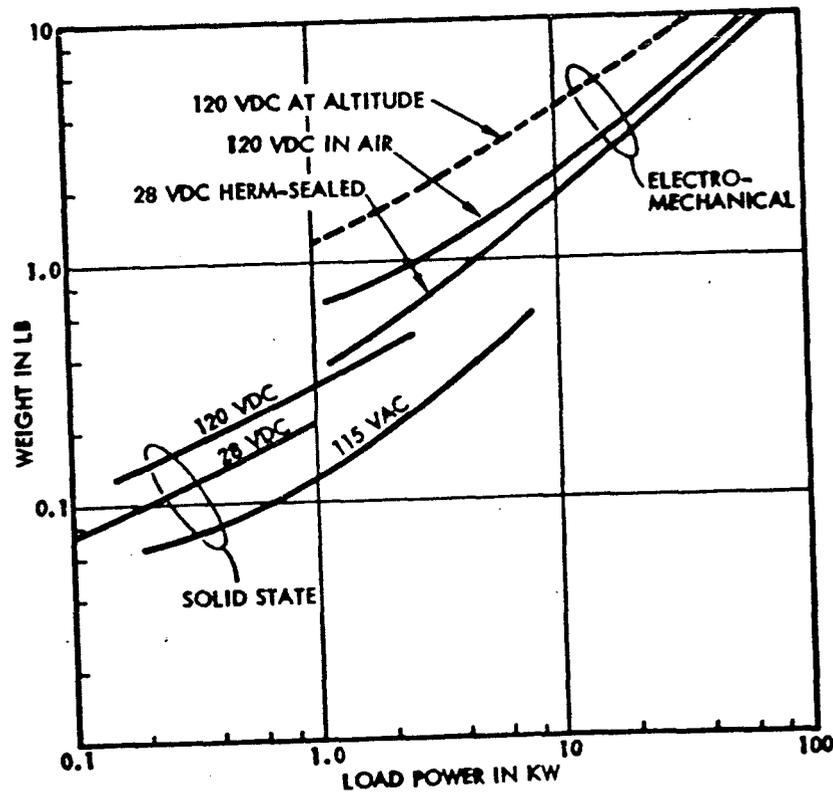
Figure 10. Weight of Circuit Breakers

3.4 Power Processing, Distribution and Control Subsystem Performance

The PDCS candidate configurations which were analyzed in detail are listed in Table 4 and shown schematically in Figures 11, 12, and 13.

Table 4. Candidate PDCS Configurations

Config. No.	Application			Redundancy (Note 1)	Transmission Voltage (Note 2)	Distribution Voltage (Note 2)	CDP Method
	Station	Shuttle	Aircraft				
1	x	x		4	28 Vdc	28 Vdc	Mux.
2	x	x	x	4	115 Vdc	115 Vdc	Mux.
3	x	x	x	4	115/200 Vac	115/200 Vac	Mux.
4	x	x	x	4	115/200 Vac	28 Vdc	Mux.
5		x		4	28 Vdc	28 Vdc	Convent.
6		x		4	±28 Vdc	±28 Vdc	Convent.
7			x	4	270 Vdc	270 Vdc	Mux.

Notes: 1 - Except for dual redundance within Space Station modules.

2 - All ac is 400Hz sine wave.
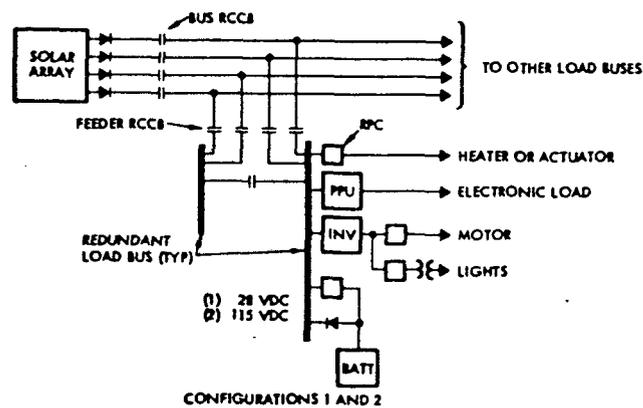
Figure 11. Candidate Configurations - Space Station
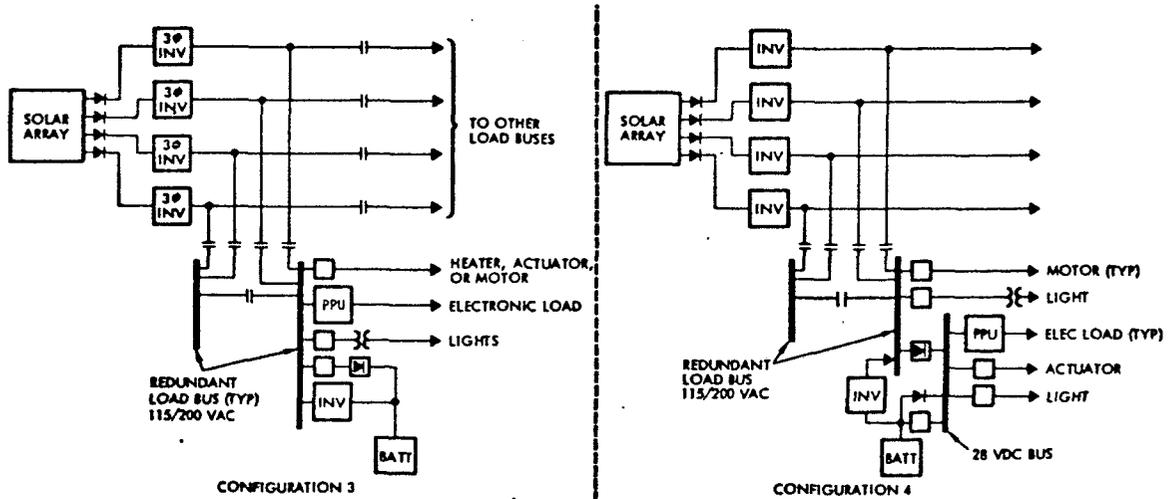
Figure 11. Candidate Configurations - Space Station
(Continued)
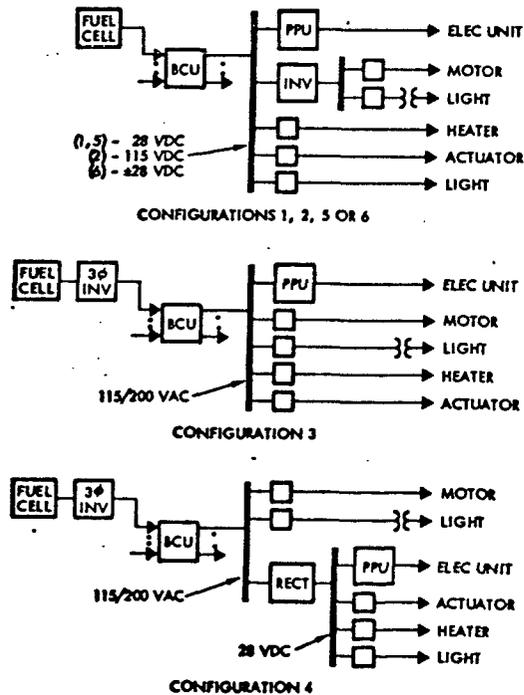
Figure 12. Candidate Configurations - Shuttle Orbiter
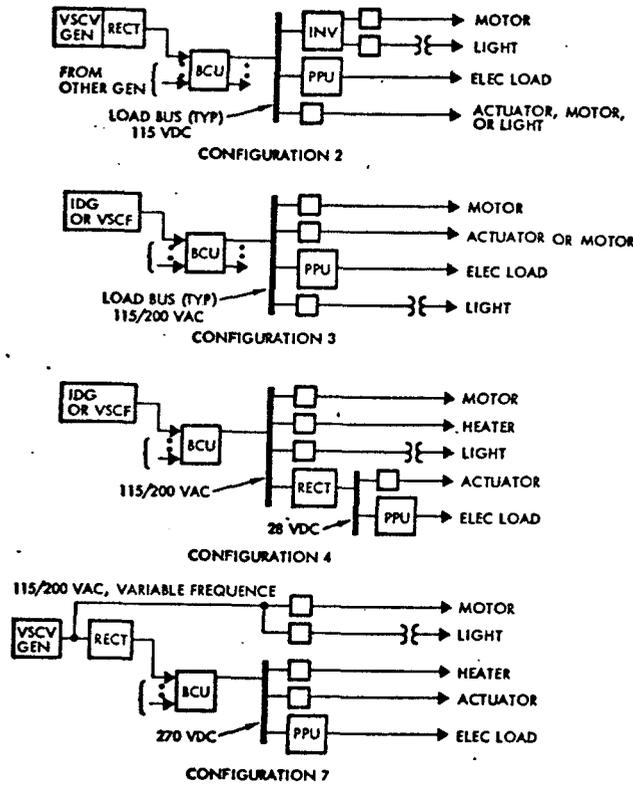
Figure 13. Candidate Configurations - Aircraft

In order to insure that the results of this study are applicable to practical situations, considerable effort was expended to estimate the quantity, rating, duty cycle, and typical location of each type of electrical load aboard future aerospace vehicles. Based on on-going Space Station and Shuttle Phase B program definition studies and informal discussions with airframe manufacturers, we have defined sets of reference or model load requirements for each type of vehicle as summarized in Table 5 and more fully described in Section 2.3 of Volume II. A 12-man modular Space Station (MSS) composed of 12 docked modules was assumed.

Table 5. Reference Load Requirements Models

Type of Load	Space Station		Shuttle Orbiter		Transport Aircraft		Military Aircraft	
	Qty	Pwr(KW)	Qty	Pwr(KW)	Qty	Pwr(KW)	Qty	Pwr(KW)
Electronic Equipment								
Analog	304	4.0	106	1.5	60	8	50	5
Digital	248	8.8	97	3.0	60	7	120	10
Electric Motor	84	4.2	38	1.7	60	45	44	26
Electromechanical Actuator	356	1.1	183	1.2	52	5	50	1
Lights	390	3.7	34	0.8	312	20	22	6
Heaters	52	2.4	28	1.6	70	40	25	12
Experiments or Payloads	112	18.0	1	0.5	-	-	14	140
Elec. Energy Storage	18	37.8	0	-	-	-	-	-
Total	1564	80.0	487	10.3	614	125	325	200

Results of detailed PDCS weight analyses for reference Space Station, Shuttle, and aircraft load requirements are summarized in Tables 6, 7,

Table 6. PDCS Equipment Weight (lb) – Space Station Requirements

	PDCS Configuration			
	1	2	3	4
	(28 Vdc)	(115 Vdc)	(115/200 Vac)	(115 Vac/28 Vdc)
Wires and Cables				
Power Module	300	71	71	130
Crew Module	282	63	63	169
Lab Module	180	36	36	99
RAM	457	99	99	376
Switchgear				
Power Module	93	179	102	96
Crew Module	95	173	115	117
Lab Module	20	37	18	19
RAM	15	31	12	15
Power Processing (PPUs)*				
Power Module	262	246	265	262
Crew Module	199	168	200	199
Lab Module	253	228	261	253
RAM	19	17	22	19
Central Conv. (CPUs)				
Power Module	50	47	972	1065
Crew Module	21	18	188	309
Lab Module	26	24	238	335
RAM	17	15	110	205
Space Station Totals				
Wires & Cables	4266	940	940	3052
Switchgear	506	964	542	554
PPUs	1542	1386	1604	1542
CPUs	296	268	3436	4648
Total PDCS	6610	3558	6522	9796

* Does not include PPUs for experiments.

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Table 7. PDCS Equipment Weight (Lb) - Shuttle Requirements

	PDCS Configuration (See Table 3)					
	1	2	3	4	5	6
Wires & Cables	647	203	207	207	917	1047
Switchgear	60	101	57	60	67	92
PPUs	786	715	860	786	786	755
CPUs	200	168	480	896	200	185
Cont/Display	52	52	52	52	140	150
Total	1745	1239	1656	2001	2110	2229

and 8 which provide the estimated weight of the PDCS equipment for the candidate configurations of Table 4. Note that the major differences in weight for the different configurations are due to the decrease in cable weight with increasing voltage and the need for central power processing units (CPUs) if the generated and distributed voltages or frequency are different. Thus, for the Space Station and Shuttle, configuration 2 (115 Vdc) yields the lightest PDCS. For aircraft, significant weight savings over present systems can be achieved if motors and lights can tolerate variable frequency input power so that configuration 7 (270 Vdc) becomes practical.

Table 8. PDCS Equipment Weight (Lb) - Aircraft Requirements

	Commercial				Military*			
Configuration →	2	3	4	7	2	3	4	7
Wires & Cables	814	1120	1120	318	924	1310	1310	390
Switchgear	300	211	226	326	271	202	202	300
PPUs	427	526	467	408	660	796	725	629
CPUs	700	-	336	-	480	-	340	-
Total	2241	1857	2149	1052	2335	2308	2577	1319

* Does not include payload PPUs

Calculations of PDCS power losses, failure rate, and recurring equipment cost produced results in line with the weight calculations. The major differences in total subsystem power loss are due to CPU requirements and differences in cable I^2R losses. Table 9 provides results of Space Station and Shuttle calculations. Maximum simultaneous losses which determine the peak heat dissipation requirements from the entire PDCS are shown. Losses were not computed for aircraft because their effect on the EPS and other major vehicle systems is not significant.

Table 9. Summary of PDCS Power Loss Calculations (KW)

Config.	Item	Space Station	Shuttle
1 28 Vdc	Cables Switchgear PPUs CPUs Total	11.0 1.8 5.8 .8 19.4	1.07 .82 2.26 - 4.15
2 115 Vdc	Cables Switchgear PPUs CPUs Total	2.9 0.5 5.6 0.7 9.7	.27 .63 2.02 - 3.02
3 115 Vac	Cables Switchgear PPUs CPUs Total	2.9 0.5 6.3 11.7 21.4	.27 .63 2.24 1.90 5.04
4 115 Vac/ 28 Vdc	Cables Switchgear PPUs CPUs Total	3.3 0.5 5.8 12.9 22.5	.43 .63 2.00 .90 4.96
5 28 Vdc Convent. Control	Cables Switchgear PPUs CPUs Total		1.07 .45 2.26 - 3.72
6 +28 Vdc Convent. Control	Cables Switchgear PPUs CPUs Total		.97 .50 2.24 - 3.71
Maximum Useful Load		80	10.3

The reliability of the PDCS depends primarily on the redundancy and the load inventory. Since both are fixed by the vehicle design, they do not figure in the choice of our PDCS candidate over any other. For any given redundancy level and load requirements model, however, we have made comparative estimates of reliability based on part count and part failure probabilities. The conclusion is reached that the configurations with the fewest components between the generator and the essential loads are the most reliable. This favors dc distribution (configurations 1 and 2) for the Space Station and Shuttle and rectified dc (configurations 2 and 7) for aircraft. DC is preferable to conventional constant frequency ac for aircraft to avoid the hydraulic constant speed drive or electronic cycloconverter in the EPGS. In every instance use of solid state RPCs with multiplexing of command and status signals greatly enhances reliability (by a factor of 3 for the Shuttle) over the conventional method using RCCBs and panel mounted toggle switches for control.

3.5 System Level Considerations

The choice between competing power processing, distribution and control concepts must include the effect of the PDC subsystem on the EPGS and the heat rejection subsystems because they are designed and sized to accommodate the power losses generated by the PDCS. Since the efficiency is different for each PDCS configuration, the generation and heat rejection capacities must also be different. These differences are important for space vehicles because the EPGS and radiator weights vary almost linearly with power handling capacity but may be ignored in aircraft because the electric power generation and heat rejection requirements are a small fraction of available vehicle power and cooling capacity. Specifically the increase in the Space Station solar array weight and cost due to PDCS power losses amounts to 100 lb/KW and $200,000/KW. The Shuttle requires a retractable radiator which is capable of withstanding re-entry conditions. It has a specific weight of 146 lbs. per KW of heat rejection capability. In addition an increase of 300-500 lbs. in fuel cell reactant consumption is chargeable to the PDCS so that the reflected (or support) weight exceeds the actual PDCS equipment weight as shown in Figure 2.

Cost differences between candidate PDCS configurations have also been evaluated in terms of their systems impact. As shown in Figure 3 this led to the conclusion that the economic value of weight is much larger than the recurring PDCS equipment acquisition cost.

Another method for comparing PDC concepts at the systems level is to consider dynamic performance. By means of rather simple arguments it can be shown (Volume II, Section 4.3) that for equal PPU weight the higher the system voltage the lower the percentage of transient and steady state interference voltages. This is due to the fact that inductive coupling varies inversely with voltage and because for a given weight capacitive energy storage varies as V^2. In addition dynamic interactions between redundant channels can be controlled more easily in dc systems than systems with ac distribution because frequency synchronization is not required for parallel operation. These factors constitute a powerful argument in favor of higher voltage dc systems.

4.0 TECHNOLOGY REQUIREMENTS

Every candidate PDCS configuration considered herein is technologically feasible and can be implemented for any specific application given adequate time and funding for development and flight certification of components and demonstration of subsystem fault clearing and dynamic performance characteristics.

Three areas of technology deficiency have been identified. They do not affect the basic feasibility of any candidate configuration but require advanced development effort prior to procurement of flight worthy hardware and subsystem acceptance. They are

a) DC current interruption in high power circuits with supply voltage above 50 Vdc

b) Lack of flight proven solid state remote power controllers

c) Suppression of dynamic interactions due to large inrush currents, inductive overvoltage, commutation, and mechanical switching.

In addition a number of technology improvements which enhance PDCS reliability and weight or reduce cost have been evaluated.

a) Circuit breakers are required to remove loads which draw excessive current and to prevent damage to the power lines or generators. Because batteries and fuel cells can deliver at least 10 times rated current without suffering much voltage drop until the stored reactants are consumed, circuit breakers which can interrupt fault current at normal system voltage are required. Since a stable arc can exist between a pair of contacts, even with relatively large separation if the voltage exceeds about 20 volts, six or more gaps in series must be used to prevent formation of a stable arc in a circuit breaker rated for 120 Vdc, or other means must be employed to prevent formation of a persistant arc. Although a number of approaches for design of reliable environment free circuit breakers have been proposed, flight proven units are not currently available. The lack of high voltage dc circuit breakers, however, does not prevent use of higher voltage transmission because means are available for reducing the supply voltage to an acceptable level which allows circuit interruption in response to an overload signal. In the past circuit breakers were not used in series with 28 volt batteries because main bus failures were prevented through adequate mechanical protection. Solid state circuit breakers are not suitable by themselves for high power dc current interruption because of their large saturated forward voltage drop and low power rating. Research and development effort to improve dc circuit breaker technology should include active consideration of the following:

- Oil or gas filled mechanical circuit breakers
- Parallel connections of mechanical and solid state circuit breakers
- Development of gate turn-off thyristors
- Multiple break mechanical contactors
- Environment free methods for arc interruption

Preliminary high altitude tests on conventional mechanical relays with magnetic blowout indicated that arc interruption at 120 Vdc is possible.

b) Development of solid state remote power controllers (RPCs) which provide automatic overload protection and low power bilevel command/status monitoring suitable for multiplexing is not yet complete. No agreement has been reached on standardized control and sensing logic levels and overload trip characteristics. Technology deficiencies can be related directly to the basic characteristics of the transistor or thyristor which is used as the switching element. Power handling capacity and efficiency are limited by device rating and switching speed. New circuits must be developed to increase the peak to average current capability so that the RPC can survive the large inrush currents drawn by lamp and motor loads.

c) Dynamic interactions become a major deficiency in subsystem performance when they cause semiconductor failures or excessive noise levels. Techniques for analysis of interference due to steady state noise, impulse functions, and typical transients have been developed previously using digital computer simulation of the interference generators and the distribution network. Suppression of interference requires design of passive or active filters with minimum loss and weight penalties. Detailed analysis of dynamic performance and interference margins can only be performed for completely defined applications but general techniques for optimized filter design and development of smaller inductors and filter capacitors are required to meet dynamic performance requirements of future PDC subsystems.

In addition to the three areas where technology deficiencies exist, our study has disclosed several items where technology improvements would yield significant increases in subsystem and system performance. Recommended subjects for technology improvement are:

- Electronic controls for induction motors

- Digital control and stabilization circuits for power processors

- Low loss mechanization of power supplies for low dc output voltages

Further details are presented in Volume II, Section 6.0.