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High Voltage-High Power Components for Large Space Power Distribution Systems

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HIGH VOLTAGE-HIGH POWER COMPONENTS FOR LARGE SPACE POWER DISTRIBUTION SYSTEMS

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ABSTRACT

For over a decade, Lewis Research Center has been developing space power components. These components include a family of bi-polar power switching transistors, fast switching power diodes, heat pipe cooled high-frequency transformers and inductors, high frequency conduction cooled transformers, high power-high frequency capacitors, remote power controllers and rotary power transfer devices. Many of these components such as the power switching transistors, power diodes and the high frequency capacitor are commercially available. All the other components have been developed to the prototype level. Series resonant dc/dc converters have been built to the 25 kW level.

INTRODUCTION

In the late sixties and early seventies it became apparent that the power requirements of future spacecraft would rise from the present kilowatt level to the hundreds of kilowatt level by the year 2000. The initial space station which is planned for the early nineties has a projected power level of 75 kW. In order to build these new high power distribution systems (high voltage, high frequency ac or high voltage dc), the component technology has to be developed to at least the prototype level and if possible to be commercially available. For over a decade, Lewis Research Center has been providing space power components (fig. 1) to this level of maturity by setting the program goals, performing in-house tests, funding of grants, hiring contractors and encouraging the commercialization of new devices.

Since the early sixties, Lewis Research Center has been developing power processors starting with the SERT I (Space Electric Rocket Test) up to the present with the 30 cm ion engine power processor, shown in Fig. 2. A power processing chronology is shown in Table I. A 25 kW dc/dc 20 kHz series resonant converter (1) was completed to the prototype level. A prototype 3 kW bidirectional converter (2) was completed which demonstrated power flow in both directions. Presently General Dynamics is performing system tests on a 15 kW high frequency (20 kHz) system using 8 kW ac and dc load modules (3). These programs provide information on component deficiencies which lead to new component development programs.

The low voltage dc distribution system will not be adequate due to the large conductor weight required to carry the currents. An obvious solution to reducing conductor weight is to raise the operating voltage. Another way to reduce system weight of ac systems is to use high frequency which decreases both weight and size of the magnetic devices such as transformers.

Lewis Research Center has been developing power components that will take advantage of both high voltage and high frequency. These components will enable the building of large space power systems such as a high voltage, high frequency power distribution system and/or a high voltage dc/dc converters for large multiple voltage dc power distribution systems. The objective of this paper is to summarize the Lewis Research Center space power component technology and provide a comprehensive report.

SEMI-CONDUCTORS

High voltage, high power switching devices are required components for either an ac or dc high voltage/high power distribution system. In 1974, Lewis started a 25 kW switching device program (4) with Westinghouse, which developed the D60T/D62T Transistor. The D60T/D62T is capable of handling 50 A continuous (200 A peak) collector currents with a gain of 10 at 400 to 500 V and a switching frequency at 20 to 50 kHz. The D60T/D62T high power switching transistor found many terrestrial applications as well as the space applications which led to its being selected for an IR-100 award as one of the 100 outstanding new products of 1978. After the D60T came the development of the D7ST (5) which doubled the power handling capability of the D60T from 25 kW to 50 kw. The D7ST can carry 100 to 150 A at a gain of 10 with operating voltages of 400 to 500 V.

The switching frequency of the D7ST is also 20 to 50 kHz. Next came the high voltage D7ST (6) which raised the operating voltage up to 1000 to 1200 V. The high voltage D7ST is capable of 25 to 50 A of continuous current (200 A peak) with a gain of 10. This device has 30 kW power handling capability of switching frequencies up to 50 kHz. The last of these devices is the augmented power transistor (7) which raises the current capability up to 70 to 112 A of continuous current (400 A peak) with a gain of 10. This last device has the power handling capability of 75 kW at frequencies of 20 to 50 kHz. The specifications of these devices is shown in Table II and three of the devices (left to right D60T, D7ST, Augmented Power Transistor) are shown in Fig. 3 with their respective chips.

Most of these devices are commercially available from Westinghouse and equivalent devices are now available from other vendors. They can be used in 25 to 50 kW high frequency inverters, high power dc/dc converters, electric motor controllers, VLF Transmitters, 20 to 50 kHz RF induction heaters, remote power controllers and power supplies for industrial applications.

Power Transistor Company developed for Lewis Research Center a fast recovery, high voltage power diode with a recovery time compatible with the D60T and D7ST. The PTC 900 diode (8) has a peak reverse voltage of 900 to 1200 V with an average forward current of 50 A. The diode can withstand peak surge currents of 1000 A and has a reverse recovery time of 200 ns at 50 A. A follow on program (9) increased the current capabilities of the diode to 150 A. These two diodes are shown in Fig. 4. These diodes are commercially available and can be used in high voltage, high frequency inverters, high power dc/dc converters, high power power supplies and motor controllers. Also a GATT (Gate-Assisted Turnoff Thyristor) (10) was developed to the prototype stage in 1976 which is capable of handling 200 A at 1000 V at frequencies up to 20 kHz.

REMOTE POWER CONTROLLERS

The ability to remove loads and to switch in spare units is accomplished on spacecraft with remote power controllers (RPC's). In the early 70's, Lewis started an RPC program with Westinghouse to develop RPC's that operate at 120 V dc (11) instead of 28 V dc. This program produced prototype units that are hermetically sealed, optically isolated, computer compatible and have over current protection or I^2t trip control. Prototypes were developed and built in 5 and 30 A ratings. Figure 5 shows the 120 V dc, 30 A model. A 1000 V, 25 A dc prototype RPC (12) has been completed which is optically isolated, has programmed transient protection and can withstand shorts. Figure 6 shows the circuit board along with the basic circuit of this RPC. A transistorized version of this RPC is also available. Lewis has not done any specific ac RPC development to date, but future work is planned in this area.

TRANSFORMERS AND INDUCTORS

In the late seventies, TRW developed for Lewis a heat pipe cooled transformer (13). The program produced a transformer that had a 30 percent reduction in weight and size. A comparison of a standard transformer to the heat pipe cooled transformer is shown in Fig. 7. The transformer shown has a 2.2 kW rating and a specific weight of 0.6 kg/kW at 20 kHz. The transformer had to be designed so that the decrease in transformer weight would only increase the thermal radiator and solar array weight by 50 percent of the decrease. This transformer was designed so that it could replace the one shown with it in Fig. 7 in the 30-cm ion engine power processor shown in Fig. 1.

In the early eighties, Thermal Technology Lab., Inc., developed for Lewis a high frequency, 25 kVa space-type transformer (14) that has an efficiency greater than 99 percent and has a 35° C lower temperature rise than a commercial transformer as shown in Fig. 8. The specific weight of the space-type 25 kVA 20 kHz transformer is 0.127 kg/kVA. Power systems using this type of transformer should show a marked improvement in system weight, size, efficiency and reliability.

In conjunction with the TRW heat pipe cooled transformer, a heat pipe cooled inductor (15) was also developed. The weight of the inductor was reduced 41 percent compared to the conventional inductor shown in Fig. 9. When used in an input filter the weight savings is about 50 percent because a larger inductance value can be used which is still lighter than the original inductor. This results in a smaller capacitor bank. This component was also designed to fit into the 30 cm ion engine power processor shown in Fig. 1. The design was also constrained to increase the thermal radiator and solar array weight by 50 percent of the inductor's weight loss.

CAPACITORS

In the early eighties, Maxwell Laboratories developed for Lewis a 600 V space type capacitor (16) with a maximum current capability of 125 A at 40 kHz. The dielectric for the capacitor is polypropylene. This capacitor also has the capability to operate with a 600 V dc bias. The calculated loss at full load operation is 22 W, which may be compared to the 75 KVA power rating of the capacitor. This capacitor has a specific weight of 0.042 kg/kVA and is compared to a commercial 40 kHz capacitor in Fig. 10. This new capacitor won a 1983 IR-100 award for one of the 100 best new products for last year. This capacitor represents a decrease in size and weight by a factor of seven and is commercially available. This capacitor can be used in high frequency dc/dc converters, dc/ac inverters, tank circuits, filtering and power factor correction.

ROTARY POWER TRANSFER DEVICES

General Electric Company performed for Lewis two design studies for high power rotary transformers (17, 18). The first analysis performed was for 100 kW, 20 kHz unit having a "pancake" geometry. The rotary transformer has a radial (vertical) gap and consisted of 4 to 25 kW modules. The second study compared the rotary transformer losses, efficiency, weight and size with an axial (axial symmetric) gap transformer having the same performance requirements and input characteristics as the first study. The second study showed that the radial gap rotary transformer is the best approach due to the excess weight of the core material of the "pancake" geometry. Lewis has a 2 kW, 2 kHz square wave demonstration model of a rotary transformer and is presently performing a rotary transformer characterization. This program will build a prototype 25 kW rotary transformer with 300 V input and 1000 V output operating at 20 kHz.

Lewis is presently under contract with Sperry Flight Systems to produce a multihundred kilowatt Roll Ring assembly (19). The Roll Ring is a device that transfers electrical power across a rotating joint through rotating flexures compressed between concentric conductors (fig. 11). The advantages of the Roll Ring over the slip ring are the elimination of sliding friction and the low torque needed to rotate the device. The Roll Ring can transfer both ac and dc power and will be more efficient (>99.6 percent) and lighter than the rotary transformer. Each power circuit will be capable of conducting 200 A at 500 V dc There will be four power circuits in the assembly.

POWER TRANSMISSION LINES

Lewis has completed, in-house, a computer model for high frequency power transmission lines both coaxial and parallel (20). At the present time we are starting a new program to build a 50 m high frequency line which will be used to determine line characteristics. The specifications of the line will be 1000 V, 100 A at 20 kHz. Fig. 12 shows two possible configurations of a high frequency power transmission line.

CONCLUDING REMARKS

Lewis Research Center has been developing space power components since the early seventies (table III). Many of the components are now commercially available such as the D60T/D62T Transistor, D7ST Transistor, power switching diodes and the high frequency capacitor. Other components are developed to the prototype stage which demonstrates the technology readiness of those components. These components will enable the construction of large space power distribution systems either high frequency, high voltage ac or high voltage dc.

Component technology is continuing with goals such as a 10 kV semiconductor switching device, high temperature semiconductors, non-impregnant capacitors and high voltage ac/dc RPC development.

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5. Final Report, High Current Fast-Switching Transistor Development, Westinghouse Electric Corporation, NASA Project Manager, Gale R. Sundberg, NASA CR-165372.
6. Final Report, High-Voltage Power Transistor Development, Westinghouse Electric Corporation, NASA Project Manager, Gale R. Sundberg, NASA CR-165547.
7. Final Report, Augmented Power Transistor, Westinghouse Electric Corporation, NASA Project Manager, Gale R. Sundberg, NASA CR-168262.
8. Final Report, Fast-Recovery Power Diode, Power Transistor Company, NASA Project Manager, Gale R. Sundberg, NASA CR-165411.
9. Final Report, Fast-Recovery, High-Power Diode, Power Transistor Company, NASA Project Manager, Gale R. Sundberg, NASA CR-168196.

10. Final Report, Fast-Switching, Gate-Assisted Turn-off Thyristor, Westinghouse Electric Corporation, NASA Project Manager, Gale R. Sundberg, NASA CR-134951.
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TABLE I. - PRIME PROPULSION THRUSTER POWER PROCESSING CHRONOLOGY

Program	Date	Package/ design life	Thruster size-power	dc input voltage	Weight	Efficiency at full beam	Screen supply	Comments
SERT I (Suborbital Ballistic)	1964 Launch	Flight Unit 45-minute Flight	10 cm - 1.5 kW	± 28 V	N/A	83%	2500 V 0.25 A	Simple controls Short term operation
SERT II (Low Earth Orbit)	1970 Launch	Flight Unit 5000 hr	15 cm - 860 W	54-75 V Solar array	32 lb	87%	3000 V 0.25 A	Simple set point control Unregulated screen voltage Relay logic
Hughes/JPL 20-cm Program	1968-1971	1 Breadbd. 2 Engrg. Prototypes	20 cm 2.5 kW	40-80 V 53-80 V	39.1 lb 30 lb	86% 89.7% at 80 V 89.9% at 57.6 V	2000 V 1.0 A	Program purpose to prove mission constraints such as weight, efficiency, reliability, EMI, and thermal requirements, could be met
TRW 20-cm Study for ERC	1969-1970	Breadboard		200-400 V	N/A	N/A		Start of series resonant SCR circuitry work. All discrete parts - no integrated circuitry
Hughes 30 cm Control Study	1970-1972	Rackmount	30 cm 2.75 kW	250 V	N/A	N/A	600-1400 V 2.0 A	Control study for 30-cm thruster - first 30-cm power processor hardware
Hughes 30-cm Lab Consoles	1971-1972	5-Consoles (3 at Hughes 2 at LeRC			N/A	N/A		Same electrical design as above - consoles used for engine testing
TRW 20-cm Breadboard	1971-1972	Breadboard	20 cm 2.5 kW	200-400 V	Parts-20 lb Total-56.6 lb	85.4-86.7% over voltage range	200 V 1.0 A	Similar to TRW study for ERC. Integrated circuits used for all logic and control
TRW 30-cm TVBB	1972-1974 Del.2Q-1974	Thermal vacuum breadboard	30 cm 2.75 kW		Parts-42 lb	82.4% at 200 V 84.1% at 400 V	1100-1500 V 2.2 A	Series resonant SCR circuitry - 20 kHz. 2 inverters - majority voting control logic computer interface for control and telemetry
Hughes 30-cm TVBB	1973-1974 Del.4Q-1974				Est. parts 38 lb	Est. 91% at 200 V 88% at 400 V	500-1500V 2.2 A	Same electrical specs. as above. Screen inverter consists of four transistor bridge inverters with outputs in series
TRW 30-cm improved Breadboard	1974-1975 Del.1Q-1975	Breadboard			Est. parts 49.6 lb	Est. 90.3% at 300 V	1100 V 2.2 A	Improved version of TRW 30-cm TVBB 3 inverters -10 kHz - improved SCR's - improved circuit concept (2 SCR's eliminated)
TRW 30-cm Electrical prototype	1976 Del.4Q-1976	Electrical prototype			Est. parts 33.3 lb	Est. 90.4%	1100 V 2.1 A	Improved version of above - two 20 kHz SCR inverters;1 - 40 kHz transistor inverter - flight-type package using heat pipes

TABLE II. - TRANSISTOR CHARACTERISTICS

Type	D60T/D62T	D7ST	High Voltage D7ST	Augmented power transistor
Voltage	400 to 500 V	400 to 500 V	1000 to 1200 V	800 to 1000 V
Current	50 A at h_{fe} = 10	100 to 150 A at h_{fe} = 10	25 to 50 A at h_{fe} = 10	70 to 112 A at h_{fe} = 10
Peak current	200 A	400 A	200 A	400 A
Power dissipation	625 W at 75° C	2 kW at 75° C	1.25 kW at 75° C	2.50 kW at 75° C
Rise and fall times	0.75 μs	0.75 μs	0.75 μs	0.75 μs
Storage time	2.5 μs	4.0 μs	3.0 μs	4.0 μs
Switching frequency	20 to 50 kHz	20 to 50 kHz	20 to 50 kHz	20 to 50 kHz
Power handling	25 kW	50 kW	30 kW	75 kW

TABLE III. - NASA LEWIS PROGRAMS FOR LARGE SPACE ELECTRIC POWER SYSTEMS

Subject	Title	Specifications	Status
D60T, D62T transistor	Development and Fabrication of Improved Power Transistor Switches, NASA CR-159254	Voltage, 400 to 500 V; current, 50 A at h_{fe} = 10 and 200 A peak; switching frequency, 20 to 50 kHz	Completed; commercially available
D7ST transistor	High-Current, Fast-Switching Transistor Development, NASA CR-165372	Voltage, 400 to 500 V; current, 100 to 150 A at h_{fe} = 10 and 400 A peak; switching frequency, 20 to 50 kHz	Completed; commercially available
High-voltage D7ST transistor	High-Voltage Power Transistor Development, NASA CR-165547	Voltage, 1000 to 1200 V, current, 25 50 A at h_{fe} = 10 and 200 A peak; switching frequency, 20 to 50 kHz	Prototype completed
High-power transistor	Augmented Power Transistor, NASA CR-168262	Voltage, 800 V at 100 A to 1000 V at h_{fe} = 10; current, 400 A peak; switching frequency, 20 to 50 kHz	Prototype completed
PTC 900 series	Fast-Recovery Power Diode, NASA CR-165411	Peak reverse voltage, 1200 V; average rated current, 50 A; surge current, 3000 A; nanosecond recovery	Completed; commercially available
High-current	Fast-Recovery, High-Power Diode, NASA CR-168196	Peak reverse voltage, 1200 V; average rated current, 150 A; surge current, 3000 A	Completed; commercially available
Thyristor	Fast-Switching, Gate-Assisted Turn-off Thyristor, NASA CR-134951	Voltage, 1000 V at 200 A; switching frequency, 10 to 20 kHz	Prototype completed
Roll ring assembly	High Power Roll Ring Assembly, NAS3-24264	Voltage, 500 V dc; current, 200 A per ring assembly	In development; prototype by November, 1984
100-kW rotary transformer	Design Study of a High Power Rotary Transformer, NASA CR-168012	Input voltage, 400 V; output voltage, 100 V; 4 to 25-kW modules	Preliminary design completed
Heat pipe cooled inductor	Heat Pipe Cooling of Power Processing Magnetics, NASA CR-159659	5.8 mH; weight, 500 g	Prototype completed
Heat pipe cooled transformer	Heat Pipe Cooling of Power Processing Magnetics, NASA CR-159659	Input Voltage, 90 V; output voltage, 1100 V and at 2.7 A and 550 V at 0.026 A; frequency, 20 kHz, 2.2 kW power rating	Prototype completed
25-kVA transformer	Design and Development of Multi-kilowatt Power Electronic Transformer, NASA CR-168082	Voltage, 1500 V; frequency, 20 kHz; efficiency, 99.2 percent; weight, 7 lb	Prototype completed
75-kVAR capacitor	High-Frequency, High-Power Capacitor Development, NASA CR-168035	Voltage, 600 V ac with 600 V dc bias; current, 120 A at 40 kHz; weight 8 lb	Completed; commercially available
High voltage solid-state dc switchgear	High-Voltage dc Switchgear Development for 1-kV dc Space Power Systems, NASA CR-168041	Voltage, 1 kV; current, 25 A; power, 25 kW; I^2t trip	Prototype completed
Solid-state dc switchgear	Solid State Remote Power Controllers for 120 V dc for Five and Ten Amperes, NASA CR-135216	Voltage, 120 V; current 5 and 30 A; over current and current limiting protection	Prototype completed
Bidirectional power converter	Bidirectional Four-Quadrant (BD4Q) Power Converter Development, NASA CR-159660	Resonant frequency, 10 kHzx; 3-kW level; bidirectional from 117 V ac (3 phase, 60 Hz) to 300 V dc and back	Prototype completed
10-kW series-resonant converter	Characterization of Westinghouse D60T and D7ST and Power Transistor; and Design, Fabrication, and Test of Single-Stage, 10-kW Series-Resonant Converter, NASA CR-165546	Input voltage, 230 V dc; output voltage, 200 to 400 V dc; current, 0 to 20 A; resonant frequency, 20 kHz	Prototype completed
25-kW series-resonant converter	Design, Fabrication, and Test of 25-kW Series-Resonant dc/dc Power Converter, NASA CR-168273	Input voltage, 300 V dc; output voltage, 200 to 1000 V dc; output power, 25 kW; resonant frequency, 20 kHz	Breadboard completed
Alternating-current power system	Resonant ac Power System Proof-of-Concept Test, NAS3-22777	Resonant frequency, 20 kHz; 8-kW modules; input voltage, 70 V dc	On going; in breadboard stage

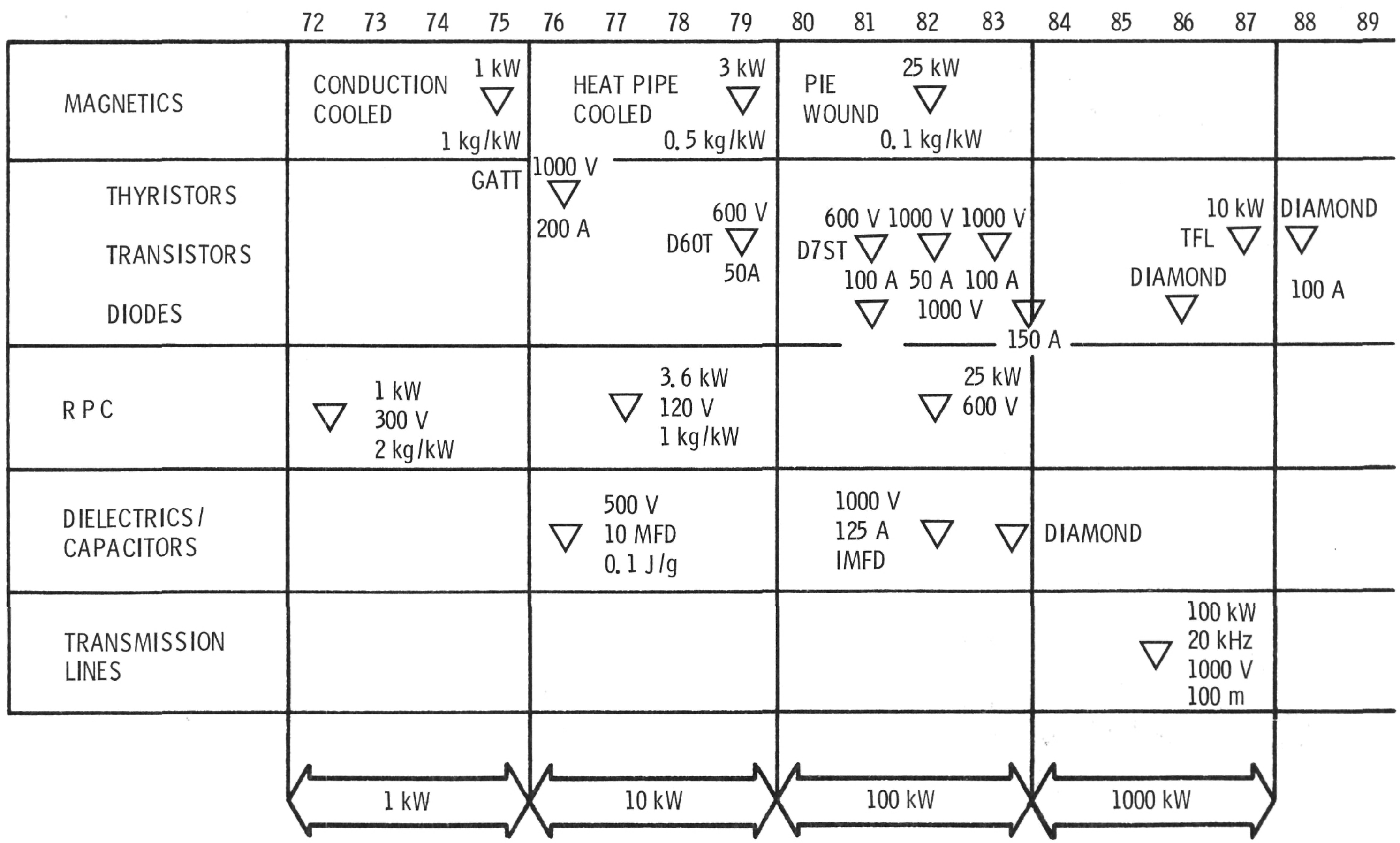

Figure 1. - Power component development at Lewis Research Center.

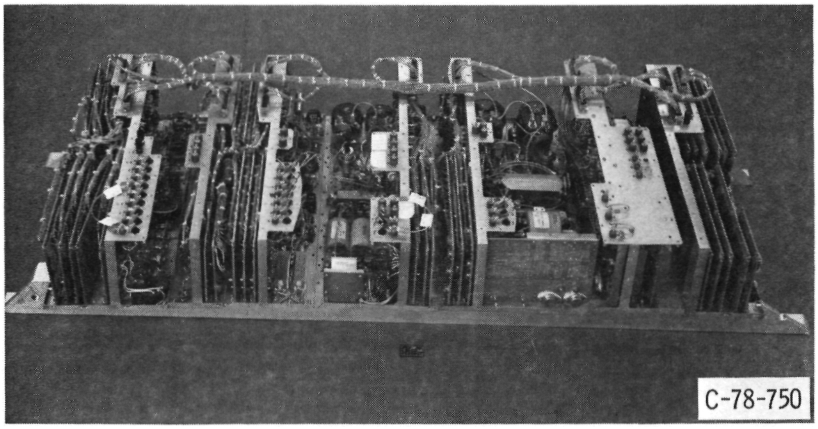

Figure 2. - 30 cm ion engine power processor.

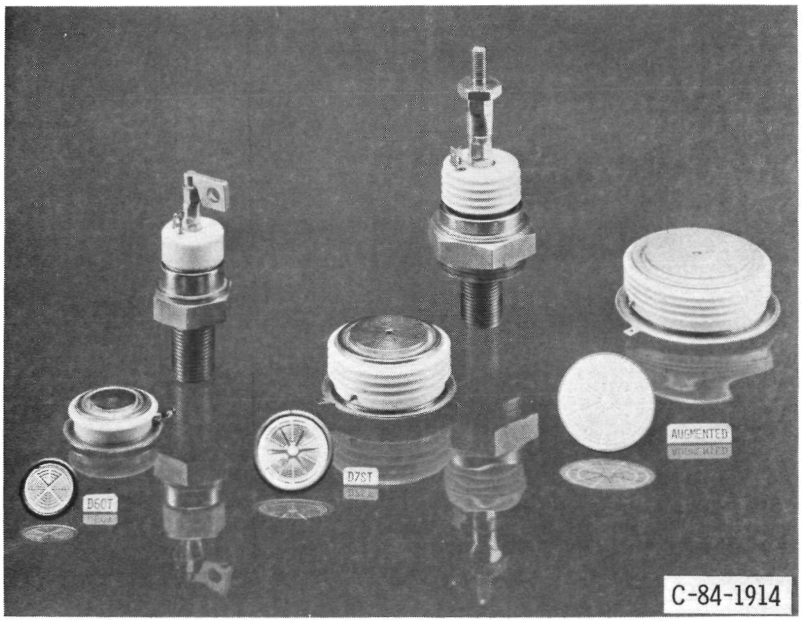

Figure 3. - D60T, D7ST, and augmented D7ST.

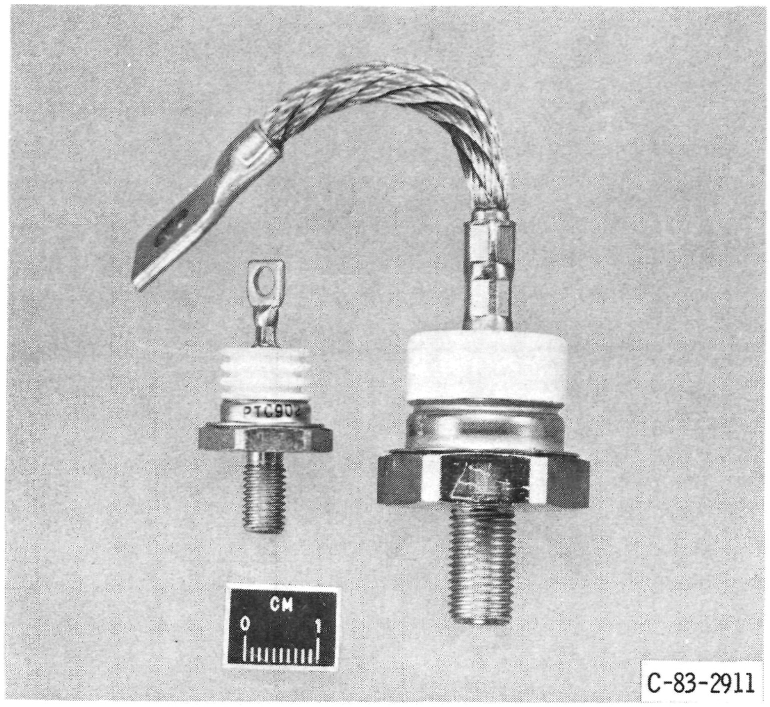

Figure 4. - Fast switching power diodes.

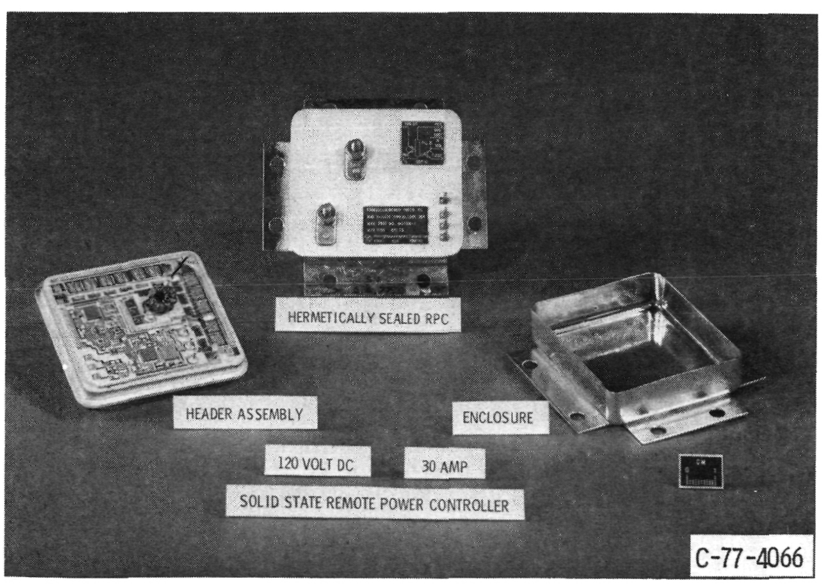

Figure 5. - Thirty ampere solid state remote power controller.

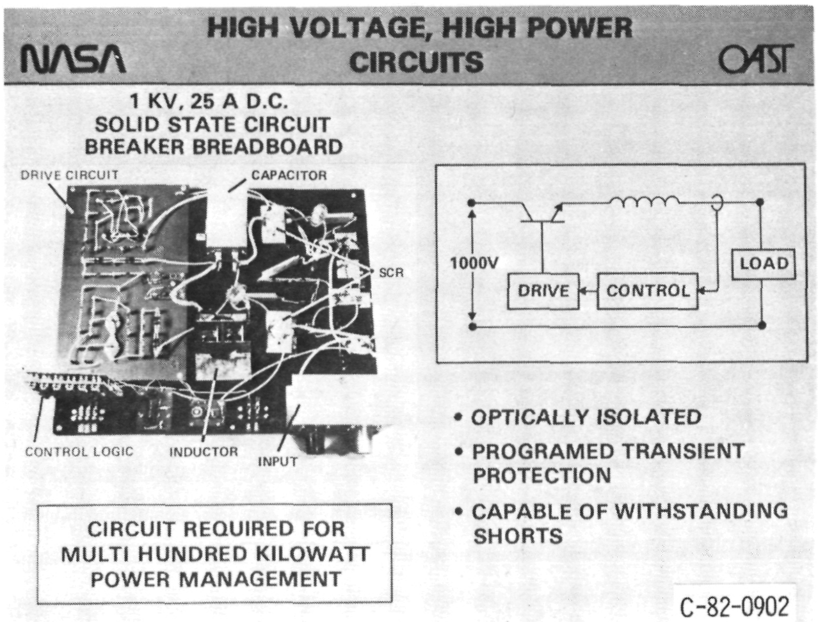

Figure 6. - 1 KV, 25 ampere dc remote power controller.

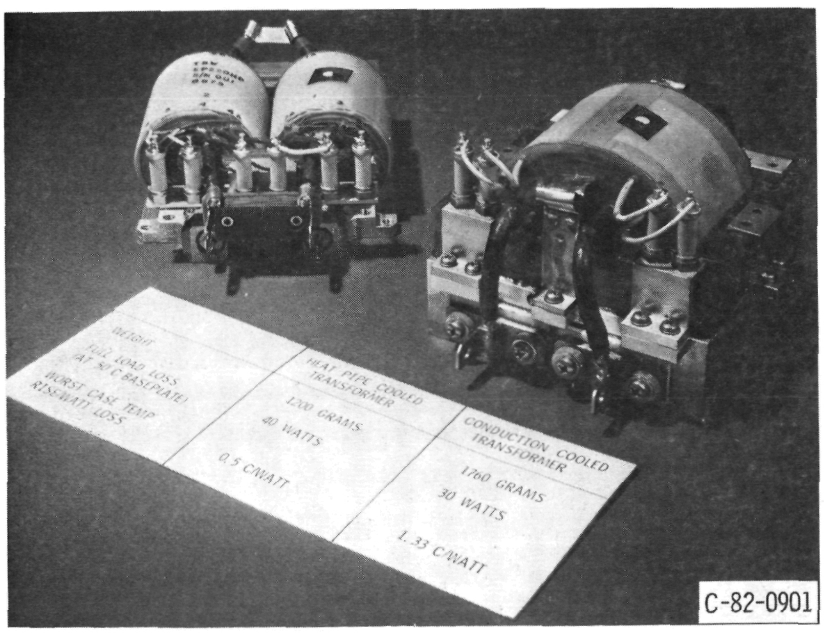

Figure 7. - Heat pipe cooled transformer.

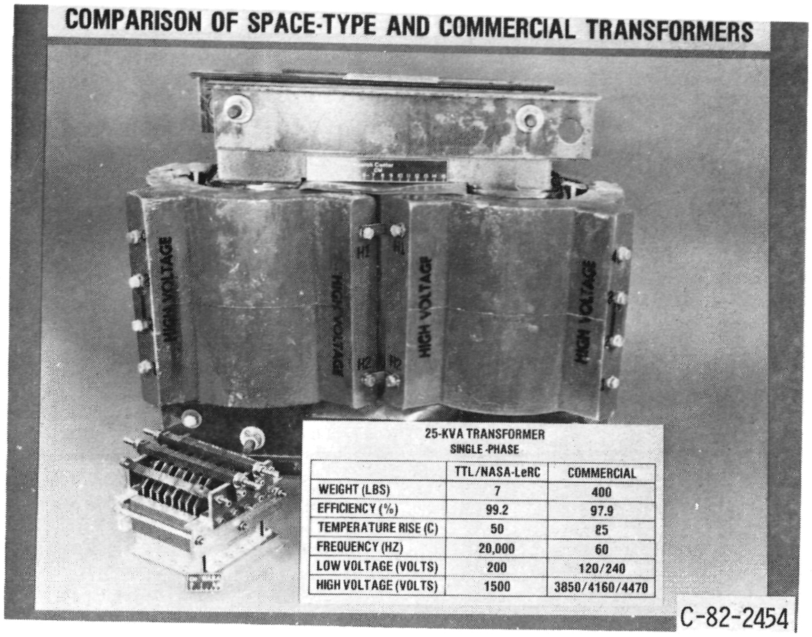

Figure 8. - High frequency, 25 KVA transformer.

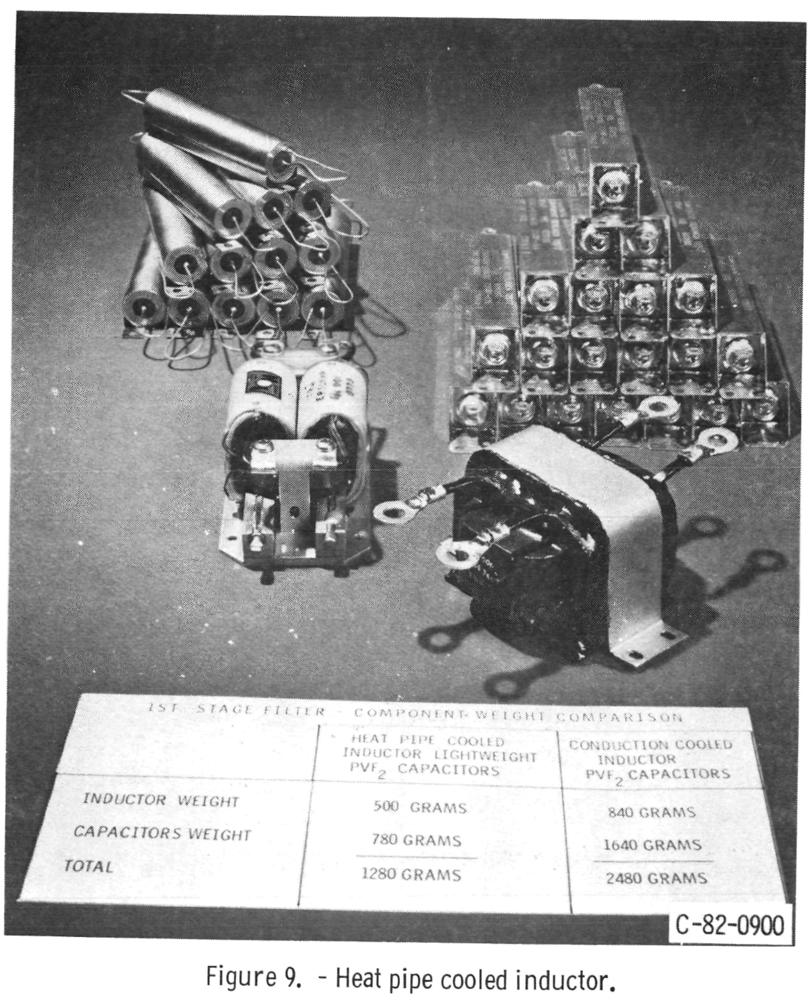

Figure 9. - Heat pipe cooled inductor.

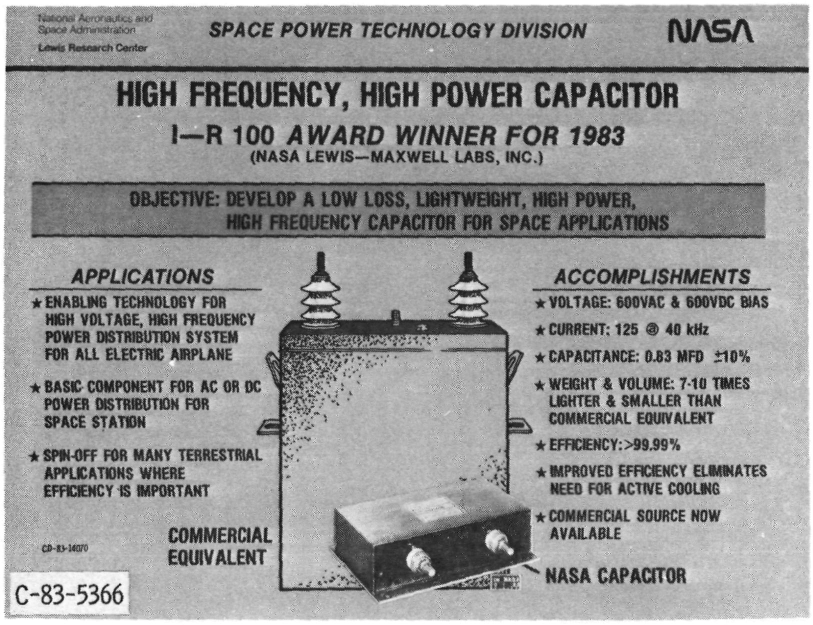

Figure 10. - High frequency, high power capacitor.

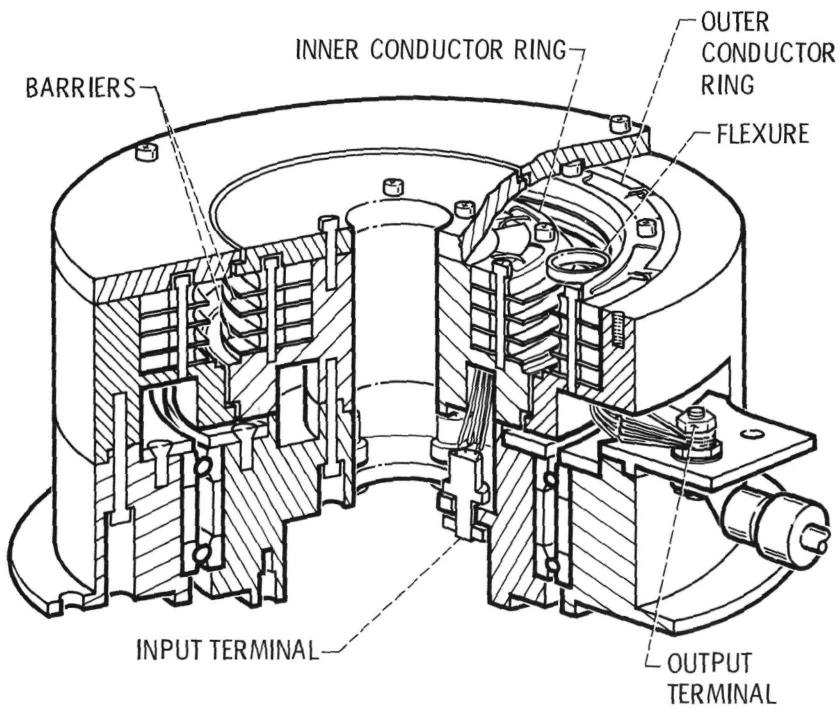

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Figure 11. - High power roll ring assembly.

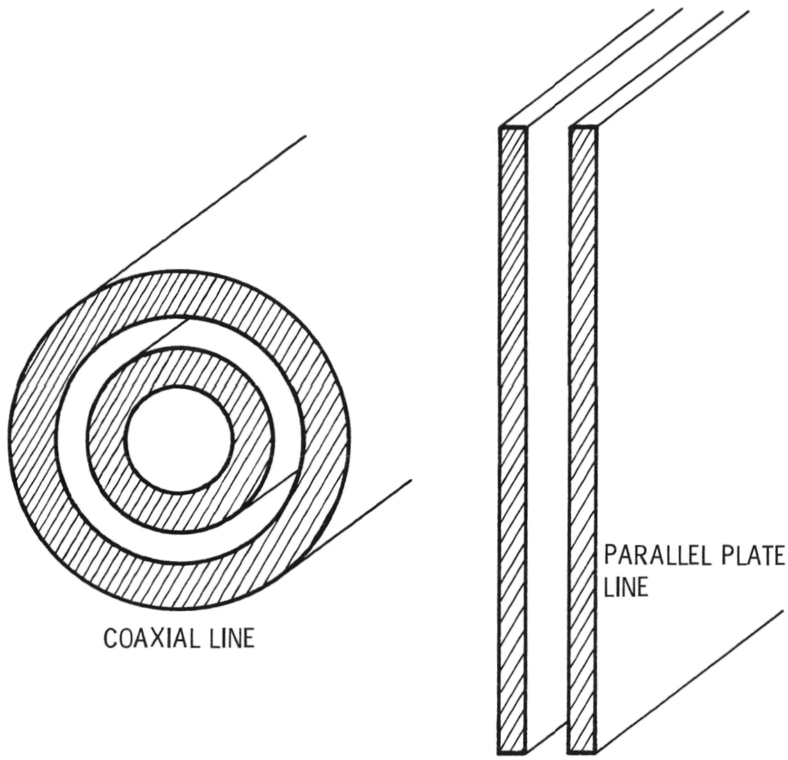

Figure 12. - High power, high frequency transmission lines.

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16. Abstract
For over a decade, Lewis Research Center has been developing space power components. These components include a family of bi-polar power switching transistors, fast switching power diodes, heat pipe cooled high-frequency transformers and inductors, high frequency conduction cooled transformers, high power-high frequency capacitors, remote power controllers and rotary power transfer devices. Many of these components such as the power switching transistors, power diodes and the high frequency capacitor are commercially available. All the other components have been developed to the prototype level. dc/dc series resonant converters have been built to the 25 kW level.

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