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Advanced Electrical Power System Technology for the All Electric Aircraft

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Robert C. Finke and Gale R. Sundberg
Lewis Research Center
Cleveland, Ohio

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ADVANCED ELECTRICAL POWER SYSTEM TECHNOLOGY FOR THE ALL ELECTRIC AIRCRAFT

Robert C. Finke and Gale R. Sundberg

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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ABSTRACT

The application of advanced electric power system technology to an all electric airplane results in an estimated reduction of the total takeoff gross weight of over 23 000 pounds for a large airplane. This will result in a 5 to 10 percent reduction in direct operating costs (DOC). Critical to this saving is the basic electrical power system component technology developed by the Lewis Research Center of NASA for future space applications. These advanced electrical power components will provide a solid foundation for the materials, devices, circuits and subsystems needed to satisfy the unique requirements of advanced all electric aircraft power systems.

The Lewis/OAST program for the development of advanced electrical power component technology is described in this paper. The program is divided into five generic areas: semiconductor devices (transistors, thyristors and diodes); conductors (materials and transmission lines); dielectrics; magnetic devices; and load management devices.

Examples of progress in each of the five areas are 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 up to 100 kV is described. Solid state power controllers for load management at 120 to 1000 V and power levels to 25 kW have been developed along with a 25 kW, 20 kHz transformer weighing only 3.2 kg. Progress on the creation of diamondlike 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

From 1968 to 1978 the direct operating costs (DOC) of passenger aircraft almost doubled, largely as a result of increases in jet fuel costs[1]. The NASA Aircraft Energy Efficiency (ACEE) and Energy Efficient Engine (E^3) programs have addressed this problem. The ACEE program has spurred development of high-aspect ratio wings, super-critical airfoils, and composite structures as a means of reducing weight, drag and, thereby, lowering the DOC. The move toward relaxed static stability aircraft also has the potential of additional fuel savings, but has the associated requirement of an all electric flight control system. The E^3 program has yielded engines with higher efficiencies and lower fuel consumption by introducing higher by-pass and compressor ratios.

Additional savings can accrue if conventional aircraft design is advanced to replace the hydraulic/pneumatic/electric/engine-bleed-air system with an all electric power system using technology presently under development for future high power space systems. Projected savings that can result from the application of an all electric airplane, including the advanced power system technology, have been estimated in the NASA/Lockheed study to be 23 500 pounds reduction in total takeoff gross weight[2]. This represents a 10 percent weight reduction in the airplane and can result in a 5 to 10 percent reduction in DOC. When the DOC for a large fleet of aircraft over their entire useful life is considered, the total impact of these technologies can be very large (several billion dollars).

The concept of the all electric airplane is not new. Several bombers flown during World War II were designed as all electric airplanes[2]. However, the technology for actuators was relatively primitive. For example, 28 volt series wound motors were geared down for actuating control surfaces by means of flexible cable drives, while the total amount of electronic control for the system was limited by the fragile and power consumptive vacuum tubes that were available. Since World War II, the advances in electronics and power system technology have been enormous. Digital electronics and microprocessors have made fly-by-wire systems a reality.

Aircraft designers have not had the advantage of similar technology advances for the aircraft power distribution and control systems. As a consequence, many of the aircraft functions are still performed by hydraulic or pneumatic systems, which add significantly to the weight and complexity of the secondary power system.

In the last ten years, rare earth permanent magnet motors and generators have achieved significant increases in energy densities, making possible electromechanical actuators that are equal in performance to hydraulic systems[3]. Technology developments in power conversion components and circuits for the nation's space program will make available to the aircraft designer the same opportunities for improving electrical power systems that digital microelectronics has done for the flight control systems.

The Lewis Research Center several years ago formulated a program to address the component needs for high power space electrical systems. The program 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 Lewis research and technology program:

- 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 $(DI)^2$ semiconductors (using Deep Impurity levels with Double Injection techniques) that promise to yield high-voltage (up to 100 kV) and high-current switches with extremely low forward voltage drop;

- dielectrics such as diamondlike films that are extremely hard, have high dielectric strengths and withstand operating temperatures in excess of 300° C;

- magnetic devices whose advanced thermal design has provided a substantial reduction in weight; and

- solid state remote power controllers and circuit breakers for controlling power to loads at voltages from 120 to 1000 V and power levels of up to 25 kW.

Results to date from this program have been a family of high-frequency transistors and diodes, a new family of deep impurity semiconductors, a feasibility study of lightweight graphite conductors, research on thin film diamond dielectrics, ultra-lightweight transformers, and a series of solid state RPC's that span wide voltage and power ranges. Examples of progress made in these areas are described in this paper. As in any program, resource limitations preclude the development of all elements simultaneously. However, the components described are foundational for creating and building an advanced electrical power system for an all electric airplane.

BIPOLAR TRANSISTORS AND DIODES

Under Contracts NAS3-21380[4], NAS3-21949[5], and NAS3-22782 with Westinghouse Electric Corporation, NASA Lewis undertook the technology development for high voltage, high power, high frequency 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 a finely interdigitated baseemitter geometry with narrow emitter fingers and long perimeter length. High current carrying capacity requires a maximum emitter-to-base area ratio with minimum contact resistance, which was achieved by compression bonded encapsulation techniques. Base resistivity at the higher current levels was reduced by means of a metallized polyimide insert. The final emitter design with the base insert is shown for a 33 mm diameter wafer in Fig. 2 and the completed package in Fig. 3. This configuration has been successfully used to carry collector currents up to 200 amperes.

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 Research Center has been sponsoring work for almost ten 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, Deep Impurity, $(DI)^2$, switching devices which consist of a p^+ (hole injection) and an 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 switching characteristics of these devices are very similar to the conventional SCR. However, threshhold voltage is proportional to the square of the interelectrode spacing for a given deep impurity doped, bulk semiconductor material[6]. Concomitantly, current-handling capacity may be adjusted by increasing or decreasing electrode area.

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. Figure 4 illustrates the apparent possibilities. If the analysis and preliminary data are correct the voltage limits for these devices could be 100,000 volts, an order of magnitude higher than presently available[7].

The recent studies of gating phenomenon have added many possibilities to the switching applications of $(DI)^2$ devices. Figure 5 shows a generalized volt-ampere characteristic curve showing the switching effects of two types of gates. The cathode gate (a MOS type gate near the cathode) alters the threshold voltage level to initiate or inhibit breakdown into the high current region. The injection gate on the other hand modifies the holding voltage - either pushing toward zero or to higher voltages to turn the device off - depending on the polarity of the gate voltage.

The application of zero forward drop devices and opening switches are numerous and varied. The Lewis Research Center is pursuing the industrial development of this device as a possible high voltage switch under contract NAS3-22247 with the Westinghouse Research and Development Center.

CONDUCTORS

As spacecraft, aircraft, 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 inert chemically, and are usable to temperatures in excess of 1000° C.

The resistivity of ordinary carbon fibers is high, however, 200 to 450 $\mu\Omega$-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 ($CuCl_2$). Exposure to $CuCl_2$ vapor at 480° C has created resistivities of 12.9 $\mu\Omega$-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 $\mu\Omega$-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, under Grant No. NAG3-95.

In addition, an in-house effort at LeRC 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 aerospace power systems. It has a thermal conductivity of 20 W/cm K, approximately 5 times greater than that of copper at room temperatures. The resistivity of natural diamond can be as high as 10^{16} Ω-cm. With sufficient impurities, diamond can have a resistivity as low as 10Ω-cm. In addition, its thermal coefficient of expansion is comparable to that of Invar[10]. Diamond may be used at temperatures to 500° C in air or 1500° C in vacuum before it decomposes.

With all these desirable properties, the Lewis Research Center formulated a program to attempt to deposit diamondlike 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 Å thick films[12].

Deposition of films with an adequate thickness for electronic application (10 to 100 μm) remains a challenge. Spontaneous peeling and spalling occurs when film thicknesses exceed 10 000 Å 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.

TRANSFORMERS

Magnetic devices have traditionally been a major item of concern for the aerospace power system designer. The mass and power loss 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 resulted in a decreased length per turn and mass of copper wire. However, with decreased core cross section came a reduction in the core's ability to conduct heat away. 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 NAS3-21372, 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 insensitive to orientation. Their performance is substantially unchanged between a one "G" environment and a zero "G" environment.

Under Contract No. NAS3-21948, the Thermal Technology Laboratories designed a 25 kW, 20 kHz transformer using pie windings and aluminum heat sinks[15]. 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.

SOLID STATE REMOTE POWER CONTROLLERS

Solid state RPC's provide well-defined, standard interfaces between power sources and loads in large, high voltage power distributuion systems. They are compatible with the multiplexed data bus power management and control interfaces required for larger power systems. Solid state RPC's are a critical component in the continued efforts to reduce system complexity, shorten power bus runs, and decrease the number of switching operations. In anticipation of this need for suitable switchgear, considerable effort has been concentrated over the past twelve years by the NASA Lewis Research Center to develop solid state RPC's that can be used on higher voltage dc and ac power distribution systems.

Through NASA and the DOD several 28 V dc and 115 V ac RPC's have been fully developed and are operational. The Space Shuttle, for example, uses over 500 solid state RPC's per vehicle in six ratings from 3 to 20 amperes at 28 V dc. RPC's for 115 V ac are available in single and three phase units for currents in the range of 10 to 100 amperes and 400 Hz. The 115 V ac controllers along with some 230 V ac RPC's for the B-1 were developed under direction of the Air Force Aero Propulsion Laboratory at Wright Patterson Air Force Base[16].

While the Air Force work was progressing in ac power controllers, NASA LeRC has systemmatically pushed the development of dc solid state RPC's up to 1000 volts and 25 kW. Specific developments have focussed at 120, 270/300, 400 and 1000 V dc. Space-flight qualifiable solid state RPC's at 5 and 30 amperes are available at 120 V dc. Figure 8 shows this RPC with a listing of some of the outstanding features incorporated into the NASA development at all voltage and power levels[17]. Breadboard units have been built and tested at 270/300 V dc that handle currents of 1, 2, 50, and 80 amperes[18]. One high current unit at 300 V dc also incorporates an electromechanical contactor with solid state arc suppression to give very low forward voltage drop.

With the new family of D7ST transistors available from NASA LeRC supported development, 400 V dc, 100 ampere solid state RPC's are possible. A 1000 volt, 50 ampere bipolar transistor developed through NASA LeRC has enabled a 1000 V dc, 25 kW RPC to be demonstrated.

Other variations using thyristors and series-parallel combinations of power MOSFETs have also been built and demonstrated at 400 to 1000 V dc and 25 kW power levels. Several prototypes have been tested successfully in space rated vacuum. Most of the RPC's demonstrate all the advantages listed for the solid state RPC in Fig. 8.

Solid state RPC's have an important role to play not only in large space power systems but also future aircraft such as the all electric airplane. Although much work has already been done on RPC's by NASA and others, much work needs to be done at the system integration level at the higher voltages and powers. However, we believe the basic technology is ready to be applied in the next generation of both spacecraft and aircraft.

SUMMARY

The development of advanced power handling devices is essential to the creation of a high voltage electrical power system. The Lewis Research Center of NASA has an ongoing program to develop power system components designed to address the unique requirements of advanced space power systems. These advanced electrical power components as described in this paper could provide the technological basis for many of the materials, devices, circuits and subsystems needed to satisfy the unique requirements of advanced all electric airplane power systems.

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 sustaining voltage of 1000 V at 100 A with a gain of 10 and a 0.5 μsec rise/fall time. A 1000 V diode with a 50 A current capability and a 0.4 μsec recovery time was developed for Lewis and is now commercially available, while a 150 A version is soon to be introduced. Development of the new class of $(DI)^2$ semiconductors that will switch 1 to 10 kV at 10 to 100 kW and display a low forward voltage drop is well underway.

A 25 kW transformer operating at 20 kHz has been developed that weighs 3.2 kg with 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/cm^3 density of a graphite fiber, yields a conductor that is nearly competitive with copper in weight and conductivity.

While other governmental agencies have demonstrated 115/230 V ac solid state RPC's for various power levels at 400 kHz, NASA Lewis Reseach Center has systemmatically pushed the development of dc solid state RPC's up to 1000 V and 25 kW power levels from the 28 V dc, 600 W level of Space Shuttle RPC's. Specific developments have focussed at 120, 270/300, 400 and 1000 V dc at power levels from 600 W to 25 kW. Various types of bipolar transistors, Darlingtons, thyristors and series-parallel combinations of MOSFETS have been demonstrated successfully as the primary switching elements in the solid state RPC's. The dc solid state RPC technology demonstrated includes full power operation with all generic types of sources, loads, microprocessor control, space flight environments, and possible applications to ac systems.

REFERENCES

1. Stewart, W.L., et al, "Preparing Aircraft Propulsion for New Era in Energy and Development, (NASA Lewis) Published Astronautics and Aeronautics, January, 1980.
2. Cronin, M.J., "The All Electric Airplane as an Energy Efficient Transport," Lockheed-California company, SAE paper, Aerospace Congress and Exposition, Los Angeles, California, 13-16 October, 1980.
3. Edge, J.T., "An Electromechanical Actuator Technology Development Program", SAE Committee A-6 Symposium, Cherry Hill, New Jersey, 12 April, 1978, Paper No. 780581.

4. Hower, P.L., "High-Current, Fast-Switching Transistor Development," Westinghouse Research and Development Center, Pittsburgh, PA., NASA CR-165372, 15 March, 1981.
5. Hower, P.L., "High Voltage Power Transistor Develoment," Westinghouse Electric Corp., Pittsburgh, PA., NASA CR-165547, 30 October, 1981.
6. Henderson, H.T., Asbrock, J., and Kapoor, A., "A New Gated (SCR-like) DI Switching Device Based upon Deep Impurity Trapping and Relaxation Effects," IEEE 1978 International Electron Devices Meeting, pp. 680-683.
7. Personal communication from Dr. Ira Myers, NASA Lewis Research Center.
8. Seminar on Intercalated Graphite by Dr. John A. Woollam at Lewis Research Center, 24 March, 1982.
9. "Electrical and Mechanical Properties of Copper Chloride Intercalated Pitch Based Carbon Fibers" by Hisashi Ohima, John A. Woollam, Andre Yavrouian, and Michael B. Dowell. Accepted for publication by J. Appl. Phys.
10. Chrenko, R.M., and Strong, H.M. "Physical Properties of Diamond," General Electric Co., 75CRD089, Oct. 1975.
11. Banks, B.A., "Ion Beam Applications Research, A Summary of Lewis Research Center Programs," NASA TM-81721, 1981.
12. Banks, B.A., and Rutledge, D.K., "Ion Beam Sputter Deposited Diamondlike Films," NASA TM-82873, 1982.
13. Angus, J.C., "Characterization of Diamondlike Films," NASA CR-165493, 1981.
14. Chester, M.S., "Heat Pipe Cooled Power Magnetics," TRW Defense and Space Systems Group, Redondo Beach, CA., (NASA CR-159659), December, 1979.
15. Welsh, J.P., "Design and Development of Multi-kW Power Electronic Transformers," NASA CR-168082, February, 1983.
16. Caputo, E. and Fox, D.G., "Future Trends in Air Force Aircraft Electrical Power Distribution and Control," AIAA Paper 77-493, St. Louis, Missouri, March, 1977.
17. Sundberg, G.R., and Billings, W.W., "The Solid State Remote Power Controller: Its Status, Use and Perspective," IEEE Power Electronics Specialists Conference-1977, Palo Alto, California, 14-16 June, 1977.
18. Billings, W.W., "High Voltage DC Switch-gear Development for Multi-kw Space Power Systems," NASA CR-165413, November, 1981.

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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, sec
D60T	400-500	50	25	625 W	0.5	2.5
D7ST	400-500	100-150	50	2 kW	0.75	4.0
D7 High Voltage	1000-1200	25-40	30	1.25 kW	0.5	3.0
Augmented	800-1000	100	100	1.25 kW	0.5	2.5

*Westinghouse Electric Corporation.

TABLE II. - HIGH POWER DIODE DEVELOPMENT*

Diode	Voltage, V	Current, A	Power handling, kW	Thermal resistance junction to case, °C/W	Reverse recovery, μsec
PTC 900	1000	50	50	0.8	0.4 (from 50 A)
PTC 150 A Diode	1000	150	150	0.5	0.2 (from 150 A)

*Power Transistor Company.

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

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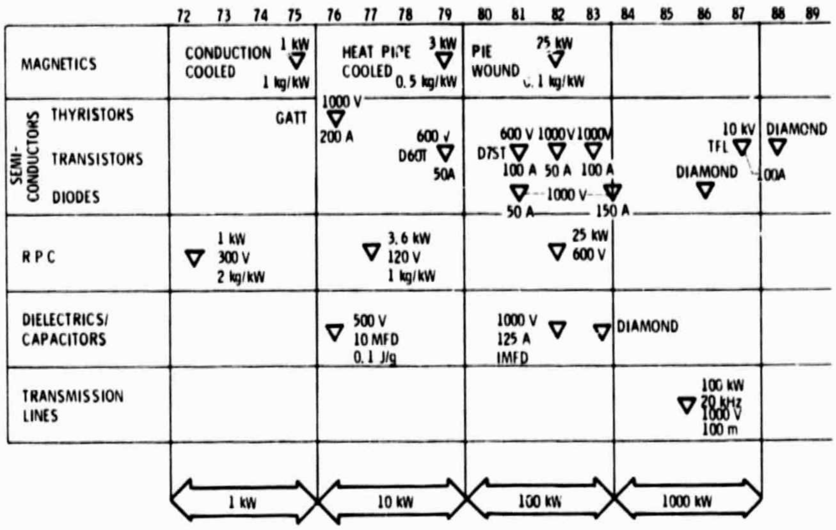

Figure 1. - Power electronic component development at Lewis Research Center.

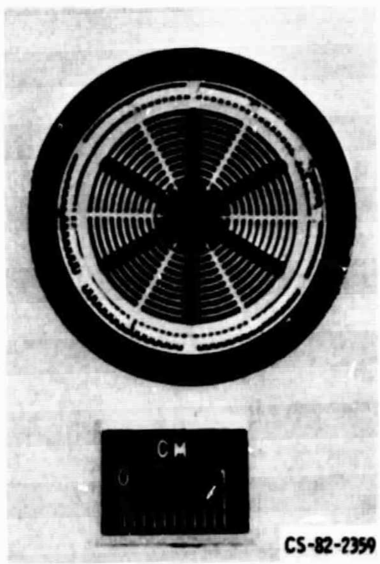

Figure 2. - Interdigitated base-emitter design for high voltage transistors.

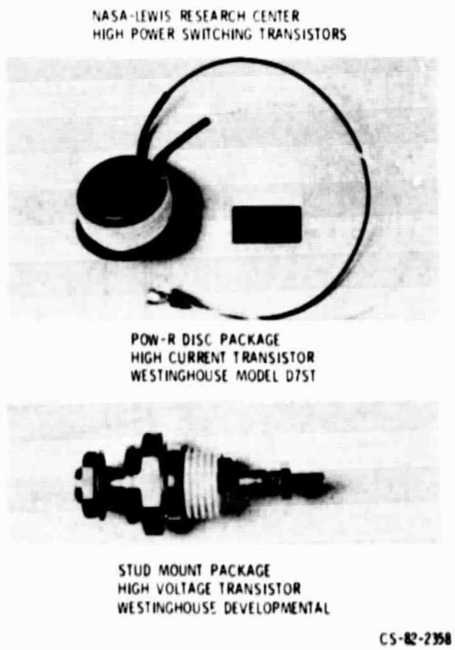

Figure 3. - Power transistors in disc and stud mount packages.

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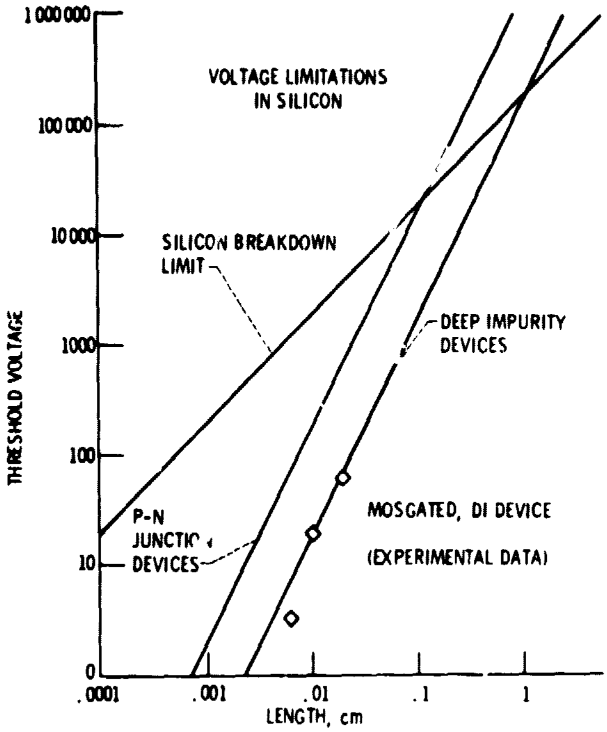

Figure 4. - High voltage capability of deep impurity devices compared to P-N junction devices.

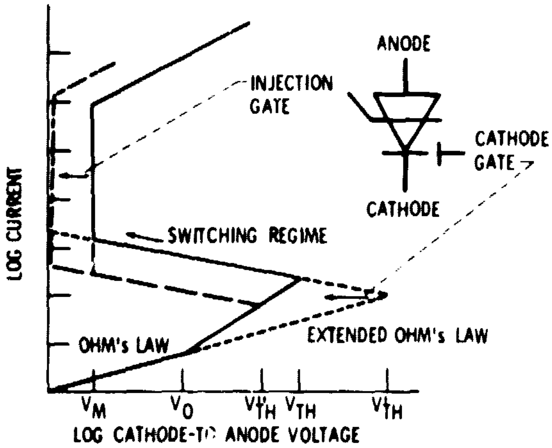

Figure 5. - Volt-ampere characteristic showing gating effects of $(DI)^2$ devices.

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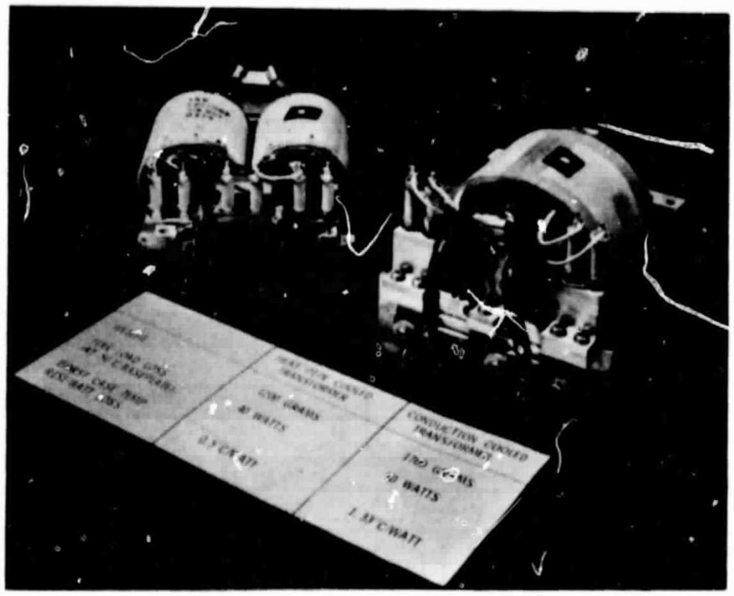

Figure 6. - Hea' pipe cooled transformer.

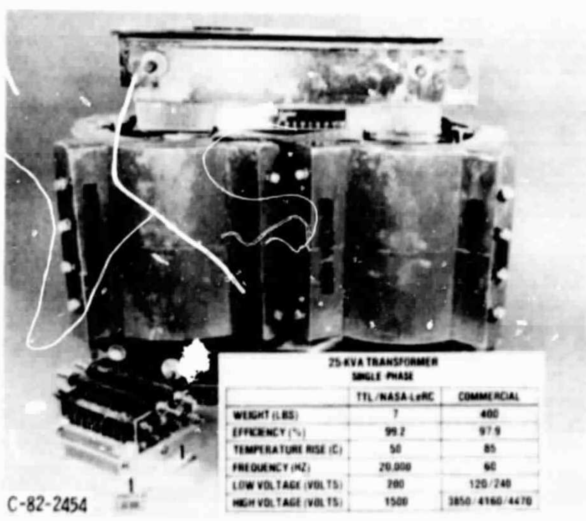

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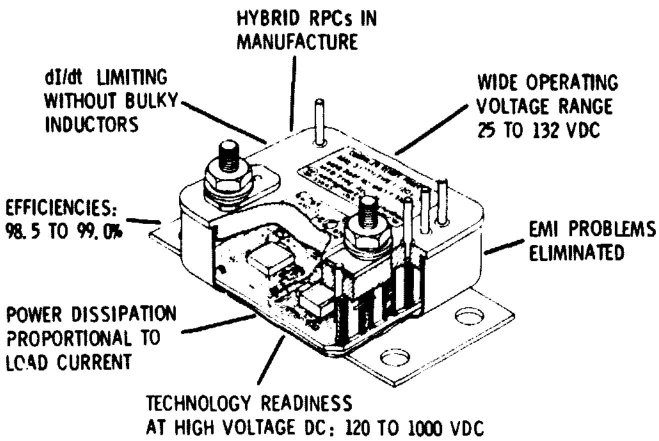
Figure 7. - Comparison of space type ultra lightweight transforrner (lower left) with commercia' transformer.



- COMPATIBLE WITH SOURCES, LOADS, COMPUTER CONTROL
- UNIVERSAL DESIGN APPLICABLE TO ANY VOLTAGE LEVEL
- SEVERAL AREAS OF POTENTIAL APPLICATION
- CONTROL 115 VAC POWER WITH SLIGHT MODIFICATION

Figure 8. - Outstanding features of NASA Lewis solid state RPC's.