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SP-100 PROGRAM

Technical Information Report

SP-100 Power System The Present Status and Assessment of Power Conditioning and Control Technologies

Khosrow A. Bahrami

November 1983

National Aeronautics and
Space Administration

JPL

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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SP-100 PROGRAM

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OF

POWER CONDITIONING AND CONTROL

TECHNOLOGIES

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September 30, 1983

Table of Contents

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1.0 OBJECTIVE

The objective of this task was to establish and evaluate what PCC technologies need to be developed and what impact the availability and development of PCC technologies will have on Ground Demonstration Development Decision.

2.0 APPROACH

The approach to this task was to begin to understand the mission requirements and the resulting system requirements, and the requirements that SP-100 imposes on the PCC subsystem. This was followed by the assessment of PCC technologies, current state-of-the-art and future developments, followed by the identification of needed technology elements.

3.0 CONTROL SYSTEM CONCEPTUAL DIAGRAMS

At this point in time not a great deal is known about the requirements of the user loads. It is not known whether the user will require ac or dc power (or both) and at what voltage or frequency. Furthermore, it is not known whether the user or SP-100 will be responsible for regulation and/or protection.

On the other hand, the generation source may be static or dynamic. The static systems which include in-core thermionics, out-of-core thermionics, and thermoelectrics, generate dc power. Whereas the dynamic systems, which include Stirling cycle, Brayton cycle, and Rankine cycle, generate ac power. In the dc systems the voltage at which power is generated is determined by the specific technology and depends on how elements are connected in series and in parallel. The insulation aspects of in-core thermionic limits the maximum dc voltage which can be generated to several tens of volts. Whereas in thermoelectric generation voltages of a few hundred volts are feasible. In the case of dynamic systems, the frequency of the generated ac voltage will depend on the speed of rotation and will vary accordingly.

Since the generation may be either static or dynamic and loads may require either ac or dc power, then four generic system concepts can be developed. These are discussed here:

3.1 DC Source, AC Loads

The block diagram of this system for a thermoelectric system is shown in Figure 3.1. The dc power generated by thermopiles is inverted to ac power through an inverter system. The inverter system regulates and conditions the power for the loads. Included is also a charge/discharge controller for the energy storage unit. The power controller is responsible for the control of power flow from the reactor to the loads, including the control of reactor power, the shorting of thermopile groups, the overall control of the inverter, and energy storage charging/discharging.

For this concept regulation of load voltage and frequency as well as the control of power flow is feasible.

3.2 DC Source, DC Loads

Figure 3.2 depicts the concept of dc source, dc loads. This concept is similar to the dc source, ac load concept already discussed except the inverter system is not used.

In this concept the voltage at the loads is mostly unregulated. The power flow balance can be achieved by shorting selected thermopile groups.

3.3 AC Source, AC Loads.

This concept is shown in Figure 3.3. AC power arises from dynamic conversion systems. The frequency of the ac power depends on, and varies with, the speed of rotation (as in a Brayton engine) or reciprocation (as in the case of the reciprocating Stirling engine). In the concept shown in Figure 3.3, ac power generated by the alternator is directly fed to loads. This implies that whatever regulation (both in frequency and voltage) that is required by loads must be done by the conversion system. Electric utilities routinely perform this regulation on their system. However, this may not be possible, or at least easy, for the SP-100 system. Utilities have a diversified load which, as an aggregate, changes slowly, whereas SP-100 load may change abruptly (e.g., in the case of radar applications). Also, utilities have very good control of their generation (by means of controlling the peaking units). In the case of SP-100, good control of generation implies good control of heat input to the engine. Otherwise, shaft speed may change beyond rates required for regulation. Voltage control is achieved by alternator field control if alternator is so equipped.

If the voltage and frequency regulation requirements of the loads are such that they cannot be satisfied by regulating the engine/alternator system, then, an ac-dc-ac conversion unit will be required. This unit will convert the ac power generated to dc, then invert the dc into regulated ac power suitable for loads. If such a unit is used, then, the control of the engine/alternator becomes, to a great extent, independent of the regulation requirements of load voltage and frequency. In any case, at all times, the balance between power generated, losses, and power going to the loads must be maintained. Any excess power must be dumped either before conversion or, if converted, then must be dissipated in dummy loads.

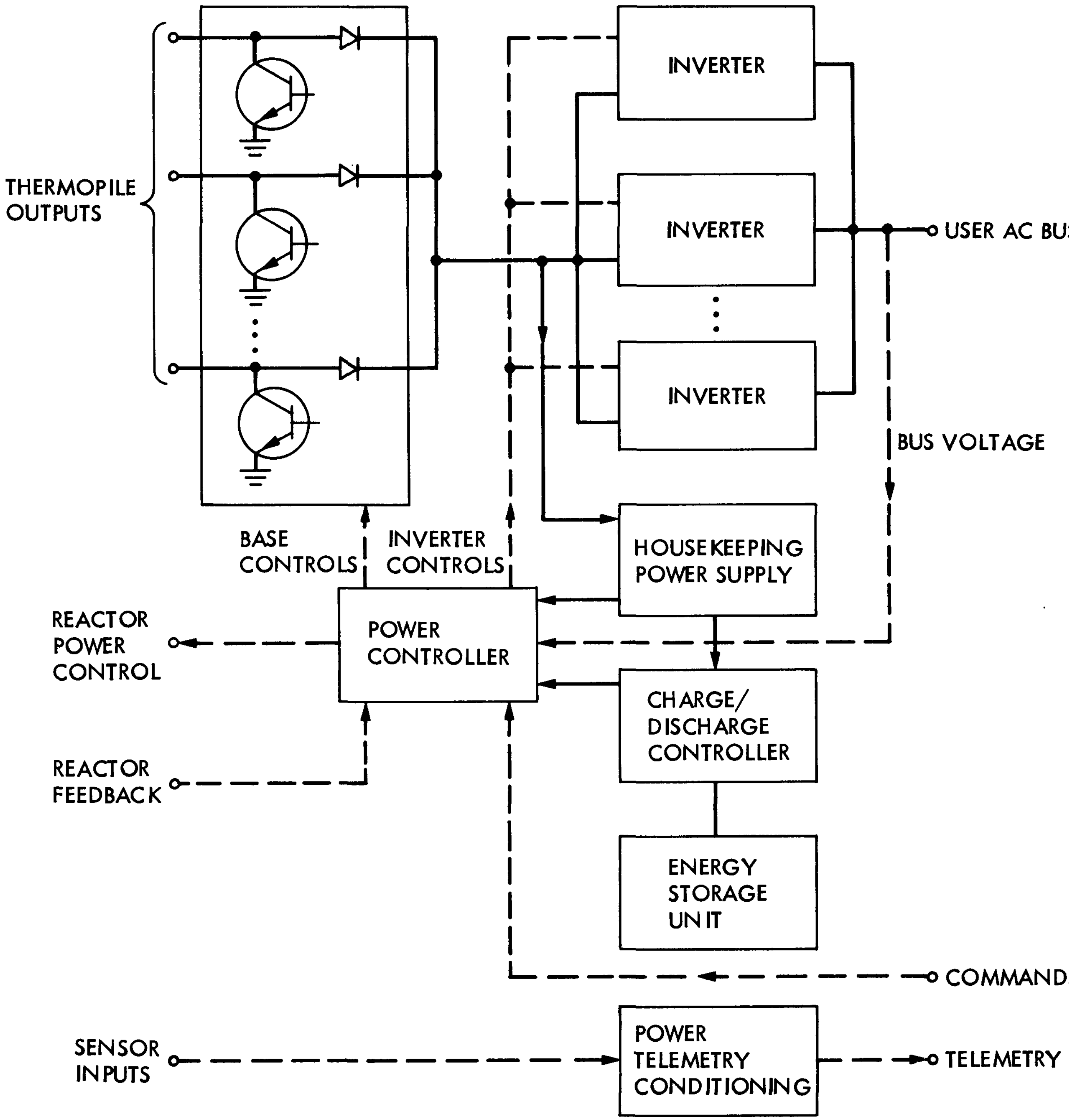


Figure 3.1. DC Source, AC Loads (Thermoelectric System)

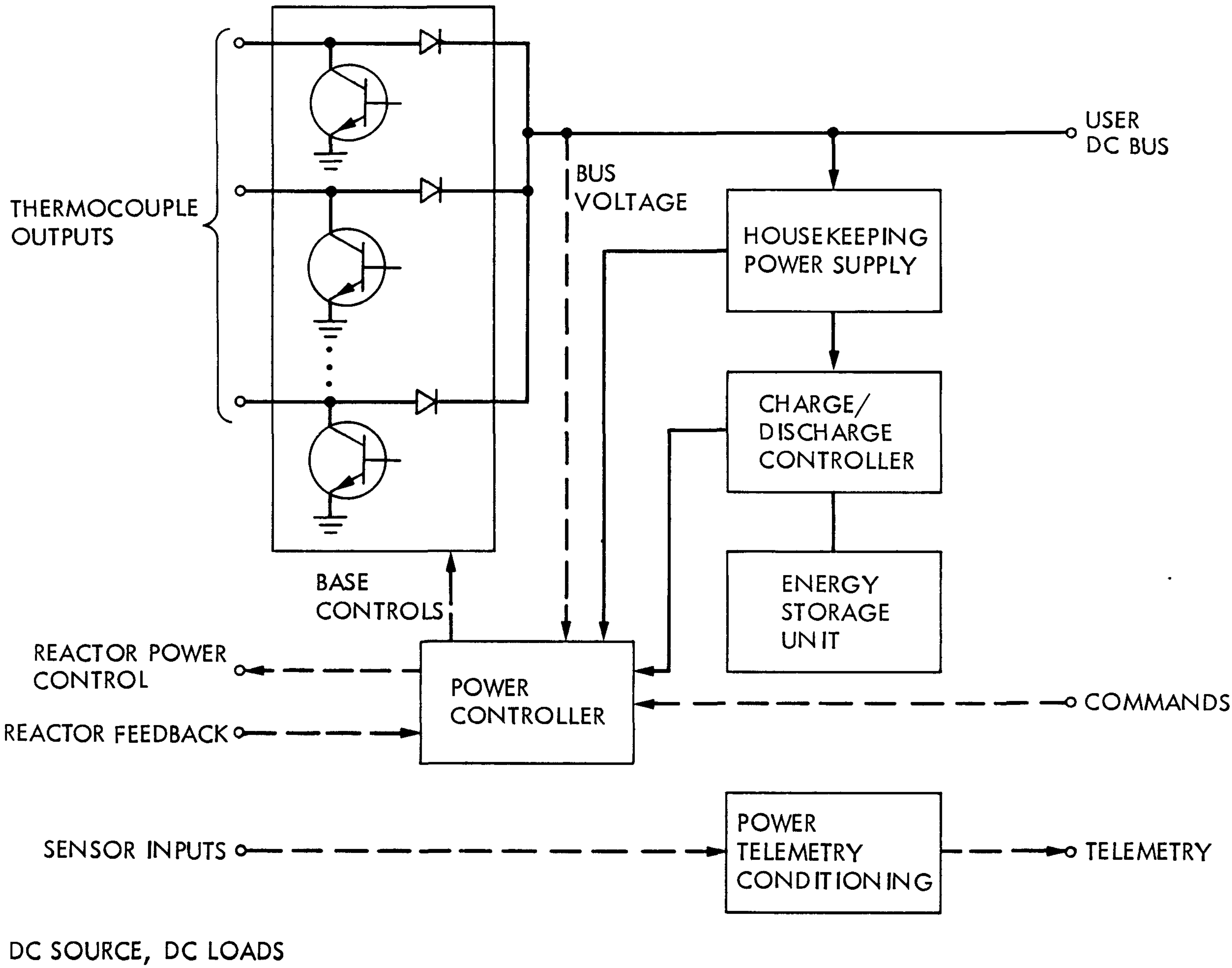


Figure 3.2. DC Source, DC Loads (Thermoelectric System)

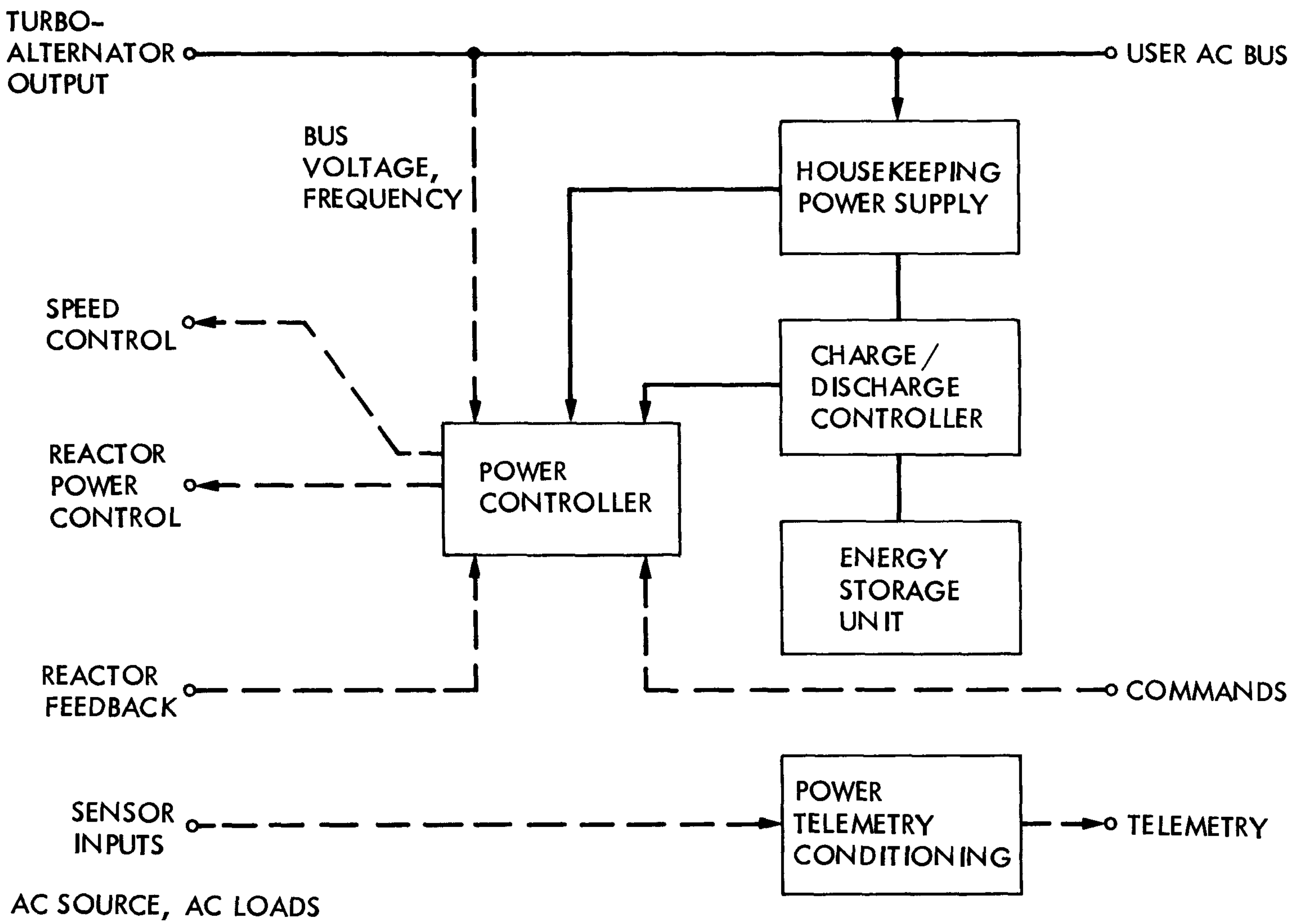


Figure 3.3. AC Source, AC Loads

3.4 AC Source, DC Loads.

Figure 3.4 depicts this concept. In this case ac power is rectified to dc suitable for user loads.

4.0 CONTROL AND POWER TECHNOLOGY/COMPONENTS

The following components or technologies have been identified to belong to, or relate to, the Power Conditioning and Control Subsystem.

1. Auxiliary Power.
2. Control Components.
    a. Semiconductor Logic Devices.
    b. Sensors.
    c. Stepper Motors.
3. Energy Storage.
4. General.
    a. Electrical Insulation.
5. Power Components.
    a. Blocking Diodes.
    b. Connectors.
    c. Power Switches.
    d. Relays.
    e. Transformers.

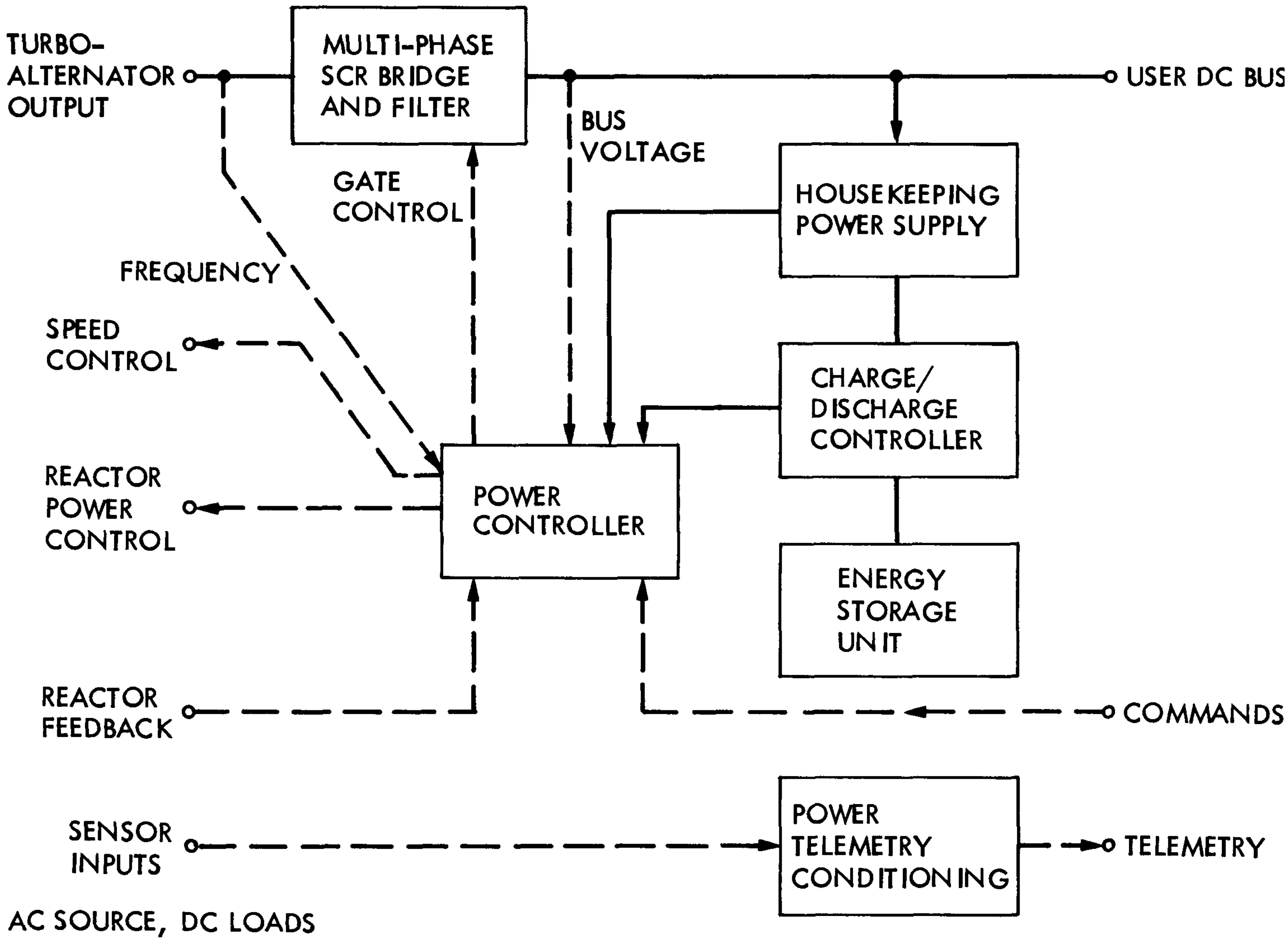


Figure 3.4. AC Source, DC Loads

5.0 ENVIRONMENT: GAMMA, NEUTRON, TEMPERATURE.

The environment within or about SP-100 is quite hostile as it relates to PCC components. Figure 5.1 shows a sketch of the SP-100 system. The temperature range of values expected close to the shield is (1100 - 1500°K), and the temperature range of values at 5 m is (800 - 900°K).

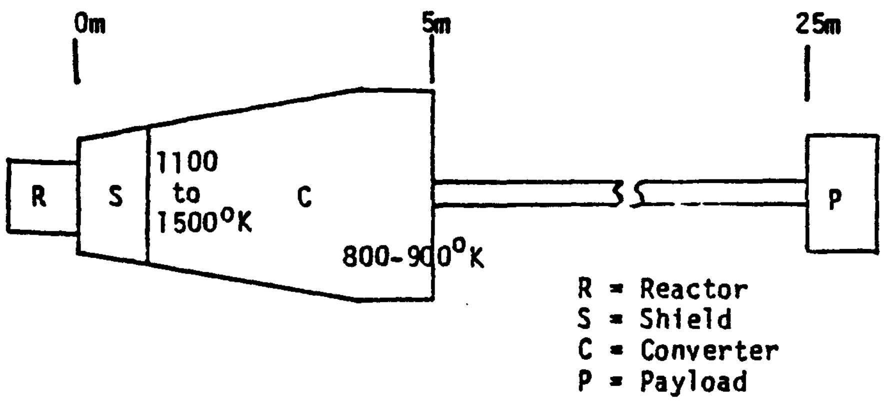
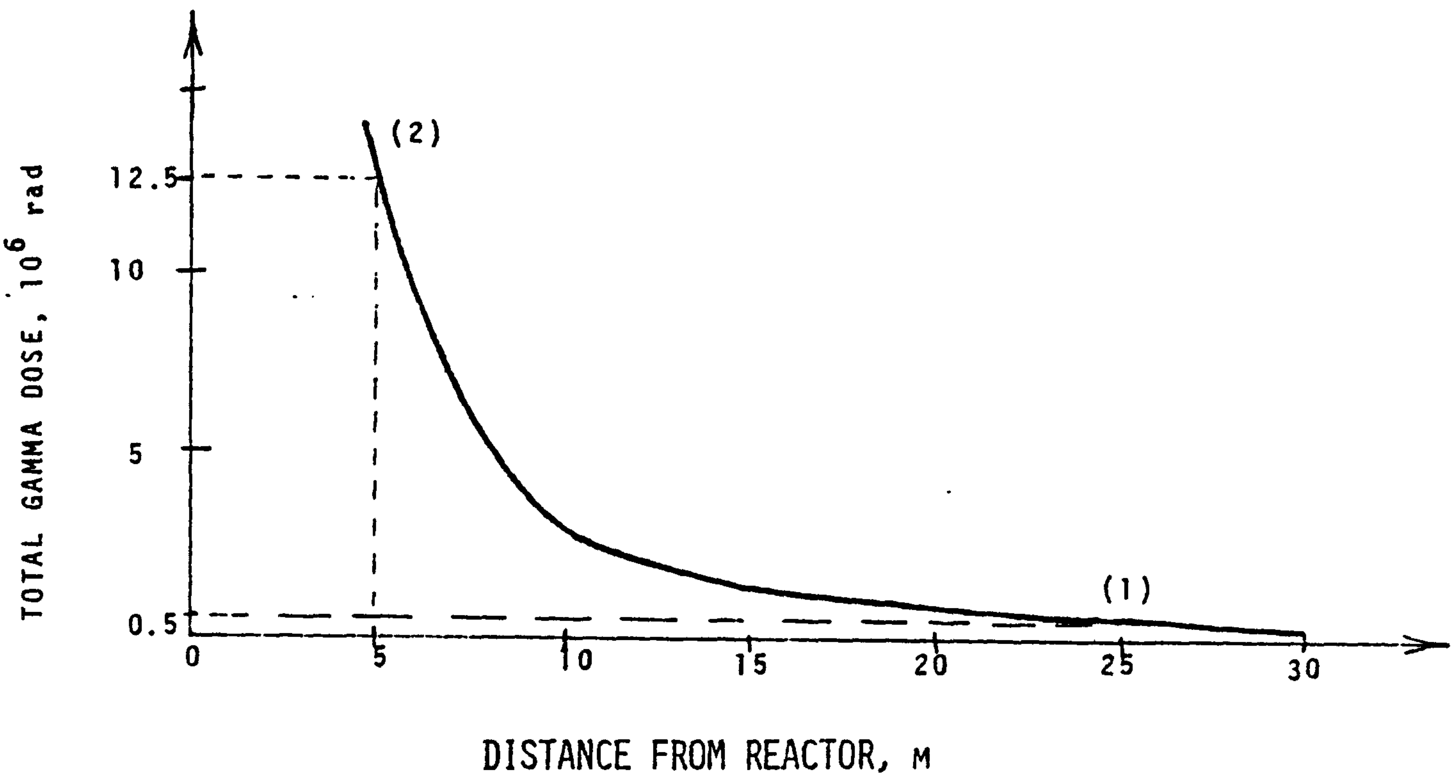


Figure 5.1. Sketch of SP-100 System

The SP-100 radiation environment of concern consists of the overall gamma dose radiation and neutron flux. The requirements set forth by the mission state that the total seven year gamma dose at a location 25 m away from the reactor (i.e, at P in Figure 5.1) must not exceed 0.5×10^6 rad, and the neutron flux at the same location must not exceed a rate of 1×10^{13} N/cm^2.

If one assumes that the radiation levels are inversely proportional to the distance from the reactor, (which is true for distances not too close to the source), then one can plot the total seven year gamma dose and the neutron flux as functions of distance from the reactor. These plots are shown in Figures 5.2 and 5.3.

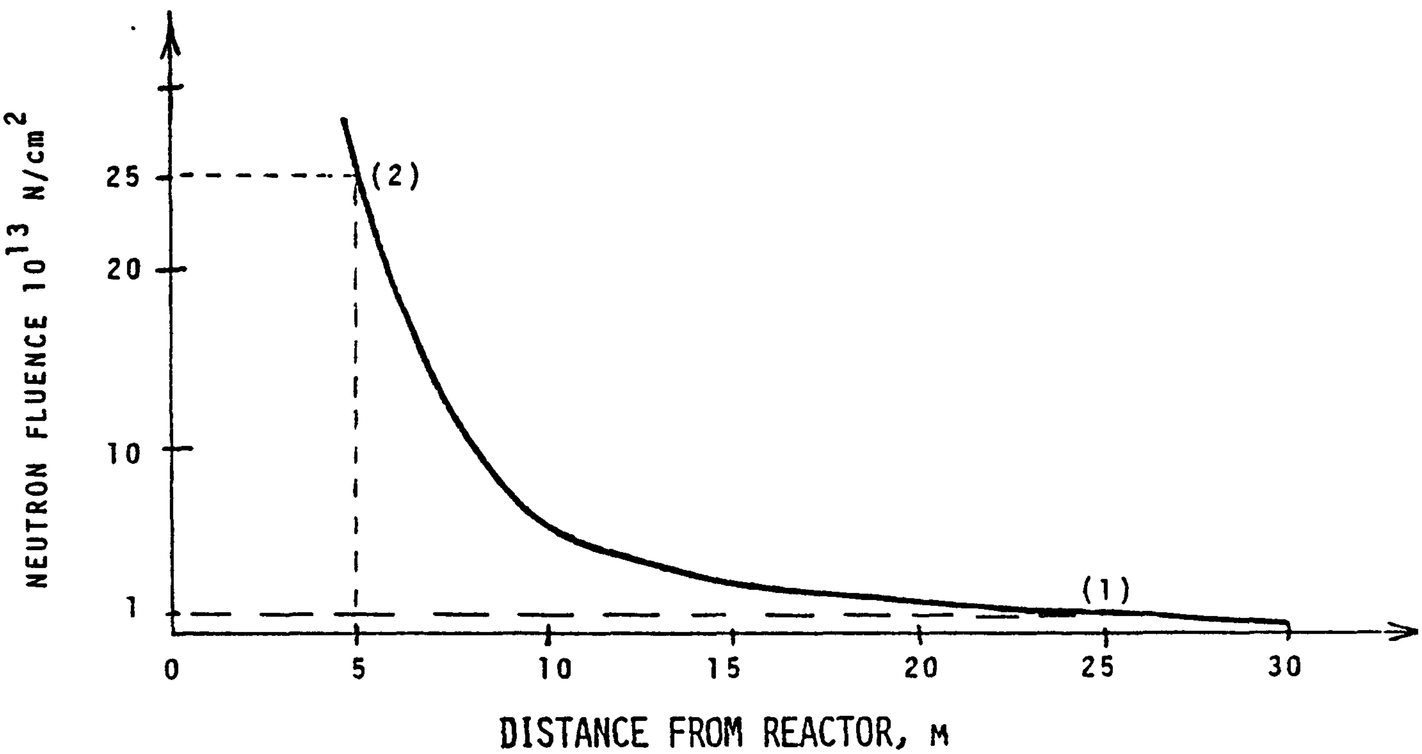
As it can be seen, the total gamma dose at the distance of 5 m from the source is 12.5×10^6 rad, and the neutron flux at 5 m is 25×10^{13} N/cm^2. The distance of 5 m is relevant since that is the edge of the radiator as it is currently envisioned, and it is the likely location for the installation of electronic packages.



(1) SP-100 REQUIREMENT AT 25m:0.5 x 10^6 rad

(2) VALUE AT 5m:12.5 x 10^6 rad

Figure 5.2. Gamma Dose Dependence on Distance



(1) SP-100 REQUIREMENT AT 25m: 1×10^{13} N/cm^2

(2) VALUE AT 5m: 25×10^{13} N/cm^2

Figure 5.3. Neutron Flux Dependence on Distance

6.0 SEMICONDUCTOR TECHNOLOGY AND THERMIONIC INTEGRATED TECHNOLOGY.

In this section the availability of semiconductor devices for operation in the SP-100 environment is investigated. The discussion which follows is based on a report entitled "Semiconductor Radiation Review" by M. K. Gauthier and D. K. Nichols, SP-100 Technical Information Report, D-1035, September, 1983 (See Ref. 1).

6.1 Trends in Semiconductor Technology.

In the past, radiation tests showed that bipolar digital ICs were hard [>1 Mrad(Si)], standard process CMOS were soft [<10 krad(Si)], and radiation hardened CMOS was hard [>100 krad(Si)]. But, recently, that has changed. With the introduction of advanced low power Schottky (ALS) and similar bipolar digital devices, circuit design and processing changes have decreased the device's hardness by factors up to 100 times. It can no longer be taken for granted that bipolar digital devices are hard. Even the older design device families are being "die-shrunk" and redesigned, with new processes being incorporated which make them more susceptible to radiation damage. Some older device families are being eliminated by manufacturers.

Future procurements of digital devices will require the same screening and testing procedures as used for linear devices and transistors in the past. This will mean wafer and lot testing and approval before acceptance for spacecraft applications.

Linear devices in general are usually softer than 100 krad(Si). A limited number are harder than 100 krad(Si) with a few being hard to at least 1 Mrad(Si). With the SP-100 environment of 250 krad(Si) a small selection of all types of linear devices are available. This includes operational amplifiers, comparators, analog to digital and digital to analog converters, voltage to frequency converters, phase locked loops, voltage regulators, switches, multiplexers, and others.

Transistor sensitivity to the SP-100 environment depends on the type (P or N), FET or bipolar, geometry, manufacturer, process technology, lot and wafer, as well as the application. Thyristors, SCRs, and other triggered silicon devices are highly sensitive to all types of radiation and should not be used unless special care is taken in the design of the operating circuit and verification of the application.

All semiconductor devices including diodes used on the project will require in-depth research, testings, data analysis, and applications analysis before it may be approved for use in each application. In addition, all semiconductor device procurements should follow the guidelines developed for total dose and neutron environments.

Passive devices, i.e., resistors, capacitors, etc., are not affected by total dose irradiation below 1 Mrad(Si) and therefore they are of no concern to this study.

6.2 Radiation Analysis of Semiconductor Technologies.

A comparison of the various semiconductor fabrication technologies to their radiation hardness in various radiation environments are given in Table 6.1 and in Figures 6.1 and 6.2. These technologies vary from very soft to very hard. They also vary from environment to environment.

A. Bi-MOS. A relatively new technology which is radiation-hard is Bi-MOS. This is a combination of I^2L and CMOS on the same chip for optimization of the analog and digital circuits. It has all the advantages of I^2L and radiation-hardened CMOS (when made with the radiation-hardened CMOS process). Honeywell is very active in this technology and plans to have its process available for testing during 1983. Several other manufacturers, including Analog Devices, Inc., are planning to use this technology in the near future.

B. Bipolar. The current bipolar technology is one of the overall most radiation-hard technologies for semiconductor devices. A number of linear and digital devices are currently available in bipolar technology.

Several manufacturers are currently fabricating high temperature devices that will operate at 200°C. Further development may increase the maximum operating temperature to 300°C.

C. CMOS. Standard CMOS is a popular technology but it is radiation-soft. Many digital devices have been designed in CMOS.

D. CMOS-Rad Hard. Recently developed radiation-hardened CMOS processes are as hard as the hardest bipolar processes. Several companies now use the radiation-hardened process for digital devices.

E. GaAs. This may be a good technology for future devices. GaAs is very hard to ionizing radiation environments, but may suffer from bulk damage problems. Therefore, they will not have the surface leakage problems of bipolar devices but may have a sensitivity to electron, proton, neutron, and heavy ion damage which is similar to bipolar.

GaAs devices have the same operating temperature range as silicon devices. The current temperature maximum is 200°C but this may be pushed to 300°C.

TECHNOLOGY	SPEED	TOTAL DOSE Rad (Si)	DOSE RATE Rad (Si)/sec	NEUTRON N/cm^2	SINGLE EVENT UPSET (SEU)	ADVANTAGES	DISADVANTAGES
BI-MOS (I^2I/CMOS)	MED	10^6	10^9	10^{13} - 10^{14}	–	ANALOG AND DIGITAL OPTIMIZED ON SAME CHIP	NEW DEVELOPMENT
BIPOLAR	HIGH	10^4 - 10^6	10^{10}	10^{14} - 10^{15}	FLIPS	HIGH SPEED ANALOG STABLE BAND GAP VOLT REFERENCE	LARGE SIZE HIGH POWER
CMOS	LOW	10^3 - 10^5	10^9	10^{15} - 10^{16}	LATCHES	LOW POWER SMALL SIZE	LOW SPEED (FUTURE CMOS WILL BE FASTER)
CMOS (RAD HARD)	LOW	10^5 - 10^6	10^9	10^{15} - 10^{16}	LATCHES	LOW POWER SMALL SIZE	LOW SPEED (FUTURE CMOS WILL BE FASTER)
GaAs	HIGH	$>10^7$	$>10^{10}$	10^{15}	–	HIGHEST SPEED INTRINSICALLY RAD HARD	NEW DEVELOPMENT EXPENSIVE
I^2L	HIGH	10^5 - 10^6	10^9	10^{13} - 10^{14}	LATCHES	SAME AS ABOVE SMALL, LOW POWER	
NMOS	LOW	10^3 - 10^4	10^8	10^{15} - 10^{16}	LOC/MOS FLIPS	LOW POWER, SMALL SIZE	RAD SOFT LOW SPEED
PMOS	LOW	10^3 - 10^4	10^6	10^{15} - 10^{16}	–	LOW POWER, SMALL SIZE	RAD SOFT LOW SPEED
SOS/SOI	MED	10^3 - 10^5	10^{10}	10^{15} - 10^{16}	NO LATCH	HARD TO RAD TRANSIENTS AND LATCHUP	CHANNEL LEAKAGE EXPENSIVE
SOS/SOI (Rad Hard)	MED	10^5 - 10^7	10^{10}	10^{15} - 10^{16}	NO LATCH	HARD TO RAD TRANSIENTS AND LATCHUP	CHANNEL LEAKAGE. EXPENSIVE
TIC	MED	$>10^8$	$>10^{10}$	$>10^{17}$	–	INTRINSICALLY RAD HARD	NEW DEVELOPMENT HIGH POWER LARGE SIZE

Table 6.1. Radiation Analysis of Semiconductor Technologies

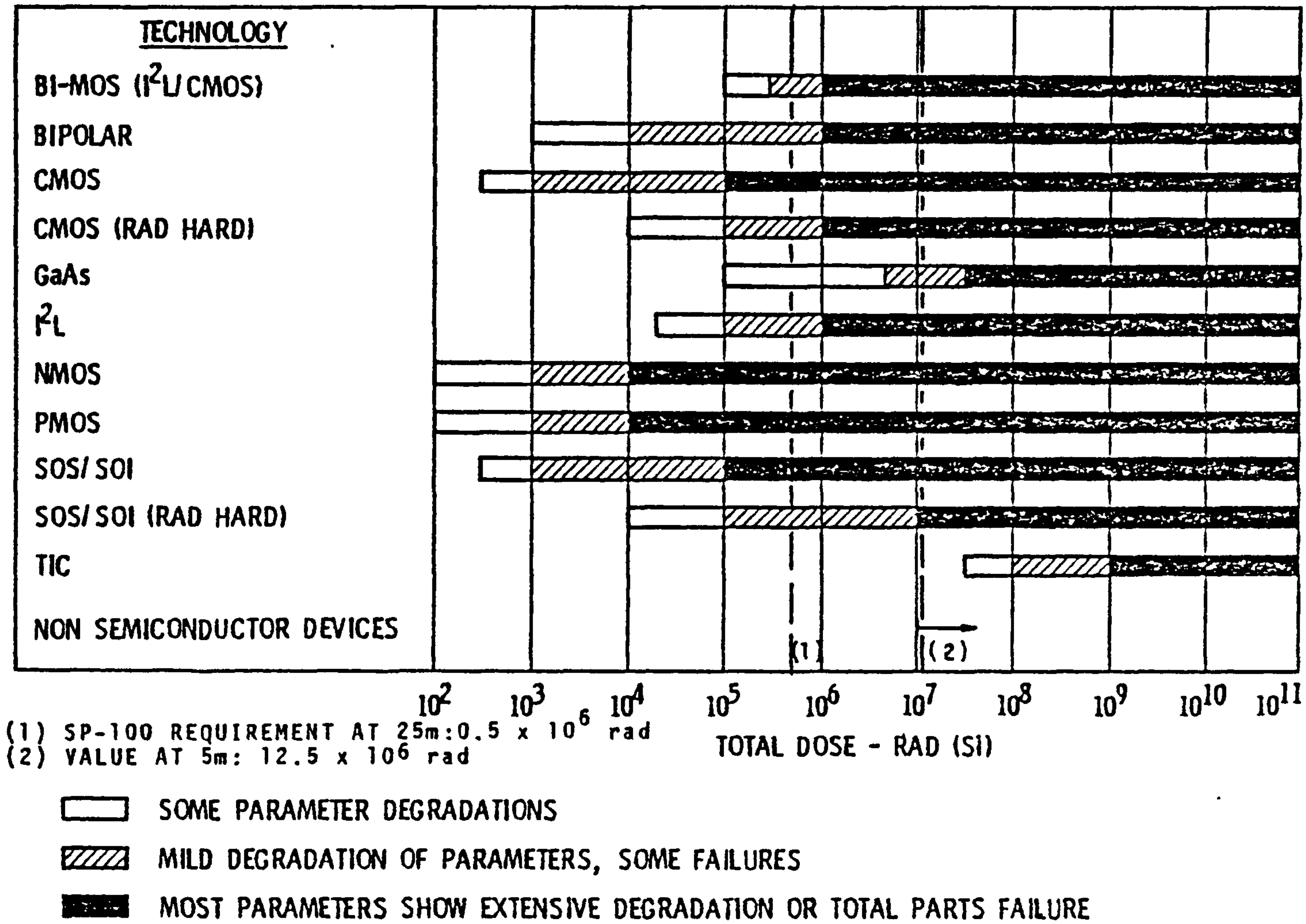


Figure 6.1. Total Dose Radiation Analysis of Semiconductor Technologies

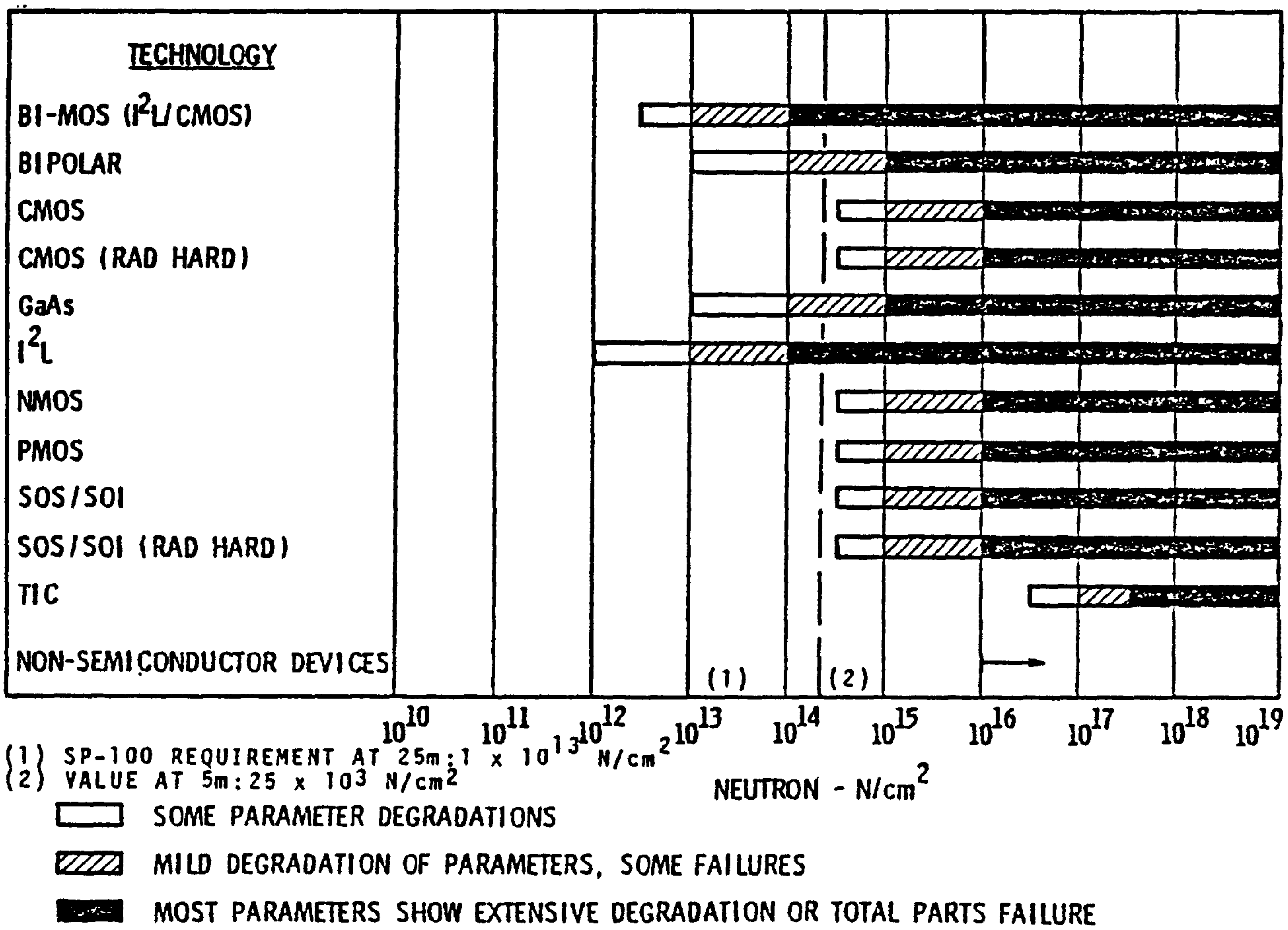


Figure 6.2. Neutron Radiation Analysis of Semiconductor Technologies

Linear devices may not be any better than high quality bipolar silicon devices and for power devices, silicon may even be better.

There is no commercial production of GaAs integrated circuits. Current plans are to have prototype production running in about three years. At that time, production is expected to be 100 wafers per week of digital devices and gate arrays.

The GaAs technology is still in its developmental stage. Although a number of companies are manufacturing UHF-SHF RF transistors, no production of commercial integrated circuits exists. Current plans are to have a prototype production line running in about three years. At that time production is expected to be 100 wafers per week of digital devices and gate arrays.

GaAs devices are hard to ionizing radiation but may suffer from bulk damage problems. Therefore, they will not have the surface leakage problems of bipolar devices but will have a sensitivity to electron, proton, neutron, and heavy ion damage which is similar to bipolar devices. Typical hardness levels are:

Neutrons	10^{15} n/cm^2
Total Dose	10^7 rad(GaAs)
Transient Upset	10^{11} rad(GaAs)/sec

The maximum safe operating temperature is 200°C, but they may be able to push them close to 300°C. These are the same maximums of bipolar devices. Linear devices made with GaAs technology may not be any better than high quality bipolar devices. For power devices, GaAs may not be as good as silicon. The conversion factor for radiation absorbtion for GaAs is as follows: 1.0 rad(Si) = 1.06 rad(GaAs).

Companies currently working with GaAs include McDonald-Douglas, Huntington Beach, CA; Sandia National Laboratories, Albuquerque, NM; Rockwell International, Anaheim and Thousand Oaks, CA; and Hughes Research Center, Malibu, CA.

F. I^2L. The most popular and overall most radiation-hard technology is I^2L. A wide range of devices are currently available in I^2L.

G. NMOS. This technology is very soft and shows little promise of being hardened. There are a number of manufacturers making NMOS digital devices.

H. PMOS. This technology, like NMOS, is very soft and shows little promise of being hardened. There are a number of manufacturers making digital devices.

I. SOS/SOI. SOS/SOI is soft to total dose but hard to other environments. Recent developments of radiation hardened CMOS/SOS have increased its total dose hardness to the same levels as radiation-hardened CMOS. Several manufacturers have made radiation hardened CMOS/SOS devices but it will be another year or so before a complete line of devices are available for flight applications.

J. TIC. The TIC (Thermionic Integrated Circuit) is a technology that combines vacuum tube techniques with modern integrated circuit techniques to yield rugged, microminiature, electronically matched devices. TICs are intrinsically hard to all types of radiation and operate at temperature ranges of 500°C to 1200°C.

TICs operate over a wide range of voltages and currents. Currently, devices are operating with anode voltages of 100 to 2000 volts and with cathode currents from microamps to 100 amps. Operating circuits such as operational amplifiers or comparators should be ready in two years and analog-to-digital converters should be ready in five years.

The Thermionic Integrated Circuit (TIC) which is being developed by the Los Alamos National Laboratory is basically a solid state vacuum tube. For a detailed description of the TIC see the unsolicited proposal made to DARPA dated March, 1982, by J. Byron McCormick, titled "Radiation Immune Thermionic Integrated Circuits.

The TIC is Rad Hard and has been tested to the following levels with no noticeable effects.

Neutrons	10^{17} n/cm^2
Total Dose	2.5×10^8 rad(Si)
Dose Rate*	4.5×10^{10} rad(Si)/sec
Protons*	2×10^8 rad(Si)/sec
Neutrons*	1.4×10^{16} n/cm^2/sec

*Response for duration of the pulse, only at the highest levels.

The main applications are for signal processing, line drivers, telemetry, amplifiers, etc. Analog and digital circuits can be made on the same substrate. With current 10 µm integrated circuit technology they can place 1000 devices per square inch.

The TIC is not a replacement for any current IC technology, but has application in high temperature environments where current IC technology can not function. TICs are much larger in size and require operating current magnitudes larger than ICs. The electrical circuits fabricated onto the substrates are simple in nature as compared to the complex circuits on ICs (See Figures 6.3, 6.4, and 6.5).

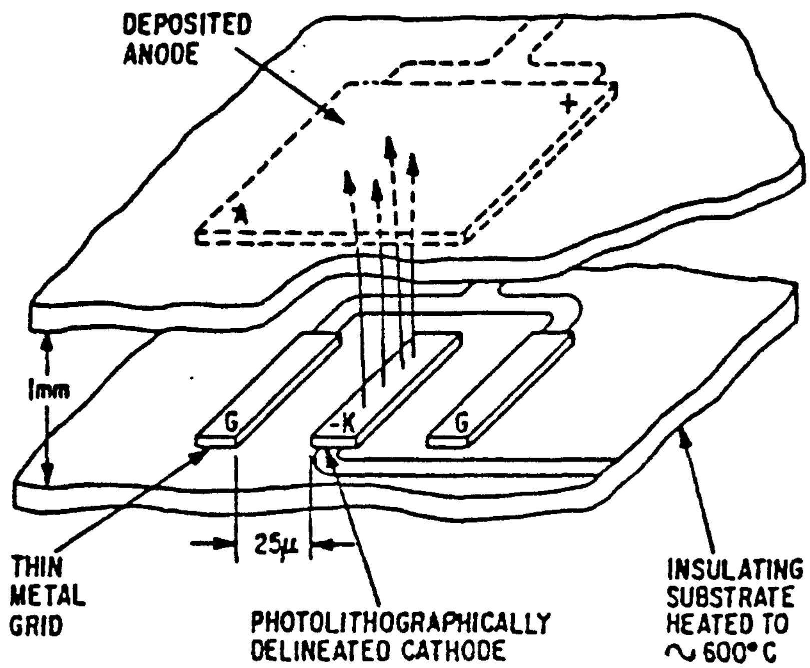


Figure 6.3. Basic TIC Gain Device

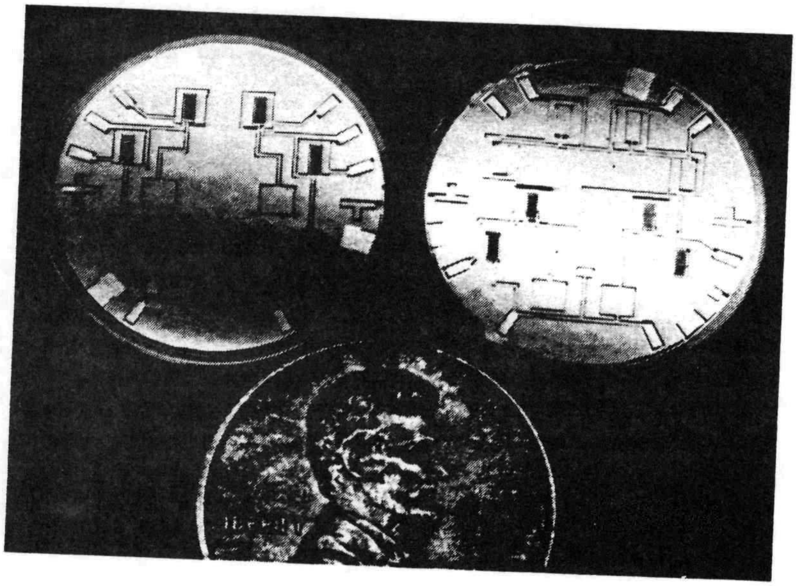


Figure 6.4. Cathode and Grid Side of Substrate, TIC

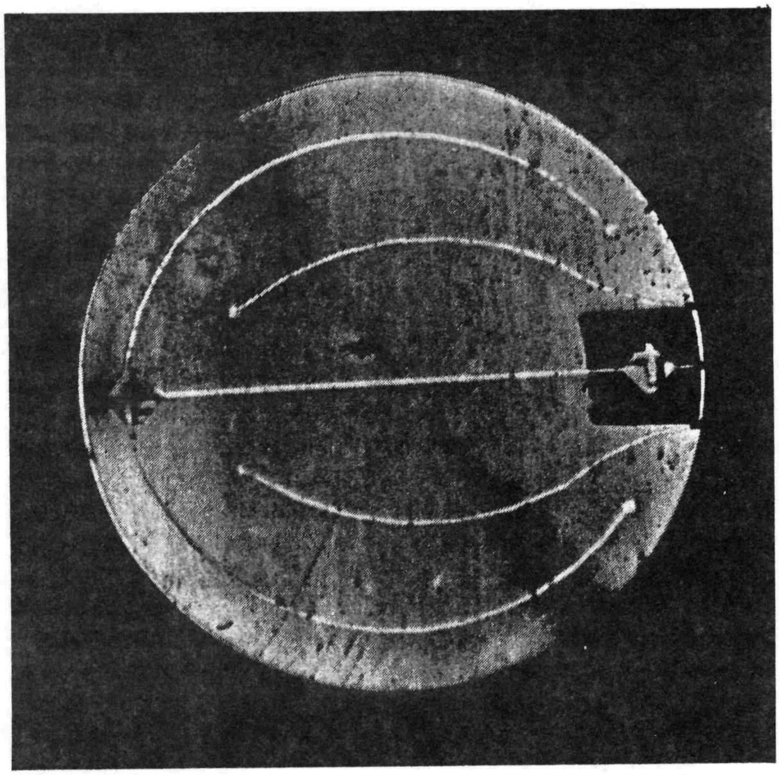


Figure 6.5. Heater Side of Substrate, TIC

The operating range temperature of the cathode is 700°C to 1000°C with the best operating temperature being 750°C. The devices can operate from 500°C to 1200°C. The cathode current density is one amp per square centimeter.

TICs can be made to operate in the current ranges from microamps to 100 amps or with voltage ratings up to 2000 peak inverse volts (PIV). A 2000 PIV 15 amp diode would be about one inch long and three-quarters of an inch in diameter. It can be packaged in a glass or metal vacuum envelope. Current lifetimes of 13,000 hours have been reached. The failure was a pin seal and the loss of vacuum. It is expected that a 7 to 10 year lifetime can be reached. The major developmental problem is in the packaging of the device.

Operating circuits such as operational amplifiers and comparators should be ready in two years and analog-to-digital converters should be ready in five years.

7.0 NON-SEMICONDUCTOR COMPONENTS.

Passive devices, such as resistors, inductors, transformers, and capacitors are not affected by the SP-100 radiation environment. The availability of these devices is basically determined by the availability of suitable insulating material. Insulating material technology is discussed later in this report (See next section).

8.0 ELECTRICAL INSULATION.

8.1 Polymeric Materials.

Commercial availability of polymeric electrical insulation materials with high temperature capability and with high radiation tolerance was investigated. Table 8.1 lists polymeric materials that are temperature resistant, along with melting and softening points. The commercial availability of the basic polymers that can withstand high temperatures and radiation was investigated. Little definitive information is currently available in this area. Radiation data that is available on polymeric material is summarized in Figure 8.1. Kapton (polymide) (260° - 371°C) and Phenolic (315°C) are the best polymeric materials identified from a high temperature resistance point of view. Phenolic filled glass is the best polymeric material identified from radiation point of view (10^{10} rad).

It should be noted that damage from radiation is usually first the loss of the mechanical properties of the material and then the loss of electrical properties of the material.

8.2 Ceramic Material.

Ceramic materials can withstand much higher temperatures than the polymeric material. Examples of ceramic materials include Aluminum Oxide (1500°C or more), Porcelain (1000°C), Woven Alumina (1500°C), Woven Silica (1000°C), and Zirconia (2000°C).

9.0 POWER CABLES.

Preliminary estimates have been made for the mass and power loss of a cable to transmit power to the spacecraft from the reactor. Conductor sizes were determined from assumed conductor surface temperatures and cross-sections large enough to radiate the cable loss. The following assumptions were made:

1. Heat loss only by radiation.
2. Surface emissivity, 0.8.
3. View factor to space, 0.5.
4. Effects of conductor insulation neglected.
5. Conductors assumed to be isothermal.
6. Conductor length (one way) is 25 meters.
7. Surface temperature held at 350°K for curves where system voltage is independent parameter.
8. System voltage held at 186 volts for curves where surface temperature is independent parameters.

Figures 9.1 and 9.2 show the dependence of cable mass and power loss respectively as a function of system voltage selection for copper cables. Figures 9.3 and 9.4 show similar plots for aluminum cables.

Figures 9.5 and 9.6 show plots of cable mass and power loss, respectively, as a function of cable surface temperature for copper cables. Figures 9.7 and 9.8 show similar plots for aluminum cables.

From the figures the following conclusions may be made:

1. Higher voltage reduces cable mass.
2. Use of aluminum rather than copper decreases cable mass but increases cable loss.
3. Increase of cable loss to reduce cable mass increases power level and mass of power source.
4. For a constant conductor surface temperature, increasing the number of conductor pairs decreases cable mass but increases cable loss.

Table 8.1. Electrical Insulation/High Temperature Polymeric Materials

Material	Structure	Useable Temp. °F	°C	Melting Temp. °F	°C	Radiation Damage Level (rads)	Specific Gravity (g/cm³)	Estimated Cost ($/Lb.)
Mylar	Polyester	446	230	482-509	250-265	10^9	1.4	22
Paraylene N	Poly-p-xylylene	600	315	761-842	405-450	10^9	1.12	> 300
Kapton (H Film)	Polyimide	500-700	260-371	— Chars —		> 4×10^9	1.42	~350
Teflon	Fluorinated Ethylene Propylene	500	260	---	---	~7×10^8	2.15	> 167
Kimfol	Polycarbonate	< 356	< 180	---	---	---	1.21	---
Kimfone	Polysulfone	< 392	< 200	---	---	---	1.24	144
Kevlar	Aramid	320	160	932	500	2×10^8	1.45	85
PPA-M	Poly-parabanic Acid	---	---	> 554	> 290	---	1.35	---
Saran	Polyvinylidene Chloride	---	---	> 315	---	10^5	1.27-1.38	---
Tedlar	Polyvinyl Fluoride	~500	260	---	---	---	1.37-1.57	---
Kynar	Polyvinylidene Fluoride	300	---	---	---	10^8	1.75-1.87	---
Astrel 360	---	500	---	---	---	1.2×10^8	1.36	---
Tefzel	Fluorocarbon	300-360	---	---	---	---	1.70	---
Lexan	Polycarbonate	275	---	---	---	10^8	1.2	---

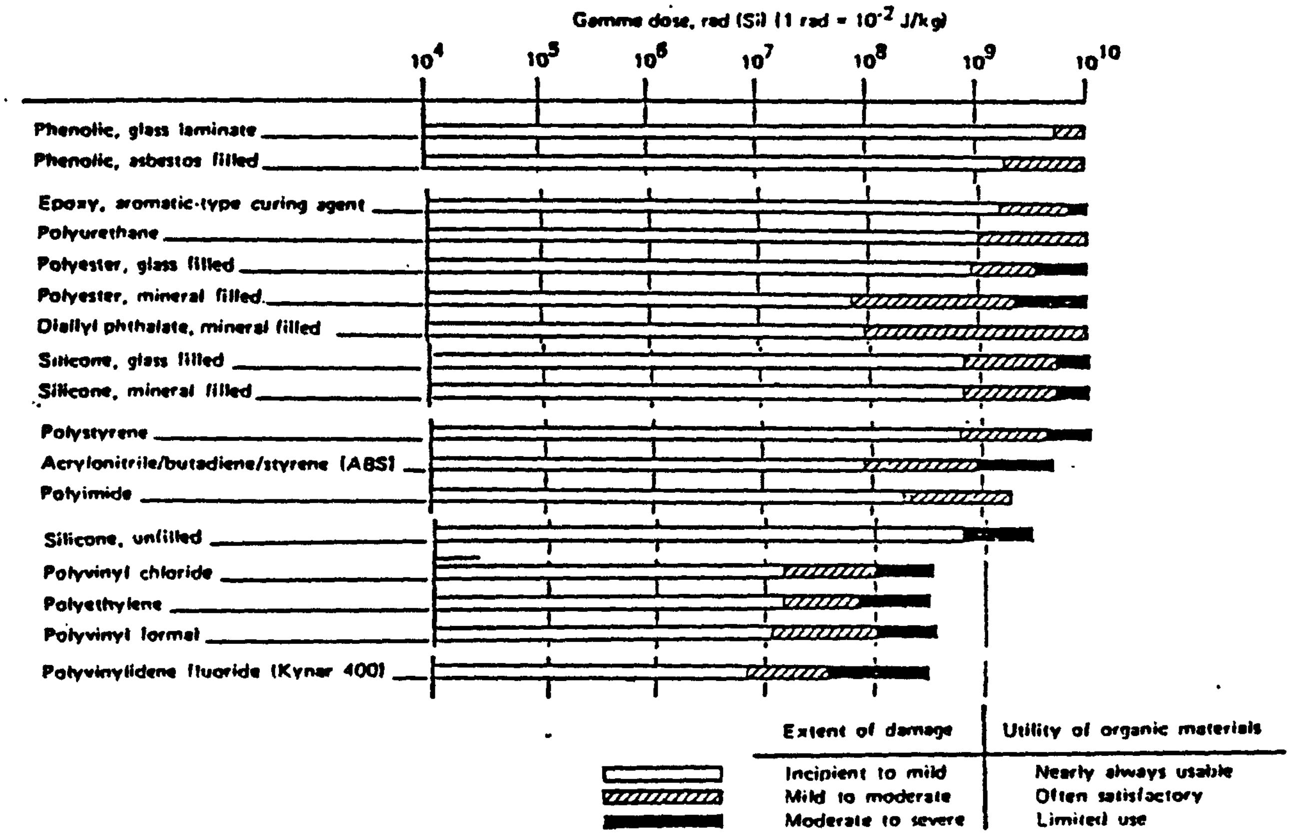


Figure 8.1. Electrical Insulation/Relative Radiation Resistance of Polymeric Insulation Materials

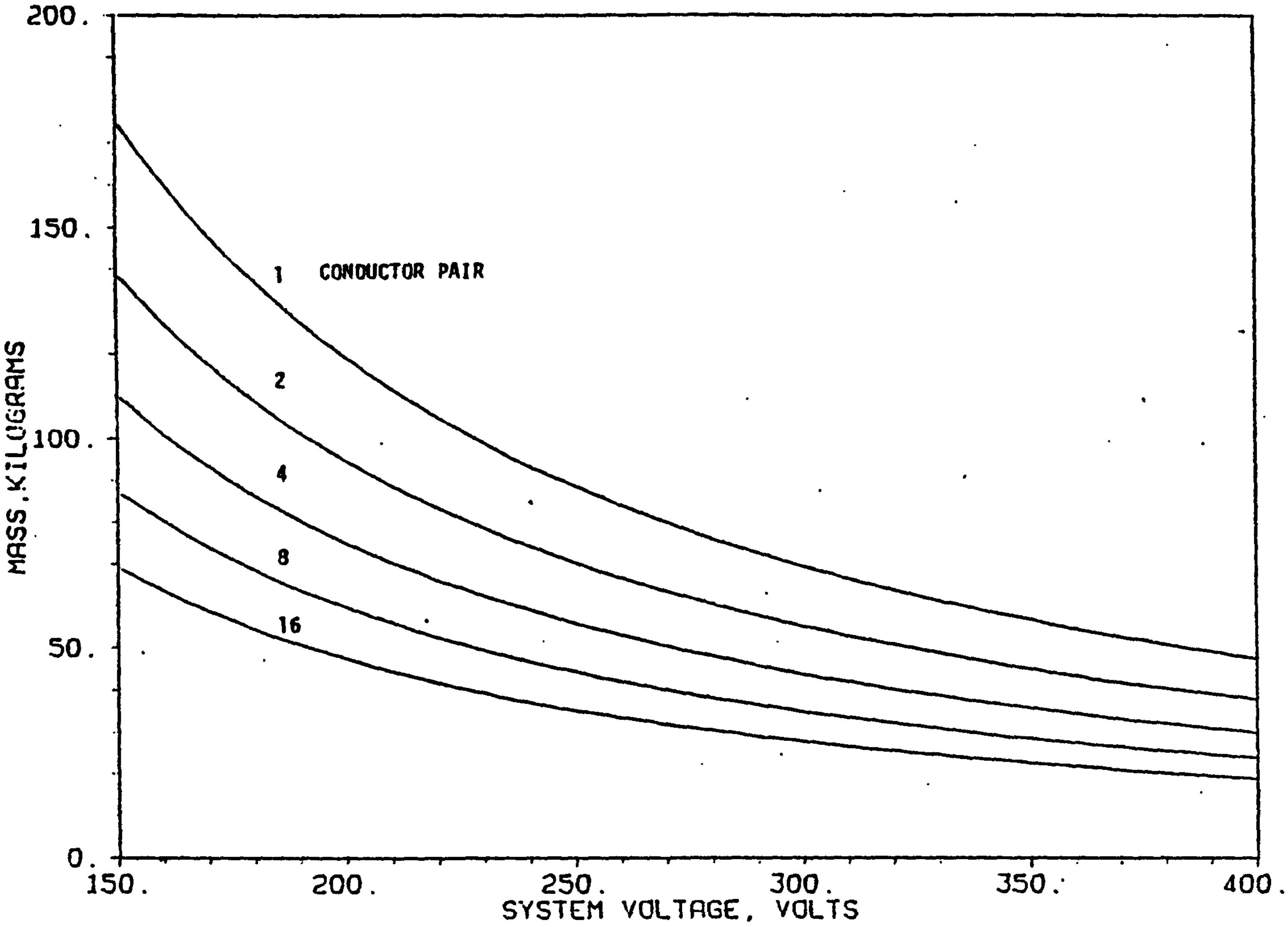


Figure 9.1. Cable Mass Dependence on System Voltage Selection (for Copper)

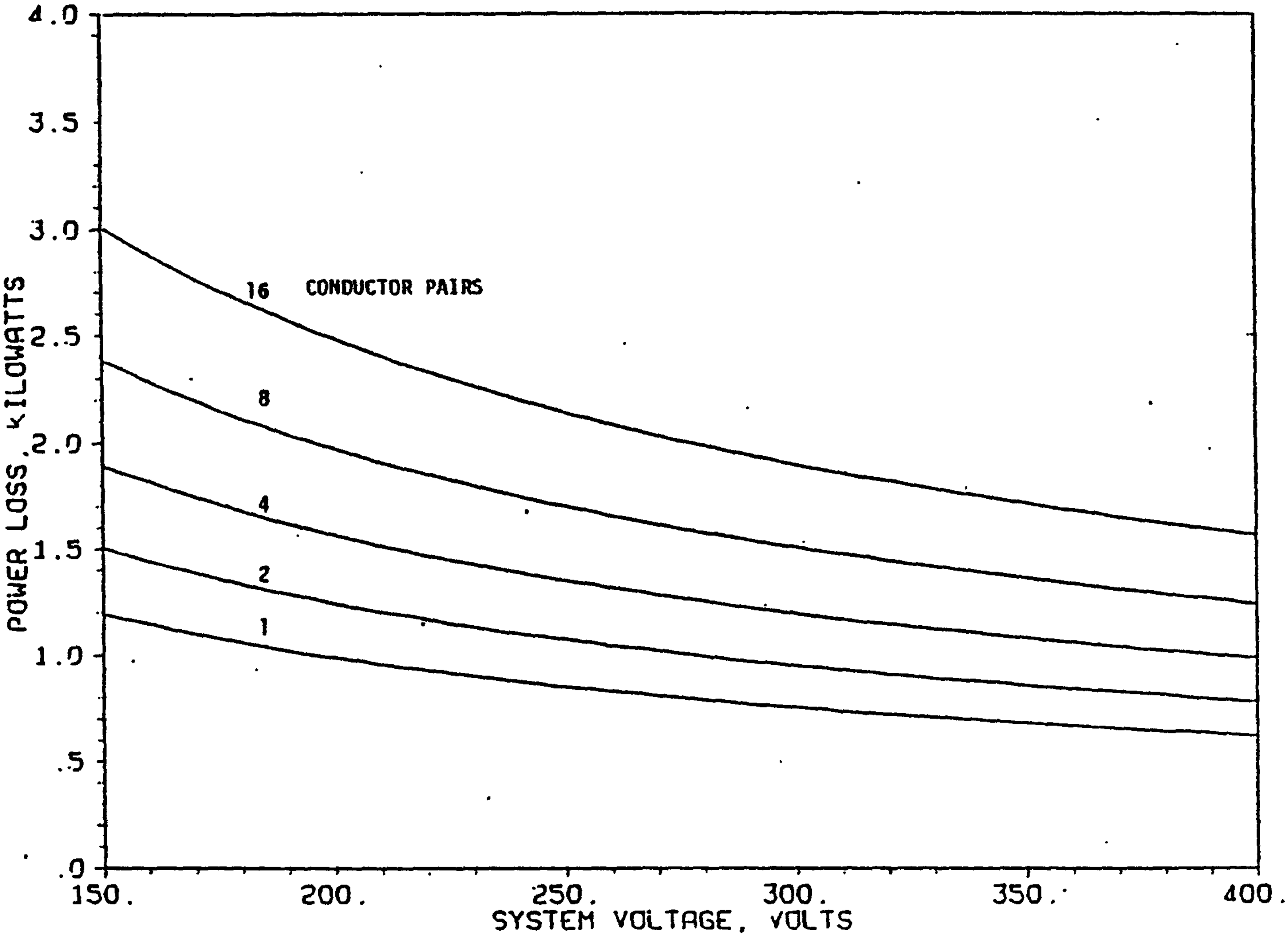


Figure 9.2. Power Loss Dependence on System Voltage Selection (for Copper)

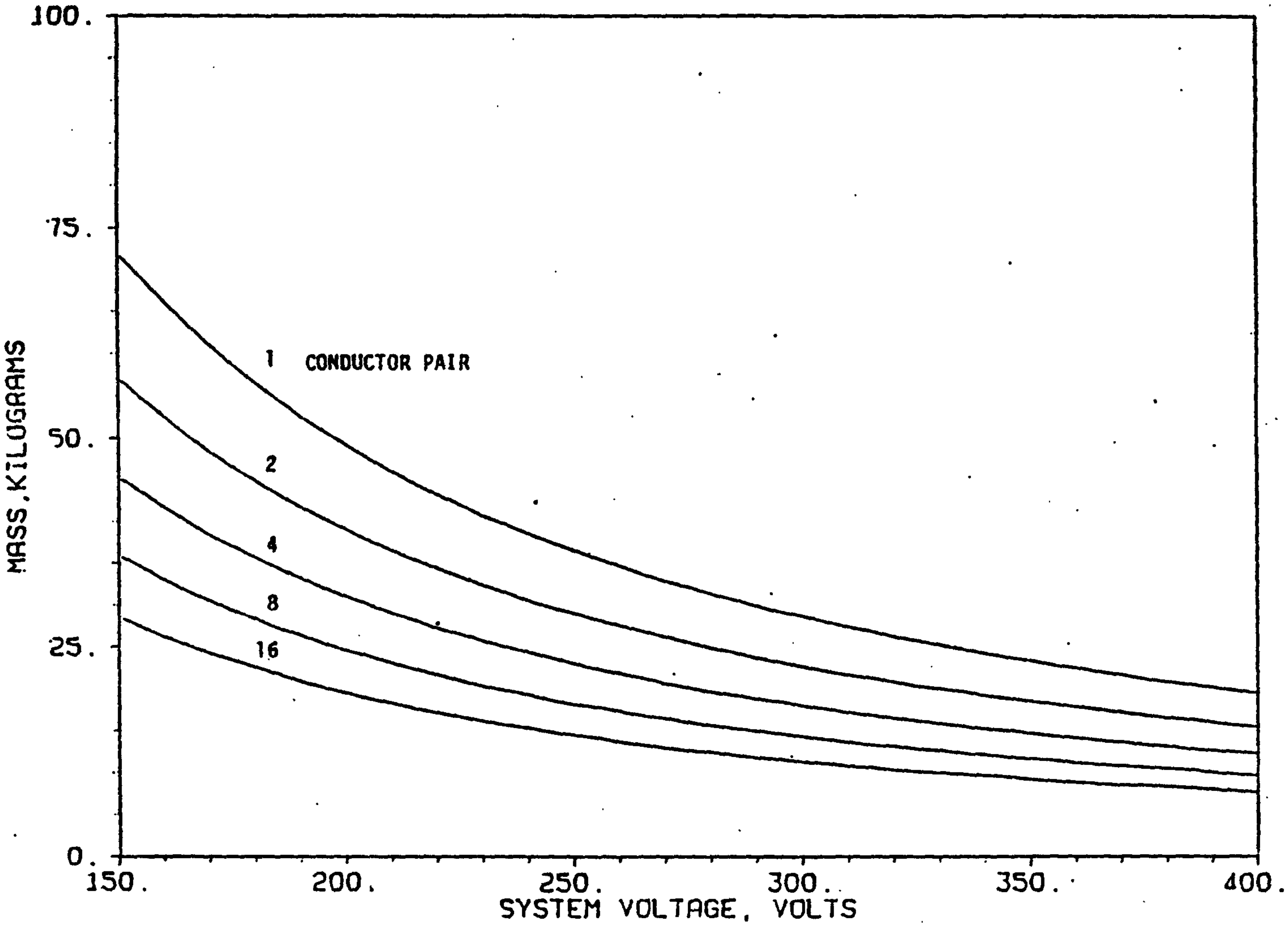


Figure 9.3. Cable Mass Dependence on System Voltage Selection (for Aluminum)

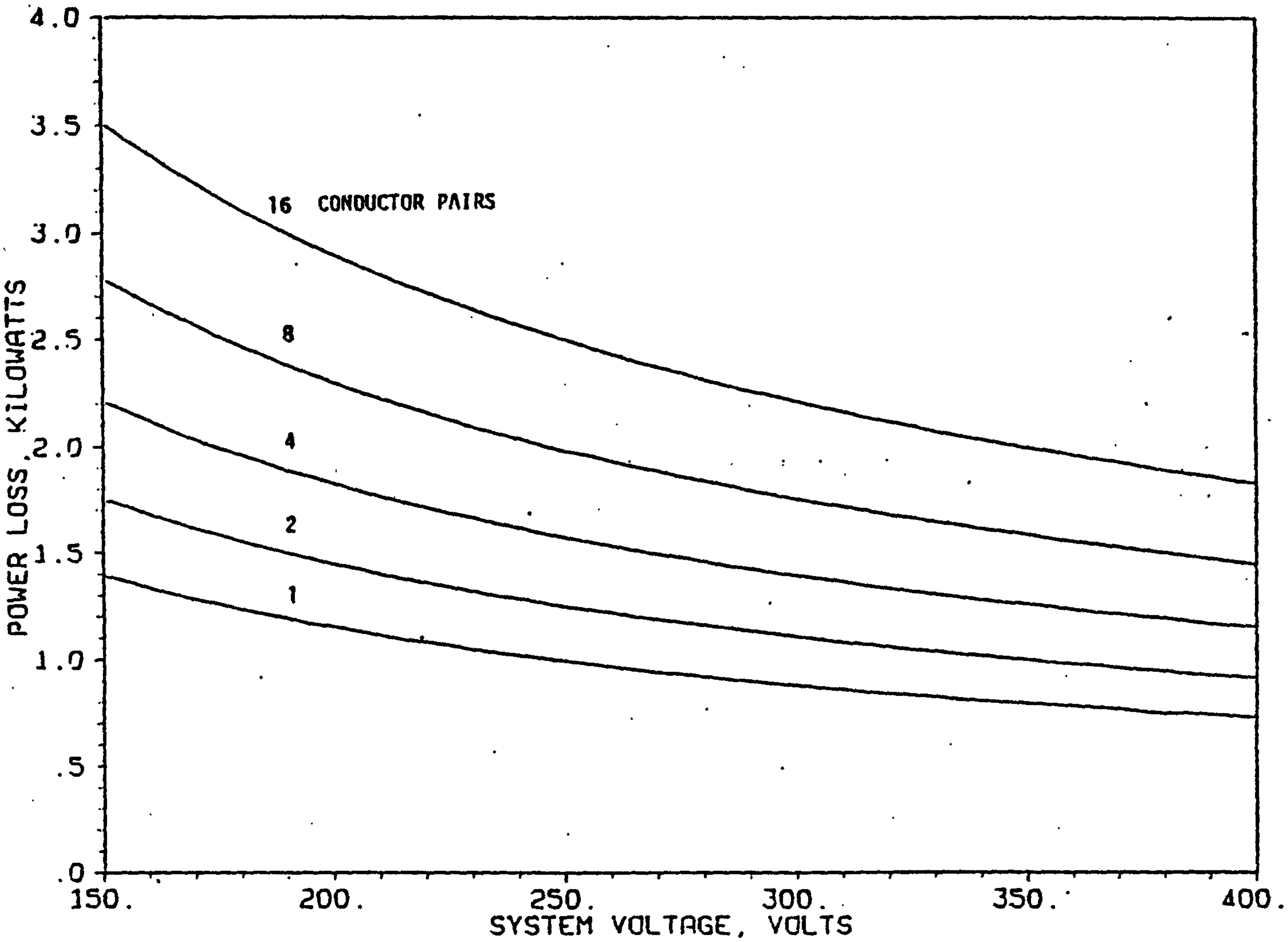


Figure 9.4. Power Loss Dependence on System Voltage Selection (for Aluminum)

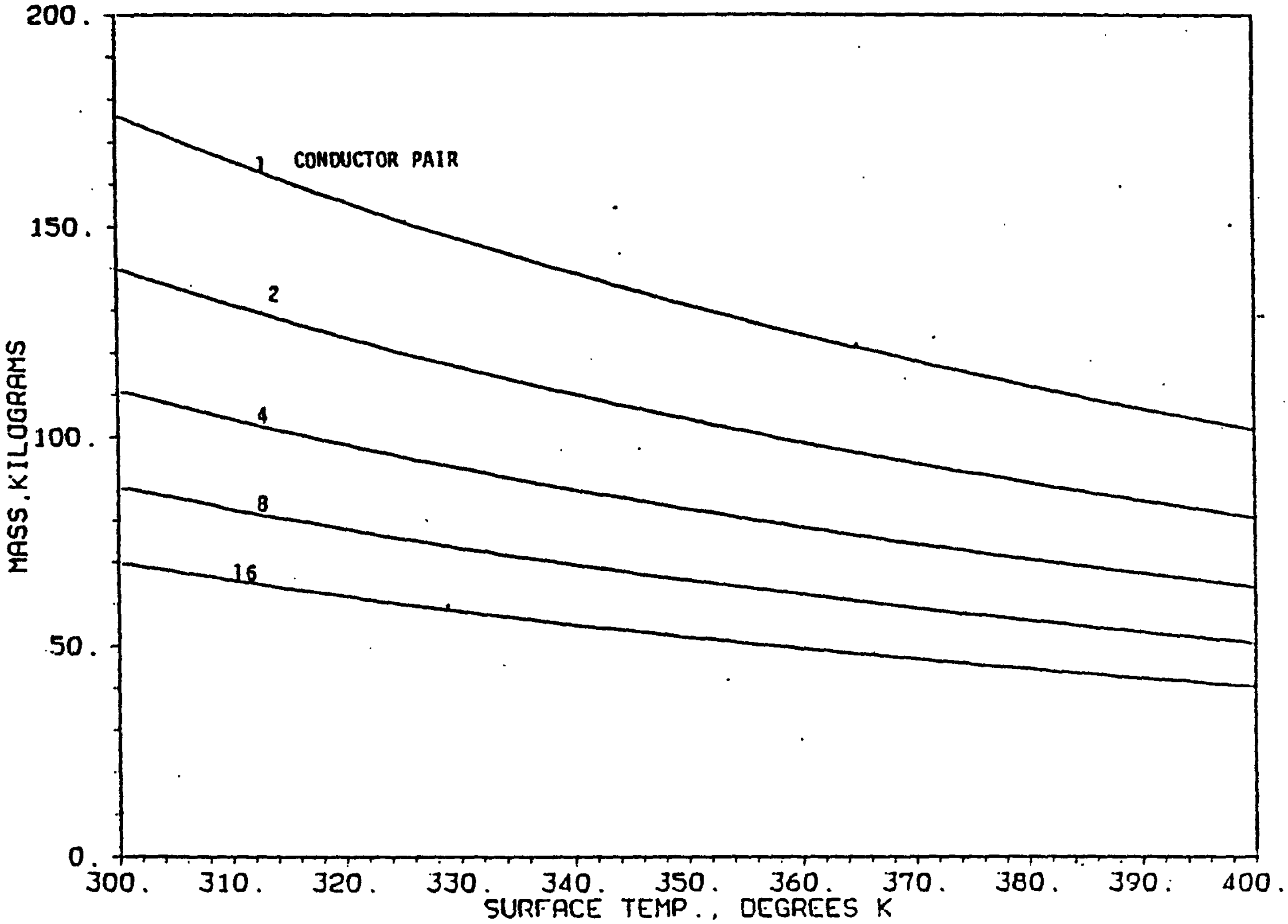


Figure 9.5. Cable Mass as a Function of Cable Surface Temperature (for Copper)

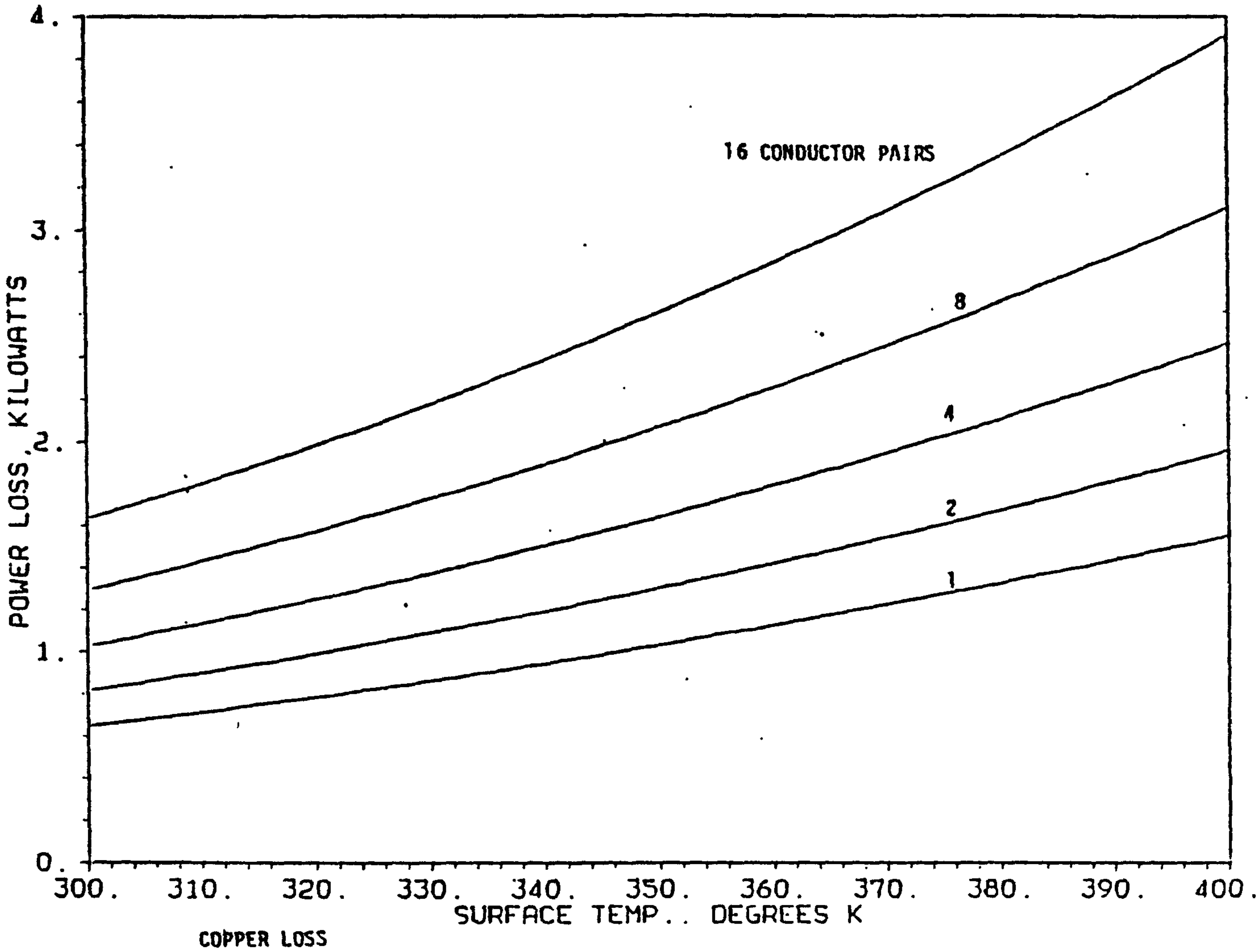


Figure 9.6. Power Loss as a Function of Cable Surface Temperature (for Copper)

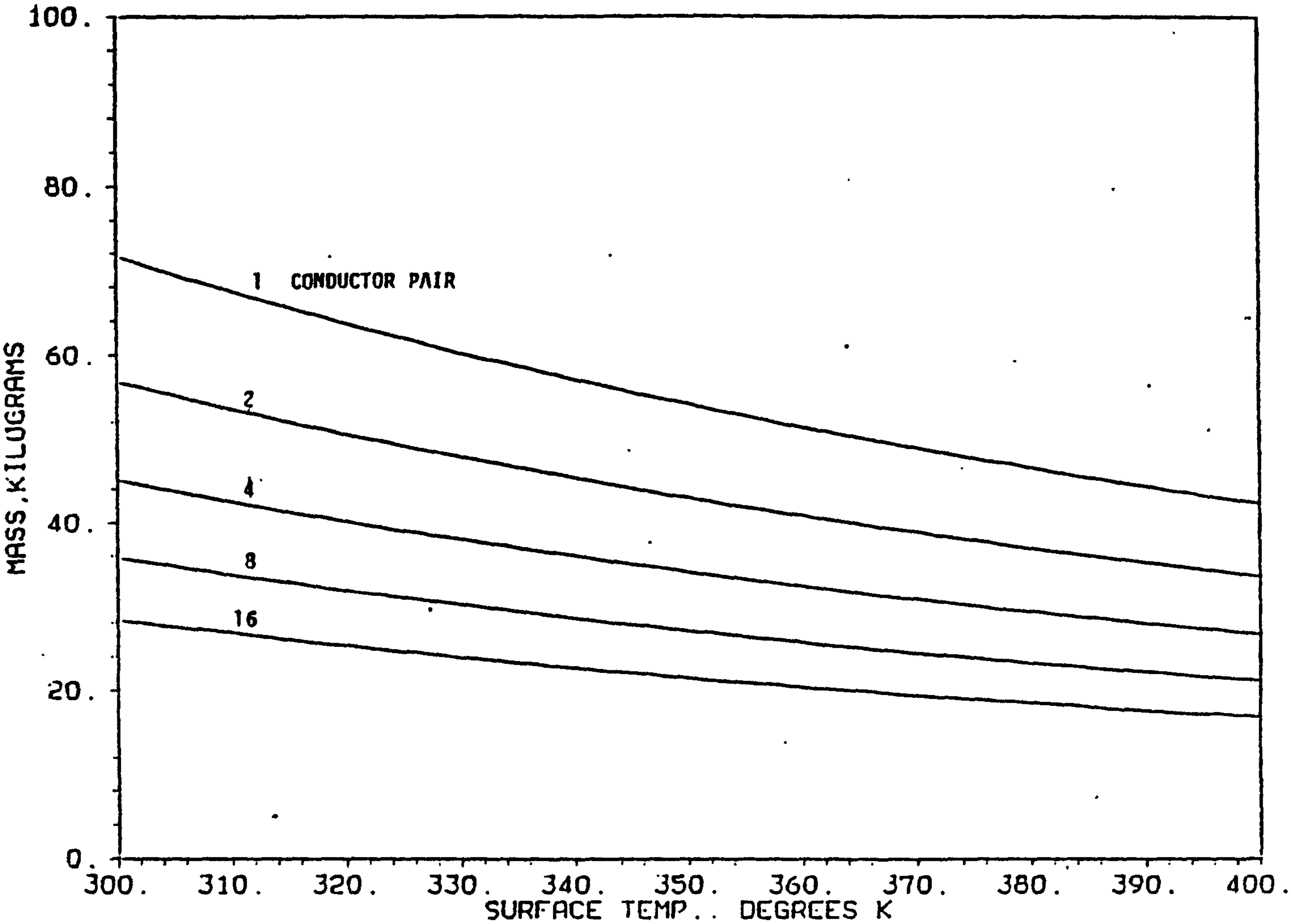


Figure 9.7. Cable Mass as a Function of Cable Surface Temperature (for Aluminum)

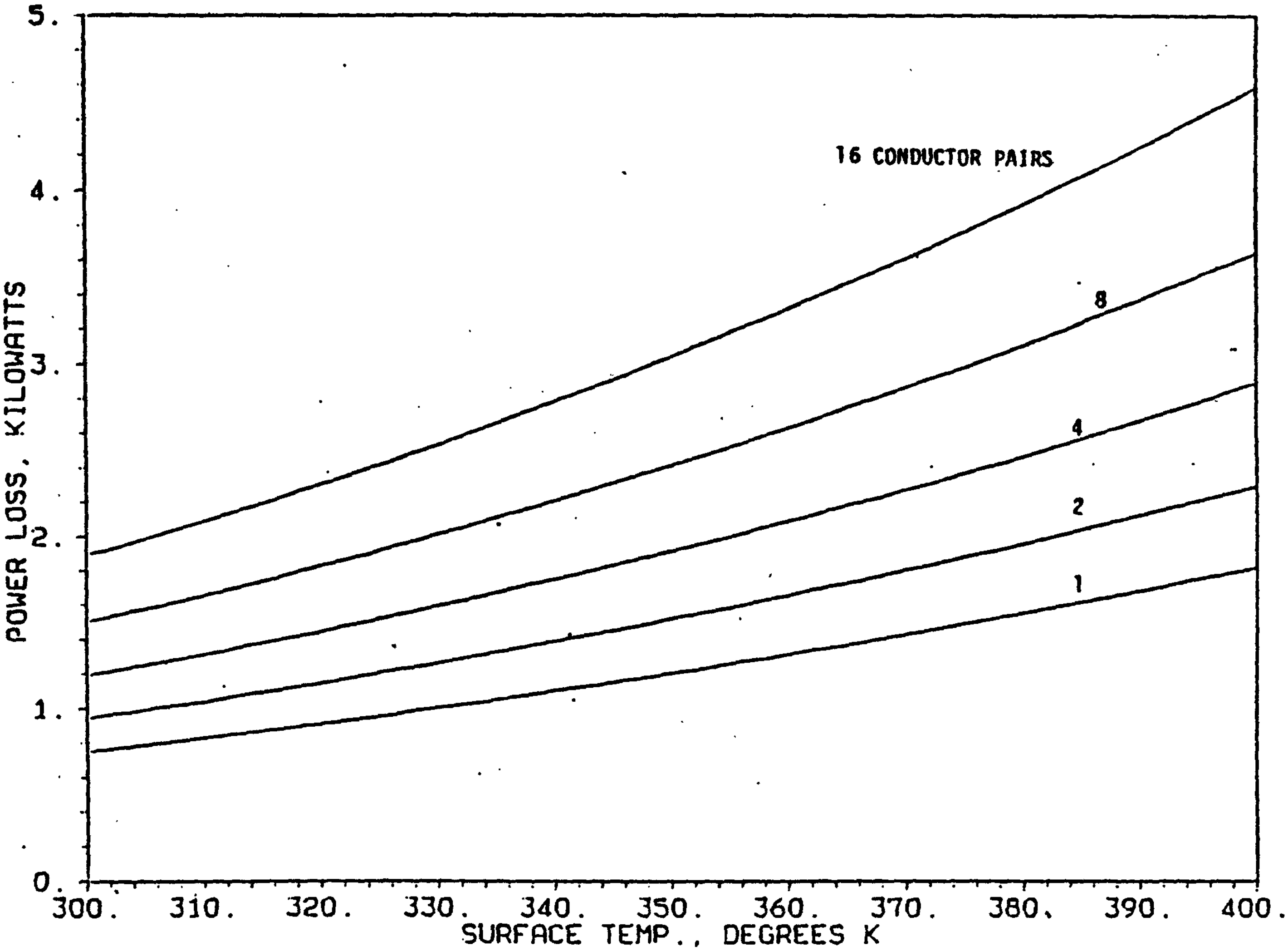


Figure 9.8. Power Loss as a Function of Cable Surface Temperature (for Aluminum)

10.0 SENSORS.

Various sensors are required to monitor key variables in the system for the purpose of assuring the system safety and for proper control. These sensors may be divided into those for reactor, conversion system, power conditioning system, and the loads.

The reactor sensors may be for the purpose of assuring safety or for the purpose of reactor control. The safety system is completely isolated from, and is independent of, the regulating system. The safety system is provided to protect the reactor against damage resulting from operation in which heat transfer and fuel element temperature limitations are exceeded. Ionization chambers may be used to provide neutron flux signals and gamma flux signals which in turn are used to activate safety action. The temperature of the working fluids provide useful information. Reactor control system (regulation) uses the same variables as used in the safety system, however, from an independent set of sensors.

For the conversion system the choice of sensors required will vary greatly depending on the concept selected. In the case of dynamic systems it is likely that variables relating to inlet temperature, flow rate, pressure, shaft speed, alternator voltage, current, and power output will be measured. In the case of static systems, voltage, current and power out of the conversion system, as well as temperatures at key locations, will be measured.

In the case of power conditioning, input and output voltages, currents, power flow, and frequency are measured. Charging and discharging rates of the storage battery are measured. The status of various protection devices is monitored.

In the case of the loads, various variables, including currents and voltages, real and reactive power flows at the load, are measured.

11.0 CONCLUSIONS.

The radiation and temperature environment of SP-100 is quite harsh. At five meters from the reactor the total seven year gamma radiation dose may be as high as 12.5×10^6 rads, the neutron flux may be as high as 25×10^{13} N/cm^2, and the temperature rage is estimated as (800 - 900^oK). In this study the SP-100 environment was investigated.

Availability of semiconductor devices was investigated. The results indicate that the total number of device types which are megarad hard are very limited. Device types which are hard to 12.5 megarad, which is the requirement at five meters from the reactor, are almost non-existent. The full line of devices needed to meet the user spacecraft environmental requirements at 25 m away from the SP-100 reactor of 500 krad(Si) are not available. There is a full line of rad-hard devices which will meet the environments of 250 krad(Si) but in some cases there is not a wide range of devices within the line. The widest selection of devices would be available if an environment similar to Project Galileo [75 krad(Si) total dose] is selected. Digital devices are most restricted with only rad-hard CMOS and CMOS/SOS being available. There is a full line of linear devices that will meet the 500 megarad requirements, but careful selection of manufacturer, lot, and wafer is required.

Technologies and analog and digital device families meeting SP-100 requirements have been identified as a result of this study (See Ref. 1). Future studies will identify device types, model numbers and manufacturers. Currently used and future process technologies need to be monitored continuously so as to keep abreast of this rapidly changing field so that devices selected for SP-100 will have been optimized for performance within its environment.

There are new technologies and processes that need to be monitored and, in some cases financially assisted, to complete development and place into production.

GaAs is a developing technology with only a limited number of devices that have been fabricated to date. Characterization has begun but there is only limited reliability data available. Prototype production is still 36 months away. At this time, GaAs technology has little to offer SP-100 that cannot be done with current rad-hard silicon technology.

There is a major problem in solid state power switching devices. Thyristors and other triggered silicon devices are highly sensitive to all types of irradiation. Power transistors would also be highly sensitive, but also may be too slow in operating speed. TIC technology may or may not solve the problem. Additional research and development work needs to be done in this area.

The TIC is a developing technology with only a limited number of devices fabricated to date. Characterization has begun and there is only limited reliability data available. There are no second sources at this time. Production is still 18 months away. Operating circuits are at least 24 months away. Packaging should be their big problems. Funding to complete development and start production is their current problem.

The TIC could be a very important technology for SP-100. Being a rad-hard technology that can also operate in high temperature environments could make it invaluable for electronic circuitry operating close to the reactor and heat pipes. This technology should be considered for support by the SP-100 program.

Availability of electrical insulatin was investigated. The results indicate that the temperature capability and radiation resistance of polymeric material are limited to 371°C and 10^{10} rads, respectively. Ceramic insulation is available to operate at much greater temperatures (1000°C - 2000°C). Some ceramic insulation is fragile, however, woven ceramics are flexible.

Effects of voltage and cable surface temperature on cable mass power loss were investigated parametrically. The results show that higher voltage improves power transmission efficiency, and reduces cable mass. However, at higher voltages there is a concern relating to plasma discharge. There may be difficulties with availability of insulation, and there is a lack of space-qualified power components.

Table 11.1 summarizes and highlights the conclusion of the study.

PRELIMINARY CONCLUSIONS

TECHNOLOGY STATUS	POTENTIAL SOLUTION	COMMENTS
• BASELINE POWER SWITCHES (AT 2-5M FROM REACTOR) DO NOT EXIST.	• LONGER, MORE COMPLEX CABLES. • THERMIONIC INTEGRATED CIRCUIT (TIC) SWITCHES.	• COMPLEXITY, POWER LOSS, AND MASS PENALTY. • TIC PACKAGING DEVELOPMENT REQUIRED. 1 1/2 YEAR LIFE IS CURRENTLY DEMONSTRATED.
• MICROPROCESSORS SUITABLE TO OPERATE AT SP-100 RADIATION LEVELS ARE EITHER NOT AVAILABLE OR ARE VERY LIMITED.	• DEVICES (BUT NOT COMPLETE SELECTIONS) FOR MICROPROCESSORS EXIST SUITABLE TO OPERATE AT 2.5 x 10^5 RADS. AT THE SP-100 REQUIREMENT OF $\geq$ 12.5 x 10^6 RADS, THEY ARE ALMOST NON-EXISTENT.	• ADDITIONAL SHIELDING. • CAREFUL SELECTION OF MANUFACTURER, LOT, ETC. • COMBINATION OF THE TIC TECHNOLOGY AND SOLID STATE TECHNOLOGY.
	• DARPA SPONSORED GaAs TECHNOLOGY.	• AT LEAST 3 YEARS AWAY. • ACTUAL HARDNESS OF EVENTUAL PRODUCT UNKNOWN.
• NO SUITABLE PRODUCTION POLYMERIC ELECTRICAL INSULATION MATERIAL IDENTIFIED.	• SPECIALLY FORMULATED POLYMERS (e.g., IMPROVED KAPTON).	• APPEAR PROMISING, SOME HAVE DEVELOPED IN LABORATORIES BUT NOT IN PRODUCTION.
• CERAMIC INSULATION.	• CANDIDATE. • ALUMINUM OXIDE (1500^oC). • ZIRCONIA (2000^oC). • WOVEN SILICA (1000^oC).	• SOME CERAMIC INSULATION FRAGILE, WOVEN CERAMICS FLEXIBLE.
• HIGHER VOLTAGE NOT USED PREVIOUS SPACECRAFT.	• HIGHER VOLTAGE IMPROVES POWER TRANSMISSION EFFICIENCY, REDUCES CABLE MASS.	• INSULATION DIFFICULTIES. • PLASMA CONCERNS. • SPACE QUALIFIED POWER COMPONENTS.

Table 11.1. Summary of Preliminary Conclusions

REFERENCES.

1. M. K. Gauthier, D. K. Nichols, "Semiconductor Radiation Review", SP-100 Technical Information Report, D-1035, September, 1983.

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