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INTRODUCTION

Solar Electric Propulsion (SEP) using mercury bombardment ion thrusters has been in a research and development stage for well over a decade. The emphasis has been on minimizing the propulsion system mass while maintaining or improving the overall system efficiency thus enabling larger payloads. A major element of the thrust system is the power conditioning which converts the solar array power to match the load requirements of the 30 cm ion thrustor.

The emphasis in the development of the power processor (refs. 1 to 3) has been directed towards reliability and higher efficiency with reduced overall weight. The baseline power processor design chosen for this application was a 2.3 kW series resonant converter which requires a high voltage transformer. This paper deals with the optimization of this major component to achieve high performance.

The emphasis on reliability is easily understood. An important part of component reliability resides in the circuit design philosophy. SCR series resonant circuitry places major emphasis on minimizing electrical stress not only during normal operation but during transient conditions such as startup, shutdown and load variations from open circuit to arc faults.

The emphasis on reducing weight is obvious. Less obvious is the manner in which improved efficiency will be reflected by corresponding weight reduction in solar arrays and thermal control systems. Thermal control techniques used with space hardware are substantially different than those encountered in terrestrial equipment. As convection does not occur in a vacuum, cooling is predominantly by conduction. If the conduction path is interrupted by an interface separation, however small, the thermal impedance is increased resulting in higher component temperatures. However, the same item with the same separation may not display an appreciable temperature rise when tested in air.

DESIGN REQUIREMENTS

Based on design tradeoffs, a series resonant inverter was selected as the main power circuit (screen supply) of the power processor (refs. 1 and 2). The circuit is shown in figure 1. The resonant tank consisting of LA, CA, and CB, with control by SCR1, energizes the load through the impedance matching transformer T during one half of the cycle and LB, CB, and CA with control by SCR2 operating T during the alternate half cycle. The output is filtered by C4 after full wave bridge rectification by CR3.

The screen supply power transformer requirements are summarized in figure 2. A detailed description of the design follows, along with a rationale of component selection.

RESULTS AND DISCUSSION

Configuration and Core Selection

The core selected was a shell type cut "C" core or "loop" design using two Supermalloy cores and a single coil (see fig. 3). The use of cut cores permits the coils to be made separately allowing the controlled placement of wire and insulation. Additionally, the circuit requires an air gap to control the balance between half cycles of operation. A controlled gap is easily implemented with a cut core.

The Supermalloy cores were fabricated of half mil tape to achieve lower losses. Although the industry standard allows a 50% stacking factor for half mil material, the vendor, Arnold Engineering, was able to provide cores with a stacking factor in excess of 80% and losses of less than 6 W/lb measured at 5 kG and 10 kHz.

The use of sheet laminated cores was discarded for several reasons. Laminations are not suitable in this application because of the limited variations available, the difficulty in removing the heat from each lamination, and the problems involved in handling large thin laminations of strain sensitive material. Ferrite materials were also discarded for this application due to their thermal constraints. Ferrite materials have a much lower thermal conductivity. The cross section needed would have to be larger than the Supermalloy to operate it within its lower limit of flux density. When operating thick sections in vacuum, its thermal conductivity is so low that the interior reaches Curie saturation. Additionally, the coefficient of thermal expansion of ferrite is different enough from potting materials that local forces experienced during thermal cycling are sufficient to cause core fracture of the material.

Wire

Litz (Litzumdraht) wire was selected for the primary and power secondary. This wire consists of many strands of individually insulated fine wire with the entire bundle twisted to insure equal strand length and uniformly distributing the position of each strand throughout the bundle.

One advantage of this wire is that at high frequencies there is reduced loss of utilization due to skin effect. Another advantage is reduction of circulating currents within the wire as the twisted strands are equally affected in a nonuniform field. The disadvantage of this wire lies in the poor volumetric utilization and problems with stripping. The latter can be overcome by the use of Nylese© insulation which permits solder pot tinning when done with care. There are several types of solderable insulation available, of these Nylese© has the highest temperature rating, 130° C.

Cooling

The cooling design which includes several novel techniques, begins with minimizing losses. The low loss cores and low loss windings, together with all other losses, dissipate only 28 W when handling the full load of more than 3000 VA.

Frame

The coil assembly is placed in a one piece aluminum frame shown in figure 4. This frame was computer modeled to provide a performance versus weight tradeoff. The one piece construction minimizes interfaces to improve heat flow. The volume between the square core and the round coil form is filled with four berylium oxide sections which provide high thermal conductivity heat paths to the frame.

Coil

The coil was wound on a tubular form to preserve physical and electrical symmetry of all windings. Symmetry reduces mechanical stress concentrations and helps prevent tiny hairline fissures from forming during thermal cycling, thereby reducing the corona inception voltage.

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The winding order used was: primary, electrostatic shield, power secondary and auxiliary secondary. This sequence provides the lowest I^2R losses and best heat removal.

An electrostatic shield is necessary to protect the primary circuit semiconductors from voltage transients reflected when the secondary operates into plasma arc faults. Without a shield, energy is stored in the dielectric between the primary and the high voltage secondary. In the event of a secondary short to ground the stored energy would then appear between the primary and ground elevating the potential of the primary circuit. The purpose of the shield is to provide a ground path for the stored energy thereby removing this source of primary voltage stress.

Leadsinks

The primary leads handle over 33 arms and are sized accordingly. The physical size of the Litz bundle is about 0.2 in. diameter. The primary ends are used as heat sinks insulated with berylium oxide insulators as shown in figure 4. These "leadsinks" provide a shunt heat path for the primary generated losses directly into the baseplate, additionally reducing the temperature of the secondary. This heat sinking method was found to be so effective that the unused center tap of a two layer primary was specifically brought out to take further advantage of the technique (see fig. 5).

Core Cooling

The core is built of many layers of half mil thick strip having a magnesium oxide coating on both sides to provide electrical insulation. This oxide layer acts as a thermal barrier so that heat sinking the broad strip face is not effective. Instead it is necessary to sink the edge of each tape layer. A review of the assembly shows the effective cooling path provided for the core. To maintain this interface between tape layers and the base, there are 6 clamps distributed around the core which overcome any inclination for separation resulting from thermal exercising.

ELECTROSTATIC SHIELD (ESS) COOLING

Another cooling technique involved thermal sinking of the electrostatic shield. Since the shield was necessary for electrical purposes and since it is in the region of the highest temperature rise, it was exploited as a thermal heat path to the frame by extending it through the coil for thermal connection to the frame via brass hardware "risers" as shown in figures 3 to 5.

ANALYTICAL MODELING

The above features and the basic thermal design were computer modeled along with other proposed cooling techniques. This analysis allowed their effectiveness to be assessed and optimized without costly iterative hardware builds.

HIGH VOLTAGE DESIGN

The high voltage design was based on experience gained from the Communications Technology Satellite Transmitter Experiment Program (ref. 4) which operated a 500 W high voltage transformer at voltages up to 11.3 kV nominal. Solid dielectric stresses were held to less than 60 V/mil, and surface dielectric stress held to less than 5 V/mil. The impregnation technique for the potting material, an OSHA approved system of a Urethane polymer, included material degassing, hot pour into a heated degassed assembly and alternate schedules of pressure and vacuum. The corona requirement of less than 5 picocoulombs corona initiation for 1.3 times working voltage assures that corona does not exist in operation. This eliminates one of the most important life related wearout mechanisms enabling long mission life.

THERMAL VACUUM TESTING

One of the designer's greatest concerns is to objectively search for problems and identify design flaws or potential wearout mechanisms. It was for this reason that a vacuum thermal profile test was devised. Its intent is to check the analytical thermal analysis, and determine the maximum winding temperature rise under actual thermal vacuum conditions, thus demonstrating the thermal and corona stability of the design as a function of thermal exercising. This test provided both a powerful engineering proof test and a manufacturing screening test. The test consisted of the following sequential events:

Corona test to inception

Full load operation in vacuum by actual circuit on thermal sink elevated to maximum operating temperature.

Continuous recording of 12 thermocouples providing a thermal profile. Please refer to figures 6 and 7.

After thermal stabilization, the winding resistances are measured using a technique which determines resistance at time of power shut-off. This establishes a baseline for later comparison.

Magnetic assembly removed from vacuum chamber and subjected to two days of thermal cycling from -50° C to $+100^{\circ}$ C in 10 cycles of about 4.5 hr each.

Assembly replaced in vacuum chamber with initial test conditions and thermocouple measurements.

Repeat corona test to inception.

Compare "before" and "after" readings of

Thermocouple measurements

Winding temperature rise

Coron test values to inception

This test procedure served to detect deficiencies and check corrective modifications. It also served to detect manufacturing imperfections such as poor soldering on the ESS or imperfect interfaces between core and base or between BeO and core. The sensitivity of this test was both surprising and gratifying because it also provided confidence in units exhibiting no changes.

SPECIAL TESTING

There are other design proof and screening tests worth mentioning. Each core was tested for losses at both the factory and at TRW. There was a special calorimeter test to check calculated losses for the whole assembly which corroborated the 28 W loss figure. Finally a number of design material screening tests were performed on a coil basis to help in the selection of the final insulation system. These tests were effective enough to detect the difference in Litz twisting that occurred between two different procurements of supposedly identical wire.

CONCLUSIONS

A high frequency high power low specific weight (0.57 kg/kW) transformer was developed for space use. The magnetic is capable of handling 3 kVA continuously with primary currents to 35 A at frequencies up to 20 kHz. High efficiency greater than 99% was obtained through careful detailed design. A number of unique heat removal techniques were developed which served to limit the maximum winding temperature rise to 35^{o} C in a simulated space environment. An analytical thermal model enabled frame weight and thermal tradeoffs to be made without the usual iterations and fabrications.

A special thermal vacuum test was developed to establish a thermal profile and maximum internal temperature. After thermal cycling of the transformer any deviation from the established profile flags a potential problem even though the winding temperature has not changed. This highly sensitive test has merit both as a design proof test and as a screening test due to its ability to detect minor fabrication defects.

ACKNOWLEDGEMENTS

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The author also wishes to thank Mr. Malcom Sheppard of Arnold Engineering for his efforts in producing the cores used in this program.

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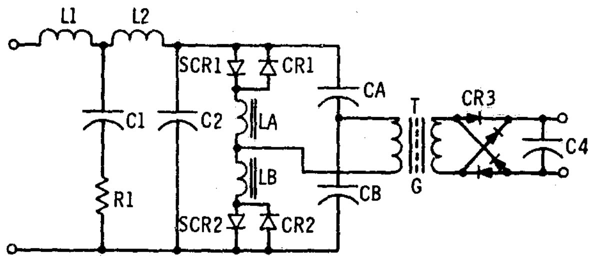
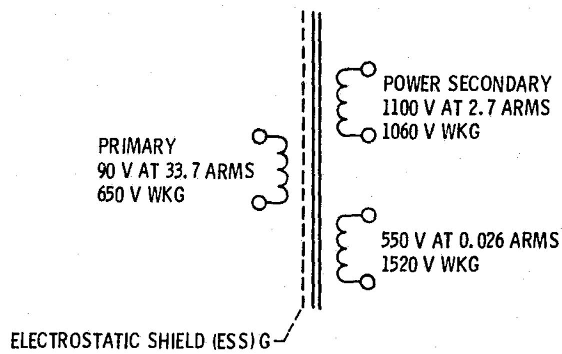


Figure 1. - Series resonant inverter with auxiliary diode configuration.



PRIMARY SOURCE:
SQUARE WAVE VOLTAGE, APPROXIMATE SINE
WAVE CURRENT, 20 kHz MAX
REPETITION RATE VARIABLE WITH INPUT VOLTAGE & COMB.
TEMP:
0 TO 50° C BASEPLATE OPERATE, -55 TO 100° C NONOPERATE
MAX AVG WINDING RISE 35° C WHEN FULLY LOADED MOUNTED ON 50° C BASEPLATE
EFF:
APPROXIMATELY 99 percent TRADED OFF AGAINST WEIGHT

Figure 2. - Screen supply power transformer requirements.

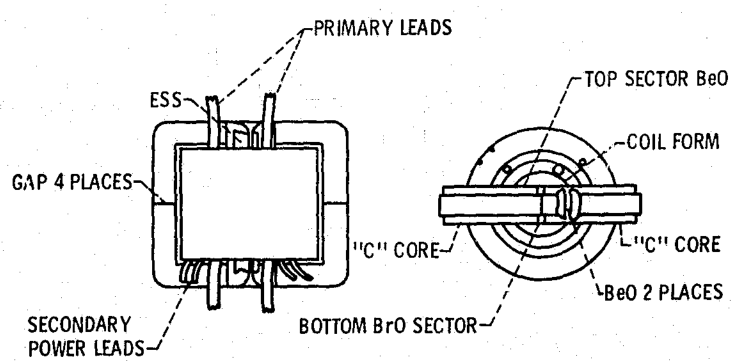


Figure 3. - Shell type construction.

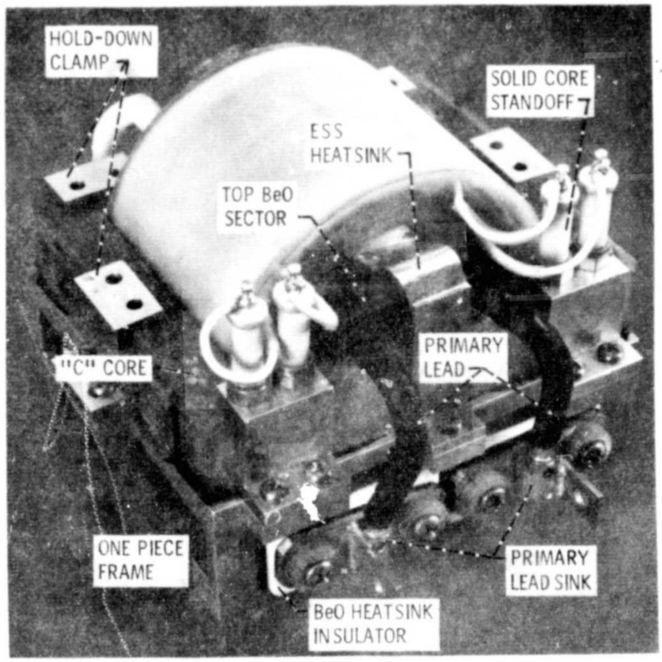


Figure 4. - Screen transformer.

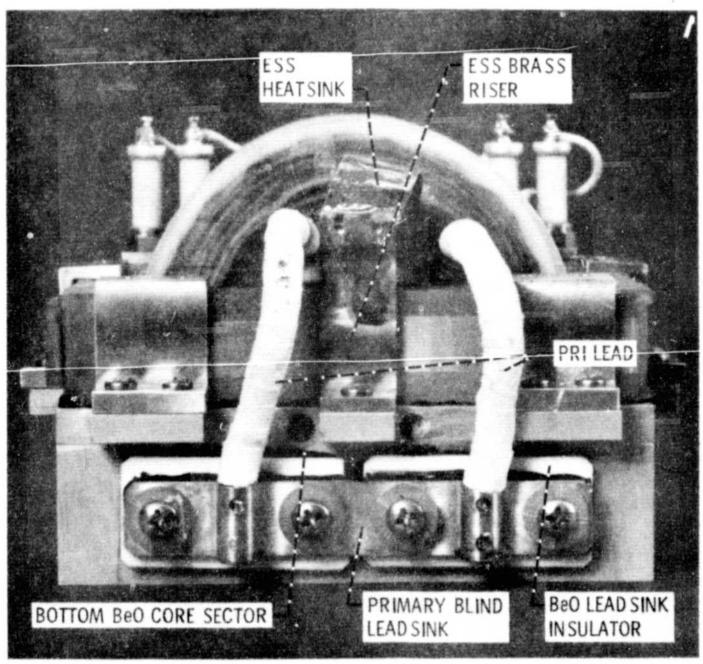


Figure 5. - Screen trai.sformer, rear view.

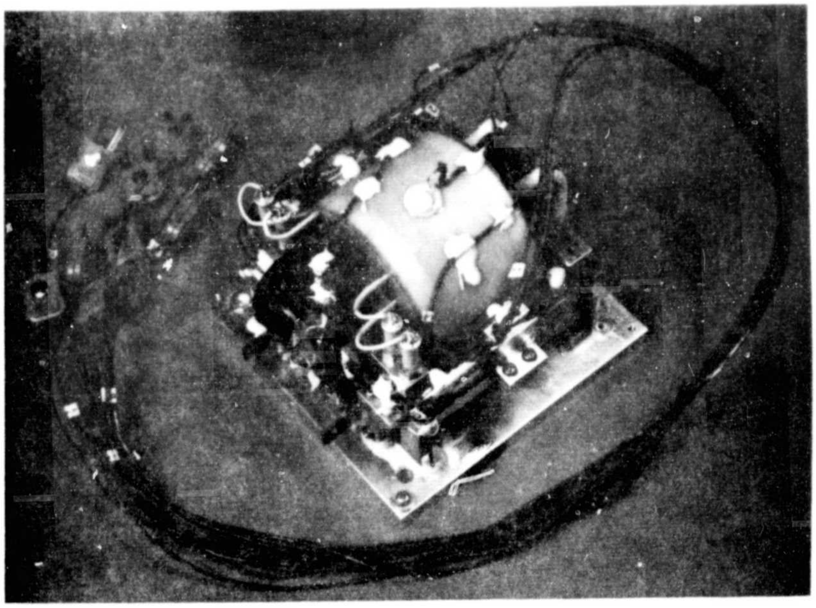


Figure 6. - Thermocouple instrumentation for thermo profile test.

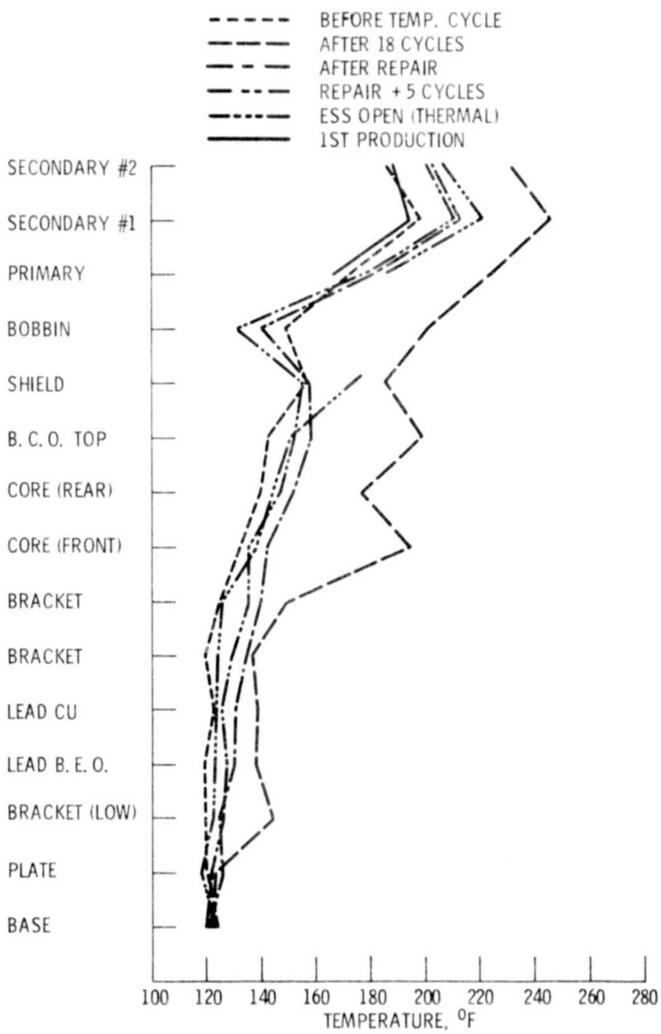


Figure 7. - Transformer thermal profile.

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