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INVESTIGATION OF POWER PROCESSING TECHNOLOGY FOR SPACECRAFT APPLICATIONS

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State University of N.Y. at Buffalo

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This report summarizes an investigation of power processing technology applicable to future satellite electrical power systems. The issues of AC vs DC distribution are addressed as is the optimum distribution voltage. DC distribution is recommended. Distribution voltage should be as high as practical but less than 270 volts.

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INVESTIGATION OF POWER PROCESSING TECHNOLOGY FOR SATELLITE APPLICATIONS

A. S. Gilmour, Jr.

State University of New York at Buffalo

March 31, 1982

Final Report

Task 7 of Contract F33615-81-C-2011

SCHOLARLY RESEARCH IN AEROSPACE POWER

Southeastern Center for Electrical Engineering Education

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INTRODUCTION AND OBJECTIVES

Within the next decade it is anticipated that satellite missions will require electrical power levels up to approximately 50 kW in orbits up to and including geosynchronous orbit (GEO). The launch to low earth orbit (LEO) of systems as large or larger than 50 kW is now possible with the space shuttle. The transfer of these high power systems to higher orbits is not presently possible because of weight limitations. To make transfer to higher orbits possible, system weight must be reduced.

As an illustration of the satellite power limitation imposed by system weight, consider Figure 1.[1] Calculations are given of the battery energy density required to provide various power levels to a 5000 pound satellite in synchronous orbit. The fraction of the satellite weight occupied by the battery is plotted as a parameter. For example, if a high energy density battery (HEDRB) with a density of 50 WH/LB (396 kJ/kG) occupies 5% of the weight of the satellite, then the maximum satellite power level is 10 kW. If that same battery could occupy 24% of the satellite weight, then the satellite power level could be 50 kW. Present plans are for battery weight to be about 10% of the satellite weight so that the maximum power level is 20 kW.

A complete satellite power system contains, not only the battery, but also the solar array, the power processing and distribution components and equipment. The total power system weight is on the order of 30% of the satellite weight. Obviously there is a premium on minimizing the weight of the power processing and distribution components and equipment so that as large a fraction as possible of the power system weight can be allocated to the batteries and solar array. This, then, maximizes the power capability of the satellite.

The above considerations lead directly to objective of the task for which this is the final report. That objective , taken directly from the Statement of Work provided by the Air Force Aero-Propulsion Laboratory is "Provide recommendations to guide power processing equipment and component development efforts supporting future satellite electrical power systems."

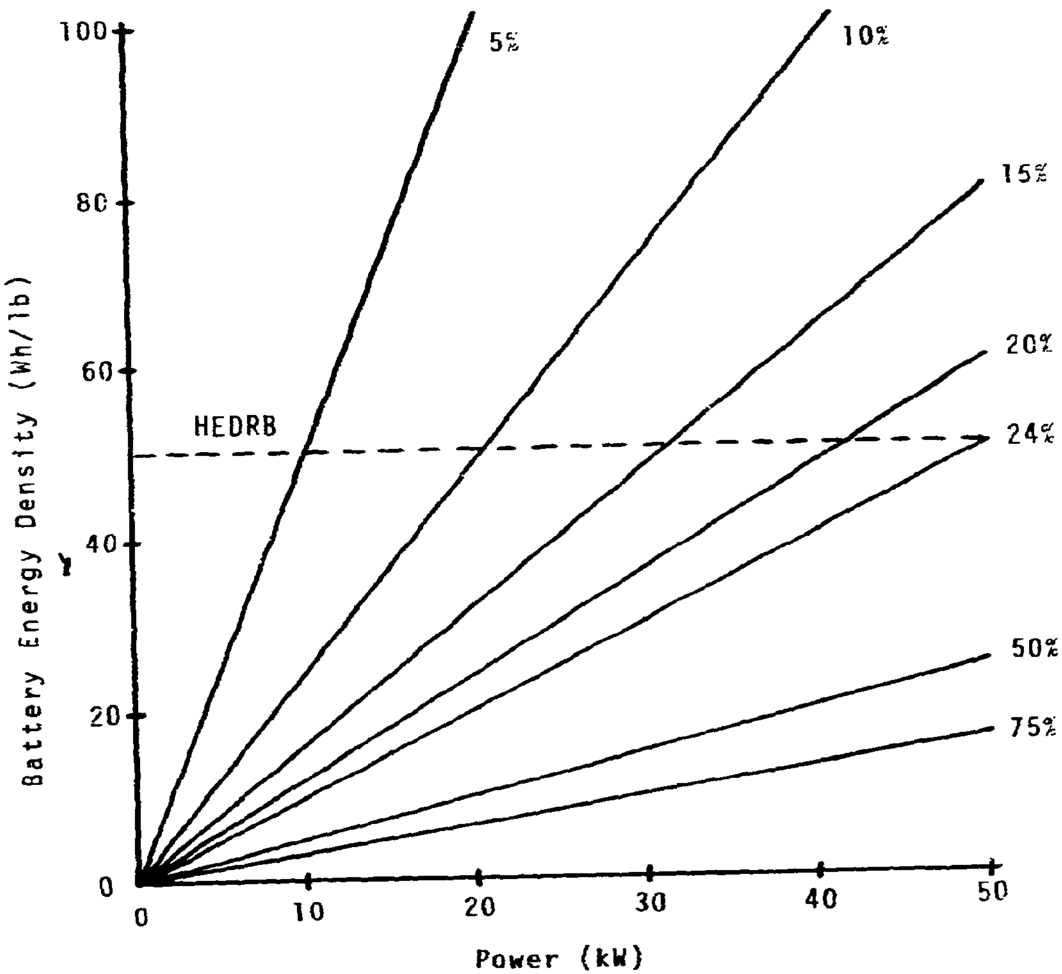

Figure 1. Required battery energy vs power level for fixed satellite weight fractions (5000# satellite in synchronous orbit).

SECTION II

DATA SOURCES

The bulk of the information for this investigation was obtained through discussions with personnel actively engaged in the development of satellite power processing equipment and components. Key discussions were held at Air Force Aero-Propulsion Laboratory personnel. In addition, Table 1 contains a list of the organizations visited one or more times during this investigation. Other discussions (mostly telephone) were held with personnel at the organizations listed in Table 2.

Table 1

ORGANIZATIONS VISITED

Martin Marietta, Denver	TRW Defense and Space Systems Group
Boeing Aerospace	General Dynamics, Convair Division
Raytheon, Wayland	Rome Air Development Center
Lockheed Missiles and Space Co.	NASA Lewis Research Center
Hughes Aircraft	NASA Marshall Space Flight Center

Table 2

OTHER DISCUSSIONS

Ball Brothers	NASA Goddard
Grumman	RCA Astro-Electronics Division
Comsat Laboratories	Thermal Technology Lab.
La Barge Inc.	

SECTION III

SATELLITE POWER SYSTEMS

1. General System

The major components of a typical solar array powered satellite power system are shown in Figure 2. Power from a solar array is used for battery charging and/or distribution to one or more loads through appropriate power control, conversion and regulation equipment.

The battery is used to provide power to the load during periods when the solar array is inactive. The energy storage requirement for the battery depends on the load power requirement and on the time period during which power must be supplied by the battery to the load. For example, if the satellite was in eclipse for a period of one hour and the load power requirement was 10 kW then, of course, the battery would have to supply an energy of 10^4 W-hr. If the battery voltage was 200 V and 50% of the battery energy was removed during eclipse (50% depth of discharge or 50% DOD), then the battery cell ratings would have to be 100 A-hr. If batteries containing 50 A-hr. cells were the only ones available for use on the satellite, then it would be necessary to effectively place two batteries in parallel. Conceivably, this could be done by directly connecting either batteries or battery cells in parallel. Because of differences in cell characteristics, the direct connection of either cells or batteries in parallel can lead to the uneven distribution of charging currents to cells or load currents from cells.

2. Parallel Power Chains

The problems associated with connecting cells or batteries in parallel are avoided by using the power distribution technique illustrated in Figure 3. Several power chains are used and are connected in parallel at the load. The basis of the power per chain is the battery storage capability. For example, if each battery contained 50 A-h cells, if the DOD was 50%, if the voltage was 200 V and the eclipse period was one hour, then the power per chain would be 5 kW.

In addition to eliminating the problems associated with connecting cells or batteries in parallel, the parallel chain technique reduces switching requirements because the power in each chain can be switched independent of the other chains.

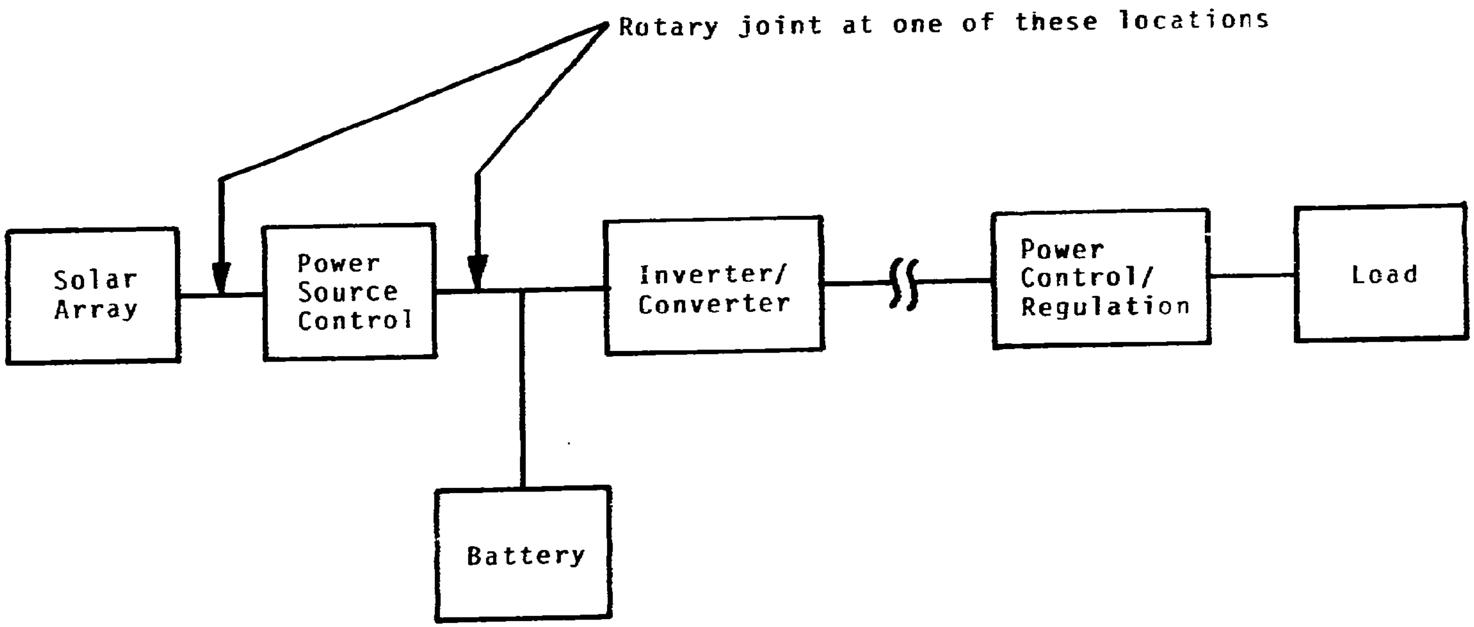

Figure 2. Major components of a typical solar array powered satellite power system.

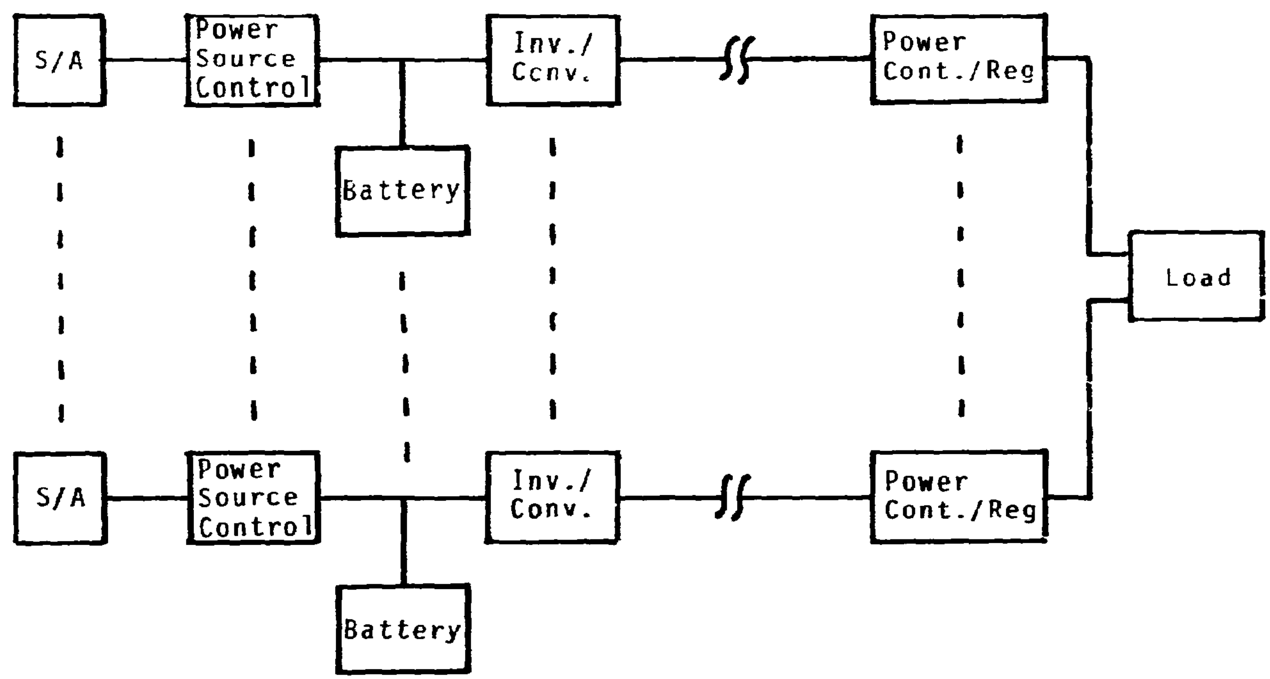

Figure 3. Use of parallel power chains. This is the approach being recommended by TRW,[2] Lockheed,[3] General Dynamics[4] and NASA Marshall.[5]

Finally, with several parallel power chains, one or more can be lost (because of faults, etc.) without losing complete power to the load. As a result, degradation can be relatively graceful.

SECTION IV

TRANSMISSION LINE OPTIMIZATION

1. Specific Weight

Assuming a two wire power distribution system [6] then, neglecting insulation*, the transmission line weight, W_{TL}, is

$$W_{TL} = 2\,d\,A\,L$$

where

d = density of transmission line material

A = cross sectional area of conductor

L = transmission line length.

Because of transmission line losses, the extra source power, ΔP, required (from solar array and battery) is

$$\Delta P = 2I^2R$$
$$= 2I^2\,\frac{\rho L}{A}$$

where ρ is the resistivity in Ω - cm.

If the marginal specific weight of the power generating system is α_{PG} grams/watt, then the extra weight of the power generating system required to make up for transmission line losses is

$$\Delta W_{PG} = 2I^2\,\frac{\rho L}{A}\,\alpha_{PG}\ \text{grams.}$$

To reject the heat generated by the transmission line, increased heat rejection system capacity will be required. If the marginal specific weight of the heat rejection system is α_{HR} grams/watt, then the added heat rejection system weight is

$$\Delta W_{HR} = 2I^2\,\frac{\rho L}{A}\,\alpha_{HR}\ \text{grams.}$$

The total weight penalty, ΔW_{TL}, allotted to the transmission line is, therefore:

$$\Delta W_{TL} = W_{TL} + \Delta W_{PG} + \Delta W_{HR}$$
$$= 2\,dAL + 2I^2\,\frac{\rho L}{A}\,(\alpha_{PG} + \alpha_{HR})$$

---

* Insulation weight is a few percent of conductor weight.

Normalizing ΔW_{TL} with respect to W_{TL} (min)

$$\frac{\Delta W_{TL}}{\Delta W_{TL}(\min)} = \frac{1}{2} \left(\frac{A}{A_{opt}} + \frac{A_{opt}}{A} \right)$$

Figure 4 contains a plot of this relation. Note that over a fairly broad range of A/A_{opt} (± 25%, for example), $\Delta W_{TL}/\Delta W_{TL}(\min)$ remains near unity ($\leq$ ± 4%).

Small area, A, reduces wire weight but increases power generation and heat rejection requirements. Large area, A, reduces power generation and heat rejection but increases wire weight. The optimum occurs when

$$\frac{d \, \Delta W_{TL}}{d \, A} = 0$$

so

$$0 = 2 \, dL - 2I^2 \, \frac{\rho L}{A^2} \, (\alpha_{PG} + \alpha_{HR})$$

and so the optimum conductor area, A_{opt}, is

$$A_{opt} = I \sqrt{\frac{\rho(\alpha_{PG} + \alpha_{HR})}{d}} \; .$$

The minimum total weight penalty is

$$\Delta W_{TL}(\min) = 2 \, d \, A_{opt} \, L + 2I^2 \, \frac{\rho L}{A_{opt}} \, (\alpha_{PG} + \alpha_{HR})$$

$$= 4IL \sqrt{\rho d \, (\alpha_{PG} + \alpha_{HR})}$$

The weight of the optimum transmission line is half the total weight penalty. (The other half is the incremental weight of the power generation and heat rejection systems.)

Thus,

$$W_{TL}(\text{opt}) = 2IL \sqrt{\rho d \, (\alpha_{PG} + \alpha_{HR})}$$

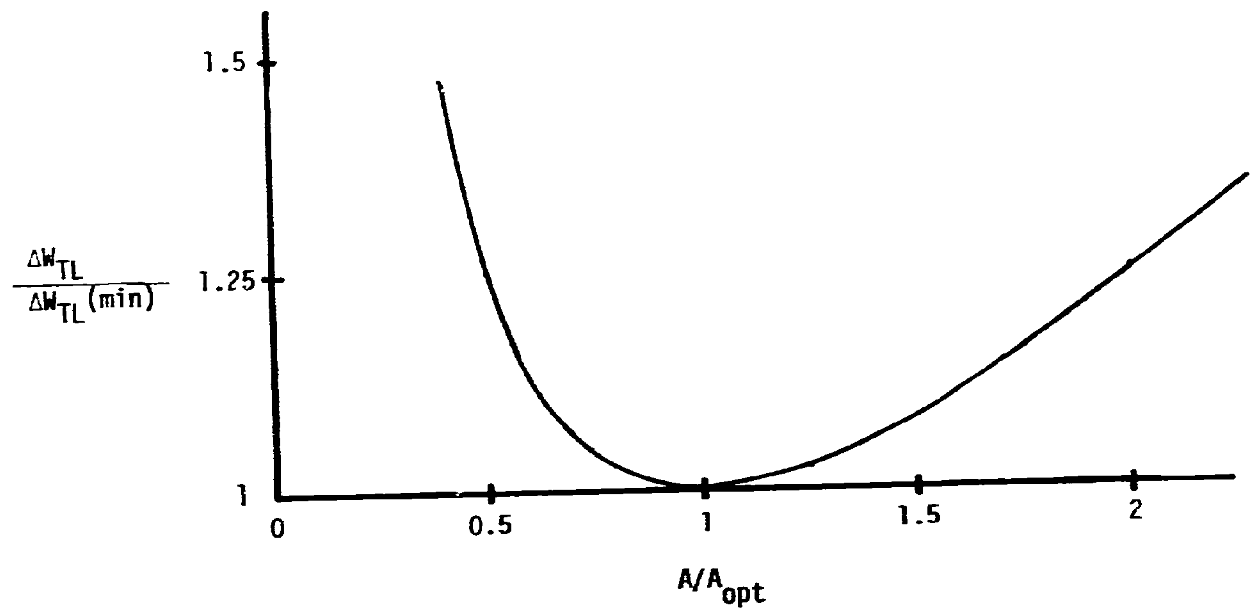

Figure 4. Normalized total penalty, ΔW_{TL}, as a function of normalized cross sectional area of transmission line.

The specific weight is

$$\frac{W_{TL}(opt)}{P} = \frac{2L}{V}\sqrt{\rho d\ (\alpha_{PG} + \alpha_{HR})} \qquad \text{g/W or kg/kW}$$

$$= \frac{4.4L}{V}\sqrt{\rho d(\alpha_{PG} + \alpha_{HR})} \qquad \text{lb/kW.}$$

where units of ρ is Ω - cm

d is g/cm^3

L is cm

α_{PG} & α_{HR} are g/W or kg/kW

and V is transmission line voltage.

The only practical transmission line materials to consider at present are copper and aluminum for which the resistivity and density are as given in Table 3.

Table 3.

RESISTIVITY AND DENSITY OF COPPER AND ALUMINUM

	$\rho(\Omega$-cm) @ 20°C	d(g/cm^3)	ρd (20°C)
copper	1.72×10^{-6}	8.96	15.5×10^{-6}
aluminum	2.82×10^{-6}	2.70	7.62×10^{-6}

Assuming* a value of $\alpha_{PG} + \alpha_{HR}$ of 30 g/W then

for copper $\quad \frac{W_{TL}\ (opt)}{PL} = \frac{.043}{V}$ kg/kW $= \frac{.095}{V}$ lb/kW

for aluminum $\quad \frac{W_{TL}(opt)}{PL} = \frac{.030}{V}$ kg/kW $= \frac{.067}{V}$ lb/kW

*This is the same assumption used by NASA[6] and Boeing.[7]

Figure 5 contains plots of specific weight per unit length as functions of voltage for copper and aluminum. The most significant feature of Figure 5 is the rapid increase in specific weight at voltages below 100 V. As voltage increases, conductor weight continues to decrease, however, the rate of decrease diminishes rapidly above the 200-300 volt range.

Calculations of conductor weights for a 50 kW, 100 meter transmission line are given in Table 4.

2. Aluminum vs Copper

From Figure 5 and Table 4 it is noted that the weight saving from using aluminum rather than copper could be about 30%. Silver plated, copper clad aluminum supplied by La Barge Inc., 2851 Alton Ave., Irvine, Cal. 92714, has been used for satellite applications. For example, this material was used for braid on Viking[8] and has been used by RCA on several synchronous satellites since 1975.[9] The weight saving was not the full 30% indicated by Figure 5 because the copper cladding occupied 15% of the cross sectional area of the conductor. Connections were reportedly made to the conductors by soft soldering or crimping. Care was taken to form conductors so that excessive stress did not occur at joints during thermal cycling. No problems in the use of the silver plated, copper clad aluminum were reported and so it appears that this material is suitable for use on high power satellites.

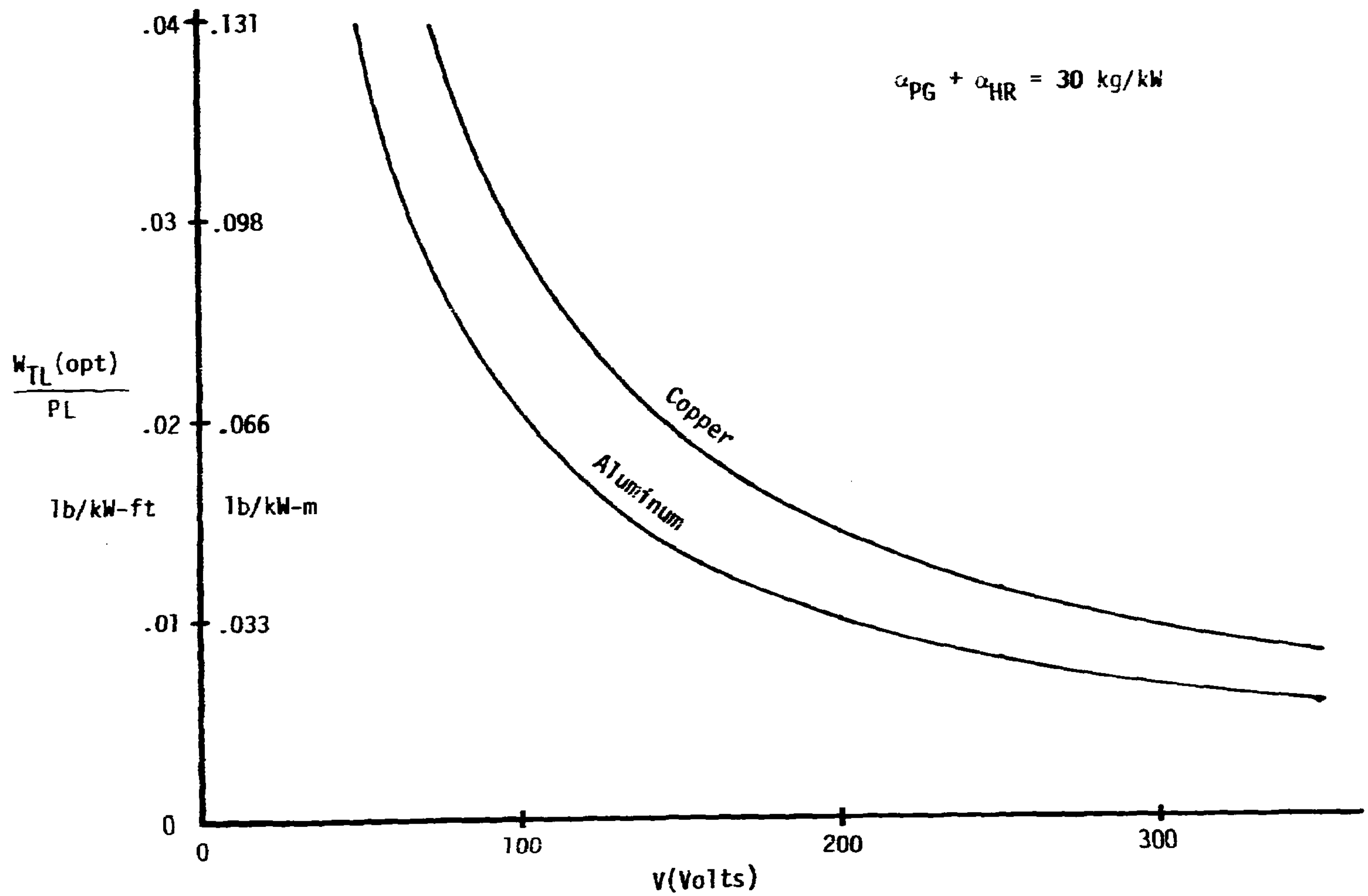

Figure 5. Specific weight per unit length of transmission line as a function of voltage.

Table 4

CONDUCTOR WEIGHTS FOR A 50 kW, 100 M
TRANSMISSION LINE

Voltage	Aluminum	[illegible]
28V*	1196 lb	1696 lb
120V**	279	396
220V***	152	216
270V****	124	176
4[illegible]0V***	76	108

* Voltage used to date for all satellites.

** Proposed in initial studies for 25 kW space platform.

*** Commercial dc voltages.

**** Developing Navy aircraft voltage and level proposed by TRW.

SECTION V

VOLTAGE SELECTION

In connection with Figure 5 the decrease in transmission line weight with increasing voltage was shown and it was noted that the rate of decrease diminishes rapidly above the 200-300 volt range. In this section the following three additional factors are discussed. Each suggests a maximum voltage less than 300 V.

1. Arcing and plasma interactions in solar array
2. Possibility of breakdown of Paschen minimum
3. Component technology status.

It must also be kept in mind that if dc distribution at the battery voltage is selected, the distribution voltage will vary over a broad range (perhaps as much as ± 20%) depending on the type of battery used and the state of charge of the battery.

1. Arcing and Plasma Interactions in Solar Array

Stevens[10] at NASA Lewis Research Center (LERC) has obtained laboratory arcing data on small segments (100 cm^2-13,000 cm^2) of solar arrays. In addition, LERC has a significant ongoing effort to determine the effects of arcing of array geometry, materials, etc. Table 5 contains some of the results to date of the LERC study.

Table 5.

LERC SOLAR ARRAY ARCING DATA

Particle Density/cm^3	Equivalent Altitude	Voltage of Arcing Onset
10^2	Synchronous	∿ 1 kV
10^4	900 kM	500-700 V
10^6	LEO	∿ 300 V (extrapolation)

Solar array arcing may disrupt the power system with voltage transients but probably will not cause physical damage to the array.

Under normal operating conditions the solar array provides power for distribution and battery charging. The array voltage is the same as the battery voltage. Immediately after eclipse, when the cold solar array is exposed to sunlight, the voltage (for a given current) is 2 to 2.5 x the warm array voltage. For a battery voltage of about 250 V, the cold array

voltage could be ∿ 2 to 2.5 x 250 V or 500 to 625 V. Arcing would not occur at GEO, might occur at mid-altitude orbits and would certainly occur at LEO.

To prevent system disturbance due to arcing, suggestions are:

1. Connect the solar array to power system after it warms up (a few minutes after exposure to sunlight),

or 2. Clamp the solar array voltage to the battery voltage at all times and make provisions to accommodate the current pulse from the cold array.

Figure 6 contains the results of calculations of solar array power losses as a function of voltage resulting from plasma currents in a 300 km orbit. As is indicated in Figure 7, the 300 km orbit is where the electron density is highest and is therefore where plasma current losses are expected to be highest. At voltage levels up to and even exceeding 300 V, plasma current losses are small (less than one percent) and are relatively insensitive to voltage level. As a result, plasma current losses are not a major factor in voltage selection.

2. Paschen Minimum Considerations

With proper design and careful selection of materials, voltage breakdown of gases should not be a problem. Still, there is the possibility that the appropriate combination of gas pressure and distance will exist someplace and that voltages above the Paschen minimum will cause breakdown to occur. For common molecular gases (see Figure 8) the Paschen minimum is in the 300 to 500 volt range. This suggests, therefore, that the distribution voltage should not exceed 300 V if the possibility of breakdown at the Paschen minimum is to be avoided.

3. Component Technology Status

Mr. William Billerbeck of Comsat Corp. points out[14] that, at present, Comsat has systems with voltages up to 42V and that voltages in the 50 V to 60 V range are being considered. The primary limitation is devices. Very few space qualified devices over 80 V are available.

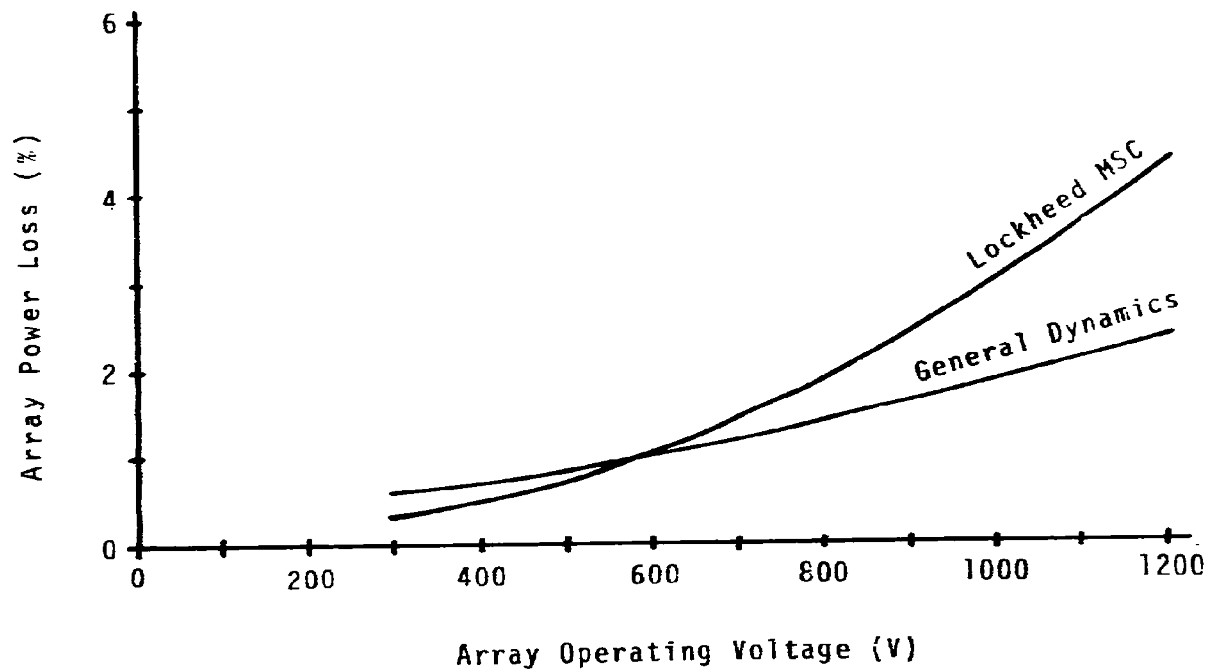

Figure 6. Calculated Plasma Current Losses to a Solar Array in a 300 km Orbit.(11)

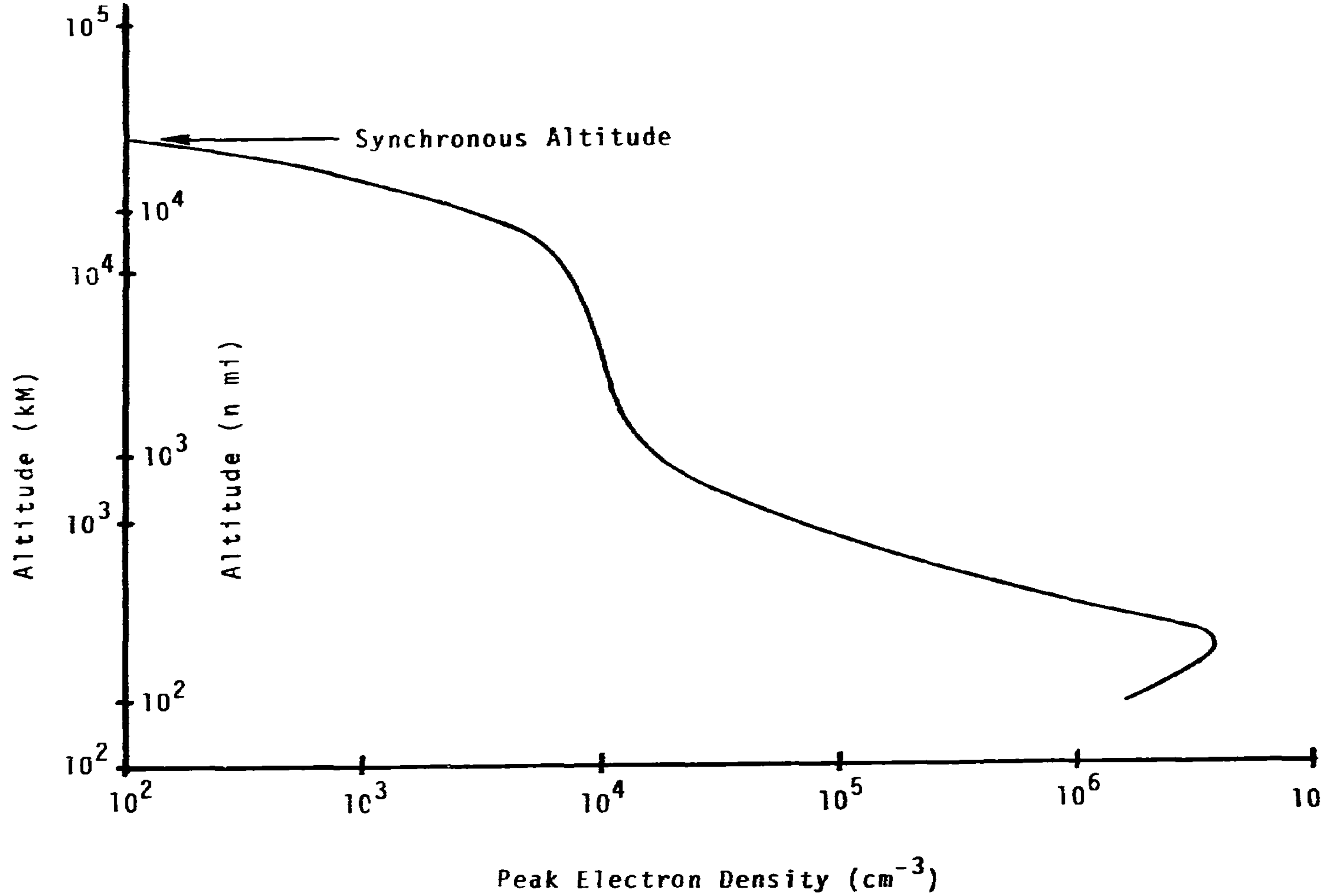

Figure 7. Electron density as a function of altitude.[12]

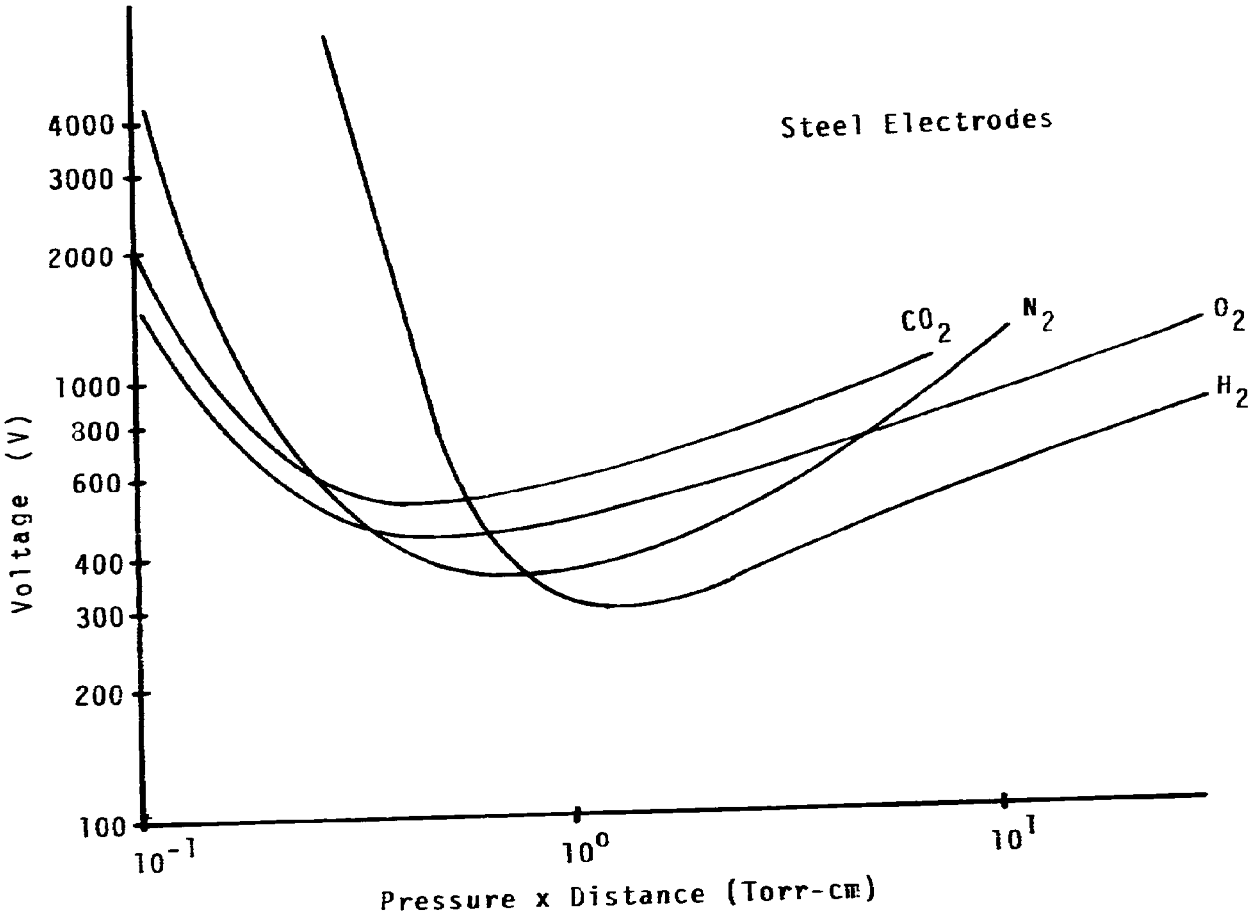

Figure 8. Paschen characteristics for some molecular gases.[13]

Assuming that a wide variety of devices could be space qualified at higher voltage levels, then the device electrical ratings become important. Many devices have electrical ratings in the 500 V to 600 V range. For example, Dr. Robert Parker at Hughes points out that[15] typical capacitors are rated at 600 V and with derating can be used at 400 V. The Westinghouse D60T transistor is rated at 500 V and is typically used at 80% of that value, or 400 V. Many other semiconductor devices are rated at 500 V and used at levels up to 400 V.

In addition to device derating, provision must be made for voltage transients. Mr. Charles Sollo of TRW assumes[2] transients to 50% above the distribution voltage. Mr. William Dunbar of Boeing notes[16] that the AWACS experience is for transients from 30 to 65% above operating voltage depending on location on the vehicle.

Assuming transients no greater than 50% above the operating voltage and peak transients no greater than 400 V (the derated component limit), then the component operating voltage should be no greater than about 270 V.

It is also noted that 270 V is low enough to prevent arcing in the solar array and is also below the Paschen minimum for common gases.

As a result of these considerations (solar array arcing, Paschen minimum and component limit) 270 V is recommended as the upper limit on operating voltage.

SECTION VI

DC vs AC POWER DISTRIBUTION

The primary consideration in choosing DC or AC power distribution is the weight of the resulting power system. In addition to component weight, efficiency is extremely important because power losses result in added weight of the solar array, batteries, and heat rejection system. As was noted in connection with the specific weight calculations for Figure 5, the additional weight associated with power losses is about 30 kg/kW. For a 50 kW system, a one percent efficiency loss converts directly to 15 kg or 33 lb of additional weight.

Figure 2 showed the major components of a typical solar powered satellite system. With either an AC or a DC system, a power source control unit located between the solar array and the battery will be required. Those loads requiring power control/regulation in a DC system will also require power control/regulation in an AC system. The inverter/converter will be required for an AC system but may not be required for a DC system if power is distributed at the battery voltage level. The typical efficiency of an inverter/converter is 97%. In a 50 kW system, the 3% power loss in the inverter/converter results in the requirement for 45 kg or 99 lb of additional weight in the power generation and heat rejection systems. This is in addition to the weight of the inverter/converter which is estimated to be[3] 212 kg or 467 lb. Thus, the total weight penalty for the inverter/converter in a 50 kW system is about 257 kg or 566 lb.

The design of the lines for transmitting AC power on a satellite especially if the frequency is high, requires very careful consideration. For example, if the coaxial transmission line described in reference 4 is used for transmitting 20 kHz power, transmission line weight may be very high. This is partially because a large conductor surface area is required because of the very small skin depth and this in turn may cause the transmission line cross sectional area to be large. Also, the weight may be high because the insulating material separating the inner conductor from the outer conductor would have to be a good thermal conductor to permit heat removal from the center conductor. This implies that the insulator would have reasonably high mass density.

As a result of this very simplistic consideration of DC vs AC distribution, it appears that there is a significant weight advantage in using a DC system.

Objectives frequently raised to DC power distribution in the 200 to 300 V range are the following:

1. DC switchgear is not available for satellite use at voltages above 28 V.

2. Electrostatic particle collection, electrolysis, and/or other DC corrosion effects may occur.

3. The reliability of rotary joings at voltages above 28 V is unknown.

Concerning the switchgear question, Westinghouse, under contract to NASA/LERC, is conducting a substantial high voltage DC switchgear development program[17]. That contract has already resulted in the development of switchgear for operation at voltages up to 1000 V DC under several different conditions on satellite high power systems. As the D60T and mosfet technology continue to advance, additional DC switchgear developments are certain to occur. Although none of the new Westinghouse switchgear is space qualified at this time, it does appear as though the switchgear problem, has, essentially, been solved.

The questions of electrostatic particle collection and DC corrosion effects were discussed with several individuals including Dr. John Park who is a chemist involved with satellite systems at NASA Goddard Space Flight Center. The consensus of opinion is that at voltages in the 200 to 300 V range, the voltage level is low enough so that with a reasonable amount of care in the use of insulation, particle collection and corrosion effects will be insignificant.

Concerning the question of the reliability of rotary joints, it was pointed out by NASA Marshall personnel[5] that at 28 V the only case of a problem with a rotary joint was when it was improperly installed. There is no reason to expect problems at voltages of a few hundred volts as long as positive and negative electrodes are properly isolated. An advantage in using slip-ring type rotary joints at voltages well above 28 V is that the voltage drop across the sliding contacts becomes much less significant. As a result, efficiency is increased and brush design becomes less critical.

As a result of the considerations in this section, it appears that an AC system would be heavier than a DC system and that objections frequently raised to DC distribution in the 200-300 V range have either been overcome or are not valid. Thus, DC distribution is recommended.

SECTION VII

SUGGESTED DISTRIBUTION SYSTEM

The considerations presented in previous sections lead to the suggestion of the dc power distribution system shown in Figure 9. This is, in fact, basically the system recommended by TRW.[2] Power from the solar array is controlled by switches for battery charging and distribution to the load. It is recommended that voltages no larger than 270 V be used for distribution. This voltage is an order of magnitude higher than the 28 V universally used in satellites at present. Still, this voltage is below the array arcing voltage, below the Paschen minimum for common gases and is low enough to permit the use of 500 V components derated to 400 V with transients 50% above the distribution voltage.

The efficiency of the distribution system in Figure 9 is greater than 95%.

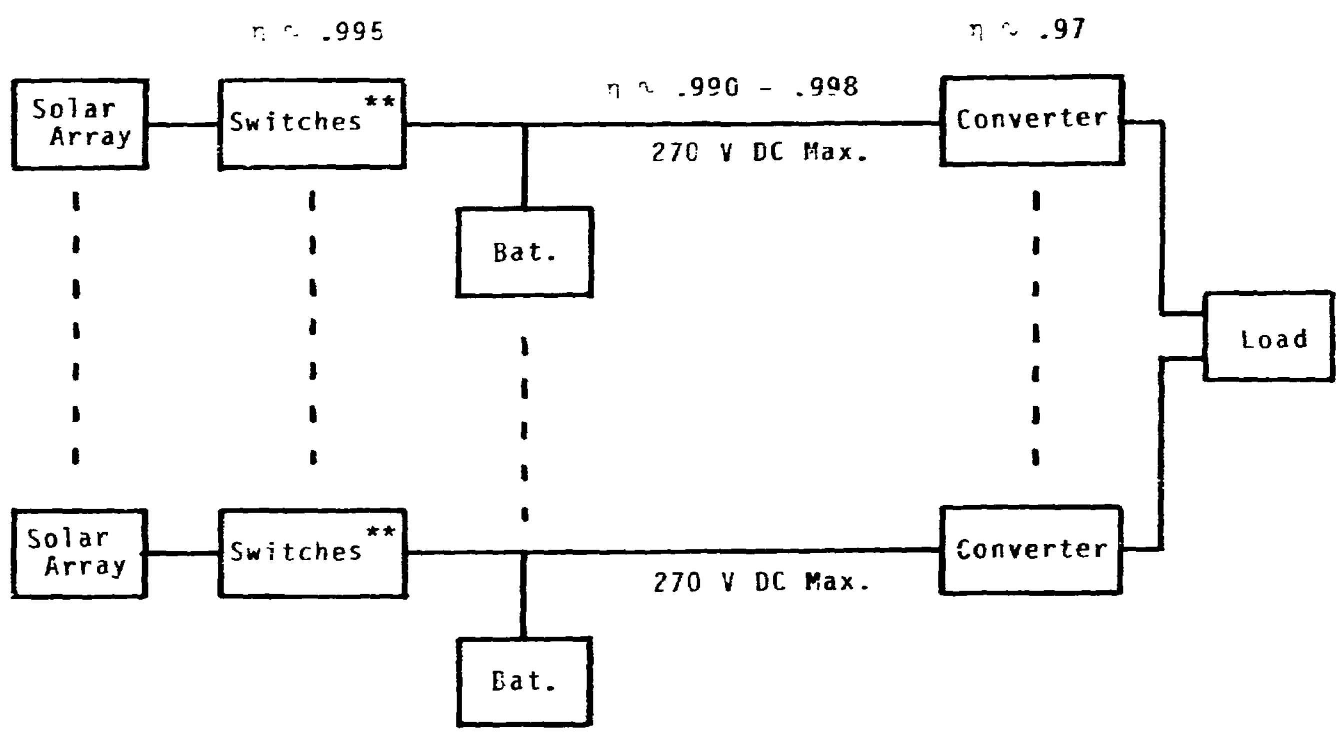

Figure 9. Suggested distribution system.

** Battery charging is controlled by switching segments of solar array.

SECTION VIII

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Power systems on future satellites operating in the 10 kW to 50 kW range at altitudes greater than LEO will be severely weight limited. To reduce conductor weight, voltages substantially higher than the 28 V in common use at present are necessary. Considerations of solar array arcing, Paschen breakdown and component ratings lead to a maximum voltage of 270 V. The use of aluminum rather than copper conductors could lead to a conductor weight saving as large as 30%.

DC distribution is recommended because of its weight advantage over ac distribution. Objections frequently raised to dc distribution in the 200-300 V range (lack of switchgear, electrostatic and chemical effects, and rotary joint problems) appear to have been overcome or are not valid.

The distribution system recommended is similar to that recommended by TRW. Parallel power chains, each sized to battery characteristics, are recommended. This eliminates problems associated with connecting batteries or battery cells in parallel. Switching requirements are reduced and power system degradation is relatively graceful because one or more power chains can be lost without losing all power to the load.

In each power chain, switches are used to control power flow from the solar array to the battery and to the distribution system. Power distribution is at the battery voltage level. Voltage conversion and regulation are accomplished as required at the load. The overall power system efficiency is expected to be greater than 95%.

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