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Component Technology for Space Power Systems

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COMPONENT TECHNOLOGY FOR SPACE POWER SYSTEMS

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Abstract

The Lewis/OAST program for the development of Component Technology for Space Power Systems is described. The program is divided into five generic areas: semiconductor devices (transistors, thyristors, and diodes); conductors (materials and transmission lines); dielectrics; magnetic devices; and thermal control devices.

Examples of progress in each of the five areas is discussed. Bipolar power transistors up to 1000 V at 100 A with a gain of 10 and a 0.5 μsec rise and fall time are presented. A new class of semiconductor devices with a possibility of switching 100 000 V is described.

Several 100 kW rotary power transformer designs and a 25 kW, 20 kHz transformer weighting 3.2 kg have been developed. Progress on the creation of diamond-like films for thermal devices and intercalated carbon fibers with the strength of steel and the conductivity of copper at one third the mass of copper is presented.

Introduction

To date, NASA has launched spacecraft with a total of less than 120 kW of solar power.[1] Most spacecraft have averaged under 1 kW total system power. As a consequence, power distribution has been a straightforward task. With compact spacecraft, the distribution system cable weight has been relatively low in comparison with other system elements allowing the promulgation of power distribution at low (nominal 28 V) lines.

With the advent of shuttle, we are entering into a new era of large highpower spacecraft where the amounts of power and the transmission distances from source to load will dictate dramatic changes in the management and distribution of power. As large space structures distributing power to a variety of users become more real, then so does the necessity for a distribution system resembling that used by the electric utility plants on the earth. For the same reason, reliability and cost effectiveness also become more important.

As system power increases, so must system voltage to avoid excessive system mass increases due to cable losses. Just as utility companies balance line losses against corona leakage loss in determining transmission voltage, spacecraft power systems must be designed to balance plasma leakage currents against line losses.

Operating voltages for such systems will range from 200 V to multikilovolts primarily to reduce harness power losses. Systems operating at these voltages can interact with the space chargedparticle environment in an as yet unknown manner since the largest operating power system voltage in space has been the 100 V used occasionally on the Skylab array.

The specific component of the charged-particle environment of concern in these interactions is the thermal plasma environment; i.e., that component that has temperatures of about 5 eV or less. It is only these plasma particles that can be significantly influenced by the fields created by power systems operating at up to kilovolt levels. Particle densities of this component peak at Shuttle orbit altitudes (300 km) and fall off as altitude increases. Hence, power system-environmental interactions are expected to be most severe at low Earth orbits.[2]

A high-power system configuration that would provide the weight savings of the optimized distribution system and take into account the potential environmental interactions is a dual-voltage system. The solar array would generate power at 200 to 300 V that would be up to voltages of about 1000 volts for distribution. The advantages of the upconverted to voltages of about 1000 V for distribution. The advantages of the upconversion would be a lower distribution current and lower I^2R losses.

In addition, system considerations such as flexibility, multiuse capability, and user friendliner may dictate distribution of high-frequency (∿20 kHz) alternating current.[3]

The technology for electronic components, suitable to space applications, required for the conversion, management, and distribution of power at these voltages and frequencies has not been available. Lewis several years ago formulated a program to address the component needs for high-power space systems. The program has been refined and matured and is shown in Fig. 1. The requirements for the components were developed by the creation of strawman generic power systems at various power levels. Five categories of components are addressed by the program: Semiconductor devices (transistors, thyristors, and diodes); conductors (materials, and transmission lines); dielectrics; magnetic devices; and thermal control devices.

Examples of progress made in some of these areas are described in this paper. As in any program, resource limitations preclude development of all elements simultaneously.

Bi-Polar Transistors

Under Contracts NAS 3-21380 (Ref. 4), NAS 3-21949 (Ref. 5), and NAS 3-22782 with Westinghouse Electric Corporation, NASA Lewis undertook the technology development for high-voltage, high-power, highfrequency bipolar transistors for space power applications.

The technology for fabricating large area, high-voltage transistors for use in advanced power switching applications required the adaptation of techniques employed in the fabrication of high-power thyristors in addition to the development of new processing methods to achieve high-voltage junctions and high lifetime in the collector region. One aspect requiring careful attention was the emitter design. Optimum switching performance requires narrow emitter width and long perimeter length. This can create attachment problems if a molybdenum preform is used to make contact to the emitter area and the resistive drop along a thin, narrow base strip could cause nonlinear current distribution. The final emitter design is shown in Fig. 2 and the completed package in Fig 3. This configuration has been successfully used to carry base currents up to

170 A. These technologies have been used to create a family of high-power, high-frequency transistors. Table I shows the progression of devices that have been or will be developed as part of this program. Table II shows the characteristics of the companion high frequency, high power diodes that are being developed to be utilized with the switching transistors. Presently, plans are to suspend further developments in this area until system needs and requirements indicate that these efforts should be renewed.

Deep Impurity Semiconductors

The Lewis has been sponsoring work for almost 10 years on a new class of semiconductor devices which do not depend upon p-n junction characteristics for their operation but instead upon the trapping characteristics of compensated deep impurities in a bulk material. Double-Injection (DI) switching devices which consist of a p^+ (hole injection) and a n^+ (electron injection) electrode in a high resistivity semiconductor containing deep traps have been created in the laboratories of the University of Cincinnati under University Grant No. NSG-3022. The characteristics of these devices are very similar to the conventional SCR except that, since the device depends on the characteristics of the bulk material the threshold voltage can be arbitrarily adjusted by varying the electrode spacing, since threshold voltage is proportional to the square of the interelectrode spacing.[6] Concomitantly, current handling capacity may be adjusted by increasing or decreasing electrode width.

The deep impurity semiconductors have a higher resistivity and consequently devices made from these materials have a higher breakdown voltage limit than conventional p-n junction devices. This characteristic, coupled with the strong dependence of threshold voltage upon electrode spacing, may enable the development of switching voltages previously unattainable in semiconductor devices. Fig. 4 illustrates the apparent possibilities. If the analysis and preliminary data are correct, the voltage limits for these devices could be 100 000 V, an order of magnitude higher than presently available.[7]

Fig. 5 shows a cross section of a DI device showing the placement of cathode and anode MOS gates. Laboratory tests have shown that a bias current supplied through the cathode gate can suppress the holding voltage across the device to levels approaching zero. The application of zero forward drop devices are numerous and varied. The Lewis is pursuing the industrial development of this device as well as the high voltage switch mentioned previously.

Conductors

As spacecraft and their power systems become larger both in power and physical size the mass of conductors to transmit and distribute the energy will become excessively large unless transmission voltage can be increased as required or unless conductor weight can be reduced.

Modifying the electrical characteristics of low density organic material appears to be a feasible approach to reducing conductor mass.

Graphite was chosen as the media to work with since it has many desirable properties. Graphite fibers are low-cost and readily available, have high tensile strengths up to 1×10^6 psi,[8] are relatively chemically inert and are usable to temperatures in excess of 1000° C.

The resistivity of ordinary carbon fibers is high, however, 200 to 450 μΩ cm, so that even with a density of 1.7 gm/cm^3, an unmodified cable made of carbon would be 30 to 50 times heavier than an equivalent conductor of copper.

The resistivity of graphite may be altered by introducing atoms of another material which alters the electron mobility. This process, intercalation, has been attempted using a variety of material. One of the more stable intercalants is Copper Chloride ($Cu\,Cl_2$). Exposure to $Cu\,Cl_2$ vapor at 480° C has created resistivities of 12.9 μΩ cm in graphite fibers.[9] This preliminary result has produced a conductor which is approximately twice the mass of copper for the same resistance. Other researchers, using Highly Oriented Pyrolytic Graphite (HOPG) have obtained resistivities of 1.5. μΩ cm which, if this could be duplicated in fibers, would yield wires and cables with one fourth the mass of copper for equivalent resistance. Research on the intercalation of graphite fibers has been conducted at the University of Nebraska in Lincoln under the direction of Dr. John A. Wollam, Grant No. NAG 3-95. In addition, an inhouse effort at Lewis is evaluating the properties of graphite fibers as wires and cables. Termination techniques, crimp and solder, are being characterized. Flexibility, durability, and differences when compared to metallic conductors are being documented. Jackets, shrink-on and extruded, are being tested.

Life and stability tests of intercalated wire and cables in air and in vacuum are planned.

Dielectrics

Diamond has properties which make it highly desirable as a dielectric in space power systems. It has a thermal conductivity of 20 W/cm K, approximately five times greater than that of copper at room temperatures. The resistivity of natural diamond can be as high as 10^{16} Ω cm K, with sufficient impurities, diamond can have a resistivity as low as 10 Ω cm. In addition, its thermal coefficient of expansion is comparable to that of Invar.[10] Diamond may be used at temperature to 500° C in air or 1500° C in vacuum before it decomposes.

With all these desirable properties, the Lewis formulated a program to attempt to deposit diamond-like film using the technology developed from the Ion Beam Applications Research (IBAR) program.[11]

An argon ion source bombarded a pyrolytic graphite sample with 1000 eV ions. The sputtered carbon arrives at the deposition sites with lower (1 to 20 eV) energies. The deposited carbon films were simultaneously bombarded with the high energy ions in an attempt to change the ratio of tetragonally to triagonally bonded atoms either through selective sputtering or impact kinetics.

The resultant deposits have an electrical resistivity of 10^{11} Ω cm and a density of 2.2 g/cm^3 for 1700 A thick films.[12]

Deposition of films with an adequate thickness for electronic application (10^1 to 10^2 μm) remains a challenge. Spontaneous peeling and spalling occurs when film thicknesses exceed 10 000A° because of the intrinsic stresses developed from the ion bombardment. Techniques are under investigation for stress reduction and the growth of thicker films.

None of the films analyzed, to date, have demonstrated any long range order of the diamond lattice structure.[13] One postulate is that of a microcrystalline structure composed of very small diamond crystallites packed together in a random array. One of the major long-range thrusts of this research will be to attempt to develop a diamond lattice structure in the films. The desired end result is a single crystal diamond film for semiconductor application. Doping the crystal would be accomplished by the same process as the original growth.

Diamond semiconductors would enable a new class of electronic devices capable of operation at junction temperatures in excess of 400° C.

Magnetic Devices

Magnetic devices have traditionally been a major item of concern for the space power system designer. The mass and power losses of transformers and inductors have been major drivers on mechanical and thermal design.

As high-power, high frequency transistors became available, as a result of this program, it became possible to consider designing transformers for up to 50 kHz operating frequency.

As the switching frequency increased, the core size and mass decreased, this also reduced the length per turn of wire, reducing wire mass. But with reduced core cross section came reduced ability to conduct away heat. One approach to addressing this problem was to design a transformer with integral heat pipes. Figure 6 shows a comparison between the resulting unit and previous technology. The heat-pipe cooled unit, designed and fabricated by TRW Space Systems Division under NASA Contract NAS 3-21372, is about 70 percent of the mass of the conventional transformer but more importantly has a temperature rise of 0.5° C/W loss instead of the 1.33° C/W loss of conventional technology.[14]

The heatpipes required to remove the heat from this transformer are sensitive to orientation, unless carefully placed, their performance can be substantially different in a one "G" environment than in a zero "G" environment.

Under Contract No. NAS 3-21948, the Thermal Technology Laboratories designed a 25 kW, 20 kHz transformer using pie windings and aluminum heat sinks. The results are shown compared to previous technology in Table III (see Fig. 7) The specific mass resulting for this transformer is 0.13 kg/kW at an efficiency of 99.2 percent. Characterization tests presently underway at Lewis will determine long-term temperature rise, corona inception voltage, core and copper losses, and efficiency versus frequency.

Rotary Power Transfer

Power systems in space employing solar arrays for power generation require an articulation between the array, which must be sun-oriented, and the spacecraft body, which is normally earth-facing. Power from the array must be transferred across this rotating joint to the loads in the spacecraft body. In the past, this has been accomplished by a cable across the joint or slip rings.

The NASA initiative for a low earth-orbit-space station has created a set of stringent requirements for a power transfer mechanism which includes power levels in the 50 to 100 kW range and 50 000 rotations at a period of 90 min/ rotation. This represents two orders of magnitude-greater-power transfer capability and an order of magnitude-greater-life than has previously been a requirement (information from a Space Operations Center (SOC) Study done under NASA contract by Boeing Aerospace Corp). One of the concepts under development at Lewis is a rotary power transformer. The concept of a rotary transformer for power transfer is appealing for several reasons; the transformer is scalable to almost any size, life is not limited by wear mechanisms, and a transformer is not subject to contact welding or frictional forces and does not create debris. In addition, the rotary power transformer can be an integral part of a converter to transform array bus voltage to spacecraft distribution voltage and serve as the isolation between the spacecraft distribution system and the array bus.

The technology areas requiring attention are efficiency, transformer mass and thermal control. NASA Lewis Contract NAS 3-22266 with General Electric has resulted in some design concepts which are still under evaluation. The characteristics of the design concept are shown in Table IV and Fig. 8.[18] Certain constraints were placed on the design; the total input inductance was specified as 75 μH so the transformer could be used in a series resonant inverter circuit.

Operating frequency was specified to be 20 kHz with an efficiency greater than 95 percent and an operating life in excess of 5 years; the input voltage was 440 V and the design was to be comprised of 4-25 kW modules.

An alternative design is under development on Contract NAS 3-23115 with General Electric which will provide a high degree of modularity and in situ repairability on early concept as shown in Fig. 9.[15]

Summary

The development of advanced power handling devices is essential to the creation of a high voltage power system. The Lewis Research Center of NASA has an ongoing program to develop power system components designed to address the unique requirement of advanced space power systems.

Research and technology is being performed on: lightweight low-cost conductors using graphite fibers intercalated with electron donor materials that may yield wires and cables with the conductivity of copper at one third the mass; new semiconductor devices for high-speed, high-current, high-voltage applications using conventional p-n junction technology and a new class of semiconductors using deep impurity levels that promise to yield high-voltage (up to 100 000 V) switches and high current switches with extremely low forward drop; dielectrics such as diamond-like films that are extremely hard, have high dielectric strengths and withstand operating temperatures in excess of 300° C; and magnetic devices whose design has provided a substantial reduction in weight.

Results to date from this program have been a family of high-frequency transistors and diodes, ultra-lightweight transformers, and lightweight graphite conductors. The latest version transistor has a max voltage of 1200 V at 100 A with a gain of 10 and a 0.5 μsec rise/fall time, and a 1000 V diode with a 50 A current capability and 0.4 μsec rise/fall time. A 25 kW transformer at 20 kHz has been developed that weights 3.2 kg at an efficiency of 99.2 percent. The specific mass of this transformer is 0.13 kg/kW. Graphite conductors intercalated with $CuCl_2$ have demonstrated resistivities of 12.9 μΩ cm, which combined with the 1.7 g/cc density of graphite fiber yields a product that is only one and one half-times as heavy as copper for equivalent resistance.

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Table I Bi-Polar Transistor Development

Transistor	Voltage, V	Current at gain = 10, A	Power handling, kW	Power dissipated at 75° C	Rise/fall, μsec	Storage, μsec
D 60T Manufacturer: w	400-500	50	25	625 W	0.5	2.5
D 7ST manufacturer: w	400-500	100-150	50	2 kW	0.75	4.0
Developmental manufacturer: w	1000-1200	25-40	30	1.25 kW	0.5	3.0
Augmented Manufacturer: w	1000-1200	100	100	1.25 kW	0.5	2.5

Table II High Power Diode Development

Diode	Voltage	Current	Power handling	Thermal resistance junction to case, °C/W	Reverse recovery, μsec
PTC 900 Manufacturer: Power Transistor Corp.	1000	50 A	50 kW	0.8	0.4 (From 50 A)
Manufacturer: Power Transistor Corp.	1000	150 A	150 kW	0.5	0.2 (From 150 A)

Table III Comparison of Transformers

Transformer	Power, kW	Frequency, Hz	Mass, kg	Per cent	Temperature rise, °C/W	Specific mass, kg/kW
Utility distribution transformer	25.0	60	180.0	97.9	0.16	7.2
Space Power trans. conduction cooled	2.2	10 K	1.8	98.6	1.33	0.8
Heat pipe cooled	2.2	10 K	1.2	98.2	0.5	0.55
Pie wound	25.0	20 K	3.2	99.2	0.25	0.13

Table IV Rotary Power Transformer

Power level:	100 kW; 25 kW/module
Frequency:	20 kHz
Mass:	40 kg
Efficiency:	98.7 percent
Operating temp: (80° C radiator)	Core: 116° C Max Coils: 138° C Max
Volume:	0.01 M^3
Inductance: (25 kW module)	Input 19 μh Secondary 30 μh

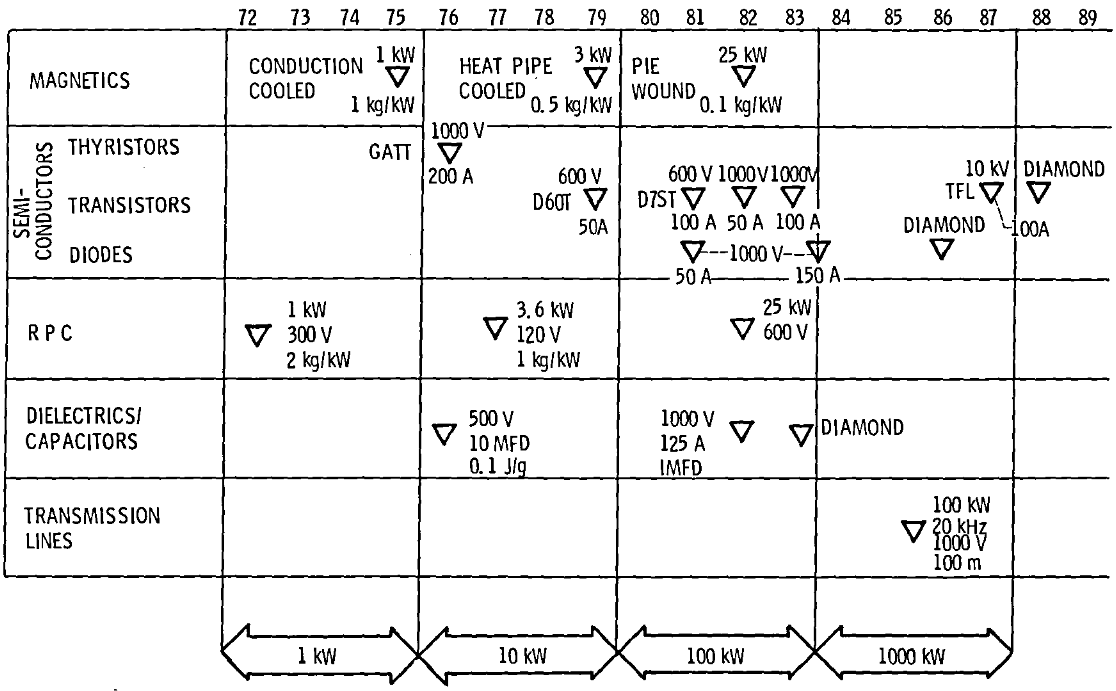

Figure 1. - Power electronic component development at Lewis Research Center.

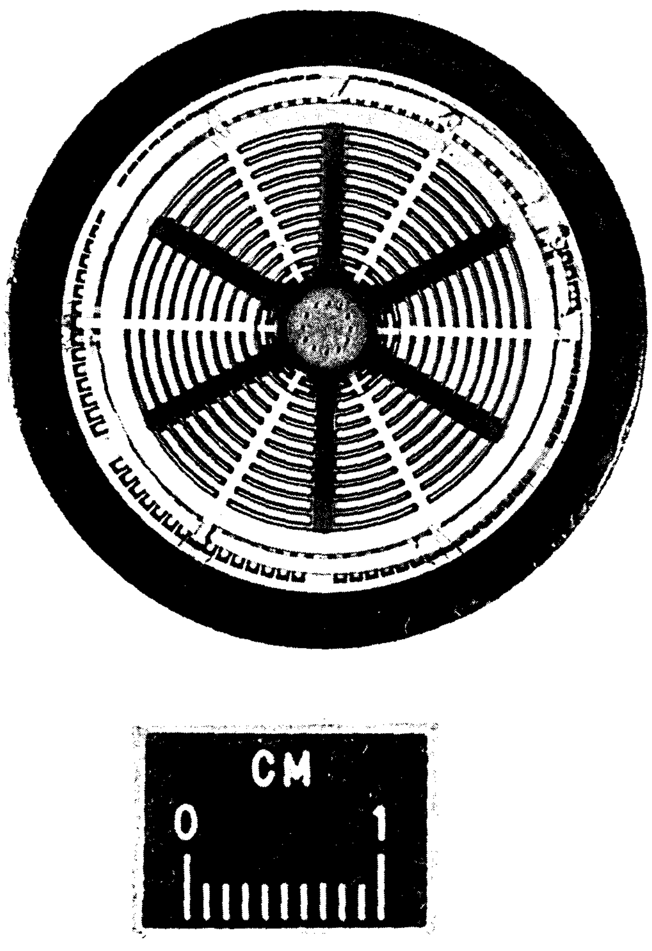

Figure 2. - Mask design for high-voltage transistors.

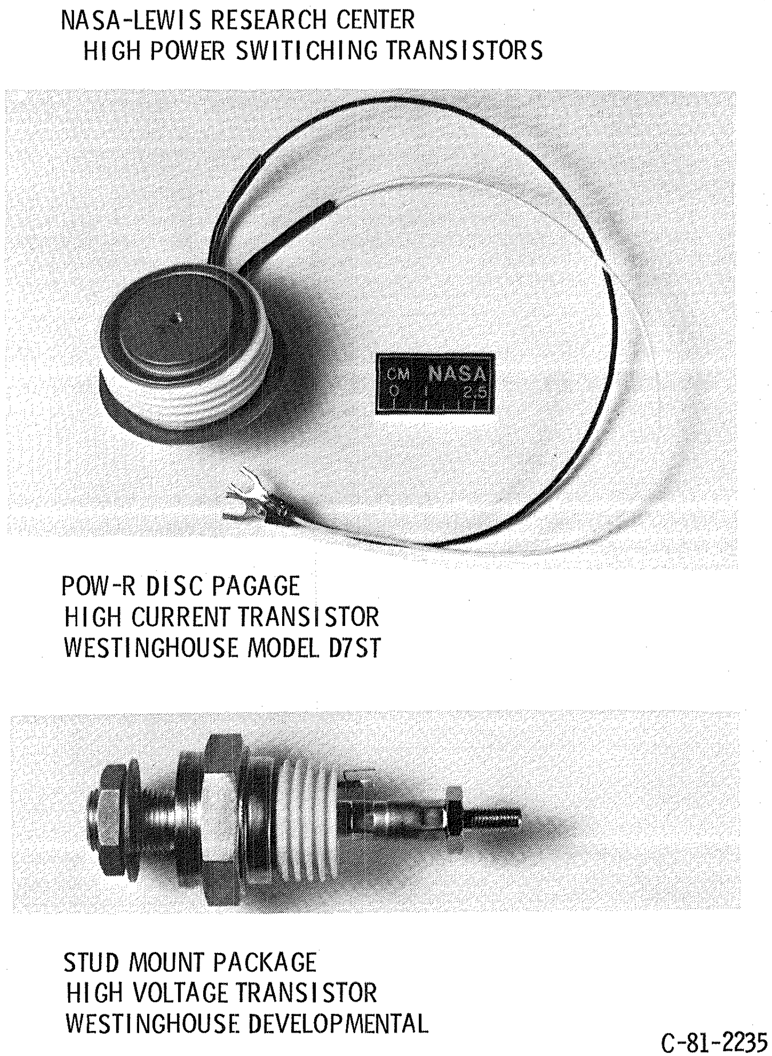

Figure 3. - Power transistors in disc and stud mount packages.

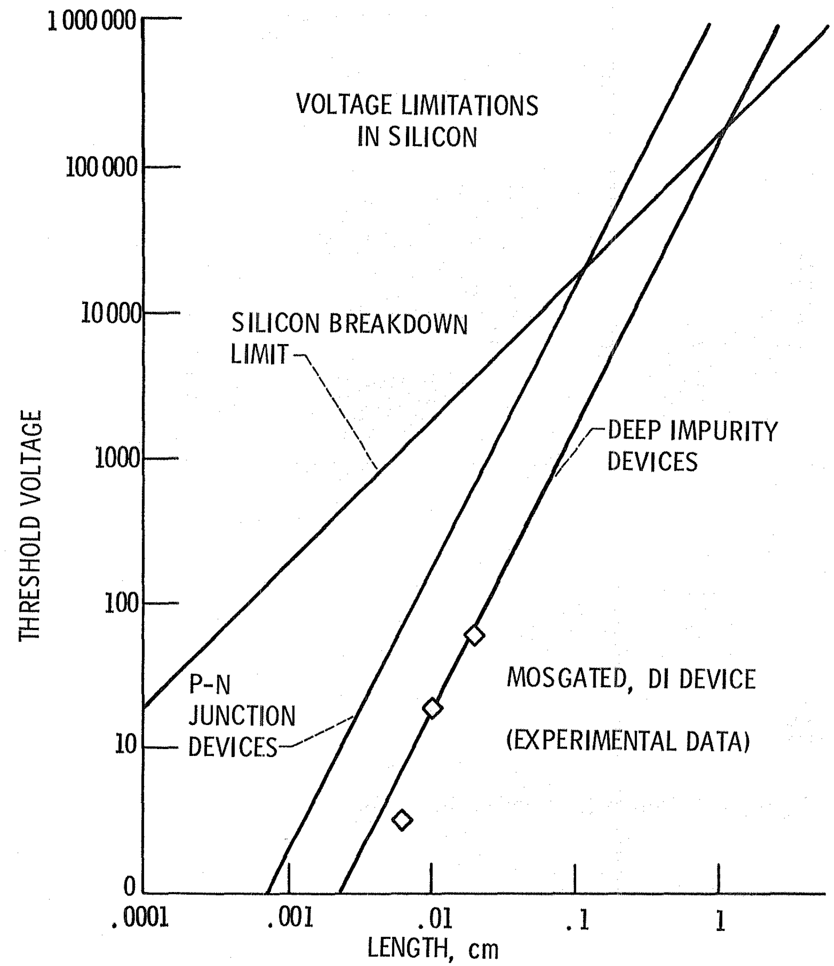

Figure 4. - High voltage capability of deep impurity devices compared to P-N junction devices.

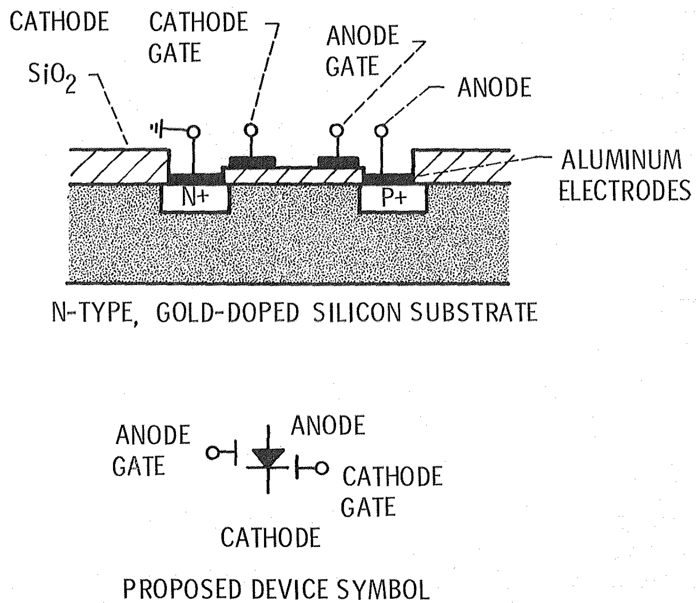

Figure 5. - Zero forward voltage drop, double gated device.

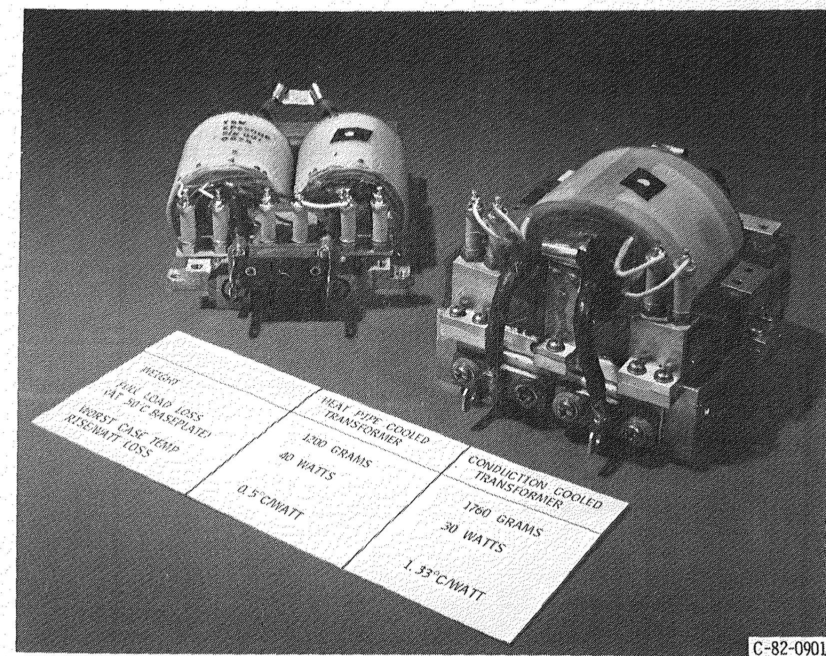

Figure 6. - Heat pipe cooled transformer.

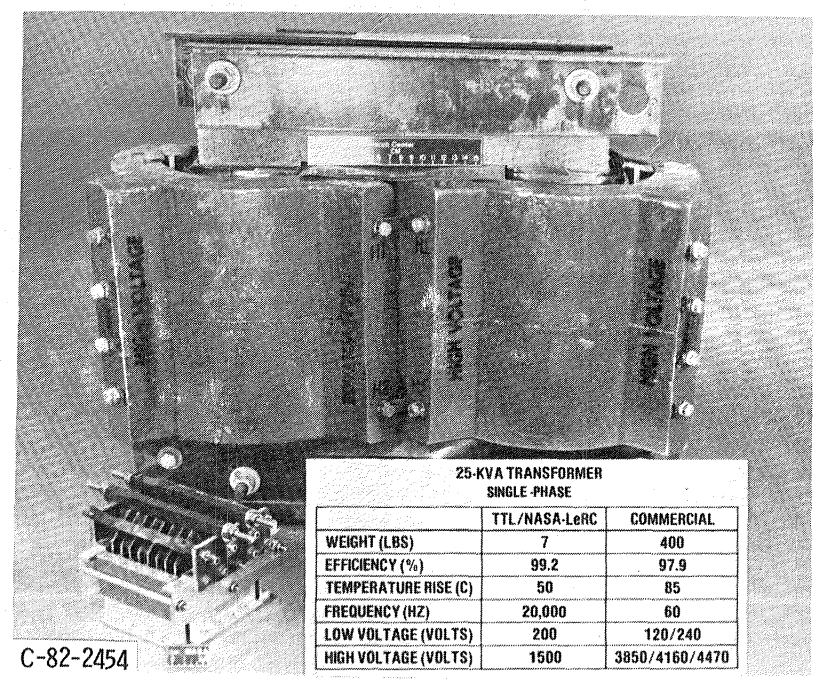

Figure 7. - Comparison of space type ultra lightweight transformer (lower left) with commerial transformer.

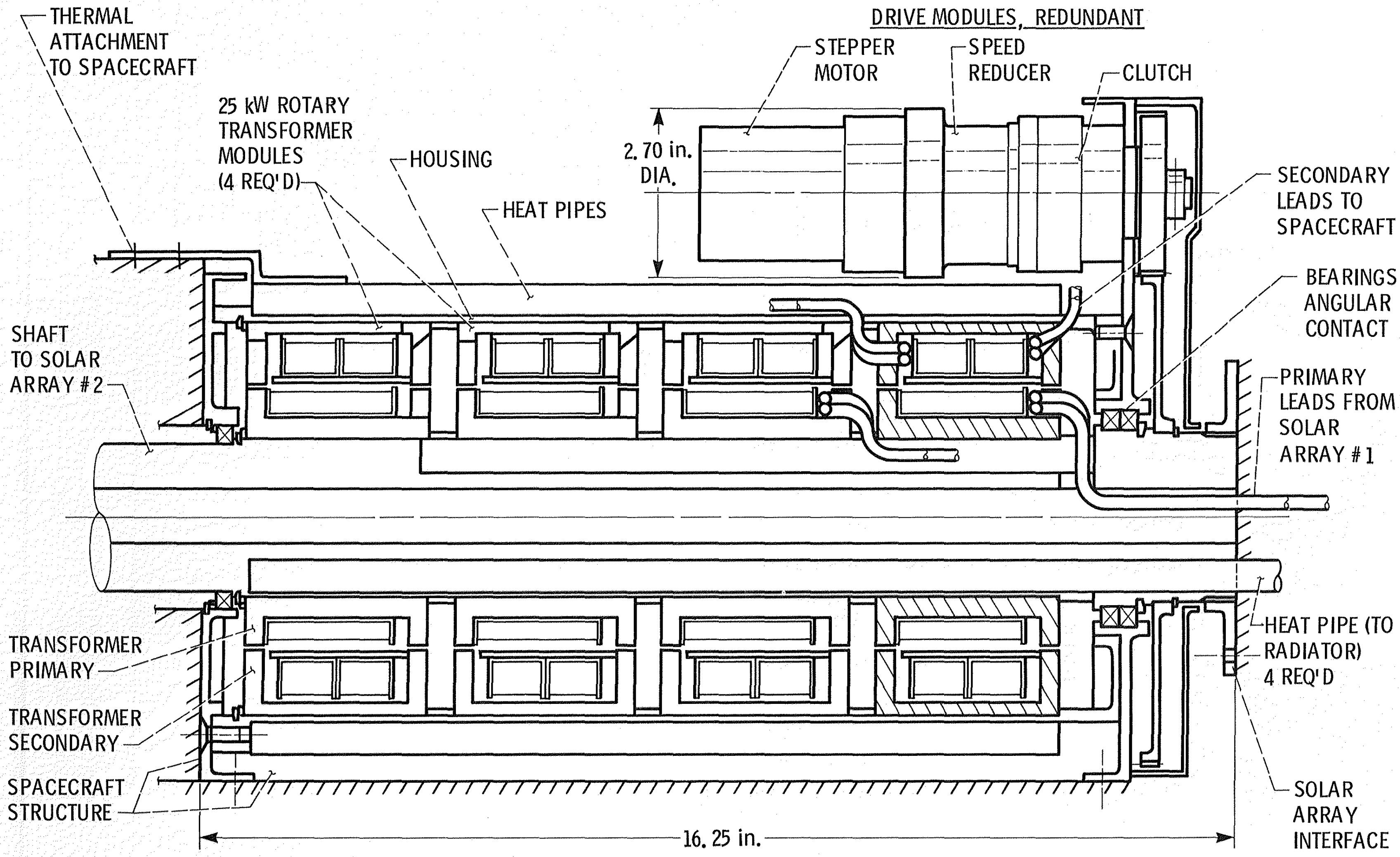

Figure 8. - 100 kW rotary power transformer, cylindrical design.

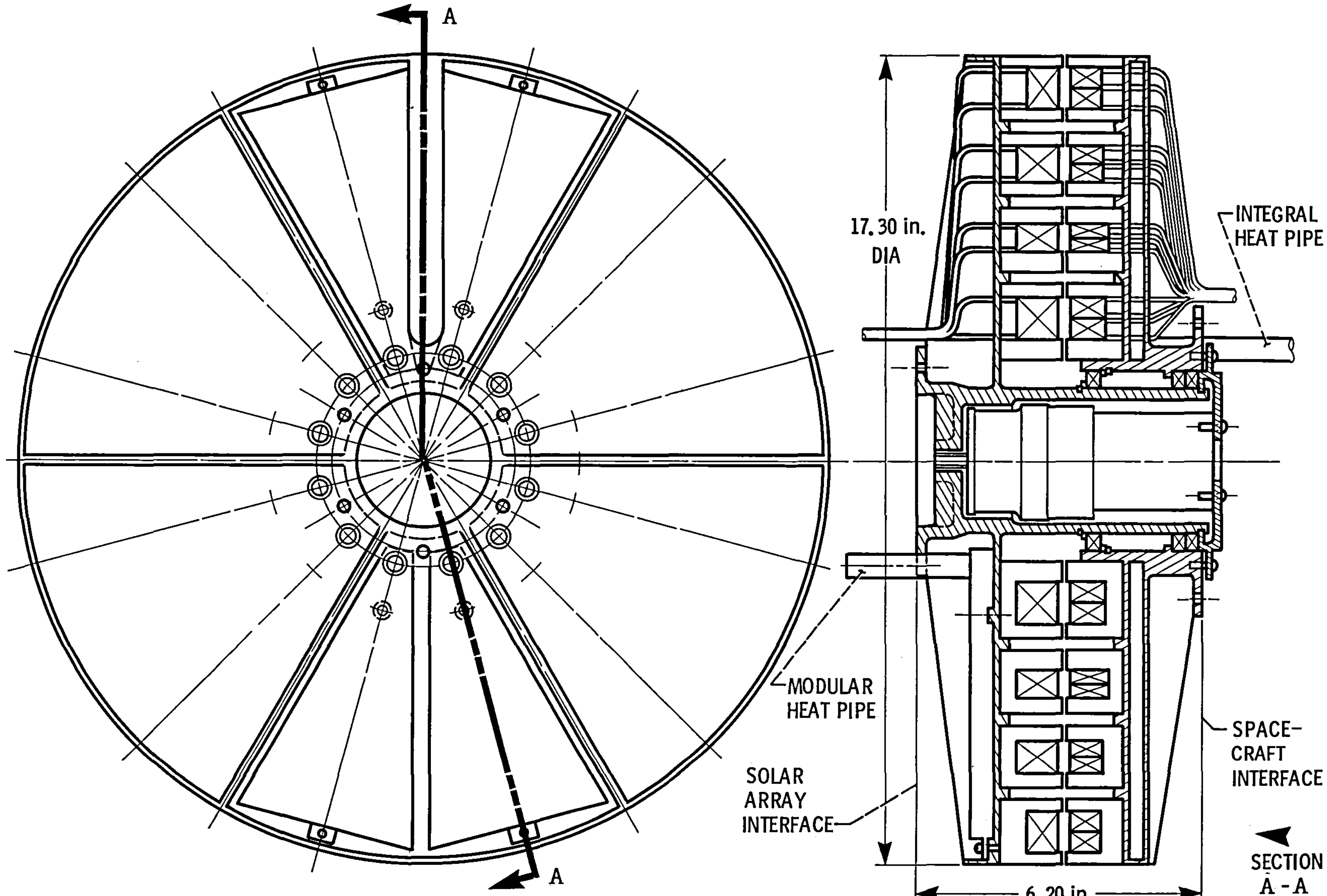

Figure 9. - Rotary power transformer, pancake design.

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