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PRELIMINARY DESIGN DEVELOPMENT OF 100 KW ROTARY POWER TRANSFER DEVICE

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NATIONAL AERONAUTICS & SPACE ADMINISTRATION

NASA-LEWIS RESEARCH CENTER

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16. Abstract

A study was made of contactless power transfer devices for transferring electrical power across a rotating spacecraft interface. A power level of 100 KW was of primary interest and the study was limited to alternating current devices. Rotary transformers and rotary capacitors together with the required dc to ac power conditioning electronics were examined. Microwave devices were addressed. The rotary transformer with resonant circuit power conditioning was selected as the most feasible approach. The rotary capacitor would be larger while microwave devices would be iess efficient. A design analysis was made of a 100 KW, 20 KHZ power transfer device consisting of a rotay transformer, power conditioning electronics, drive mechanism and heat rejection system. The size, weight and efficiency of the device were determined. The characteristics of a baseline slip ring were presented. Aspects of testing the 100 KW power transfer device were examined. The power transfer device is a feasible concept which can be implemented using presetly available technologies.

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SUMMARY

A study was undertaken to investigate the feasibility of utilizing a contactless power transfer device to transfer electrical power in a spacecraft across a rotating interface between the solar arrays and the spacecraft body. The power was between 100 KW and 1 MW with primary emphasis being at the 100 KW level. The study consisted of three major tasks; Systems Study, Design Study, and Recommendations and Testing Requirements.

The System Study was an analysis of several ac power transfer approaches: rotary transformers and rotary capacitors, and a review of microwave methods. In addition, dc to ac power conditioning techniques were analyzed. As a result of the System Study, the rotary transformer was selected as the power transfer device, and the Schwarz resonant circuit for the power conditioning.

The Design Study covered the design of a 100 KW rotary power transfer device, consisting of a rotary transformer, power conditioning electronics, mechanical design, drive mechanism and heat rejection system. This effort showed that a 100 KW power transfer device is feasible and there are no fundamental reasons that it cannot be achieved with present state-of-the-art technqiues.

The final task, Recommendations and Testing Requirements, covered a baseline brush type slip ring, test program and recommendations. Testing could be a problem because of the need for 100 KW electrical power; however, the use of back-to-back test methods could alleviate the power requirements substantially. It was recommended that a 10 KW, 20 KHZ rotary transformer and power conditining electronics be built and tested to demonstrate the concept of the rotary power transfer device.

INTRODUCTION

The future requirements for spacecraft appear to be in the magnitude of 100 KW to 1 MW. In spacecraft which have sun-oriented solar arrays, this power must be transferred across the rotating interface between the solar arrays and the spacecraft body. Presently, power transfer across a rotating surface is usually achieved by brushes sliding on slip rings. As the spacecraft power, voltage and life requirements increase, other techniques for transferring power must be addressed. The plan of this study was to investigate alternating-current contactless power transfer systems in the range of 100 to 200 KW with primary consideration being given to the 100 KW level of power.

Brush-type slip rings are most commonly used for transferring power across a rotating spacecraft interface. These are primarily direct current, low voltage devices. Their most severe limitations are brush wear and brush debris. The brush wear limits the operational life while the debris can result in voltage breakdown in the slip ring. A number of alternatives to slip rings have been proposed: hard wired rotating coupling, power clutch, and liquid metal slip ring. Extensive testing or application of these have not been accomplished. Rotary transformers and to a lesser extent, rotary capacitors, have been also considered, generally having power requirements up to several kilowatts. The major concern with rotary transformers in this power regime was their size and weight together with the need for dc to ac power conditioning electronics. However, the power requirements for future spacecraft indicate that contactless power transfer methods might be feasible, especially when the total spacecraft power characteristics are considered.

TASK I

SYSTEM STUDY

TASK I

SYSTEM STUDY

1.0 INTRODUCTION

Task I, System Study, is an analysis of two contactless power transfer techniques, rotary transformer and rotary capacitor, and the requisite power conditioning electronics. In addition, there is a review of microwave power transfer devices. One of the ground rules for this study was to consider AC power transfer systems rather than DC. Since the power is derived from spacecraft solar arrays, power conditioning is necessary to convert the DC solar array power to AC in order to be utilized by the rotary transformer or rotary capacitor power transfer device. The design of the power transfer device is not independent of the power conditioning because their electrical parameters are mutually interdependent: the design of the power conditioning circuitry must always be considered in context with the design of the power transfer device, and vice versa.

The System Study was evolutionary in nature with assumptions changing as work progressed and as a fuller understanding of the problem areas and their solutions became evident. For example, the initial approach assumed a 100 kW transfer device operating with a square wave converter at a frequency of either 25 KHz or 50 KHz. An analysis of this sytem indicated that the requisite rotary transformer would have to be very long in relation to its diameter, because of the low leakage inductance necessary for best converter operation. It was felt that the square wave might not lead to an optimum system and that another approach might be more advantageous.

Discussions were held with LeRC and it was decided to use the recommendations of the General Dynamics system study as the baseline for the contactless power transfer device. One of the features of their recommendation was the use of a resonant circuit for power conditioning which eliminated the stringent requirements for low leakage inductance.

The thermal design of the power transfer device was also addressed. This is a critical area because thermal problems could be a design limiting aspect since in a space environment the heat generated by losses must be thermally conducted to a heat sink and then radiated. If the quantity of heat is large there will be large thermal gradients and high internal temperatures.

As a result of the Task I, System Study, it appears that the most feasible approach to contactless power transfer is the use of a rotary transformer in conjunction with resonant circuit power conditioning. A frequency of 20 KHz is recommended although higher frequencies could be used if there are overall system advantages. There are no inherent limitations to the power levels, 25 kW modules as well as 100 kW or larger ratings can be used.

2.0 REQUIREMENTS

The requirements that were used as general guidelines for the rotary power transfer device study were as defined by LeRC:

1. Input Power from Solar Array
   a) 100 kW - 200 kW
   b) 120 - 1000 volts dc
2. Load Requirements

a) dc 300 - 3000V	Electric Thrusters
b) dc 10,000 - 20,000V	Communications
c) ac/dc 28 - 300V	Industrial Processing

3. Efficiency - greater than 95 percent
4. Minimum weight
5. Lifetime - five years
6. Rotational Period - 90 minutes to 24 hours
7. Zero gravity operation
8. Ability to withstand shuttle launch environment

More specific system requirements were derived from the recommendations of the General Dynamics study which were based upon their study of a 250 kW system. These were as follows:

Input voltage	440 volts
Output voltage	1,000 volts
Power per module	25 kilowatts
Input frequency	20 KHz
Power transfer device	Rotary transformer
Rotary transformer	
Primary windings	Each module winding connected in parallel
Secondary windings	All module windings connected in series. Two windings on secondary for redundancy
Power conditioning	Resonant circuit

These recommendations were used as a basis for power transfer device study with the exception of frequency. The operating frequency was considered in the 20 KHz to 50 KHz range because of the possible weight saving attainable in the rotary transformer.

3.0 POWER TRANSFER ELECTRONICS

3.1 Introduction

The power transfer electronics studies were predicated on the results of a General Dynamics study performed for NASA-LeRC, which recommend resonant A.C. power distribution. Figure 3-1 presents a block diagram of the parts of the system which involve the rotary power transfer device. Figure 3-2 provides details of the 25KW "module" assuming a series resonant converter. It was presumed that the rotary transformer primary would be an efficient place to obtain the series inductance needed. The studies objectives were to determine circuit element values, power losses, and sizing parameters to provide a basis for rotary transfer devices designs and system effectiveness evaluation.

3.2 Summary Conclusions

Using a 20KHz switching frequency design as a basis, there is no advantage in the electronics to go to higher frequencies. The basic parts for a set of electronics for a 25KW module would weigh about 15 pounds and have about 500 watts (2%) losses. There are few obvious advantages to the series resonant topology for the rotary transfer elements; it will take detailed circuit simulations to evaluate a "non-resonant" approach. There is no electronics trick to make a rotary capacitor a viable system approach.

3.3 Optimization Factors

In order to evaluate electronics designs in the system environment, the designs were optimized for minimum weight (equating cost to weight since there were no design, development, or production difficulties caused by the optimization). Weight parameters for the electronics parts are explained in section 3.6. The weight was optimized based on a system weight penalty of .0122 pound per watt. The .0122 lb/watt (82 watt/lb) is derived from a heat rejection penalty of 4.75 lb/Kwatt and an array source power weight (to offset the losses) based on 135 watt/lb (300w/Kgm). The heat rejection factor is based on holding 80°C "baseplate" in Figure 2-19 of Reference 1. The array factor is an engineering estimate.

3.4 Resonant Circuit Topology Discussion

The resonant, or Schwarz topology, is described in literature (References 2 and 3). Its primary advantage is improved efficiency due to reduced switching losses because the switching devices turn off at essentially zero current and turn on at a current considerably lower than the peak circuit current. This is accomplished by having a

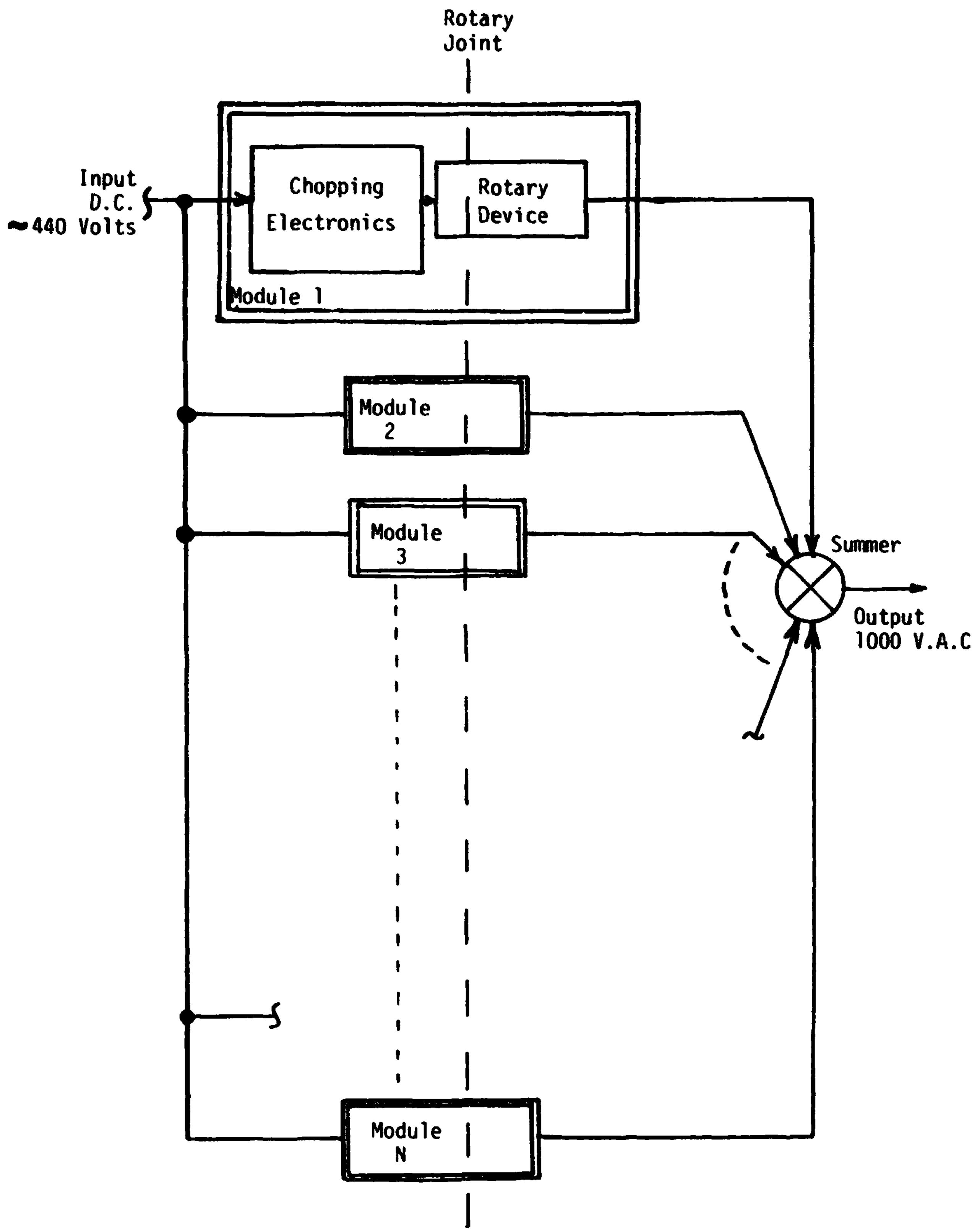


Figure 3-1. 250 Kilowatt Power Transfer System

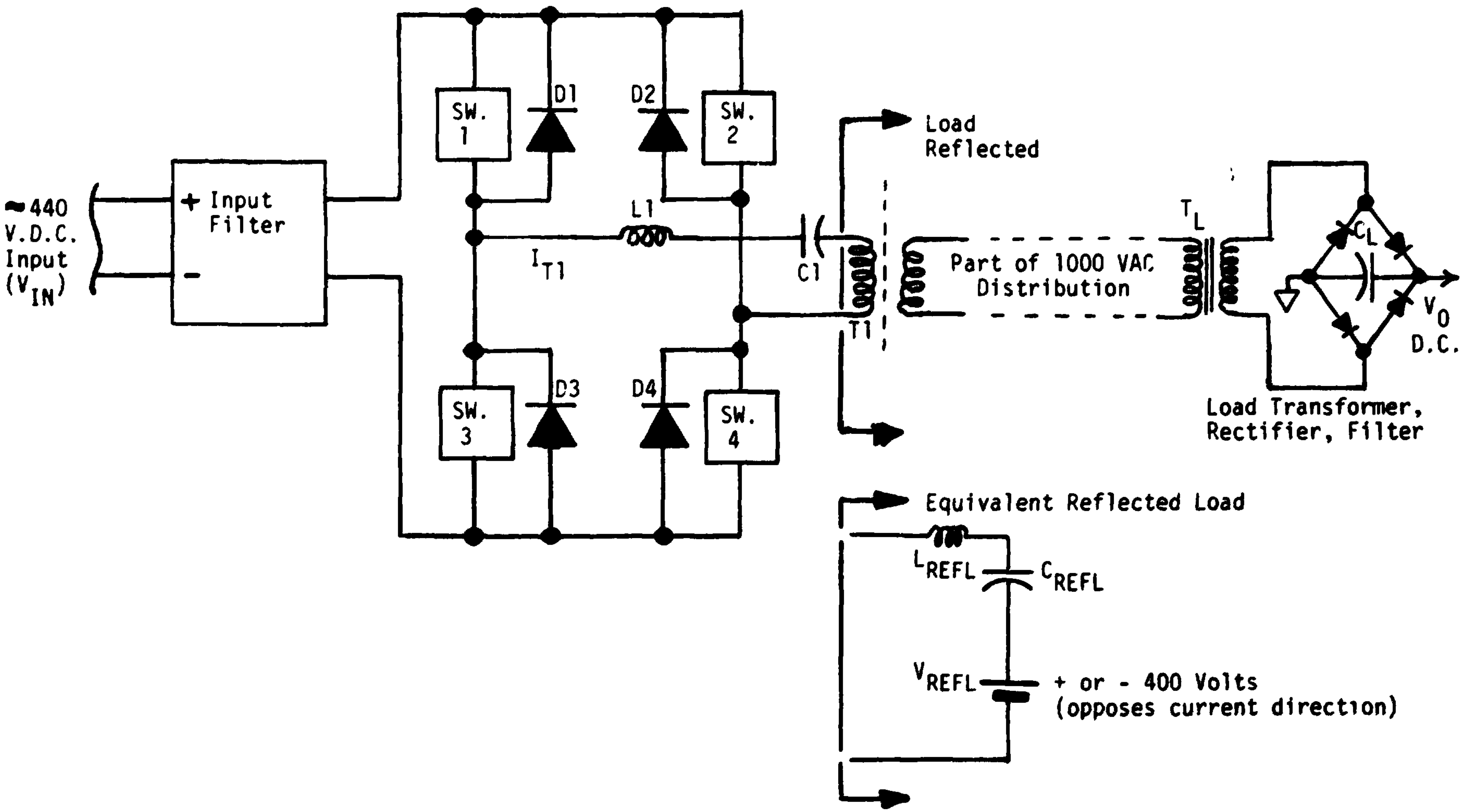


Figure 3-2. 25KW Module-Resonant Converter

sinusoidal current waveform in a basically series resonant L-C circuit. By judicious design of the circuit element values and control of the turn on time of the switches, the resonant circuit is made to ring in a safe manner. The dominant capacitance in the circuit must be the primary side, C1 in Figure 3-2, so the loads are required to reflect a large capacitance. Likewise, the inductance must be design controlled, so the reflected inductance must be either negligible or known and stable. For this study, it was presumed that the system will reflect large capacitance and negligible inductance. While the current is sinusoidal, the transformer primary and secondary voltage waveforms are square.

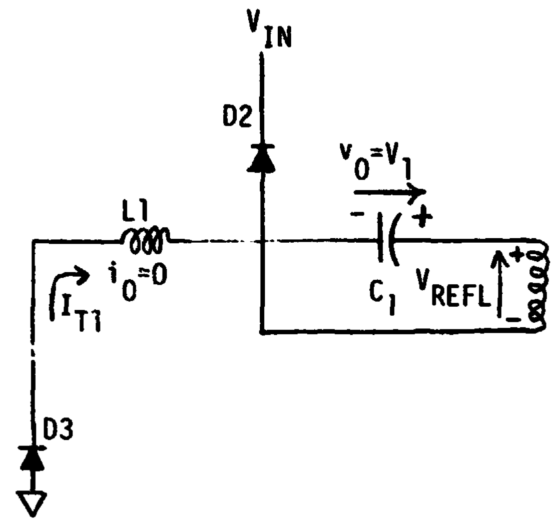
Several basic principles control the circuit waveforms and component values. When a set of switches turn on, it has the effect of putting a step function on a series L-C circuit which has a set of initial voltage and current conditions as depicted in Figure 3-3. If the loads truly reflect as capacitive and the other series resistive elements are quite small (and they must be if there is to be high efficiency power transfer), then the current will be an undamped sinusoidal waveform with a characteristic frequency determined by the primary side L-C values. When the resonating current goes through zero, the voltage on the transformer (instantaneously) reverses and the current flows in the clamping diodes. This again, produces the effect of a step voltage on the L-C circuit with an initial voltage on the capacitor. For normal, full load operation, the capacitor voltage at the instant of primary current reversal, is greater than V_{IN} plus the reflected transformer voltage, so the current continues to increase in the reverse direction. After some delay, the opposite set of switches turn on and we are back to the beginning.

Using the above description and the waveform and definitions of Figure 3-4, the circuit can be analyzed starting at the peak capacitor voltage, V_1, when the resonant current reverses. Since the waveforms are always sinusoidal with a characteristic frequency, F-resonance, it is convenient to define events in terms of degrees of that resonant characteristic.

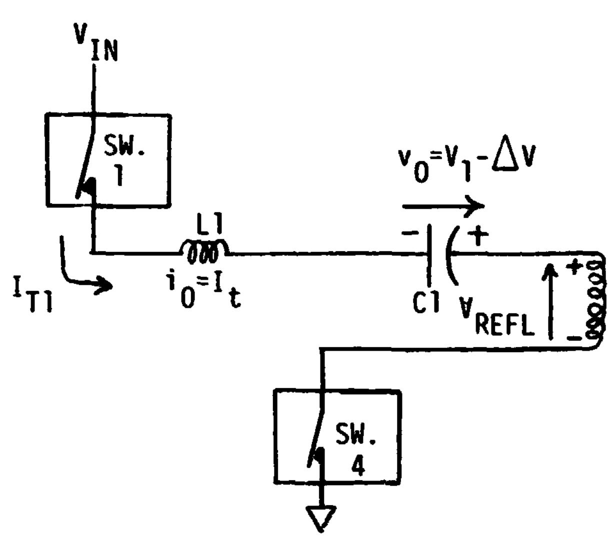
Then:

$$I_{T1} = [V_1 - V_{IN}(1+Q)]\sqrt{\frac{C}{L}}\,\sin\,(t/\sqrt{LC}) \qquad (1)$$

- describes the current while the clamp diodes are conducting from resonant current reversal until the next set of switches turn on.

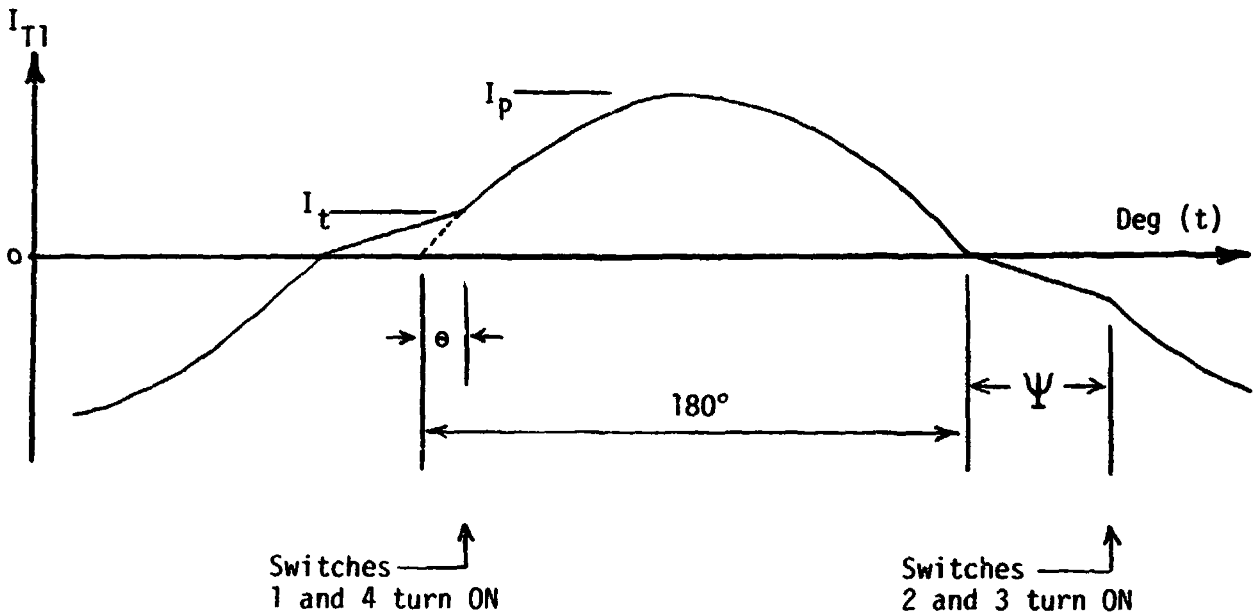


A. Conditions just after current reversal before S1 and S4 turn ON



B. Conditions just after S1 and S4 turn ON

Figure 3-3. Resonant Circuit



Define:

$Q = V_{REFL}/V_{IN}$ (=396/440)

Ψ = angle between resonant current zero crossing and bridge switch activation in terms of degrees.

θ = the startup angle of the high power (switches conducting) portion of the resonant cycle.

V_1 = voltage across C1 when the resonant current I_{T1} is zero before SW 1 and 4 turn ON.

I_p = peak sinusoid current.

I_t = primary current when power switches turn ON.

Figure 3-4. Waveform Description and Parameter Definitions

$$I_{T1} = [V_1 - V_{IN}(1+Q)]\sqrt{\frac{C}{L}}\,(\sin\Psi)\,\sqrt{A}\quad \sin(t/\sqrt{LC} + \theta) \tag{2}$$

where $$\sqrt{A} = \sqrt{\frac{[2V_{IN} + (V_1 - V_{IN}(1+Q))\cos\Psi]^2}{[V_1 - V_{IN}(1+Q)]^2 \sin 2\Psi} + 1}$$

- describes the current after the switches turn on until the current direction again reverses.

Since the half cycle waveforms must by symmetrical in steady state operation, at the second current reversal the capacitor voltage must now be $/V_1/$, but with opposite polarity. Using $\Delta V_C = \frac{1}{C}\int I_{T1}dt$ and the fact that the half cycle ending voltage is $-V_1$, an expression for V_1 can be obtained:

$$V_1 = 1/2\left\{[V_1 - V_{IN}(1+Q)]\sin\Psi\ \sqrt{A}\ (1+\cos\theta) + [V_1 - V_{IN}(1+Q)]\,[1-\cos\Psi]\right\} \tag{3}$$

where $$\theta = \tan^{-1}\frac{[V_1 - V_{IN}(1+Q)]\sin\Psi}{2V_{IN} + [V_1 - V_{IN}(1+Q)]\cos\Psi}$$

Notice that equation (3) does not contain any L, or C, or power related terms; the characteristics of V_1 and the current waveforms are a function of the circuit topology. Table 3-I presents the results of solving equation (3) by numerical methods.

Table 3-I. Peak Capacitor Voltages

Ψ- Deg.	V_{IN} = 440 Q = 0.9		V_{IN} = 660 Q = 0.606	
	V_1-Volts	θ-Deg.	V_1-Volts	θ-Deg.
170	880	0.5	1322	2.5
135	888	2.5	1378	11.6
113	901	4.0	1479	18.4
90	929	6.0	1749	28
77	960	7.6		
67	1000	9.1		
45	1265	14.5		
35	1862	19		

A 45° Ψ minimum is recommended (References 2 and 3), and, since that already represents over 2500 Vpp on the capacitor, this seems reasonable. 2500 volts of A.C. will present some corona control challenges, but this level should not require technology advances. Notice that the voltage rapidly increases if the V_{IN} is unregulated. A Q of .606 and a V_{IN} of 660 provides the same 400 volt "output" as 440 volts in and a Q of 0.9. Once the Ψ angle gets to 180°, the circuit goes into a different mode of operation which was considered beyond the scope of this study to investigate, because it does not appear to necessitate any changes to the circuit element values or higher stress on the power transfer device. More detailed analyses, using computer simulations would be needed to accurately evaluate the system and transfer device operation in this mode.

Since the power delivered to the load is 400 volts (the transformer primary voltage) times $\int_T idt$ and $\frac{1}{C}\int_T idt = \Delta V_{CAP}$, then the power delivered each half cycle is 400 x C x $2V_1 \times \frac{1}{T}$. The correct C value for a given power level, V_1 (a function of V_{IN}, V_{PRIM}, and Ψ_{MIN}), and switching frequency (F_{SW}) is:

$$C = \frac{\text{Power}}{400 \times 2V_1 \times 2F_{SW}} \qquad (4)$$

From equation 4 we see that for a given power, voltage, and switching frequency, C can only be made smaller by increasing V_1. V_1 can only be increased by reducing Ψ_{min}, which is impractical due to circuit control problems. (As $\Psi \longrightarrow 0$, you approach applying a square wave excitation on a very underdamped series L-C circuit right at its resonant frequency, which would produce enormous voltage and current waveforms. The Ψ angle controls the amplitudes because it means the excitation frequency is a little below the resonant frequency.) Therefore, the C in equation (4) is the smallest practical value, which precludes making a rotary capacitor transfer device viable by using a considerably smaller value.

The resonant and switching frequencies are related by Ψ and θ (see Figure 3-4) since a half cycle of the switching frequency corresponds to Ψ +(180-θ) degrees of the resonant characteristic. Thus:

$$F_{RES} = \left(1 + \frac{\Psi - \theta}{180}\right) F_{SW} \qquad (5)$$

Using equation (5), and $F_{RES} = 1/(2\pi\sqrt{LC})$, and equation (4), the term $\sqrt{C/L}$ in equations (1) and (2) becomes

$$\sqrt{\frac{C}{L}} = \frac{\pi\left(1 + \frac{\Psi - \theta}{180}\right)\text{Power}}{2QV_{IN} \quad V_1}$$

so the current equations can be written in terms of power, Q, and the parameters determined by a selection of Ψ.

The results of the above analysis provide values for capacitance, inductance, and the current/voltage waveforms. Values for the parameters were determined to provide design constraints (I_{RMS}, V_{RMS}, Primary Inductance) for the rotary transformer where the circuit inductance was developed by building in leakage reactance.

The factors contributing to power losses were studied and a model developed to analyze the effects of frequency, Ψ min, and switching electronics parameters on system weight and losses. Since the capacitor function cannot be done with existing components, it was assumed the ESR would be about 33% better than existing lower voltage types of metalized plastic capacitors. A seriesed/parallel arrangement of 400 volt types would produce about 40 milliohm μf ESR. The 33% reduction to 30 milliohm μf should result from using specially made higher voltage rated devices so the seriesing factor will be reduced. The losses in the capacitor were computed by:

$$P_{LOSS} = I_{RMS}^{2} \frac{.03}{C(\mu f)}$$

Since a very small capacitor would result in large losses, the capacitor losses were optimized by determining the capacitor weight corresponding to minimum system weight penalty. It was assumed that the unit capacitance could be reduced while holding the ESR μf factor approximately constant (for instance by shortening the length) then adding more units in parallel to obtain reduced effective ESR.

One could then say the system weight penalty is: $C_{WT} \times (KC) + P_{LOSS} \times .0122$

where: .0122 is the system lb/watt optimization factor

C_{WT} = 3 lb/μf (capacitance specific weight)

and $P_{LOSS} = I_{RMS}^{2} \times \frac{.03}{KC}$; where K is the ratio of basic specific capacitance to optimized specific capacitance

As an example, if the specific capacitance was reduced 50%, K would be 2, the power losses would be halved and the capacitor weight would be doubled. Substituting, differentiating, and solving for the K_{OPT}:

$$K_{OPT} = \frac{I_{RMS}}{C} \sqrt{\frac{0.03 \times 0.0122}{3}}$$

Looking at the equation for capacitor weight and the losses, the C will cancel out and these factors become only a function of I_{RMS}. This means minimum system weight is constant with frequency, since I_{RMS} will be later shown to be a function of only Ψ for a given power level. Therefore, when the capacitor loss factors tendency to increase with higher frequency (because less capacitance is needed) is optimally compensated for by adjusting the capacitor design, there is constant total system weight penalty.

Some simplifying assumptions were made to compute power losses in the switching parts of the electronics. While the switches (transistors) are on, the current is assumed to be a half cycle of a sinusoid. The V_{CE} characteristic is approximately a resistor defined as $R = V_{CEP}/I_P$ where V_{CEP} is the saturation voltage at I_P, the peak value of the sinusoidal current. The $I^2_{RMS} \times R$ value is then $1/2\ I_P\ V_{CEP}$. The base drive voltage was assumed to be constant and the drive was 1/8 of I_C. This power is then $.637\ I_P/8 \times V_{BE}$. The clamp diode was assumed to have a constant voltage and the current to have a triangular waveform from zero to an I_t, so the power dissipation is $1/2\ I_t \times V_F$. The transistor turn on and diode turn off losses were estimated per Figure 3-5. The transistor turn off losses associated with base drive were assumed as 1/25 of the peak collector current being drawn off a 5 volt supply for the duration of the transistor storage time. Accounting for the upper and lower part of the bridge drive, the equation for power loss is:

$$P = 2 \times \left\{ I_P \left(.5V_{CEP} + \frac{.637}{8} V_{BE} \right) \times \left(\frac{180-\theta}{180-\theta + \Psi} \right) + V_F \times \frac{I_t}{2} \times \frac{\Psi}{(180-\theta + \Psi)} + V_{IN} \left[\frac{I_t}{2} \times t_{RISE} + \frac{I_{REC}}{2} \times t_{REC} \right] \times 2\ F_{sw} + 5 \times \frac{I_P}{25} \times t_{storage} \times 2\ F_{sw} \right\}$$

Where: I_P = peak resonant current

I_T = current at switch turn

V_{CEP} = switch drop at I_P

V_{BE} = switch base-emitter voltage

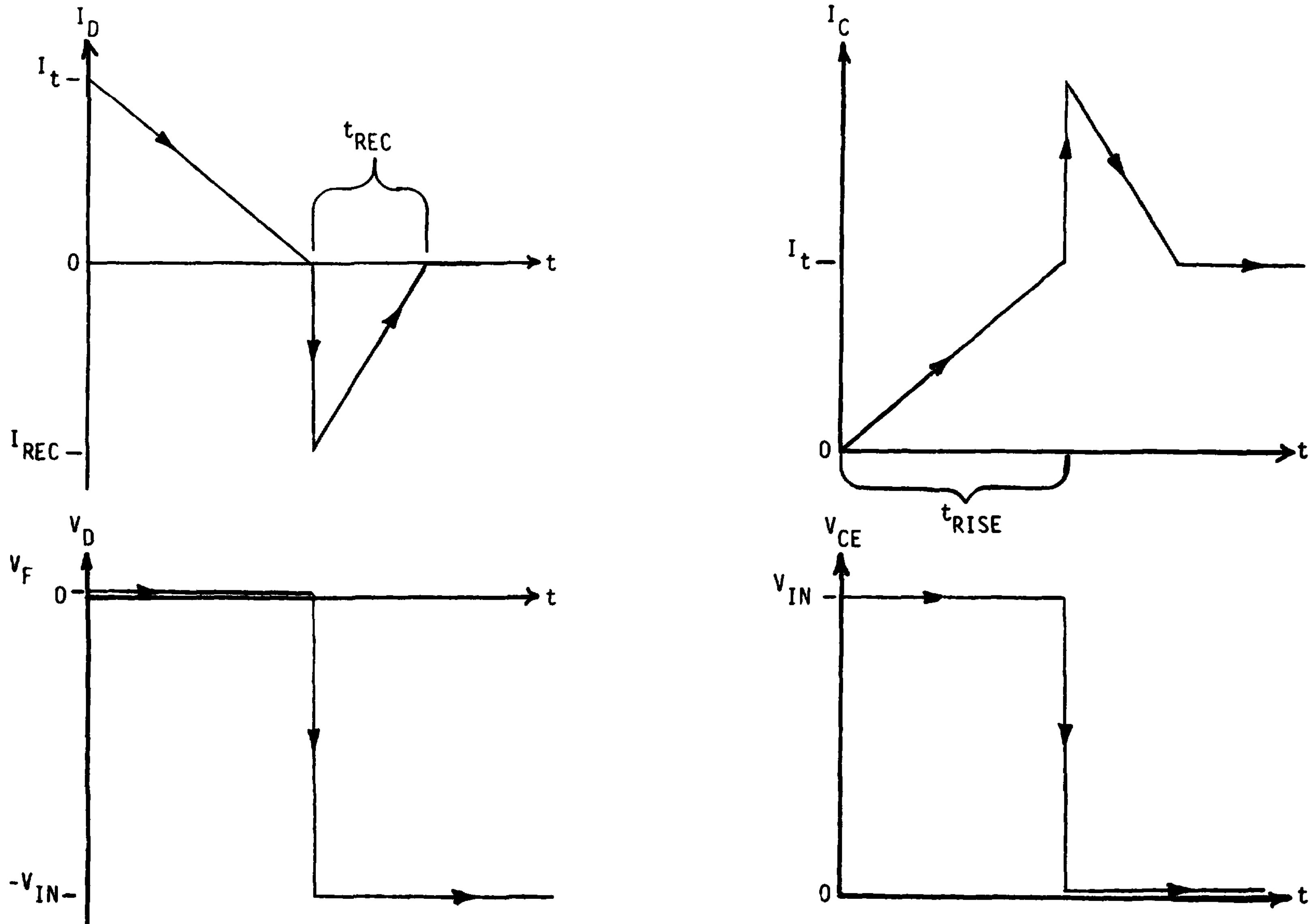
V_F = diode forward voltage

t_{RISE} = switch current rise time

t_{REC} = diode reverse recovery time

I_{REC} = diode peak reverse current

$t_{storage}$ = switch storage time



Diode Waveform

Transistor Waveform

Figure 3-5. Power Loss Waveforms

F_{SW} = switching frequency

V_{IN} = 440 volts

θ and Ψ per Figure 3-4 .

3.5 Non-resonant Switching Approach

It may be possible to remove the series capacitor and drive a minimum inductance transformer with a somewhat pulse width modulated square primary waveform. Such an approach would certainly work if all user loads reflected a high impedance (i.e. an inductance). This approach requires minimum leakage inductance, but the pulse width modulation capability (which also exists to modulate Ψ in the resonant approach) would overcome voltage uncertainties and permit load and line regulation. Modest values of parasitic inductance would not significantly raise losses if the reactive kick is efficiently recaptured instead of dissipated. The clamping diodes on the primary will accomplish this for the major stored parasitic energy, the primary leakage reactance.

The transformer primary voltage is now just 400 VRMS and the current about 65 ARMS. Assuming about 90% duty cycle at full load and power losses for turn on and turn off, per the transistor turn on diagram of Figure 3-5, the switching electronics power losses would be:

$$P = 2 \left\{ I_P \left[V_{CEP} + \frac{V_{BE}}{10} \right] \times .9 + V_{IN} \left[\frac{I_P}{2} \left(t_{RISE} + t_{FALL} \right) \right] 2F_{SW} + 5 \times \frac{I_P}{25} \times t_{storage} + 2\, F_{SW} \right\}$$

where: I_P = peak square current - 69 amp

t_{FALL} = switch current fall time

t_{RISE}, $t_{storage}$, F_{SW}, V_{IN}, V_{CEP}, V_{BE} same as series resonant definitions previously given.

If the primary current could be ramped on and off somewhat, using the leakage reactance to advantage, the transistors may not have to turn on the full power current. This could reduce the transistor dissipation, making the non-resonant approach more attractive.

3.6 Size and Weight Factors

Both the resonant and non-resonant topologies will require an input filter to keep the array load approximately constant. For 0.1% (25 watt) loss, a sufficient inductance input choke will weigh about 1.5 pounds. Four hundred volt, low ESR capacitors will cost about 0.075 pound per μf. The resonant design will require about 45 μf and the non-resonant about 30 μf to stay within device current ratings. Both designs will require 2 1/2 to 4 pounds of controlling electronics and wiring. A basic 20KHz resonant design, when about 2 1/2 pounds, is included for the high power capacitors, would contain about 15 pounds of parts. There will be additional weight required to mount and cool these parts, but this weight will be determined by the mechanical/thermal constraints of the actual usage. A low weight approach would keep the electronics very close to the rotary power transfer device and would attempt to use the structure that supports and cools the transformer to also support and cool the electronics to minimize system weight. Another approach would be removable modules, located somewhat together to facilitate construction, test, and repair, which would probably be the heaviest approach. Thus, the weight penalty for the electronics could be from 19 to 30 pounds. The volume needed to contain the electronics would likewise have about a +33% uncertainty. In addition, if you add the array and radiator penalty to cover the losses (.0122 lb/watt x 510 watt), the system weight penalty is 25 to 36 pounds.

The above weights are for the transfer electronics; the system will require a master clock and control function to control the different modules and provide the logic for the regulation of the ultimate output.

3.7 Tradeoff Analyses Results

Starting with waveform definitions from equations (1) and (2), the terminal voltage for a transformer containing the resonant circuit inductance was determined. This was needed to determine the rotary transformer actual operating voltage. Figure 3-6 presents these waveforms. The RMS voltage and currents were determined graphically from these waveforms. As was noted in section 3.4, the nominal design is a Ψ min of 45°C. A 35° Ψ min curve is given to show the large increase in voltage that produces. A Ψ of 45° is only 2 μs at a switching frequency of 50KHz. The control electronics and switch storage times may need 3 μs minimum delay, (based on current technology), so 77° may be the smallest Ψ min obtainable if the switching frequency was to be 50KHz. Accordingly, Figure 3-6 also shows the waveforms for a 77° Ψ. To illustrate what happens when a lighter load condition occurs, Figure 6 also shows the waveform for a 45° Ψ min design actually operating at a Ψ of 170°. What happens is the applied switching frequency has been reduced to 60% of the design (or full power) switching frequency. The important thing to check here was the resulting V_{RMS} applied to the transformer at the lower actual frequency to determine the operating flux. The 170° actual Ψ means the power being transferred would be about 42% of the design load.

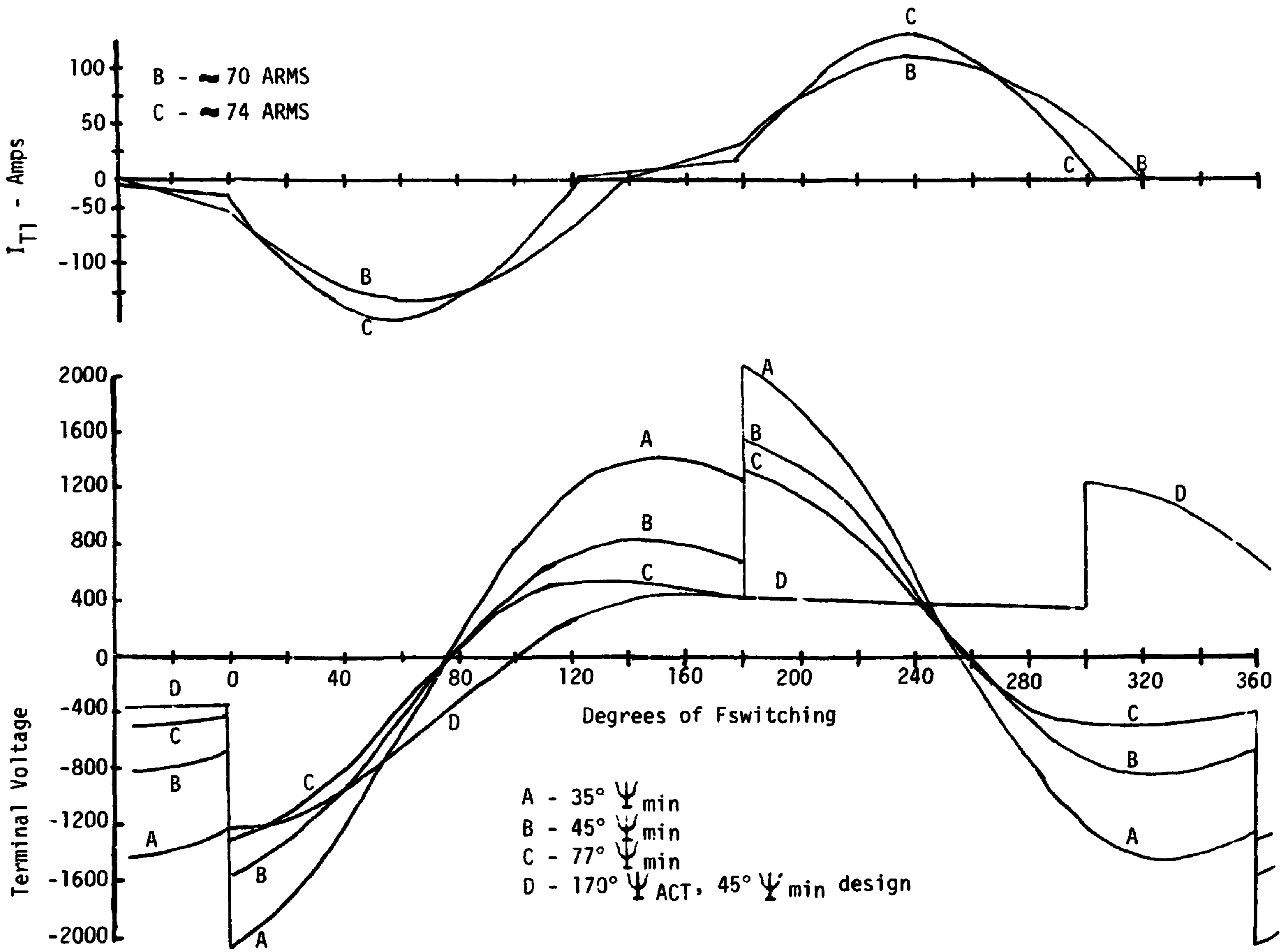


Figure 3-5. Integral-Inductance Transformer Waveforms

Table 3-II presents the circuit element values and other design parameters for the different designs that were studied. Notice that the current is only a function of Ψ for constant V_{IN}, Q, and power. Using these values, and assumed values for loss contributing parameters as listed, the results of Table 3-III were computed by the methods described in sections 3.4 and 3.5. The top 3 sections are resonant approach, the bottom 3 are the non-resonant approach. The worst case parameters reflect "spec" values for conceivable parts without special test and selection. The nominal values are what the parts would usually do. With the high cost of watts for this application, it was presumed that part selection and test (for a somewhat higher price) would be done to assure the worst case part would meet the nominal parameters.

The comparison analysis is based on the 20KHz, 45° Ψ resonant design. The other designs are compared to the basi for delta weight by adding .0122 lb/watt for any chopper or capacitor losses over 459 watts (subtracting weight for losses less than 459 watts), and any capacitor weight over 2.3 lb (subtracting 4.5 lb for the non-resonant design to cover the input filter and power capacitor differences). This comparison shows higher frequency offering no savings in the electronics, even if the switch to FETs is made. The natural tendency for increased losses at higher frequency in the transformer is not easily compensated for by weight reduction due to size constraints posed by the application in a high power rotary transformer. Thus, there will not likely be enough weight saving in the rotary transformer to offset the electronics and transformer system weight penalty for the higher power losses. The only apparent potential for weight saving would be in non-resonant drive (a negative Δ in the comparison). Since the transformer voltage is also reduced, there may also be weight saving in the transformer. This saving in the rotary device and electronics may be offset, though, by weight penalties at the ultimate power user due to the different voltage/current waveforms. When considering the total weight of electronics, rotary device, and heat dissipator, no significant differences can be found between designs. A review of the loss equations shows that all factors are related to the power being processed, the small base power needed for controls is negligible. Since the capacitor weight and losses are also directly related to power (equation 4), these comparisons are virtually independent of the power level.

3.8 Parts Investigation

To determine circuit feasibility and to develop parameters for the loss analysis, current capacitor, diode, and transistor devices capabilities were examined.

The input D.C. filtering application requires low ESR capacitors capable of withstanding 440 to 1000 volts. Currently, there are several metalized plastic film

Table 3-II. Trade-off Designs Parameters

Assumptions		Study Results						
Switching Frequency KHz	Ψ Deg.	Resonant Frequency KHz	V_1 Volts	θ Deg.	L μh	C μf	I_{RMS}	I_{T1} at Switch turn ON Amps
20	45	23.4	1265	14.5	75	.62	70	27
20	35	21.8	1862	19	127	.42	<70	33
25	45	29.2	1265	14.5	60	.49	70	27
50	45	58.5	1265	14.5	30	.25	70	27
50	77	69.3	960	7.6	16.2	.33	74	17

V_{IN} = 440V

Q = 0.9

Pow = 25Kwatt

Table 3-III. Switching Electronics Losses Analysis

Description	Fsw kHz	Ψ Deg	θ Deg	I_F Amp	I_t Amp	V_{CEP} V	V_{BE} V	t_{RISE} μs	t_{FALL} μs	t_{STOR} μs	V_F V	I_{REV} (I_{FL})	t_{REC} ns	Total Chopping Circuits Losses	% of Chopper Losses in "ON" Portion	Comparison Analysis: Capacitor μF	I_{RMS}	Cap F_{OPT}	Optimized Cap Wt lbs	Optimized Capacitor Losses Watts	System Weight Comparison Δ lbs
Worst Case Loss Factors	20	45	14 5	107	27	8	1 2	7		1 5	95	1	60	453	20						
	50	35	19	101	33	8	1 2	7		1 5	1 0	↓	↓	532	17						
	50	45	14 5	107	27	8	1 2	7		1 5	95			990	9						
	50	77	7 6	125	17	85	1 25	7		1 5	90			646	11						
Nominal Loss Factors	20	45	14 5	107	27	6	9	4		1 0	8	5	40	768	25	62	70	1 24	2 3	191	Basis
	50	45	14 5	107	27	4	9	4		1 0	8	↓	↓	570	12	25	70	3 08	2 3	191	+3 7
	50	77	7 6	125	17	65	95	4		1 0	75			392	19	33	74	2 40	2 66	201	+1 8
Nominal Loss Factors, FET Switches	50	45	14 5	107	27	1 1	0	2		4	8	5	40	360	27	25	73	3 08	2 3	191	+1 1
	50	35	19	101	33	1 0	0	2		4	85	5	40	409	[illegible]	.7	70	4 51	2 3	191	+1 7
Worst Case Loss Factors	20			69		5	1 2	7	7	1 5				930	8						
	50			69		5	1 2	7	7	1 5				2206	4						
Nominal Loss Factors	20			69		4	9	4	35	0				517	12				0	0	-2 7
	50			69		4	9	4	35	1 0				1202	5				0	0	+5 6
Nominal Loss Factors, FET Switches	20			69		7	0	2	2	4				330	26						
	50			69		7	0	2	2	4				495	13				0	0	-0 5

types with ratings of 400 volts. Seriesing could be done to obtain satisfactory performance and perhaps special devices could be obtained with about 1000 (D.C.) volt ratings. The power coupling capacitor will require ultra low ESR and very high A.C. ratings. The most likely best-dielectric material would be teflon, to obtain the low losses and high temperature rating, raising the concern of radiation effects. According to Component Research Co., teflon capacitors for a 2500 Vpn application would require seriesing for voltage rating and the bare capacitors would weigh about 1.5 pounds per μf. Due to this type of capacitor's low weight but bulky characteristic, the packaged weight (potting, wiring, and mechanical support) would be about 3.0 pounds per μf.

Switching devices are available today with sufficient voltage rating, or sufficient current rating, but not both with fast enough switching characteristics. Devices such as the Westinghouse D60T or Power Tech PT-3515, have voltage ratings nearly adequate if the system input voltage range is limited. These two devices could be used in the resonant approach since splitting the capacitor function will provide current splitting, so the devices would be effectively paralleled. It would take two devices for each switch to approach the 25KW level. The same approach could be used to split the current among more smaller, faster, and more derated devices. To stay with the faster devices, it will still be necessary to constrain the system input voltage. The sat voltages, V_{BE}, and switching times used in the power loss analyses are consistent with the large devices listed above. A promising device for reduction of switching power losses is the power FET. The International Rectifier HEXFET devices have voltage ratings approaching the 500 volt region. The devices appear to offer ease of paralleling to obtain a desired ON resistance. For the loss analysis, it was simply presumed that this rapidly advancing technology would soon be capable of providing a 10 milliohm ON resistance by paralleling an acceptably small number of devices. The results showed that the devices speed (assumed consistent with the I.R. IRF350 device) was so effective in reducing switching losses, that a higher ON resistance is probably competitive.

Power diodes for the clamping function with good speed are available at 400 volt ratings (1N3913), and also with excellent speed (Unitrode UES806). It seems likely that selection from these families will produce suitable devices if the input voltage range can be constrained. The loss equations parameters were based on the UES806 characteristics.

3.9 Future Study Recommendations

Basic weights of the electronics and rotary transformer are minimized around 20KHz switching frequency and are proportional to the power being processed. The system weight penalty will depend on power losses. To trade off resonant versus non-resonant drive topologies, detailed circuit operation simulations are needed to better determine chopping electronics and rotary transformer losses. A high power (>2KW) rotary transformer should be built to verify loss and reactance effects models. This is necessary because a serious system design would seek to optimize the rotary transformer then design the switching frequency around the actual reactive characteristics of the optimum transformer. System requirements must be refined concerning input voltage range. Switching electronics device availability drops rapidly if input voltage will swing 2 to 1 (up to 800 or 1000 volts). The resonant approach will require ultra low loss, high voltage capacitors. A feasibility prototype must be made to accurately determine power loss factors. The single most promising development to reduce system weight would be high speed switches, most likely FETs. Due to the marketplace needs of switches for offline power supplies, devices rated at 300 to 400 volts are already available and will proliferate. There is much less commercial impetus to 500 to 1000 volt devices which are needed for this application if input voltage variation must be tolerated. Therefore, device development may have to be stimulated by technology development funding.

3.10 References

1. General Electric Co., "Preliminary Designs Development of 100KW Rotary Power Transfer Device", SD Proposal No. C79138, 2 July 1979, Volume I

2. Schwarz, F. C., "An Improved Method of Resonant Current Pulse Modulation for Power Converters", IEEE Transactions on Industrial Electronics and Control Instrumentation, Vol. IECI-23, No. 2, May 1976

3. Schwarz, F. C., Klaassens, J. B., "A 95 Percent Efficient 1KW DC Converter With An Internal Frequency of 50KHz", Proc. IEEE Power Electronics Specialists Conference, San Francisco, 1977

4.0 ROTARY TRANSFORMER

The rotary transformer is a prime candidate for the power transfer device: its principles of operation are well known, it is a relatively efficient device, it can provide any desired voltage output, and there are no inherent difficulties for operation in a space environment. The rotary transformer transfers electrical energy between its windings by electromagnetic induction. The windings are placed in magnetic cores to minimize the excitation required and to increase their coupling. The cores are separated by an air gap, made as small as possible to reduce losses, and rotate relative to each other.

Rotational periods of between 90 minutes and 24 hours required for space applications do not present any problems. However, very high rotational speeds might present some mechanical problems or increase in losses.

4.1 CONFIGURATION

There were two baseline configurations which were considered for the rotary transformer: concentric cylinder and parallel cylinder. These are shown in Figures 4.1 and 4.2. An advantage of the concentric cylinder configuration is that the magnetic forces between the primary and secondary cores are low, being a function of the mechanical eccentricity of the gap between them and can be kept small. The secondary winding is somewhat harder to wind than the primary because it is on the inside diameter of the core. However, this can be overcome, at the expense of adding a small air gap, by having a split secondary core and inserting the winding into one half of the core. The two core halves would then be attached to each other. The parallel cylinder approach is easier to wind; however, the axial magnetic forces between them will be very large. Some reduction of these magnetic forces can be attained by using multiple cores stacked linearly on the shaft and in the housing. This adds mechanical complexity to the design.

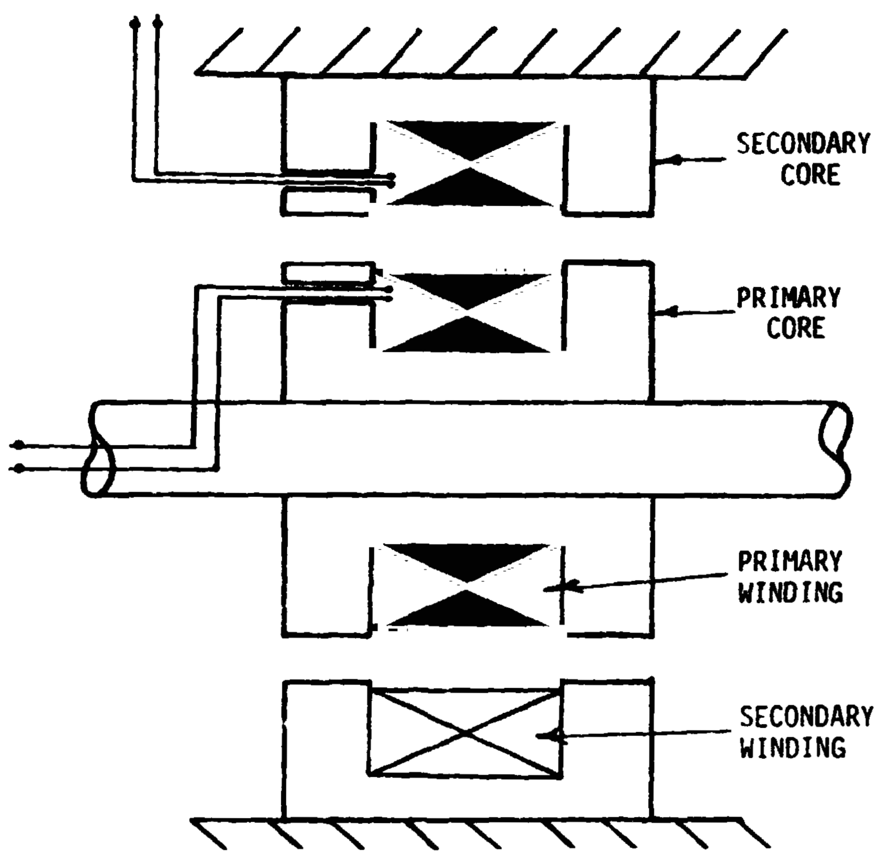


Figure 4.1. Rotary Transformer
Concentric Cylinder Approach

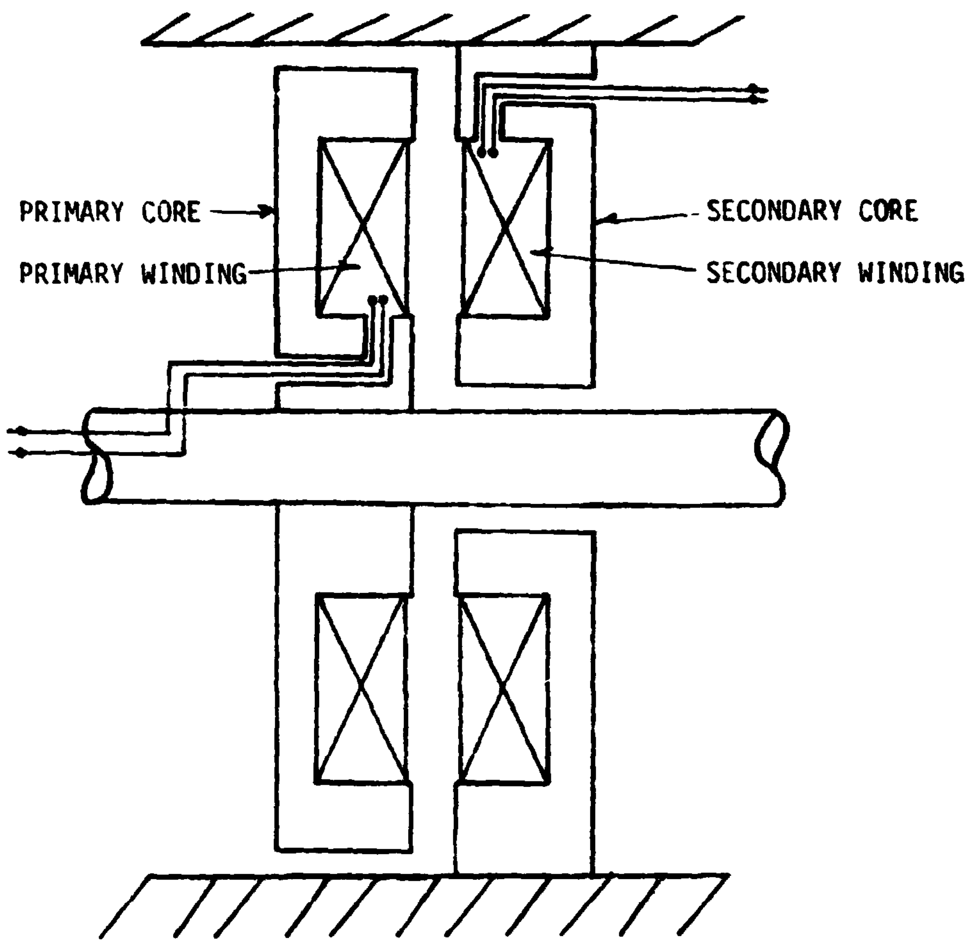


Figure 4.2. Rotary Transformer
Parallel Cylinder Approach

The selection of the rotary transformer core geometry is complicated by the fact that the magnetic flux in the core has to travel in two directions, radially and axially. This means that the magnetic core material must be either isotropic or that two separate magnetic cores must be used to preclude magnetic flux from having to traverse the air gaps between laminations.

The concentric cylinder approach was selected as being the most applicable for this application for the following reasons:

1. Permits the use of modules as recommended by the General Dynamics study.
2. The failure of a module would not cause axial magnetic forces.
3. Easier to maintain small air gap clearances.

4.2 CORE MATERIALS

The primary requirements for magnetic materials are high permeability, high saturation flux density and low losses. In the rotary transformer, the advantages of high permeability for the core material is not as significant a factor as in closed magnetic circuits because of the presence of the air. Two categories of materials were considered for the rotary transformer: ferrous and ferrite. The following is a summary of the properties of candidate materials:

Magnetic Properties of
Candidate Core Materials

Properties	50% Ni - 50% Fe Deltamax (Arnold Engrg.)	Amorphous Alloy Metglas 2605 (Allied Chemical)	Ferrite MN 60 (Ceramic Mag., Inc.)
Saturation Flux (gauss)	16,000	15,000	4,500
Maximum Permeability	130,000	200,000	10,500
Coercive Force (oersteds)	.1	.04	.08
Core Loss (watts/lb)			
f = 1000 Hz/B = 10,000 Gauss	8	.5, as cast .1, annealed	50 mw/cc at 20 KHz, 2000 gauss
f = 10,000 Hz/B = 10,000 Gauss	80	50, as cast 25, annealed	
Curie Temperature (°C)	480	375	185
Availability	Wire, Ribbon & Sheet	Ribbon	Rods

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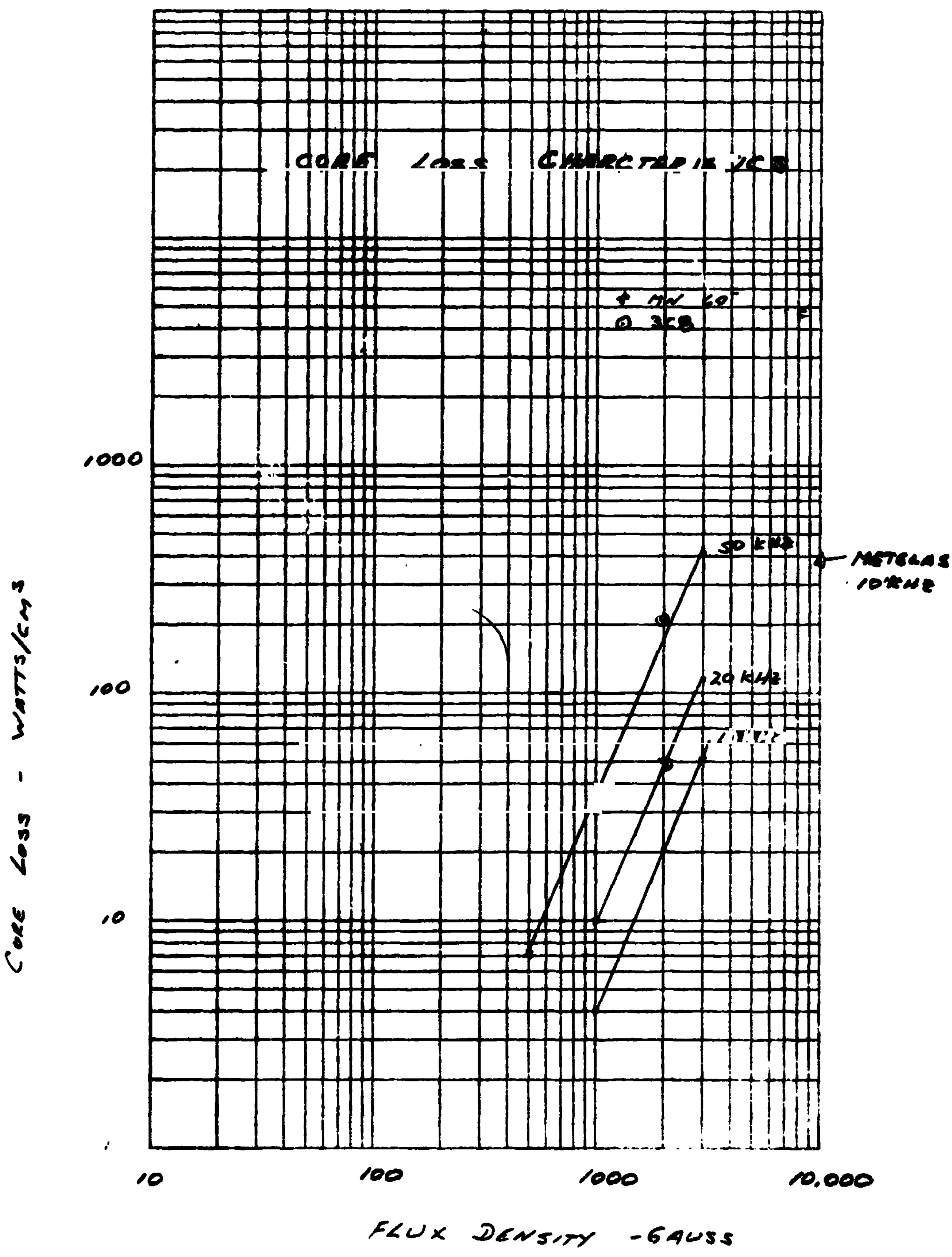


Figure 4.3.

The following summarizes the characteristics of the ferrite and ferrous materials.

	Advantages	Disadvantages
Ferrite	Magnetically isotropic. Low losses at high frequency.	Low operating temperature, 125°C max. Low operating flux density, 2500 gauss, max.
Ferrous	High operating flux density. High operating temperature.	Large high frequency losses. Requires complex magnetic core structure.

MN60 ferrite material was selected rather than a ferrous material primarily because of its isotropic characteristics and low losses that it exhibits at high frequencies. It was recognized that the ferrite material did have shortcomings because of its low flux capability and its temperature sensitivity. Figure 4.3 shows the core loss as a function of frequency and flux density for MN60, 3C8 and Metglas.

4.3 WINDING DESIGN

The transformer winding can be fabricated as a wound coil of insulated round wire. An alternative winding configuration would consist of a strip-wound coil having conductors which are wide insulated thin strips. The optimum coil geometry is based on criteria which include: eddy-current losses, fill-factor, and ease of fabrication.

The strip-wound coil has the primary advantages of good fill factor and could have low eddy current losses. This type of winding does have a potentially serious disadvantage of producing high eddy current losses which would result from radial components of leakage flux which cross the conductor. In addition strip-wound coils are difficult to transpose if this were required to reduce the eddy current losses.

A wound coil consisting of transposed insulated wire, litz wire, was assumed for the rotary transformer. The major disadvantages of litz wire are its low fill factor and many conductors. However, because of the concern for eddy current losses, possible radial components of leakage flux and ease of transposition, it was felt to be superior than strip wound coils. It might be possible that for rotary transformers having power ratings in excess of 25 Kw or those requiring low inductance because of square wave operation, strip wound coils might be better.

4.4 ROTARY TRANSFORMER DESIGN

In the design study of rotary transformers there were many parameters which could be varied. In order to be able to compare various designs and to keep the number of variables to a minimum, guidelines were established.

1. Maintain minimum air-gap clearance to reduce the magnetizing current. Assume minimum air-gap clearance of .01 inches.

2. Match the leakage inductance to that required by the power conditioning to eliminate the need for external inductors.

3. Use MN60 ferrite. Do not exceed a core flux density of 2,500 gauss, regardless of frequency. Do not exceed a temperature of 125^{o}C in any part of the core.

4. Use stranded insulated conductors, such as litz wire to reduce eddy current losses. Conductors must be completely transposed.

The initial design effort on rotary transformers was based on operation using a square wave converter. E. Landsman in his paper "Rotary Transformer Design", Power Conditioning Specialists Conference (PCSC) Record, 1970 pg 139, analyzed the rotary transformer operating with square wave excitation. Based on Landsman's analysis, square wave operation imposes a constraint to maintain low leakage inductance in the transformer. He indicates that the magnitude of his factor K should be kept in the vicinity of 5, where K is defined as:

$$K = \frac{T}{2}$$

$$T = \frac{1}{f}$$

T = winding time constant

$$T = \frac{\text{winding leakage inductance}}{\text{winding resistance}}$$

This results in very tight limitations on the allowable radial depth of the winding. The following table, based on Landsman, shows the total radial depth of primary and secondary windings as a function of frequency to attain a magnitude of K equal to 5:

Frequency (KHz)	Total Winding Depth (inches)
10	.051
25	.032
50	.023

These depths, necessary to keep the leakage inductance of the transformer small, result in a very wide slot necessary to accommodate the primary and secondary windings, and as a consequence, the transformer is long and has a small diameter.

A second important parameter in the rotary transformer design is the air gap clearance. This should be kept as small in order to reduce the magnetizing current and also to reduce the leakage inductance. The air gap clearance was taken as .010 inches based on mechanical considerations; however, it will be noted from the above table, the air gap clearance is not insignificant compared with the total allowable winding depth.

In order to obtain a perspective, a number of rotary transformer designs were sketched out. These ranged in power from 100 Kw to 25 Kw, frequency from 25 KHz to 2.5 KHz, square and sine wave. Some of the results are presented in Table 1. This table should be used as a guide in a general way rather than as a trade-off study since all the designs were not carried out completely. The basic conclusions of this design effort are as follows:

1. The transformer weight is an inverse function of Landman's K factor.

2. "High" efficiencies can be achieved.

3. Current densities of 10,000 amps per square inch do not necessarily cause heating problems.

4. There is no great disadvantage to using four 25 Kw modules instead of one 100 Kw unit.

5. Eddy currents in the core (in addition to core losses) may become a problem when large cores are used.

6. The power conditioning electronics requirements can impose severe constraints on the rotary transformer design.

Because there did not appear to be any great advantages of square wave operation, discussions were held with LeRC and it was decided to base the rotary transformer design upon the General Dynamics study of a 250 Kw system. In addition, input current, voltage, wavesharp and inductance parameters as determined by the power conditioning system analysis were used for the rotary transformer. The rotary transformer requirements were as follows:

Table 1. Rotary Transformer

P (KW)	f (KHZ)	Δ (amps/in²)	N (turns)	Bg (Kilogauss)	Bc (Kilogauss)	Do (inches)	L (inches)	W (lbs.	% Eff.	K
100	25 (square)	1,000	4	.8	2.0	8	6	40	99.6	.01
100	25 (square)	5,000	4	1.6	2.0	7	27	119	99.4	2.5
100	25 (square)	10,000	1	1.6	2.2	8.5	9	86	98.7	10.6
100	2.5 (square)	10,000	3	2.0	3.2	12	11.5	221	99.5	7.9
100	2.5 (square)	10,000	4	2.0	3.1	10	10	133	99.6	2.2
100	25 (Sine)	10,000	10	2.5	2.5	3	1.0	10	99.5	.45
25	25 (Sine)	10,000	2	3.0	2.8	8.3	3.5	31	98.4	10.2
25	25 (Sine)	10,000	10	3.0	2.5	4	2.0	4.0	99.6	.8
25	50 (Sine)	10,000	5	2.5	2.5	4	2.2	4.4	98.6	1.2

Input voltage	440 volts
Output voltage	1000 volts
Power per module	25 kilowatts
Input frequency	20 KHz
Power transfer device	Rotary transformer
Rotary transformer	
Primary windings	Each module winding connected in parallel
Secondary windings	All module windings connected in series Two windings on secondary for redundancy
Power conditioning	Resonant circuit

$f_{switching}$ (KHz)	Input Current (Amps, rms) Preliminary	Final	Inductance (μH) Preliminary	Final
20	84	70	70	75
25	84	70	55	60
50 (Future technology)	84	70	28	30
50 (Present technology)	100	74	14	16.2

The characteristics of rotary transformers were investigated at two frequencies, 20 KHz and 50 KHz. For the 50 KHz frequency, the "present technology" power conditioning was used since it represented a smaller inductance than the "future technology" even though the input current was larger.

The columns titled Preliminary and Final, in the above, results from additional analyses performed on the power conditioning circuitry.

Sample rotary transformer designs were made for 20 KHz and 50 KHz operation based on the preliminary requirements of the power conditioning system. These designs were done for the purpose of determining whether there were any substantial advantages to either frequency. The designs were not optimized so that some gains may be obtained in size, weight or efficiency.

20 KHz Rotary Transformer

Power		25 KW
Frequency		20 KHz
Input Current		84 amps
Output Voltage		1,000 volts
Inductance		70 μH
Outside Diameter		8.9"
Inside Diameter		2.0"
Length		2.6"
Weight		22 lbs
Core Material		MN60
"Average" Flux Density		2,000 gauss
Primary winding		12 turns 1,428 #36 AWG
Secondary winding		30 turns 510 #36 AWG Redundant windings
Core Loss ($100^{o}C$)		100 watts
I^2R Loss (AC, $100^{o}C$)	Primary	75 watts
	Secondary	120 watts
Efficiency		98.8%

50 KHz Rotary Transformer

Power		25 KW
Frequency		50 KHz
Input Current		100 amps
Output Voltage		1,000 volts
Inductance		14 uh
Outside Diameter		7.5"
Inside Diameter		2.0"
Length		2.2"
Weight		13.0 lbs
Core Material		MN60
"Average" Flux Density		1,500 gauss
Primary Winding		6 turns 3,175 #38 AWG
Secondary Winding		15 turns 794 #38 AWG Redundant windings
Core Loss ($100^{o}C$)		150 watts
I^2R Loss (AC, $100^{o}C$)	Primary	130 watts
	Secondary	60 watts
Efficiency		98.6%

A comparison of rotary transformers at 20 KHz and 50 KHz indicates that there is some weight advantage at the higher frequency but there is concern that the core losses might be higher than indicated. The primary differences between 50 KHz as compared with 20 KHz operations are:

Operating flux density must be reduced because of core losses

Wire size must be reduced because of eddy current loss in winding.

It is possible that a lower operating frequency than 20 KHz could result in smaller and more efficient rotary transformers due to core loss and winding eddy current loss.

A more detailed design was made of the 20 KHz, 25 Kw rotary transformer based on the "Final" power conditioning circuit parameters:

Power	25 Kw
Frequency	20 KHz
Input Current	70 amps, rms
Input Voltage	775 volts, square wave equivalent (See Figure 4.4)
Output Current	25 amps, rms
Output Voltage	1000 volts
Inductance	75 μH

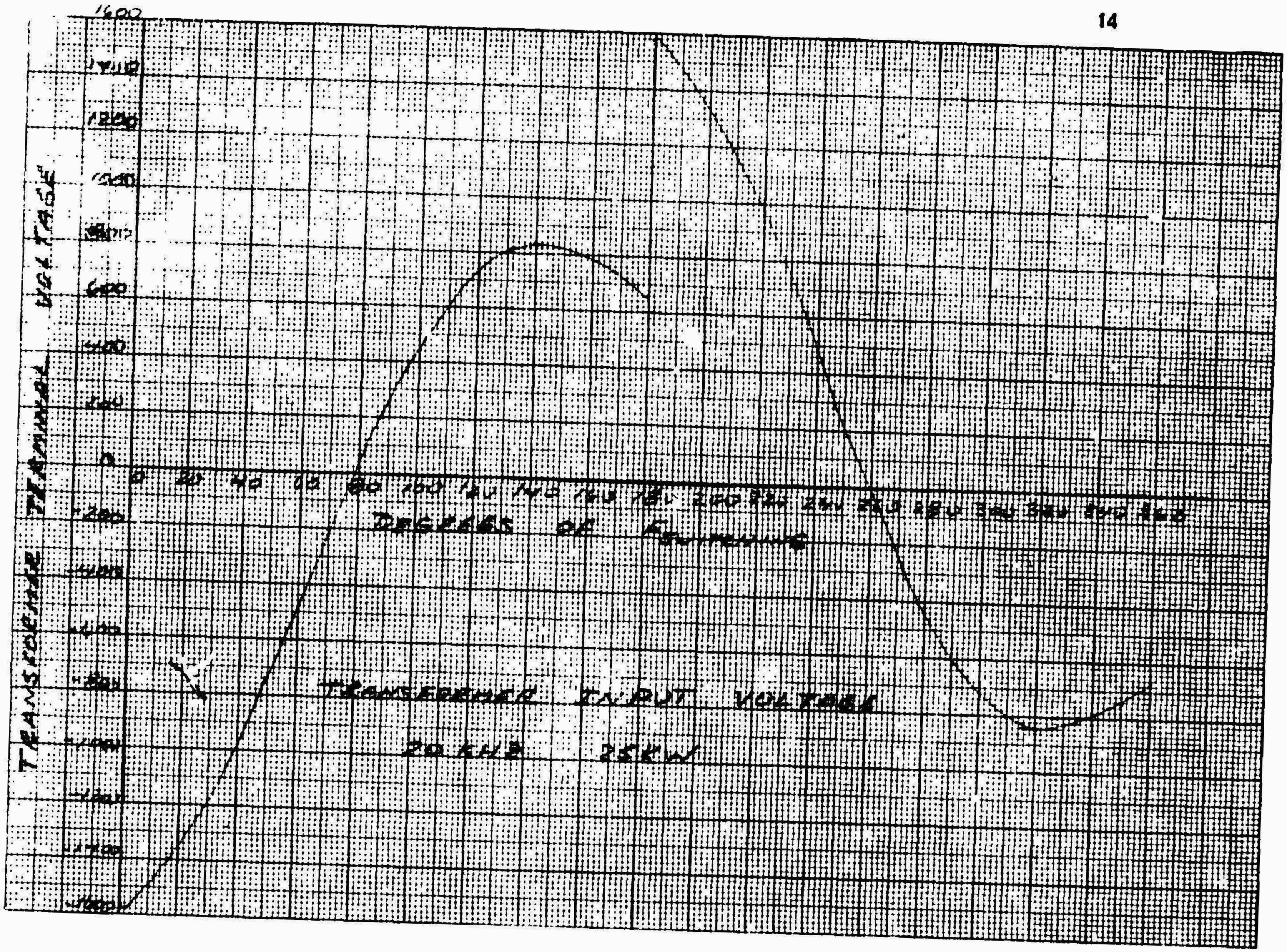

TRANSFORMER TERMINAL VOLTAGE
DEGREES OF
TRANSFORMER INPUT VOLTAGE
20 KHZ 25KW

Figure 4.4.

The transformer characteristics are summarized as follows (see also Figure 4.5):

Core	
Outside Diameter	9.0"
Air-gap Diameter	5.35"
Inside Diameter	2.0"
Air-gap Length	.01"
Width of pole	.6"
Depth of Slot, Primary	.95"
Width of Slot, Primary	1.3"
Depth of Slot, Secondary	1.55"
Width of Slot, Secondary	1.3"
Flux Densities	
Air-gap	1240 gauss
Primary Pole, Root	1925 gauss
Primary Core	2020 gauss
Secondary Pole, Root	985 gauss
Secondary Core	1660 gauss
Winding	
Primary Winding	12 turns 1428 #36 AWG
Secondary Winding	12 turns 510 #38 AWG Redundant Windings
Primary Resistance ($100^{o}C$)	.0053 ohms, dc .0136 ohms, ac
Secondary Resistance (Redundant Windings) ($100^{o}C$)	.029 ohms, dc .120 ohms, ac
Primary Inductance	19 μH
Secondary Inductance (Referred to primary)	51 μH
Total Inductance	70 μH

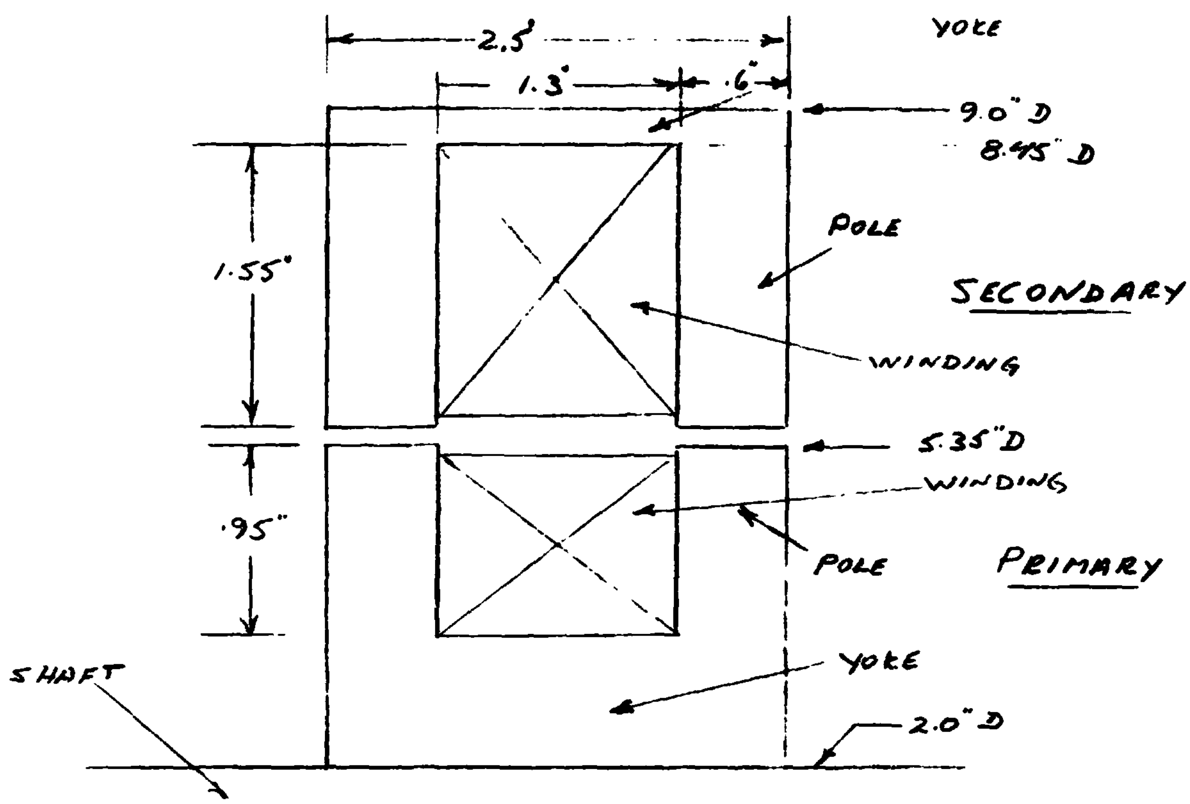


Figure 4.5. Rotary Transformer Configuration

Weight (lbs)

	Primary	Secondary	Total
Copper	2.0	5.1	7.1
Core	5.4	10.3	15.7
Total	7.4	15.4	22.8

Losses

I^2R	66	75	141
Core	51	38	89
Total	117	113	230

Efficiency 99%

Thermal

Primary

Sink Temperature	60°C
Core Temperature	100°C
Coil Temperature	105°C

Secondary

Sink Temperature	60°C
Core Temperature	63°C
Coil Temperature	66°C

Weight of Thermal Sink (Fig 4.6)
(6 lbs/kw, 60°C)

Primary	.8 lbs.
Secondary	.8 lbs.

Area of Thermal Sink (Fig 4.6)
($35\ ft^2$/kw, 60°C)

Primary	$4.4\ ft^2$
Secondary	$4.4\ ft^2$

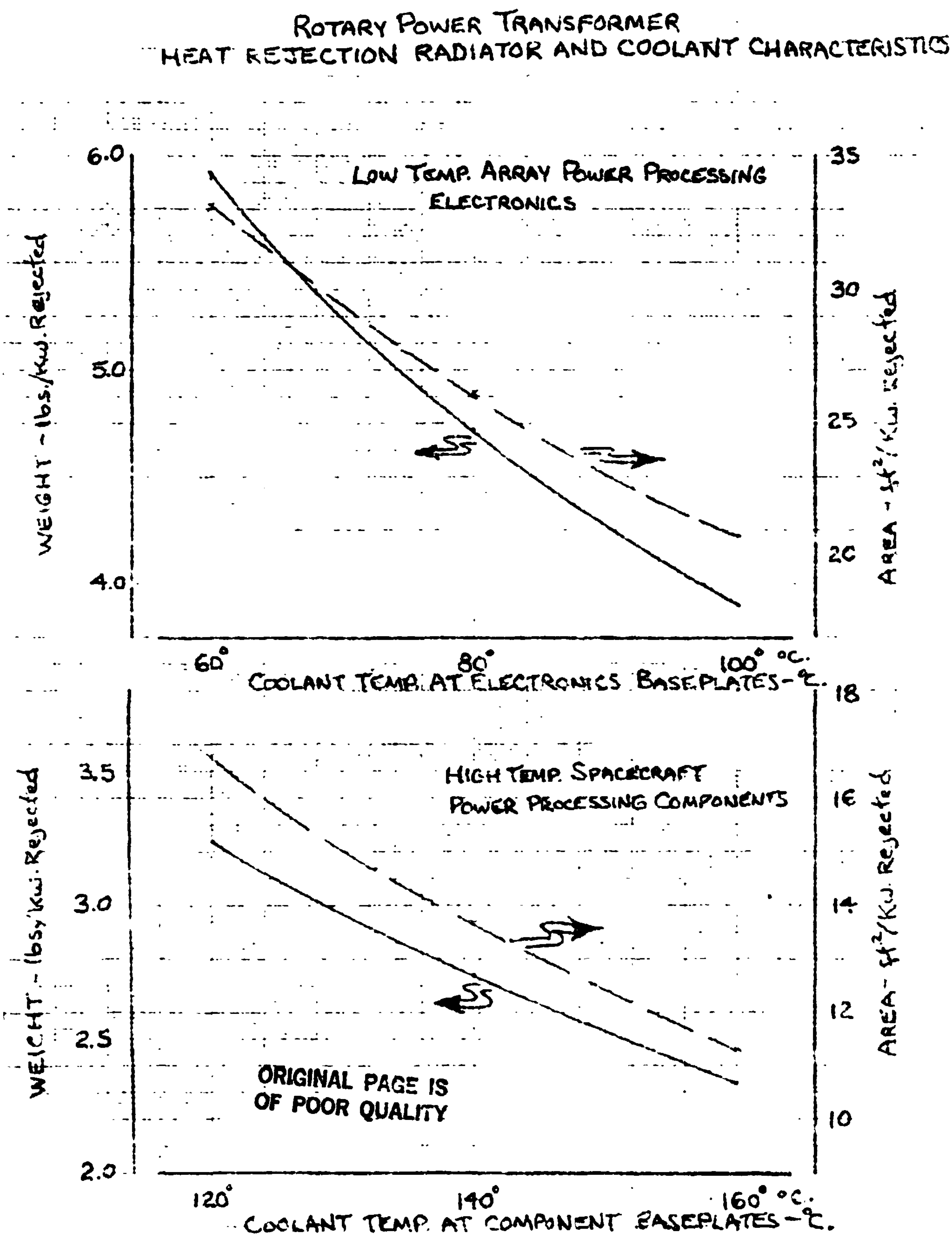


Figure 4.6.

6/18/79 GCH

A design consideration which will impact the size, weight and efficiency of the rotary transformer is the eddy current losses in the transformer winding. These losses are due to skin effect in individual conductors and the effects of the proximity of adjacent conductors with the proximity effects being the more severe. The skin and proximity effect are lumped together and are considered as AC I^2R losses (I^2Rac), or eddy current losses from an analytical point of view, the I^2Rac is considered as being produced by the leakage flux of the transformer. The eddy current losses can be reduced by using multiple standard insulated conductors in parallel and transposing them. In practice, this is achieved by using litz wire.

The eddy current loss in the transformer winding is given by H. W. Taylor, Journal I.E.E.E., 1920, Vol. 58, p. 279,

$$\frac{R_{ac}}{R_{dc}} = 1 + q^2 \left(\frac{D}{9} - \frac{17}{3790} D^2 \ . \ . \ . \right) - \frac{D}{45} + \frac{D^2}{900} \ . \ . \ .$$

$$D = \left[\frac{h^2 fw}{8.23S} \right]^2$$

h = height of rectangular conductor, inches

f = frequency, hz

w = width of conductors in slot

s = total width of slot

q = number of conductors in height (radially)

For the rotary transformer, this equation can be simplified to

$$\frac{R_{ac}}{R_{dc}} = 1 + q^2 \ \frac{D}{9}$$

The eddy current losses in the rotary transformer were discussed with personnel in the GE transformer group and large motor group. Although their experience was more in the 60 Hz frequency regime, they felt that the approach to the determination of eddy current losses in the rotary transformer was valid. The following points were made:

1. There should not be a significant difference in the eddy current loss by the use of round wire rather than the rectangular wire.

2. A transposed conductor such as litz wire should be used.

3. The use of thin flat strip conductors instead of round wire could result in substantially higher eddy current losses if there is a radial component of leakage flux relative to the conductor in the slot.

4. The eddy current loss is independent of the position of the winding in the slot. The placement of a given winding will not change the eddy current loss: a winding at the bottom of a deep slot will have the same eddy current loss as the same winding placed at the top of the slot.

The implication of (4) are quite important in achieving the requisite inductance defined by the power conditioning. It allows changing the position of the primary or secondary winding in an oversized slot or the use of a magnetic shunt technique to trim the transformer inductance. It should be noted that there is a direct relationship between rotary transformer inductance and its eddy current loss since the eddy current loss is a function of inductance. This serves to complicate the design of the rotary transformer because changes in inductance are accompanied by changes in the winding eddy current losses.

In order to ascertain its quantitative characteristics, the eddy current losses in a sample rotary transformer design were examined. The transformer had the following parameters:

Number of turns (primary)	18 turns
Wire	#25 AWG
Number of turns in parallel	111
Width of winding	3.0"
Width of slot	3.2"
q (number of conductors in height)	18
Frequency	20 KHz

The #25 wire was selected based on its copper diameter being .0179 inch which compares with an effective skin penetration on each side of a flat conductor of .0165 inch (total penetration = 2 x .0165 = .033 inch). The number of turns in parallel, 111, was selected on the basis current density. For this case, it was found that

$$\frac{R_{ac}}{R_{dc}} = 14.3.$$

This represents an unacceptably high I^2R loss. In order to reduce the R_{ac}/R_{dc}, a number of other cases were examined using the same slot dimensions but with smaller wire sizes. Ac lly, large slots would be required with the smaller wire sizes because of their poorer spac factors.

N	Wire	Copper Diameter	Parallel Turns	R_{ac}/R_{dc}
18	#25	.0179"	111	14.3
18	#29	.0113"	280	6.4
18	#36	.005 "	1428	2.4

Thus, by using sufficient small wire. the eddy current loss can be reduced to acceptable limits. It is not sufficient to use small wire, but a litz wire construction must be used in which, ideally, every wire is rotated so as to occupy every position in the slot. In other words, merely reducing the wire size and insulating every turn from each other is not sufficient to reduce the eddy current loss to the values shown above. It is also necessary to have complete transposition of each turn.

Another source of eddy current losses is in the core of the rotary transformer. The transformer are to be viewed as a shorted-circuit turn around the primary winding through which current flows causing losses. These losses can be considered as being E^2/R where E is the induced voltage in the core and R is the resistance of the core. Fortunately, the transformer core is fabricated of a ferrite material which has very high electrical resistance and this reduces the losses substantially. Since the electrical resistance of MN60 ferrite is quite high, being 200 ohm cm as compared to 1.7×10^{-6} ohm cm for copper, it would indicate that the losses should be small. However, Ceramic Magnetics, Inc., the vendor of MN60, has stated that they observed higher than anticipated losses in large cores. The eddy current losses in the core are difficult to compute. The loss can be approached from the aspect of the eddy current loss in a cylinder and in a thin sheet. The cylinder corresponds to the cylindrical portion of the magnetic circuit and the thin corresponds to the end disks. The eddy current loss in a solid cylinder is

$$P = \frac{(\pi dBf)^2 \times 10^{-16}}{16\rho} \text{ watts/cm}^3$$

and the loss in a thin sheet is

$$P = \frac{(\pi tfB)^2 \times 10^{-16}}{6\rho} \text{ watts/cm}^3$$

Where P = eddy current loss, watts/cm^3

B = flux density, gauss

f = frequency, Hz

ρ = electrical conductivity, ohm-cm

t = thickness of sheet, cm

d = diameter of cylinder, cm

The eddy current loss in the core is one component of the core loss, the other being the volumetric core loss. The volumetric core loss is the core loss usually published by vendors and is expressed in units of watts per unit volume or watts per unit weight and is given as a function of flux density. This data is usually obtained from small test cores: the test core for MN60 is .917" OD, .588" ID and .302", height and has a volume of approximately .1 in^3 which is small compared with a typical rotary transformer which about two orders of magnitude larger.

Because of the possibly high core losses which may occur, it will be necessary to determine the magnitude of these losses more closely using the actual core geometry.

The rotary transformer was designed with two parallel windings on the secondary to provide redundancy in the case of failure. The use of a redundant winding results in a substantially larger transformer secondary since extra copper and core must be provided, perhaps 5 lbs, or more, could be saved by eliminating them. Evaluating the monitoring system which senses and corrects faults could result in a better fault protection approach.

The thermal requirements on the rotary transformer core which limits the allowable core temperature to 125^{o}C necessitates the use of heat pipes to transfer the loss , axially, to the heat sink with a minimum thermal gradient.

The question arises regarding the characteristics of a single 100 Kw transformer relative to four 25 Kw transformers. A detailed analysis was not made of the 100 Kw transformer, however, some general statements can be made:

	25 Kw	4 - 25 Kw	100 Kw
Inductance	75 μH	75 μH, each	18.8 μH
Diameter	9" OD	9" OD	9" OD
Length	2.5"	10"	6.4"
Weight	22.8 lbs	91.2 lbs	63.3 lbs
Efficiency	99%	99%	> 99%

The single 100 Kw rotary transformer appears to have size, weight and some efficiency advantage over four 25 Kw transformers. This advantage stems from the fact that only two pole pieces are required for the 100 Kw whereas eight pole pieces are needed when four 25 Kw units are used. There will be a slight increase in efficiency because of reduced pole piece core losses. On the other hand, there will be a tendency for the temperature of the coil to be higher because there will be relatively less axial heat flow in the 100 Kw transformer.

5.0 ROTARY CAPACITOR

Contactless power transfer can be achieved by the use of a rotary capacitor. The power transfer is achieved by energy being stored in the electric field in the gap between the capacitor electrodes. Since the quantity of energy stored in an electrostatic field is less than that stored in an electromagnetic field because of low dielectric constants and limitations on voltage gradients, electrostatic devices, generally, have not been considered viable alternatives to their electromagnetic counterparts because a larger size is required to achieve the same power rating. The rotary capacitor is simple in construction since it requires only electrically conducting disks separated by gaps: it does not require the windings or the magnetic core structure of the rotary transformer. The limitation of the rotary capacitor is on input voltage because of the allowable voltage gradient. The vacuum environment of space is an excellent dielectric media for a rotary capacitor because of the high dielectric strength of vacuum and because there are no dielectric losses present.

Other possible dielectric media includes gases, liquids and solids. Gases, under pressure, have high dielectric strength while liquid and solid dielectrics have high dielectric constants. However, liquids and solid have significant dielectric losses. Gaseous and liquid dielectrics could require rotary seals while solid dielectrics would necessitate close mechanical clearances.

The requirement for a rotary seal for use with gaseous or liquid dielectrics can be fulfilled by the use of a ferrofluidic rotary seal such as manufactured by Ferrofluidics Corp. of Burlington, Mass. The ferrofluidic seal is used to seal against vacuum and pressures up to 100 psi with negligible leakage. The ferrofluidic seal is non-wearing low friction, and consists of colloidal-size ferromagnetic particles suspended in a hydrocarbon fluid in the presence of a strong magnetic field. Ferrofluidic seals of this type have been successfully used by GE/Space Division on components and test equipment as rotary vacuum seals.

A possible configuration of the rotary capacitor is shown in Figure 5.1. This configuration can be used with a vacuum, gaseous or liquid dielectric. It can be used with a solid dielectric by placing the solid dielectric in the inter-electrode gap. The diameter, length and number of electrodes of the rotary capacitor are functions of the dielectric constant, dielectric strength and dielectric losses of the media, as well as the input voltage and frequency.

5.1 ENERGY STORAGE

In order to minimize the size of the rotary capacitor, the quantity of energy stored in its electric field must be as high as possible. The size of the rotary capacitor is inversely proportional to the stored energy. The energy stored in an electrostatic field is given by

$$W_e = \frac{K E^2}{8\pi}$$

Where W_e = energy, ergs/cc

K = dielectric constant

E = electric field intensity, statvolts/cm

It can be seen that the critical parameters for energy storage are dielectric constant and electric field intensity. Both of these are characteristics of the dielectric material with the electric field intensity being the voltage gradient allowable without breakdown (dielectric strength). There are four material categories which can be considered for the dielectric media: vacuum, gas, liquid, and solid. Table 5.1 shows the dielectric breakdown characteristics of a number of these dielectric media. It is appropriate to obtain an insight into the electrostatic energy storage

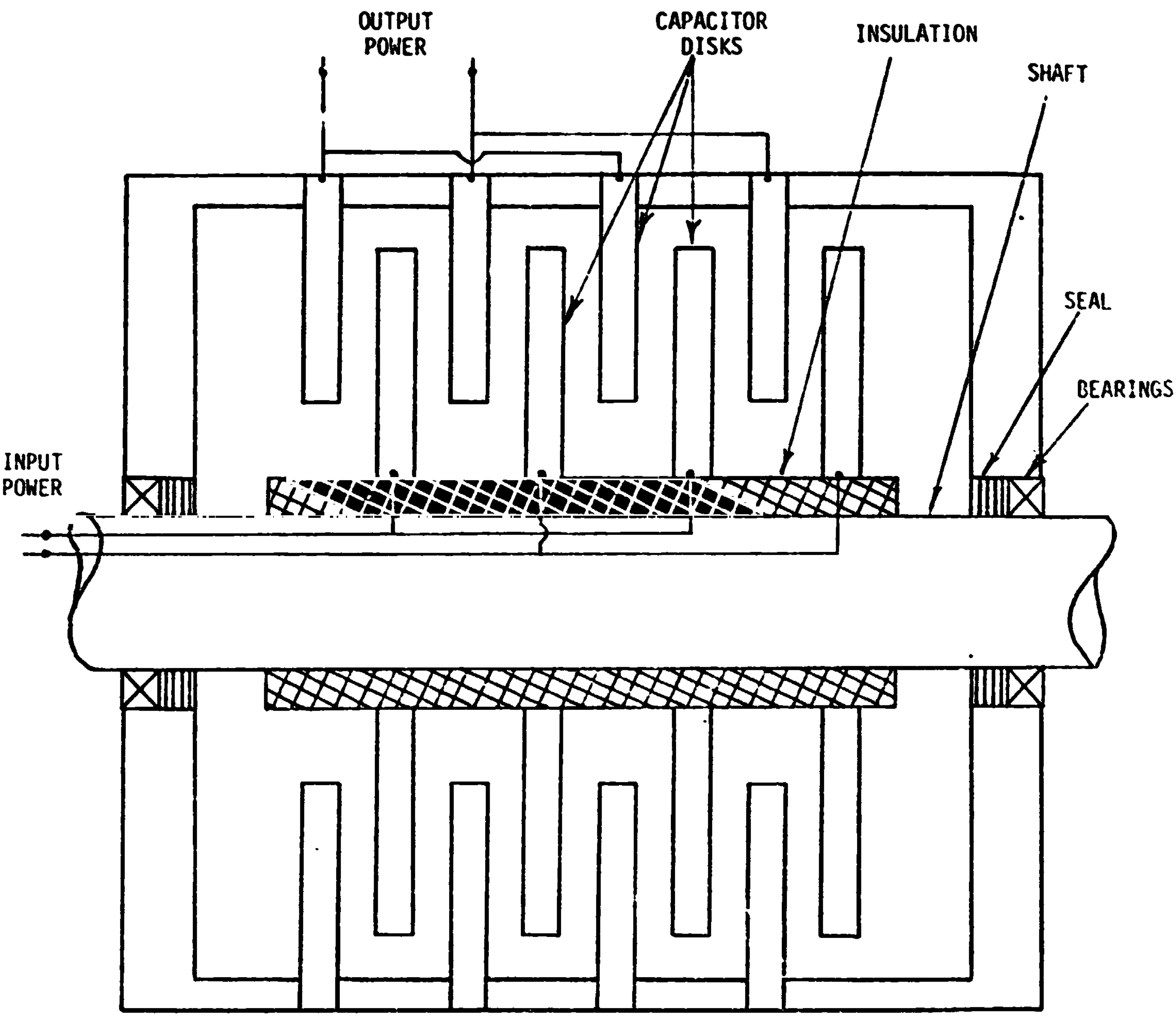


Figure 5.1. Rotary Capacitor Concept

capacity of various materials, and to compare with the electromagnetic energy storage. This is shown in the table below:

Table 5.1. Dielectric Breakdown Characteristics of Dielectric Media

Media	Dielectric Constant (K)	Breakdown Voltage (kV/cm)	Stored Energy (ergs/cc)
Vacuum	1	100	4,400
		300	40,000
		1000*	440,000
Air 1 atm	1	30	400
1 atm	1	75*	2,500
7 atm	1	250	28,000
Sulfur Hexafloride			
(SF_6) 1 atm	1	70	2,200
7 atm	1	350	54,000
Askarel Oil	4.8	35	2,600
	4.8	350*	133,000
Forsterite	6	100	27,000
Titanium Dioxide	90	100	400,000
Barium Titanate	10,000	75	25×10^6
Electromagnetic	$\mu = 1$	B = 1000 gauss	40,000
	$\mu = 1$	B = 10,000 gauss	4×10^6
	$\mu = 1$	B = 20,000 gauss*	16×10^6

* Upper limits of dielectric and magnetic properties

It can be seen from this table that the energy storage capabilities of vacuum, pressurized gases, fluids and solid dielectrics are significant compared with electromagnetic systems and do represent a viable alternative. It should be noted that the breakdown voltage of dielectric materials is subject to a wide range of variation. In general, it is dependent upon a great number of variables such as electrode size, shape and spacing; electrode material and surface finish; humidity, temperature and waveshape and duration of applied voltage. Therefore, care must be exercised in the comparison of various dielectrics and in the design of the rotary capacitor to select values for the breakdown voltage that are appropriate for the geometry and operating parameters of the system.

5.2 SKIN EFFECT

The use of high frequency for the rotary capacitor does not present problems with regard to skin effect. The skin depth of a larger flat isolated conductor is given by

$$\delta = 5033 \sqrt{\frac{\rho}{f}}$$

Where δ = skin depth, per side, cm

ρ = electrical resistivity, ohm-cm

f = frequency, Hertz

The following table gives the skin depth per side for isolated aluminum conductor:

(Hz)	(cm)	(inches)
1000	.266	.105
2000	.188	.075
5000	.119	.0469
10000	.0842	.033
25000	.0533	.021
50000	.038	.015

This indicates that for higher frequencies the effective thickness of the conductor is of the magnitude desired for mechanical purposes so that skin effect should not be a problem. The effects of other conductors in close proximity would be to decrease the effective skin thickness and thus increase the ac resistance, however, they are far enough away so that their effects should be negligible.

5.3 VACUUM DIELECTRIC

The use of a vacuum for the energy storage media for the rotary capacitor looks very promising. It results in a high level of energy storage, does not require seals and is not subject to degradation. Vacuum can be considered to exist when the breakdown strength is independent of gas pressure. This occurs when the mean free path of a gas molecule is large compared with the electrode spacing. From a dielectric strength point of view, vacuum exists below 10^{-4} to 10^{-6} mm Hg. The breakdown voltage in vacuum is a function not only of the voltage gradient, but also of the absolute magnitude of the voltage. Below 20 KV, breakdown is initiated by electron emission from the cathode surface; gradients as high as 5000 KV/cm have been obtained from well polished cathode surfaces and 50,000 Kv/cm from well polished anode surfaces. With higher absolute voltage magnitudes, these high gradients decrease. The gradient at the cathode decreases from 5000 KV/cm at 20 KV, to 1000 KV/cm at 100 KV. This phenomenon does not affect the rotary capacitor since it is not anticipated to operate power supplies at these voltage levels.

The voltage breakdown in vacuum is a function of the surface finish and electrode material. For electrodes having surface areas of several square centimeters, polished but not buffed, and separated by .1 cm, the breakdown voltages are as follows:

Material	Breakdown Voltages (KV/cm)
Steel	1220
Stainless Steel	1200
Nickel	960
Monel	600
Aluminum	410
Copper	37

If the electrode surfaces are highly buffed, the breakdown voltage characteristics can change. For example, buffed aluminum will produce a higher dielectric strength than stainless steel. A general rule for the breakdown characteristics of electrodes in vacuum is that the breakdown voltage is proportional to the melting temperature of the electrode material.

The dielectric strength of vacuum is a function of the length of gap and area of gap. Increasing the gap from .1 cm to 1.0 cm, decreases the breakdown gradient by a factor of 3. Similarly, electrodes having an area of 1000 cm^2 will have 1/3 of the dielectric strength of that of small electrodes, such as shown in the above table. A general rule for electrode area effects is that the breakdown voltage gradient varies as the logarithm of the area. Figure 5.2 shows the vacuum breakdown characteristics of a one-inch diameter steel ball and a two-inch diameter steel disk.

The General Electric Switchgear Department has developed a proprietary dielectric coating which can be applied to electrode surfaces. This serves to reduce local areas of high voltage gradient resulting from discontinuities in the geometry of the electrodes. The use of this coating permits operation at higher voltage gradients than would be normally expected.

In summary, it appears that in the rotary capacitor operating in a vacuum, voltage gradients of 100 KV/cm are obtainable, and, in addition, if care is exercised in the design and selection of materials, gradients of 300 KV/cm may be attained. This makes the vacuum dielectric rotary capacitor a very encouraging possibility.

5.4 GASEOUS DIELECTRICS

The rotary capacitor could utilize a gas as the dielectric media. Gases have dielectric constants close to unity, display no dielectric losses and have low viscosities. If operated under pressure, their dielectric strengths increase and can

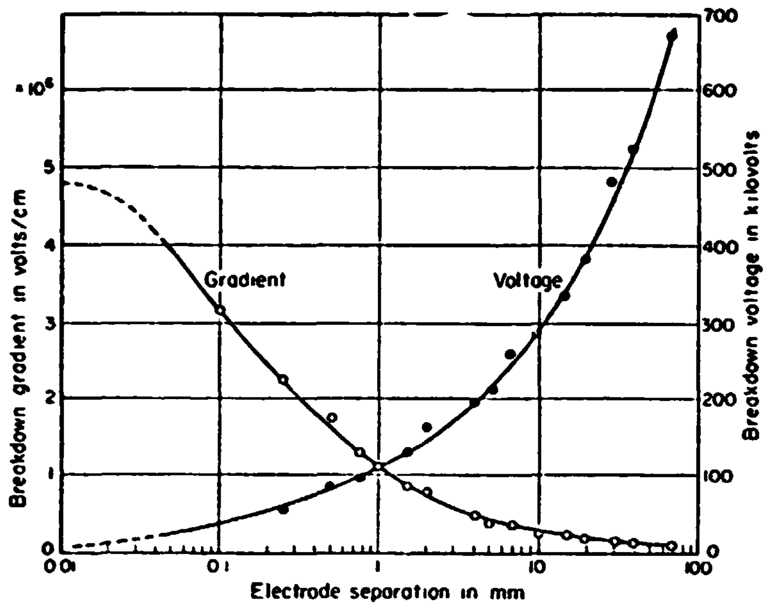


Figure 5.2. Breakdown Voltages and Gradients Between a 1-inch Diameter Stainless Steel Ball and a 2-inch Diameter Steel Disk in Vacuum

approach the strength of vacuum. There are a number of gases which could be considered for rotary capacitors such as air, nitrogen and electronegative gases CCl_2F_2 C_3F_8 and SF_6. Sulfur hexafluoride is used extensively as a dielectric in electrical circuit breakers and is an effective supressant.

Gases are normally non-conducting; however, as the gas is subjected to an increasing electric field intensity, a point will be reached at which the gas no longer acts as an insulator but will begin to conduct. The conduction process is not simple, manifesting itself in various modes such as corona, glow discharges, spark and arc discharge. The breakdown phenomena in gases is more complex than in vacuum being not only dependent upon electrode characteristics, but also upon the dielectric properties of the gas. The breakdown of gases obeys Paschen's law which states that the breakdon voltage is a function of the product of the length of gap and the density of gas.

The following table shows properties of a number of gases, for various pressures and electrode spacings.

Gas		Dielectric Constant (K)	Breakdown Voltage (KV/cm)	Viscosity (poise)
Argon		1.0005	8	220×10^{-6}
Nitrogen		1.0005	35	175×10^{-6}
Oxygen		1.0005	26	200×10^{-6}
Hydrogen		1.0002	20	90×10^{-6}
Air	1 atm	1.0005	30 (1 cm)	180×10^{-6}
	1 atm	1.0005	45 (.1 cm)	
	1 atm	1.0005	80 (.01 cm)	
	7 atm	1.0	250 (.1 cm)	
	14 atm	1.0	350 (.1 cm)	
SF_6	1 atm	1.0	70	
	7 atm	1.0	350	
CCL_2F_2	1 atm	1.0	70	250×10^{-6}
C_3F_8	1 atm	1.0	70	

The use of a gas, especially at high pressure, is not desirable in the rotary capacitor becasue of the necessity for a rotating seal against the vacuum environment. Although the breakdown voltage between planes increases with increasing pressure, much of this advantage is lost if there is a distortion of the electric field. For example, the voltage breakdown at high pressures between a point and a plane is substantially less than would be obtained between planes because of the distortion of the electric field. Electronegative gases such as CCl_2F_2 and C_3F_8 have dielectric strengths greater than twice that of air; however, these gases are not stable, tending to dissociate if subjected to ionization or arc-over, forming chemically active compounds which could be detrimental.

5.5 LIQUID DIELECTRICS

Liquids are another category of dielectric materials which can be considered for the rotary capacitor. Liquid dielectrics are extensively used in capacitors, high voltage cables, transformers and circuit breakers. The important electrical properties are dielectric constant, dielectric strength and electrical conductivity. Liquid dielectrics have higher dielectric constants than gases ranging between 2 and 5 for non-polar fluids and up to 80 for polar fluids such as water, acetone and ethanol. Their breakdown voltages are slightly better than unpressurized gases and are quite dependent upon temperature, frequency and electrode geometry. The electrical conductivity of liquids is significantly higher than that of gases. This is detrimental since it can result in appreciable losses and heating. The electrical conductivity of non-polar liquids is about four orders of magnitude less than that of highly purified polar liquids. The high conductivity of polar liquids and their susceptibility to contamination probably precludes their use. This is unfortunate since the polar liquids do possess significantly high dielectric constants. The viscosity of liquid dielectrics will produce mechanical drag; however, because of the low rotational speed of the rotary capacitor, .01 rpm to 1 rpd, this drag will not be appreciable unless the temperature approaches the pour point of the fluid.

The following table shows typical properties of a number of liquid dielectrics.

	Conductivity (ohm/cm)	Dielectric Constants (K)	Dielectric Strength (KV/cm)	Viscosity (Poise at 100°K)
Transformer Oil	10^{-14} to 10^{-16}	2.2	100	10×10^{-2}
Askarels	10^{-13} to 10^{-14}	4.8	125	10×10^{-2}
Silicones	10^{-14}	2.8	100	100×10^{-2}
Fluorochemicals	10^{-14} to 10^{-16}	1.9	150	3×10^{-2}

The liquid dielectric would necessitate the use of a seal to prevent leakage. A ferrofluidic seal could be used but care would have to be exercised to assure fluid compatibility, and no mixing of the fluids since this could result in seal or capacitor failure.

Perhaps the most serious deficiency of liquid dielectrics is the possibility of fluid deterioration. This is a complex phenomenon which manifests itself ultimately as voltage breakdown or increased conductivity. There are a number of theories to explain the deterioration of fluid dielectrics. The basic phenomenon is that under the influence of dielectric stress, various chemical and physical processes occur in the dielectric fluid which causes a bridging of the gap between electrodes with contamination causing a breakdown. The rate at which the processes proceed is a function of the magnitude of the electrical stresses, temperature and any impurities that accelerate the chemical activity.

5.6 SOLID DIELECTRICS

An approach that should be considered is the use of a solid dielectric as the energy storage media. These materials have dielectric strengths of the same order of magnitude as gases and liquids; however, their dielectric constants are higher being between 2 and 10 for ceramics and refractory materials while ferroelectric materials which are the electrostatic analogies of ferromagnetic materials display very high dielectric constants and significant losses.

A rotary capacitor using a solid dielectric would have the dielectric placed in the gap which separates the capacitor plates. The dielectric would be attached to one set of plates and have a minimum clearance to the other set. Clearances reduce the effectiveness of the solid dielectric since the voltage across it, and therefore, the energy stored in it would be smaller.

The following table shows some typical electrical properties of solid dielectric materials:

Material	Volume Resistivity (ohm-cm)	Dielectric Constant (k)	Breakdown Voltage (KV/cm)	Loss Tangent X 10^{-4}
Alumina	10^{12}	9	160 - 500	5
Fosterite	10^{14}	6	100	4
Porcelain	10^{13}	6	100 - 250	75
Titanium Dioxide	10^{11}	90	75	5
Titanates	10^{8} - 10^{15}	15 - 12,000	20 - 120	1 - 200

The application of solid dielectrics to the rotary capacitor is very appealing because of the very high levels of energy storage capability achievable using high dielectric constant materials. The energy storage of electrostatic systems using these solid dielectrics approaches that of electromagnetic systems. However, the materials which have high dielectric constants tend to have high dielectric losses, and have dielectric properties which are sensitive to time, temperature and voltage.

Since the insulation resistance of a dielectric is often established by the surface resistivity of the material rather than the volume resistivity, particular care would have to be exercised in the electrical design of the rotary capacitor to minimize conduction over the surface of the dielectric. Dielectric failure is sometimes caused by mechanical failure resulting from electrostatic forces induced by high dielectric stresses, by high field gradients resulting from sharp electrodes, or by thermal breakdown.

5.7 ROTARY CAPACITOR DESIGN

Based on the study of vacuum, gaseous, liquid and solid dielectrics as the dielectric for the rotary capacitor the most feasible appears to be vacuum. This is because the operating space environment will be vacuum and the large voltage gradients and low losses attainable in vacuum. The gaseous media requires seals; liquid requires seals and is subject to deterioration; and solid dielectrics necessitate small mechanical clearances. The major disadvantages of vacuum is its low dielectric constant of 1.0.

The rotary capacitor is simpler to design than a rotary transformer because of the fewer variables involved and the only losses are I^2R losses in the capacitor plates. The major concerns in the rotary capacitor design would be dielectric considerations and mechanical design. The dielectric gradient in the vacuum probably should not exceed 100 kv/cm although 200 kv/cm might be attained. The clearances between the moving plates and the stationary plates must be kept as small as possible consistent with the allowable voltage gradient and mechanical criteria.

The basic design formula for a rotary capacitor is

$$A = \frac{36\pi Cd \times 10^{11}}{K}$$

where A = area of capacitor plates, cm^2

C = capacitance, farads

d = plate separation, cm

K = dielectric constant

The weight of the rotary capacitor plates can be found from

$$W = nAt\delta$$

where W = weight, lbs.

n = number of plates

t = thickness of plate, inches

δ = density of plate material, lbs/in^3

It should be noted that a specific weight, pounds per farad, can be obtained. This would be

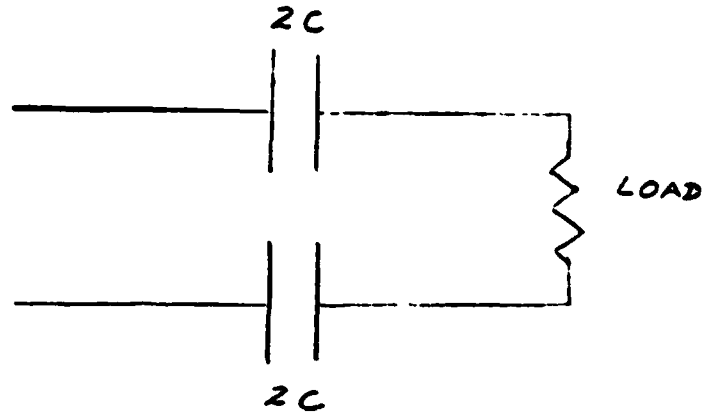
$$\frac{W}{C} = \frac{36\pi d \times 10^{11}}{K} \; nt\delta$$

For a vacuum, the dielectric constant, K, is unity. It is desirable to keep the plate separation to a minimum in order to reduce the area of plate required. However, for the dielectric and mechanical reasons stated above, there are limitations to the minimum clearance between plates.

The required capacitance and operating voltage for the rotary capacitor is defined by the power conditioning electronics and is as follows:

Fs (KHz)	C (uF)	V (volts)
20	.62	1265
20	.42	1862
25	.49	1265
50	.25	1265
50	.33	960

It should be noted that because of the rotational requirements of the rotary capacitor, the capacitance defined above is the total capacitance of the rotary capacitor and it consists of two capacitors physically in series, each having a capacitance of 2C.



The general size characteristics of a rotary capacitor was determined based on the following:

Frequency	20 KHz
Power	25 Kw
Capacitance (C) (2C)	.62 uf, total 1.24 uf, per path
Clearance between plates	.01"
Plate material	Aluminum
Plate thickness	.018"

The size and weight of the rotary capacitor plates as a function of the number of plates is given below:

Plates per path (Primary and Secondary)	Total Plates	OD (in)	Length (in)	Weight (lbs)
100	200	18.8	5.6	100
200	400	13.3	11.2	100
500	1,000	8.4	28.0	100

For this analysis, it was assumed that the plates were .018" thick. Actually, the plates attached to the shaft might have to be thicker than .018" because they must be supported on their internal diameter, however, the outer plates being supported on their OD could be thinner.

The following table shows the rotary capacitor weight and voltage gradient with the capacitance and voltage gradient as a function of frequency and defined by the resonant power conditioning circuit parameters. The weight is that of the plates alone and does not include shaft, housing, leads, etc.

fs (KHz)	C (μ)f	Weight (lbs)	Voltage Gradient (KV/cm)
20	.62	100	50
20	.42	68	75
25	.49	79	50
50	.25	40	50
50	.33	53	38

The specific weight of the rotary capacitor is approximately 161 lbs. per microfarad.

In the rotary capacitor, the cross sectional area of plate through which the current flows is determined by mechanical considerations relating to the plate thickness, rather than by electrical considerations as for the rotary transformer. As a result, the current density and losses will be much lower in the rotary capacitor. For example, taking the 200 plates per path design, the current density at the root of the plate is as follows:

$$A = \pi Dt$$

$$A = 2\pi \times .018 = .113 \text{ in}^2$$

$$I = \frac{70}{100} = .7 \text{ amps/plate}$$

$$\Delta = \frac{.7}{.113} = 6.2 \text{ amps/in}^2$$

This low current indicates that much more than 25 Kw can be transferred through this rotary capacitor without significant losses or heating occurring.
However, the power rating of this rotary capacitor cannot be increased because an increase in power rating must be accompanied by an increase in capacitance due to power conditioning circuit requirements.

The weights of 25 Kw rotary capacitors are in excess of those of rotary transformers. A comparison is shown below.

	Weight (lbs)	
Frequency	Rotary Capacitor	Rotary Transformer
20 KHz	100	23
50 KHz	40	13

Decreasing the plate separation of .01" would result in a reduction of capacitor size but this would be at the expense of mechanical considerations. The rotary capacitor also requires an inductor in its resonant circuit whose weight is signifigant and is not included.

Based on these analyses, it does not appear that the rotary capacitor is a viable alternative to rotary transformers as a rotary power transfer device because of its weight and size disadvantages. One advantage of the rotary capacitor is its higher efficiency which results from the lower I^2R losses and no core losses.

6.0 Microwave Rotary Power Transfer Devices

Rotary transformers and rotary capacitors are devices whose dimensions are very small relative to the wavelength of the AC power. Devices such as oscillators, magnetions and klystrons have dimensions large relative to the wavelength, see Figure 6.1. When the wavelength is comparable to device dimensions, microwave techniques have been developed for high peak power and modest average power applications.

Microwave power transfer devices are sometimes called rotary joints. One type occupies a volume along the rotating axis and another is an annular volume surrounding and concentric with the axis, see Figure 6.2. The first type is called axial rotary joint and the second, annular rotary joint.

Axial Rotary Joint

Axial rotary joints have been developed utilizing non-radiating waveguide modes such as TEM (Transverse Electromagnetic Mode), TM_{01_v} (Transverse Magnetic Mode), TE_{01} (Transverse Electrical Mode), and circularly polarizes TE_{11} modes since all of these have electromagnetic fields that are rotationally symmetrical. Another axial rotary joint not using a metallic waveguide is a beam waveguide propagating a circular polarized beam. Each of these are discussed in the following paragraphs.

TEM Rotary Joint

The usual coaxial transmission line propagates the TEM (transverse electromagnetic) mode between the inner cylindrical indicator and outer tubular indicator. The maximum power that can be carried based on breakdown considerations is given by:

$$P_{max} = \frac{E^2 a^2}{120} \ln (b/a) \text{ watts}$$

Where E = maximum voltage gradient
a = inner conductor radius
b = outer indicator radius

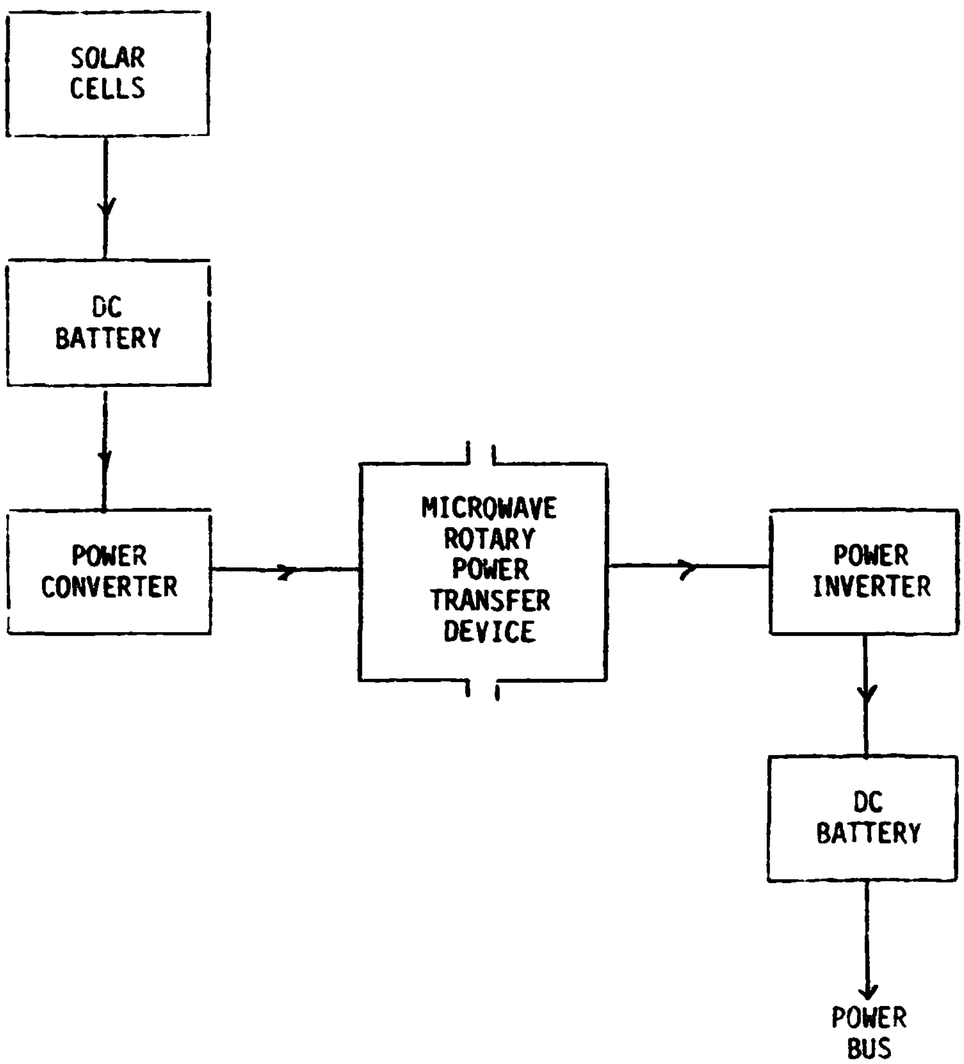
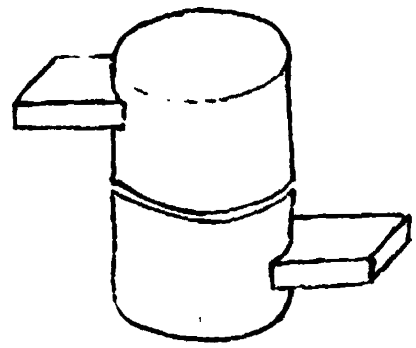
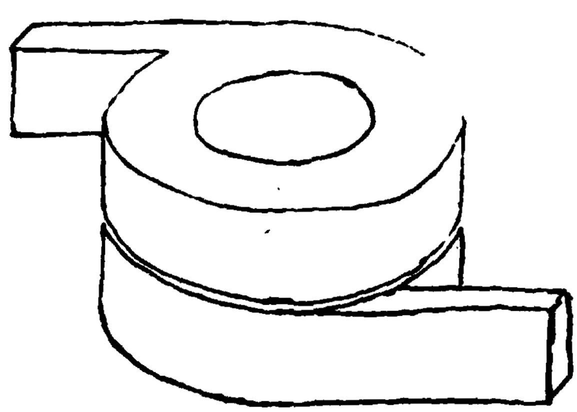


Figure 6-1. Power Transfer System



a) Axial Rotary Joint



b) Annular Rotary Joint

Figure 6-2. Microwave Rotary Joints

Megavolts of power have been handled by TEM rotary joints for radar applications under pulsed conditions, but the problem at hand represents a serious thermal and hence loss problem.

The TEM losses are governed by conductor material, dimensions and frequency. The attenuation in dB/unit length for a copper line is given by:

$$\alpha = 2.99 \times 10^{-9} \sqrt{f} \left(\frac{1}{a} + \frac{1}{b} \right) \frac{\sqrt{\epsilon_1}}{\ln (b/a)} \text{ dB/unit length}$$

where

f = frequency, Hz
a = inner conductor radius
b = outer conductor radius
ϵ_1 = relative dielectric constant of medium between conductors

Low losses can be attained by using low frequencies and large diameter conductors. A thermal design problem is the greater power loss and much greater loss density on the inner conductor, and the more difficult task of heat removal from the inner conductor. At the non-contacting gap, a resonant choke is placed in each of the conductors to provide a low impedance. If the conductor diameters are made increasingly larger to achieve low loss there is a possibility of propagating the next higher order TE_{11} mode so that a fractional shortest limit on the AC power wavelength λ_c is given by

$$\lambda_c = \pi (a + b)$$

Another problem in the design of a rotary joint to operate in space vacuum is the potential for a resonant multipactor discharge. This may occur in the main line or even in the choke section. A unique set of three conditions is required and this involves dimension, surface material and AC voltage. For resonant multipactor to occur, an interior dimension parallel to the electric field should be between 1/400 and 1/50 wavelength. The conductor surface material should be one that exhibits a secondary electron emission coefficient which exceeds unity. Bare metals have values close to unity but some when oxidized have very high values. Finally, the AC voltage should be about 50 to 2000 volts for narrow and wide gaps,respectively.

Between the microwave generator and rotary joint, it is likely that waveguides will be employed and mode transducers will be required to couple to the rotary joint. These transducers typically have greater losses than unperturbed transmission lines.

The TEM rotary joint to transmit exceedingly high average power with low loss should be examined in detail to establish capability limits for the present application. As mentioned above, a very serious problem is thermal effects,especially on the inner conductor.

TM_{01} Rotary Joint

The circularly symmetric transverse magnetic TM_{01} mode in circular waveguide has been often used in waveguide rotary joints for solar application when high peak powers and low average powers are encountered. The frequency must be high enough to be above cutoff, and the frequency, f, in MHz, must exceed 4517/a where a is waveguide radius in inches. The peak power level based on breakdown is given by

$$P_{max} = \frac{E^2 \pi a^2}{2790} \frac{\lambda_c^2}{\lambda \lambda_g}$$

where
- E = maximum voltage gradient
- a = waveguide radius, inches
- λ = wavelength
- λ_c = mode cutoff wavelength - 2.61a
- λ_g = waveguide wavelenth

The maximum field intensity occurs at waveguide center when $\lambda > 0.5\,\lambda_c$. For the present application, attenuation is a very important parameter and for the TM_{01} mode, the attenuation for a vacuum field copper waveguide is given by

$$\alpha = \frac{0.00485}{a^{3/2}} \quad \frac{(\lambda_c \; \lambda)^{3/2}}{\sqrt{(\lambda_c/\lambda)^2 - 1}} \quad \text{dB/ft}$$

where a = waveguide radius in inches

Low loss can be achieved with large diameter waveguide, but a very large waveguide will increase the possibility of undesired higher order modes.

Transducers are required to connect rectangular waveguide to the circular waveguide TM_{01} mode. These transducers are subject to bandwidth and power limitations. A chok of the same type as that for the TEM rotary joint is required to place a low impedanc across the gap. The thermal problem involves mostly outside surfaces which can be radiatively cooled. Multipactor problems may occur in the choke region and must be avoided by design.

<u>TE_{01} Rotary Joint</u> - The circular electric TE_{01} mode in circular waveguide has been used in rotary joints. The peak power level based on breakdown is given by

$$P_{max} = 2 \times 10^{-3} \, E^2 \, a^2 \, (\lambda/\lambda_g)$$

The attenuation of this particular mode in a fixed size guide decreases indefinitely with increasing frequency. The attenuation for vacuum filled copper waveguide is given by

$$\alpha = \frac{0.00611}{a^{3/2}} \quad \frac{1}{\sqrt{\lambda_c/\lambda} \; \sqrt{(\lambda_c/\lambda)^2 - 1}}$$

where $\lambda_c = 1.64_a$ = cutoff wavelength

a = wavelength radius

A choke is not required for this rotary joint since the gap does not interfere with currents. The thermal problems are less stringent because of the low loss mode. The most severe design problem entails the transducer to launch the TE_{01} mode from rectangular waveguide. An oversized waveguide and tape for a high power application was designed and built by K. Timiyasu.*

Circularly Polarized TE_{11} Rotary Joint

The TE_{11} mode in circular waveguide can be used provided it is circularly polarized. Circular polarization requires a polarizer entailing a quartz-wavelength plate or section. To propagate this mode, the wavelength λ must be shorter than the cut-off wavelength λ_c given by

$$\lambda_c = 3.41\ a$$

The peak power level based on breakdown is given by

$$P_{max} = 2 \times 10^{-3}\ E^2\ a^2\ (\lambda/\lambda_g)$$

The attenuation for vacuum-filled copper waveguide is

$$\alpha = \frac{0.00423}{a^{3/2}} \quad \frac{(\lambda_c/\lambda)^{-1/2} + \frac{1}{2.38}(\lambda_c/\lambda)^{3/2}}{\sqrt{(\lambda_c/\lambda)^2 - 1}}$$

a = waveguide radius, inches

The thermal problem will probably be more critical than breakdown. A choke will be required to provide a low impedance across the joint gap in the circular waveguide. In this choke a TE_{11} higher order coaxial line mode will be present.

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* K. Tomiyasu, "17.5 ft-long multiconical taper for TE_{01} mode in 29.7 in. diameter waveguide at X-bands", Proc IEE, Vol. 116, pp. 373-376, March 1969.

Beam Waveguide Rotary Joint

Another class of axial rotary joint is one that involves a beam waveguide. This is an unenclosed structure to transmit high power. This is similar to the method of energy transmittal from a Solar Power Satellite System which sends microwave power over a beam from a geosynchronous satellite to Earth. For the proposed application the distance will be essentially zero and the energy can be restricted to propagate between two antennas facing and almost touching each other as in a confocal cavity. The cavity must be coherently excited by multiple apertures. To permit rotary motion the cavity mode can be TE_{01} or circularly polarized TE_{11} mode. Illumination taper will minimize radiation loss and eliminate the need for a choke. Each cavity end should be at least several wavelengths in diameter. The amount of power that can be transmitted will not be limited by the confocal cavity rotary joint but by the cavity excitation scheme. The thermal problem will be limited to the excitation region.

Annular Rotary Joints

A rotating joint that does not fill the axial region is called an annular rotary joint. Such a joint has been developed for a radar application requiring high peak power and relatively low average power.** The joint comprises two adjacent non-contacting rings formed from rectangular waveguides. Coupling apertures transfer the power between rings. The ring circumferential length is an integral number of wavelengths. In an experimental model an insertion loss of about 0.3 dB was measured and this represents a six percent loss.

The on-axis beam waveguide rotary joint men ioned earlier designed into a annular configuratuion by using basically a TE_{01} mode in the confocal cavity and shaping the cavity resonator walls with large central openings to provide high efficiency coupling.

** K. Tomiyasu, "A New Annular Waveguide Rotary Joint" Proc. IRE, Vol. 44, pp. 548-553, April 1956.

7.0 CONCLUSIONS

As a result of Task I, System Study, the following conclusions can be drawn:

1. The rotary transformer and rotary capacitor are feasible contractless power transfer devices.

2. Rotary transformers are smaller than rotary capacitors.

3. There are no obvious advantages of either resonant approach or non-resonant (square wave) for the power conditioning electronics.

4. There is no advantage for the power conditioning to operate above approximately 20 KHz.

5. Rotary transformer operation at 50 KHz as compared to 20 KHz results in smaller size. Increased eddy current and core losses may be detrimental at 50 KHz.

6. The requirement for redundant secondary windings on the rotary transformer results in a weight penalty.

7. Chopping electronic topologies result in inductance constraints on rotary transformers causing them to have small diameters and long lengths.

8. Chopping electronics constraints on minimum capacitances does not permit reduction in rotary capacitor size.

9. Chopping electronic device ratings are sensitive to input voltage range, 50% range has a serious effect.

8.0 RECOMMENDATIONS

The following recommendations are made for future design studies:

1. Perform a detail design study on 25 Kw, 20 KHz rotary transformer using resonant circuit power conditioning.

2. The requirement for redundant secondary windings on the rotary transformer be eliminated.

3. System requirements concerning input voltage ranges be examined. Considering the chopping electronics sensitivity to input voltage range.

TASK II

DESIGN STUDY

TASK II

DESIGN STUDY

1.0 INTRODUCTION

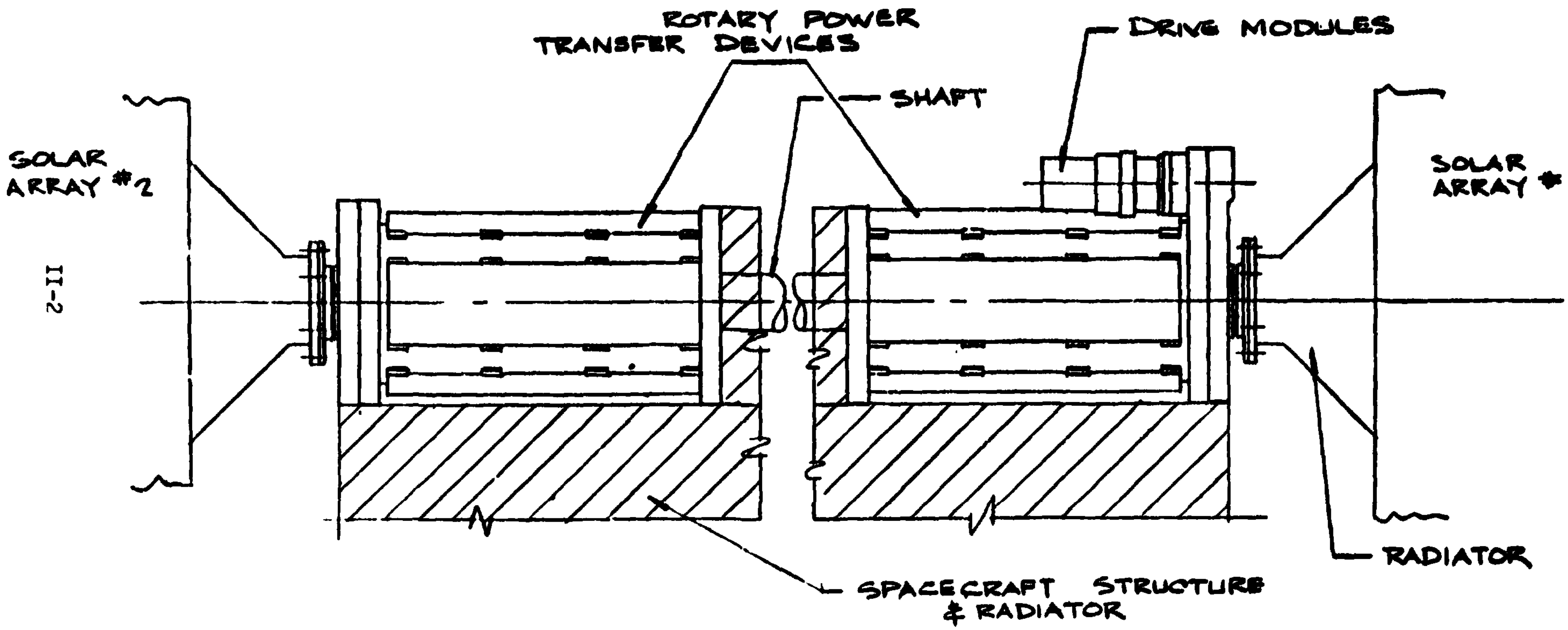
As part of the Systems Study, Task I, various types of devices were analyzed for transferring electrical power across the rotating interface betw en the solar arrays and the spacecraft body, among them were rotary transformer, rotary capacitor, microwave and ionized gas techniques. As a result of the Systems Study, the rotary transformer was selected as the most promising approach, the follow-on effort, Design Study, Task II.

For the Task II effort, the design of a Rotary Power Transfer Device for transferring 100 KW electrical power across a rotating spacecraft interface was addressed. The power transfer device is a complete system and includes a rotary transformer, power conditioning electronics, housing, shaft, heat rejection methodology (heat pipes and radiators), and drive mechanism.

A Rotary Power Transfer Device was designed as part of Task II and its concept is feasible with no fundamental reasons why it cannot be implemented. Figure 1.1 shows a conceptual Solar Array/Rotary Power Transfer Device Configuration. It indicates how the power transfer device can be mechanically integrated with solar arrays and into a spacecraft.

A summary of the Rotary Power Transfer Device characteristics is as follows:

Overall Envelope (Excluding power conditioni g)	8.25" x 10.40" x 16.25" (21.0 cm x 26.4 cm x 41.3 cm)
Overall Weig	190.8 lbs. (86.6 Kg) w/o radiators 209.1 lbs. (94.9 Kg) w/ radiators



SOLAR ARRAY/ROTARY POWER TRANSFER DEVICE CONFIGURATION
(CONCEPTUAL)

FIGURE 1.1

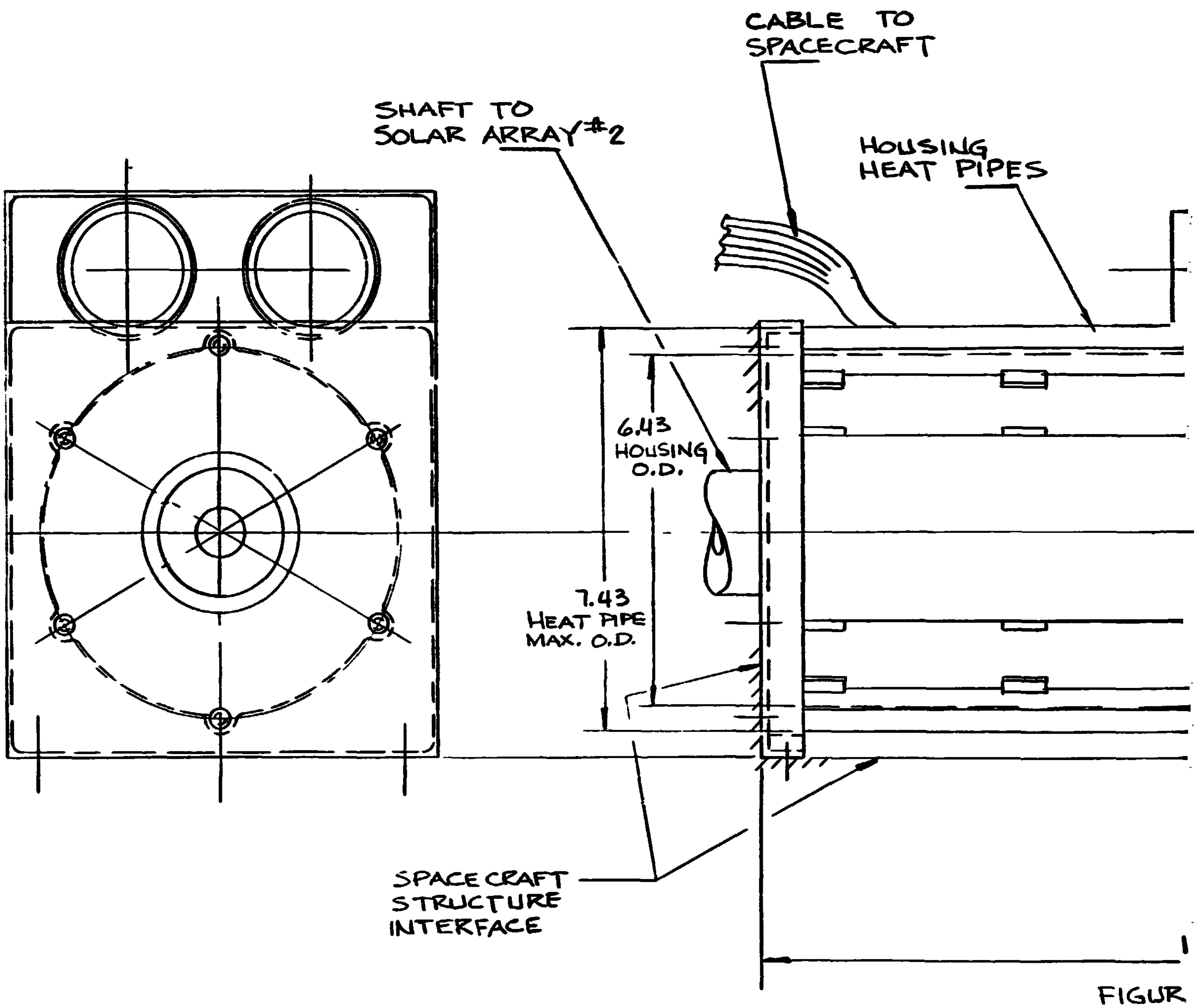
Rotary Transformer	Type:	Concentric Cylinder
	Size:	6.43" diameter, 14.3" long
	Weight:	46.4 lbs. (21.1 Kg)

Power Conditioning Electronics	76.0 lbs. (34.5 Kg)
Efficiency	
- Rotary Transformer	96.6%
- Power Conditioning Electronics	98.0%
- Overall	96.6%

The geometry of the power transfer device is shown in Figure 1.2, Outline, 100 KW Rotary Power Transfer Device.

Two possible approaches were considered for the rotary transformer: concentric cylinder and parallel plate. Either configuration could be used; but, the concentric cylinder was chosen because it would be easier to fabricate and would have lesser thermal problems. The concentric cylinder transformer has a relatively small diameter and long length, while the parallel plate transformer would have a larger diameter along with a shorter length. Although the concentric cylinder approach appears easier to implement in hardware, there is no inherent reason why the parallel plate approach could not be achieved if its configuration were found to be more appropriate to spacecraft constraints.

This Design Study task delineated a 100 KW Rotary Power Transfer Device which is attainable and does not necessitate materials or techniques which are not presently state of the art. Although the rotary transformer design was examined in some depth, a design optimization was not pursued in detail. An optimization would include a trade-off between losses,



FIGUR

FOLDOUT FRAME

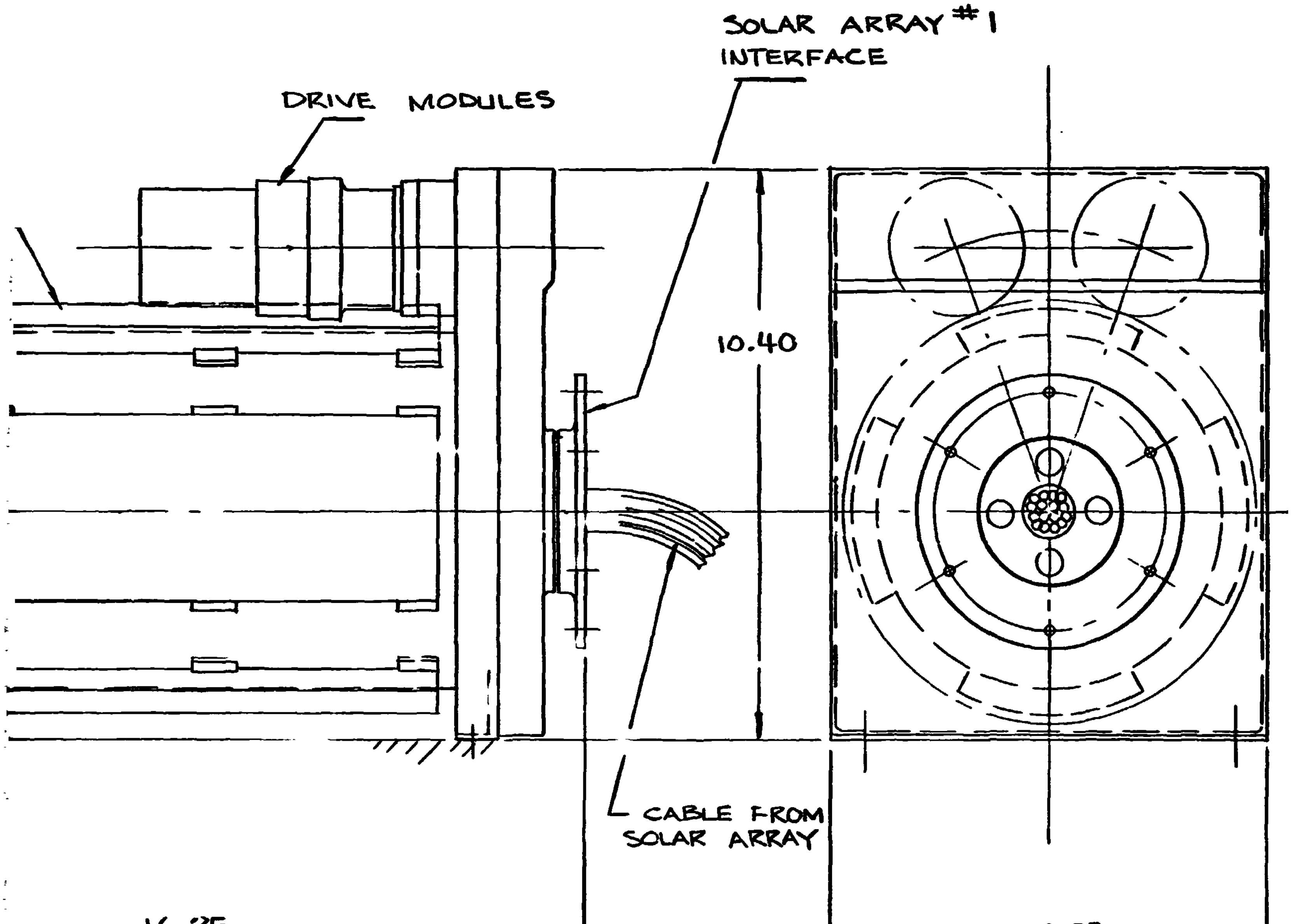


FIGURE 1.2

OUTLINE, 100 KW ROTARY POWER TRANSFER DEVICE

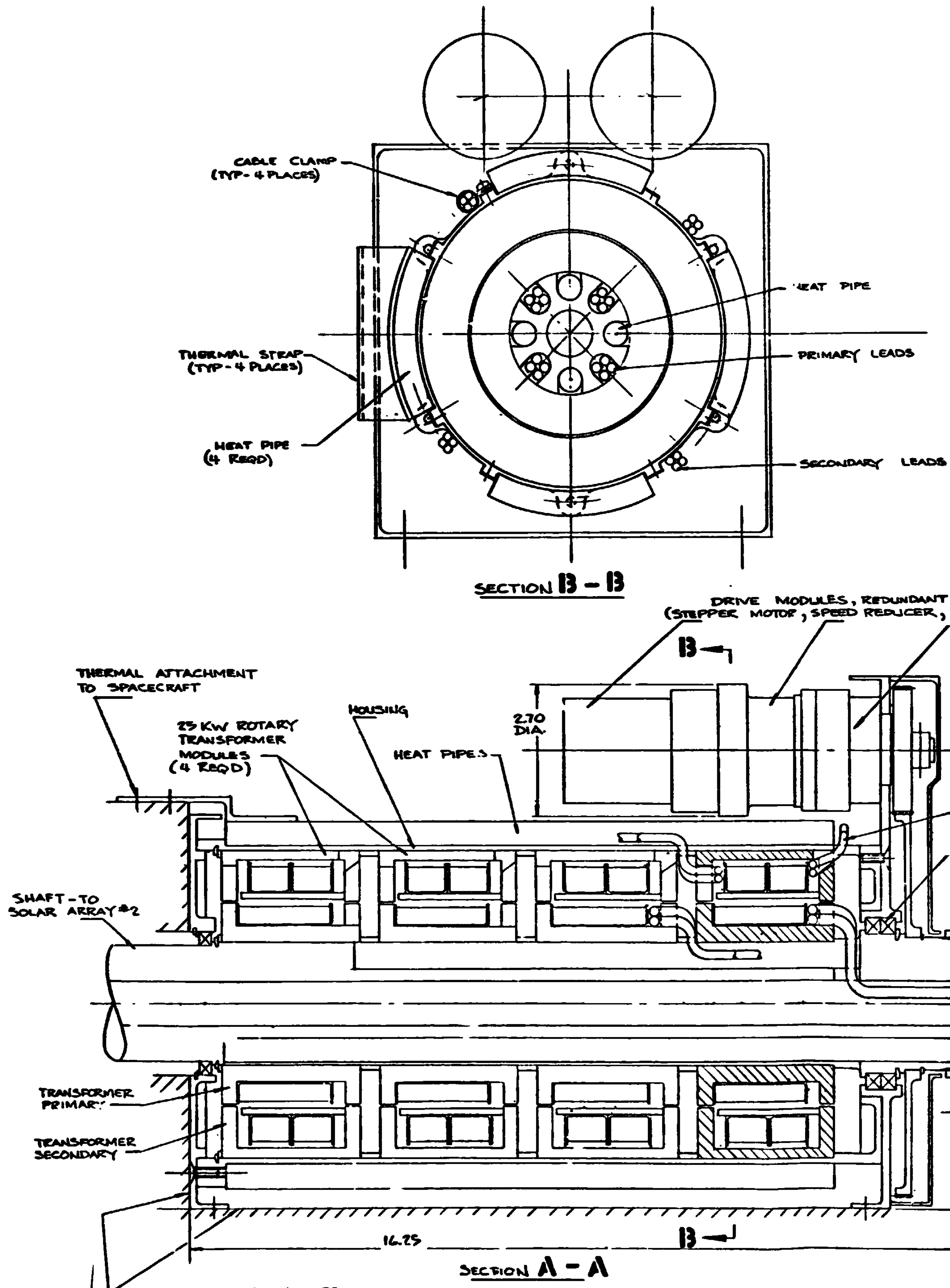


FIGURE 1.3 100 K
TRAN

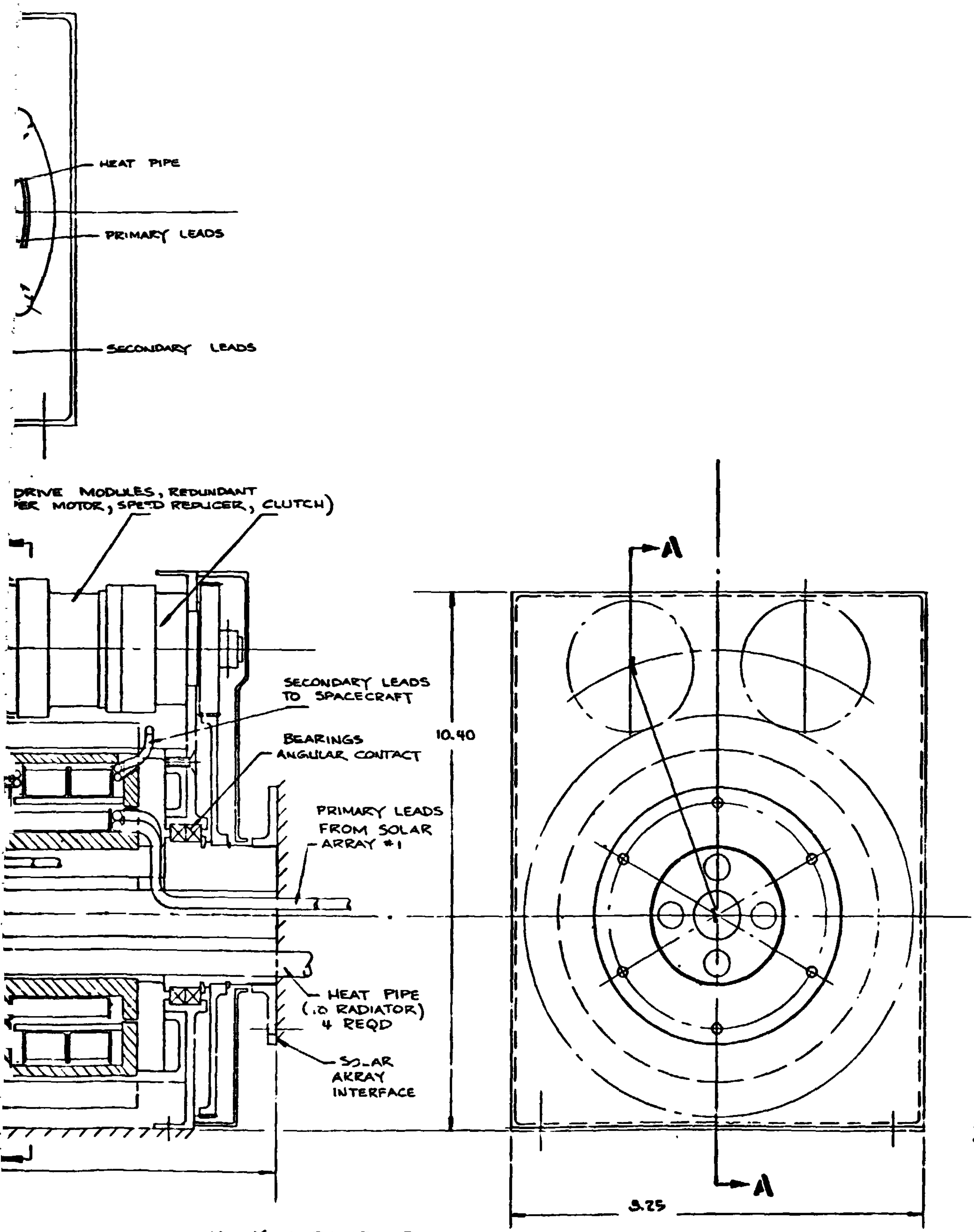


FIGURE 1.3 110 K.W. ROTARY POWER TRANSFER DEVICE

FOLDOUT FRAME 2

temperature, heat rejection, materials, etc., and could result in a significant improvement in the characteristics and performance of the device. The design, Figure 1.3, 100 KW Rotary Power Transfer Device, is generally conservative in approach with the tendency to overdesign in preference to having a marginal or underdesigned device.

2.0 REQUIREMENTS

The requirements for the Rotary Power Transfer Device were derived from LeRc and some of the recommendations presented by the General Dynamics "Study of Power Management for Orbital Multi-100 KWE Applications", NASA CR 159834. In addition, the power conditioning electronic circuitry imposes some constraints on the rotary transformer. The requirements which were used as guidelines are as follows:

Input from Solar Array

Power	100 KW
Voltage	440 Volts

Output from Rotary Power Transfer Device

Voltage	1000 Volts
Frequency	20 KHz

Power Conditioning Electronics

Resonant Circuit (Schwarz)

Rotary Transformer

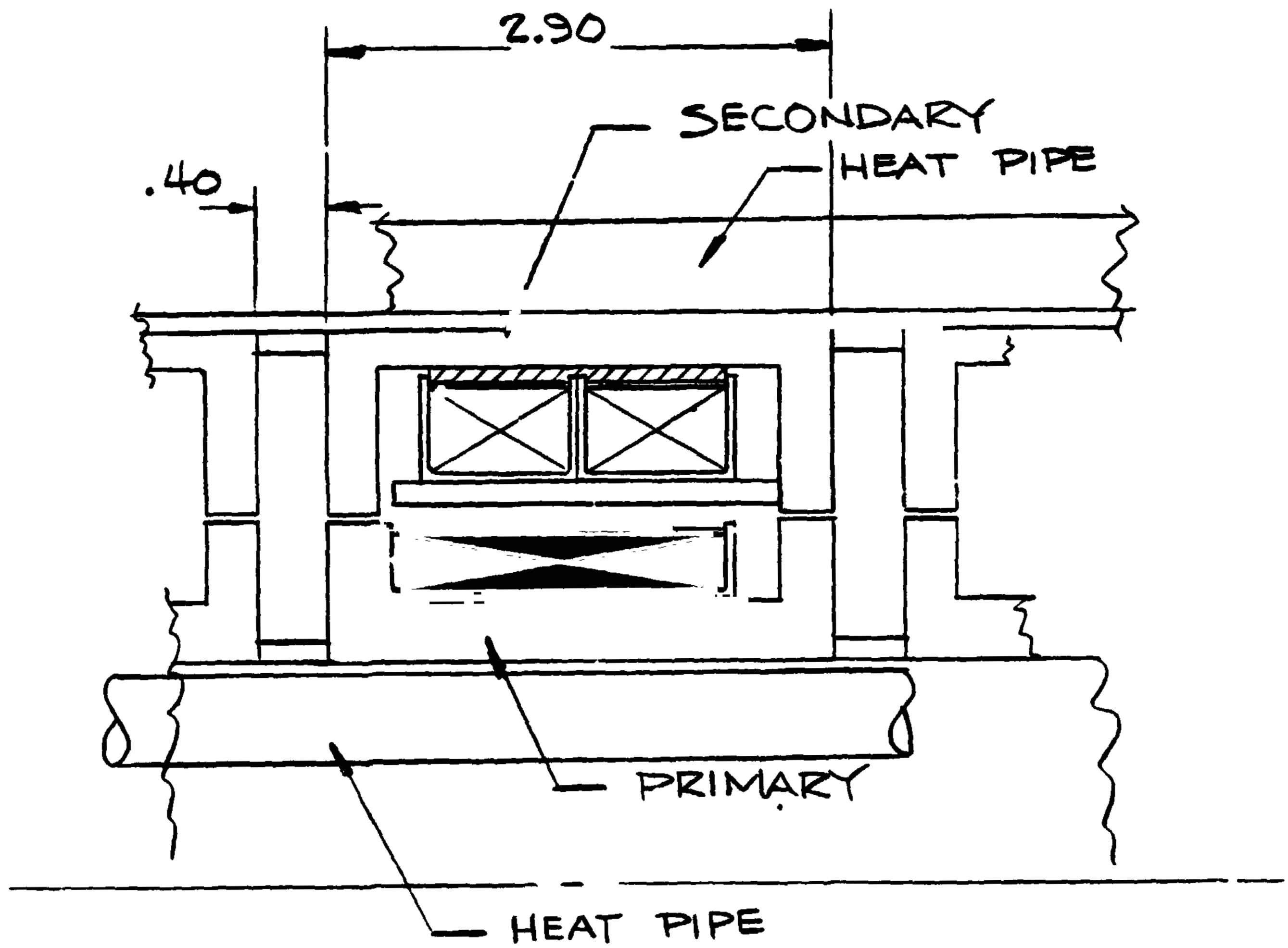
Power	100 KW
Input Voltage	400 Volts
Input Current	70 Amps
Output Voltage	1000 Volts
Frequency	20 KHz
Inductance	75 μH
Configuration	Concentric Cylinder 4-25 KW modules Two parallel secondary windings per module

Rotational Period	90 minutes to 24 hours
Efficiency	Greater than 95%
Environment	Shuttle Launch
Temperature	
- Non-operating	-20° to 80°C
- Operating	80° Heat Sink, Rotary Transformer 60° Heat Sink, Power Conditioning Electronics
Life	5 Years

3.0 CONFIGURATION

The rotary transformer transfers power across the rotary interface of the spacecraft by electromagnetic coupling between the primary and secondary winding. The 100 KW power transfer requirement could be achieved by using a single rotary transformer having a full 100 KW capability. However, from a system and transformer fabrication standpoint, it was determined that 4 - 25 KW modules would provide a greater advantage. The use of 4 - 25 KW modules would result in a somewhat larger size transformer than a single 100 KW unit. Figure 3.1, Rotary Transformer, 25 KW Module, shows the configuration of a concentric cylinder transformer module.

The primary, consisting of a core and winding, is mechanically attached and electrically connected to the solar array. The secondary, also consisting of a core and winding, is attached to the spacecraft and electrical power is delivered from its winding to the spacecraft load. The power from the solar array is converted from dc to ac by the power conditioning electronics which is a Schwarz resonant circuit. The heat generated by losses in the primary and secondary is removed by heat pipes to thermal heat rejection surfaces. A drive module provides a rotational capability from 1 revolution per day to 1 revolution every 90 minutes using a stepper motor, speed reducer and clutch.



ROTARY TRANSFORMER
25 KW MODULE

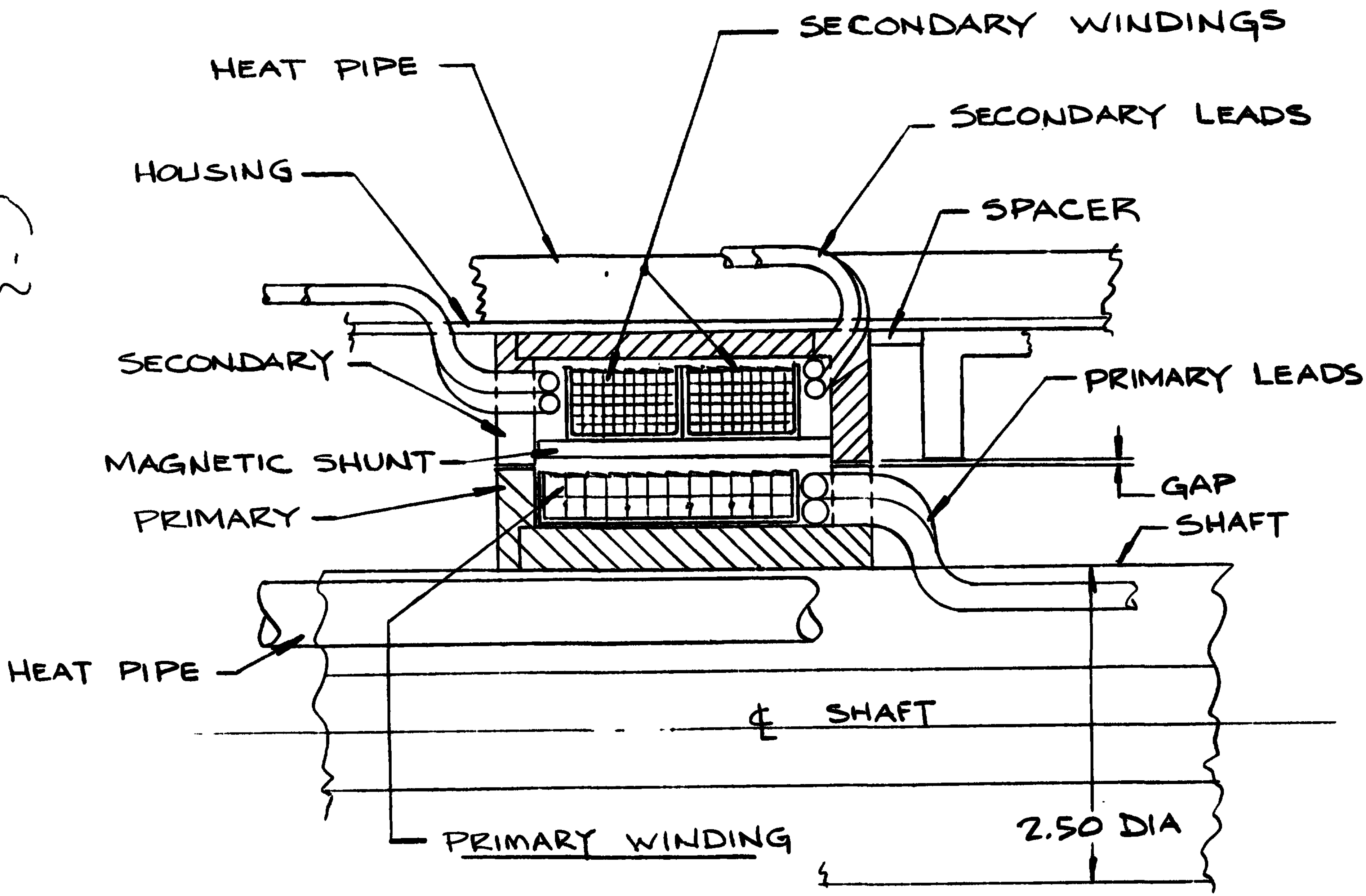
Figure 3.1

3.1 ROTARY TRANSFORMER DESIGN

The design of the rotary transformer involves four closely inter-related major regimes: magnetic, electrical, mechanical and thermal. In addition, the power conditioning circuitry imposes inductance and voltage parameters on the ro⁺ y transformer. Because of the desire to keep the overall rotary power transfer device small in size and weight, and the losses low, the design procedure is somewhat complex and involves iterations among the four regimes.

Both the primary and secondary of the rotary transformer consist essentially of a core and winding. The cores are a ferrite material and are attached to the shaft and housing by an epoxy. Since heat must be conducted across this joint, a path of good thermal conductivity must be present. This can be attained using a filled, thermally conducting epoxy, or if the bond line can be made small, an unfilled epoxy. The primary and secondary windings are bobbin wound, impregnated and bonded into the cores. Heat pipes placed in the shaft and on the housing remove the transformer heat and carry it to the heat rejection surfaces. Figure 3.2, Rotary Transformer, Module Detail, shows the configuration of a rotary tranformer module.

The rotary transformer design is treated in detail in the following sections. Table 3.1 is a summary of the critical materials used, the reason for their selection and their limitations. This will provide an insight into the advantages and possible problems involved in their use.



ROTARY TRANSFORMER, MODULE DETAIL

FIGURF 3.2

Table 3.1. Critical Materials

Design Regime	Material	Reason for Selection	Limitations
Magnetic	MN 60 Ferrite Core	a) Isotropic b) Low core loss c) High permeability	a) Flux density/temperature b) Coefficient of expansion c) Low Thermal conductivity d) Low Strength
Electrical	Litz wire Nyleze	a) Low eddy current loss b) Solderable	a) Connections b) Life/temperature
Mechanical	Inconel housing and shaft	a) Coefficient of expansion b) Non-magnetic	a) Fabrication b) Weight c) Availability
Thermal	Inconel heat pipes, curved	a) Coefficient of expansion b) Thermal gradients	a) Weight b) Availability
	Radiator	Thermal dissipation	a) Size, weight
	Thermally conducting epoxy	Thermal conductivity	a) Shear strength b) Bond line thickness

3.1.1 CORE DESIGN

The primary and secondary cores are fabricated from a manganese zinc ferrite, MN60, made by Ceramic Magnetics, Inc. A more detailed study of various core materials may show that, while there may be a ferrite which has more desirable characteristics such as flux density/temperature, thermal conductivity and thermal expansion, the MN60 will perform satisfactorily in this application. MN60 was specifically chosen because of its low core loss and its being magnetically isotropic. Some of the magnetic, thermal and mechanical properties of MN60 impose constraints on the rotary transformer design. These constraints are not unique to MN60 but are generally inherent in ferrite materials.

Some specific properties of MN60 and their effects on the design are as follows:

	PROPERTY	EFFECTS
1.	Maximum operating flux density is a function of temperature.	Core size affected by operating temperature. Thermal run-away could occur. Monitor operating temperature.
2.	Coefficient of thermal expansion. $\alpha = 11.5 \times 10^{-6}/^{o}C$	Housing, shaft heat pipes cannot be fabricated from aluminum or titanium, Inconel used.
3.	Low thermal conductivity. $K = 3.6$ BTU/hr/ft^2/^{o}F/ft	Large circumferential thermal gradients in secondary core if few heat pipes used, circumferential heat pipes necessary.
4.	Mechanically weak	Minimum allowable thickness, 0.2". Secondary core thicker than necessary for magnetic reasons.

Table for item 1:

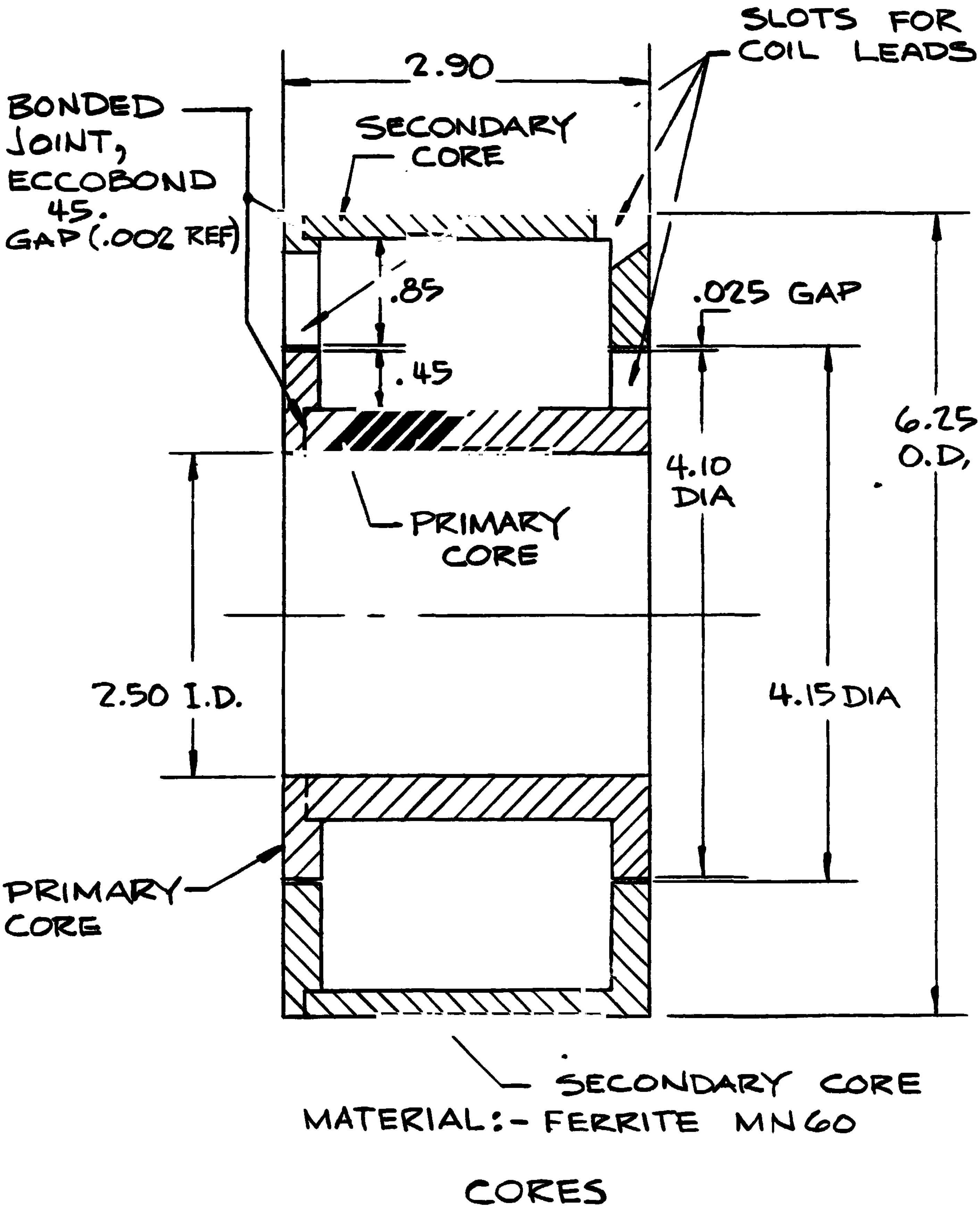
Temperature (^{o}C)	Bmax (Gauss)
75	3500
100	3000
125	~2400
150	~1400
185	0 (Curie point)

The flux/temperature constraints of MN60 could be alleviated by using MN67. MN67 material has a higher Curie temperature, and higher flux carrying capability than MN60, however, its core losses are higher.

	MN 60	MN 67
Bmax at 125^{o}C	2500 gauss	3700 gauss
Curie temperature	185^{o}C	280^{o}C
Core Loss at 9.6 KHz, 1000 gauss	4 mw/cc	20 mw/cc

The substantially higher losses in MN 67 might preclude its use even though its temperature characteristics are significantly better than MN 60.

The primary and secondary cores are shown in Figure 3.3.
The cores are basically cylinders with a slot on the outside diameter of the primary and on the inside diameter of the secondary to accomodate the primary and secondary windings, respectively. To facilitiate the assembly of the windings, the cores are not integral pieces but have a separate pole. The poles are epoxied to the other portion of the core after the windings are in place with core being exercised not to have an excessive gap between them. The primary and secondary leads are brought out through slots cut in the cores. Lead slots cannot be in adjacent primary and secondary poles, but must be placed in opposite ones to keep the air gap reluctance constant independent of rotational position and preventing the presence of a large reluctance torque. The inside diameter of the primary core, 2.5 inches, was determined by the shaft diameter, which, in turn, was established by the room in the shaft required for the primary leads and heat pipes.


SLOTS FOR COIL LEADS
2.90
BONDED JOINT, ECCOBOND 45. GAP (.002 REF)
SECONDARY CORE
.85
.45
.025 GAP
6.25 O.D,
4.10 DIA
PRIMARY CORE
2.50 I.D.
4.15 DIA
PRIMARY CORE
SECONDARY CORE
MATERIAL:- FERRITE MN60
CORES

FIGURF 3.3

An air gap length of .025" was selected based on mechanical and magnetic considerations. A somewhat larger air gap probably could be used without substantial effect on the magnetic circuit.

Table 3.2 shows the magnetic characteristics of the rotary transformer. As will be noted, the flux densities are all below the design limitation of 2500 gauss. The maximum flux density (2080 gauss) occurs at the base of the primary pole (root) while the lowest (1140 gauss) is at the secondary pole root. The flux density in the secondary yoke is 1650 gauss. This flux density is determined by the minimum allowable thickness of core material, 0.2". The low flux density in the secondary pole is the result of the inherent pole geometry. Increasing the overall flux density levels would result in a reduction in weight but would be accompanied by an increase in core losses. Some increase in core losses might be acceptable because the core losses are smaller than the copper losses and represent only 18% of the transformer losses.

Table 3.2. Magnetic Characteristics

	FLUX DENSITY (GAUSS)	LENGTH (CM, APPROX)	AMPERE TURNS
Primary Yoke	2000	6.6	1.3
Primary Pole	1925 (avg) 2080 (root)	1.1	.2
Secondary Yoke	1650	6.6	1.2
Secondary Pole	1460 (avg) 1140 (root)	4.3	.7
Air gap (2)	1620	.127	206
Primary Core Gap	2000	.005 (.002")	10.2
Secondary Core Gap	1650	.005 (.002")	8.2
TOTAL AMPERE TURNS			227.8

$$\frac{\text{TOTAL AMPERE TURNS}}{\text{AIR GAP AMPERE TURNS}} = 1.11$$

$$\frac{\text{TOTAL CORE AMPERE TURNS}}{\text{AIR GAP AMPERE TURNS}} = 1.02$$

Weight of Primary Core	2.1 lbs.
Weight of Secondary Core	3.3 lbs.
Primary Core Loss	22 Watts
Secondary Core Loss	37 Watts

3.1.2 WINDINGS

The power input to the rotary transformer primary winding comes from the solar array after having been converted from dc to 20 KHz ac by the power conditioning electronics. The output power is provided by the secondary winding which feeds into the spacecraft. Two parallel secondary windings have been incorporated to permit some degree of redundancy. Complete redundancy is not provided since a full 25 KW module power drawn on a single winding would result in overheating the secondary. Complete secondary winding redundancy would necessitate an additional secondary winding and an increase in weight and size. Some of the winding characteristics which have to be addressed are number of turns, wire size, insulation, heating and method of lead connection. In this application, the requirements of the resonant circuit power conditioning imposes a constraint of having the rotary transformer input inductance fixed at 75 μH.

Generally, increasing the number of primary turns serves to increase the inductance, number of secondary turns, copper losses and winding area; at the same time, it decreases the core cross section area and flux density. A trade-off has to be made to determine the best winding design.

Because of the high frequency operation of the transformer, and to keep the eddy current losses small, the primary and secondary windings will be made of stranded, insulated, transposed conductors in the form of Litz wire. Two major disadvantages of using Litz wire are the reduction in winding space factor and a more complicated connection being required to the power leads. The winding wire insulation will be a heavy polyurethane with nylon overcoat such as manufactured by Phelps Dodge under the trade name Nyleze. This is a solderable magnet wire with good windability

PRIMARY WINDING

Turns per winding	24
Wire	576 Strands, Litz #36 Awg. Heavy Nyleze
Turn Size	.165" by .165"
Turns per layer	12
Number of layers	2
Resistance at 135° C	.024 ohms, dc .030 ohms, ac
I^2R_{ac} @135° C	147 watts

SECONDARY WINDING

Turns per winding	60
Windings in parallel	2
Wire	225 strands, Litz #38 Awg, Heavy Nyleze
Turn Size	.084" by .084
Turns per layer	10, each winding
Number of layers	6
Resistance at 135°C	.331 ohms dc, per winding .417 ohms ac, per winding
I^2R_{ac} @135° C	130 watts

WINDINGS

and is compatible with most impregnants. The temperature-life characteristics are conservatively given by the vendor as follows:

TEMPERATURE (°C)	LIFE HOURS	LIFE YEARS
155	8,000	.9
145	20,000	2.3
135	35,000	4.0
138	44,000	5.0
130	80,000	9.0

As will be seen in Section 3.2, Thermal Analysis, the winding temperature will be approximately 138°C, based on a 80°C radiator, so that, as far as the winding is concerned, the 5 year life requirement can be achieved. The coils are wound on bobbins with insulation between layers and impregnated with epoxy to provide mechanical rigidity, electrical insulation and a good heat conduction path.

Attaining the input inductance requirement of 75 μH represents a unique problem. One method for doing this would be by defining the number of turns and winding geometry. However, this is not amenable to easy adjustment of inductance to compensate for small unit to unit variations; or for large variations necessary for a different application. It is proposed that a magnetic shunt be used to attain the required inductance. The magnetic shunt would consist of a ring placed in the secondary core slot adjacent to the air gap as shown in Figure 3.2. The ring would consist of a "powdered" iron of appropriate permeability, thickness, and gap which could be varied to obtain the requisite inductance. The ring is shown as being in the secondary core for somewhat easier assembly; it could have been placed in the primary.

The electrical characteristics of the primary and secondary windings of a 25 KW rotary transformer module are as follows:

	Resistance (ohms, at 135°C)	Inductance (μH)
Primary	.024, dc .030, ac	19
Secondary	.331, dc, per winding .417, ac, per winding (secondary has two identical windings)	30, w/o magnetic shunt 56 w/ magnetic shunt

The primary and secondary winding designs are given in Table 3.3. Discussions held with personnel of New England Electric Wire Company, Lisbon, N.H., indicate that there should be no problem procuring the Litz wire in the size and stranding required. Although a square Litz wire geometry is defined, it is possible to achieve aspect ratios up to 6:1. This large an aspect ratio is not desirable for the rotary transformer because of the larger bend and radius, 2:1 to 3:1, needed. Smaller wire diameters than #38 AWG can be manufactured but tend to be more subject to breakage. If the winding eddy current losses are found to be greater than anticipated, smaller wire diameters would be required. An alternative to smaller wires would be a change in coil geometry to one having a smaller radial thickness.

Figure 3.4, Assembly, Primary 25 KW Transformer Module and Figure 3.5, Assembly, Secondary, 25 KW Transformer Module, shows the configurations of the primary and secondary windings and cores.

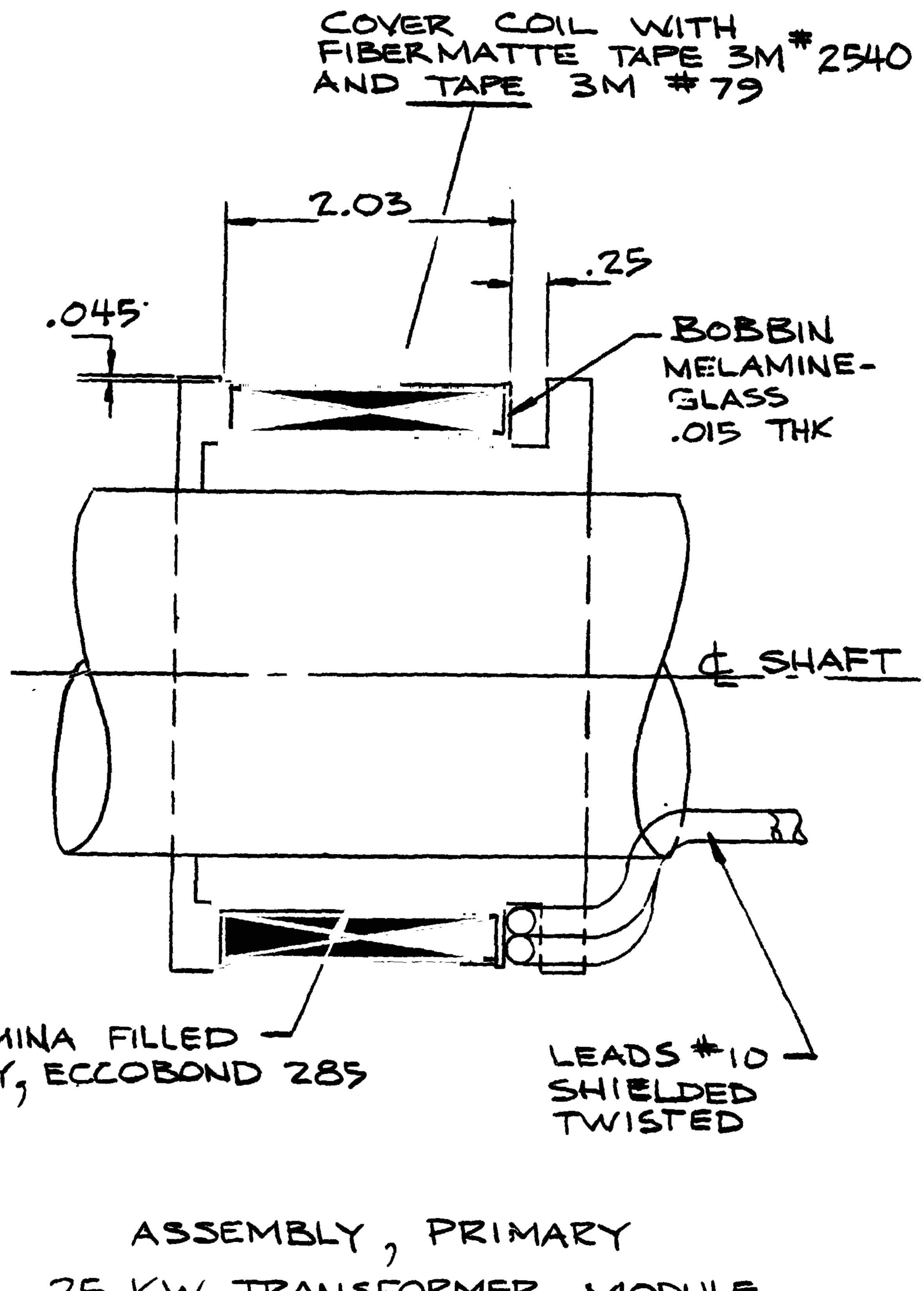
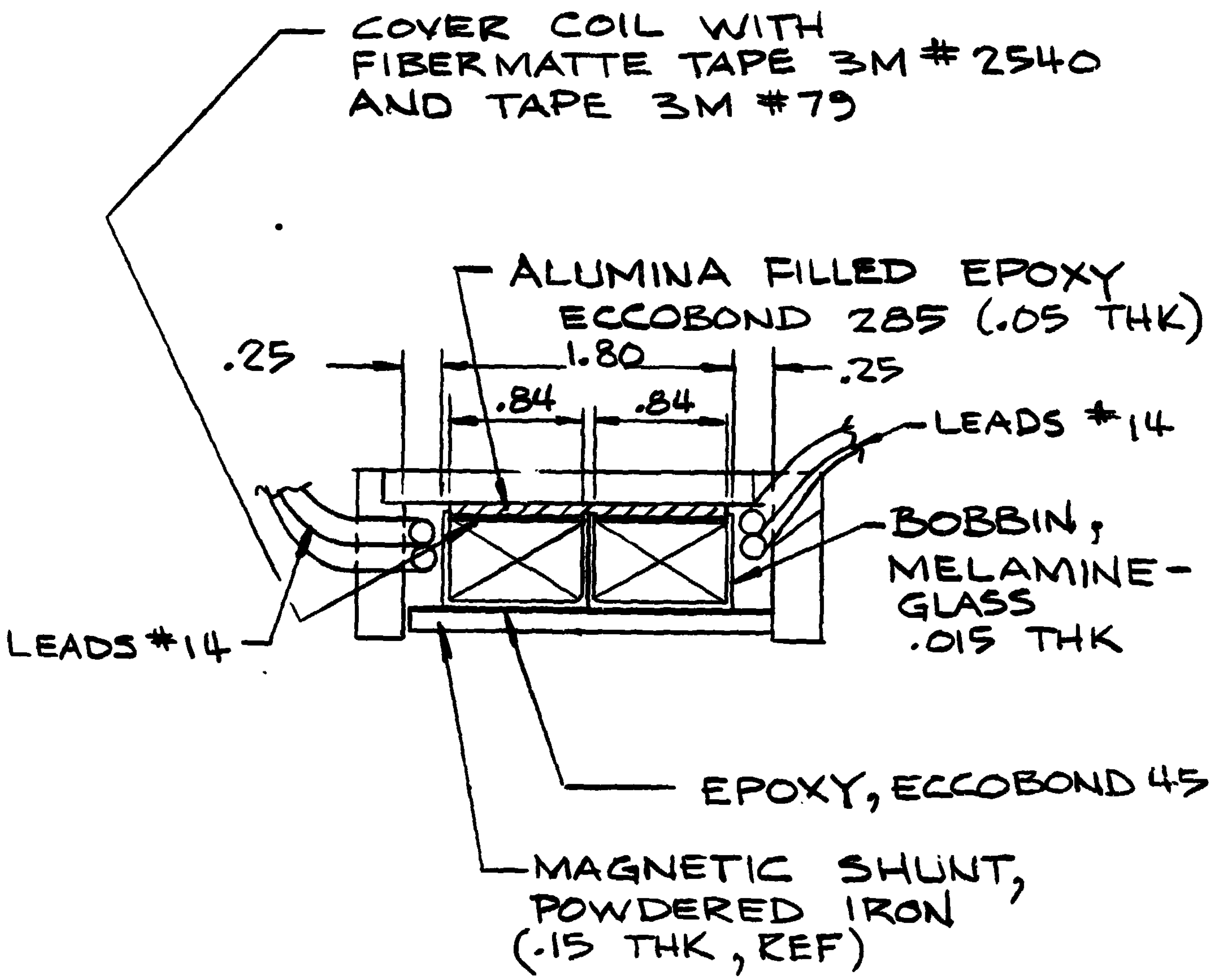

COVER COIL WITH
FIBERMATTE TAPE 3M #2540
AND TAPE 3M #79
2.03
.25
.045
BOBBIN
MELAMINE-
GLASS
.015 THK
℄ SHAFT
ALUMINA FILLED
EPOXY, ECCOBOND 285
LEADS #10
SHIELDED
TWISTED
ASSEMBLY, PRIMARY
25 KW TRANSFORMER MODULE

FIGURE 3.4



ASSEMBLY, SECONDARY
25 KW TRANSFORMER MODULE

FIGURE 3.5

3.1.3 LEADS

The power leads to the primary winding and from the secondary will consist of insulated, stranded conductors. The primary will use #10 wire and the secondary will use #14 wire. In addition, the leads will be shielded and used as twisted pairs in order to keep electromagnetic interference to a minimum. The primary leads are placed in longitudinal slots in the shaft and held in position with an alumina filled epoxy which also serves as a heat conducting media. The secondary leads are clamped to the transformer housing.

3.1.4 HOUSING

From the aspect of weight, availability and ease of fabrication, it would be desirable to make the housing from aluminum and attach the transformer cores and heat pipes to it with an epoxy. However, a problem arose because of the differences of coefficients of expansion of the cores, housing material and heat pipe material; and the necessity for transferring the heat from the ferrite cores to the heat pipes across epoxy bonds. It was originally assumed that thermally conducting epoxy was desirable in order to reduce the temperature gradients. Since thermally conducting epoxies are filled, usually with alumina, they are rigid and require a thick bond in order to withstand thermal differential expansion between the parts. A thick bond, even using thermally conductive epoxies, can result in high temperature gradients. The alternative approach is to use an unfilled epoxy with a thin bond-line. A thin bond of epoxy results in a better mechanical design and comparable or improved thermal characteristics. However, the use of a thin bond-line necessitates closely matching the thermal expansion of the core, housing and heat pipes.

Studies were made based on using various combinations of the following materials:

- Housing Aluminum, Titanium, Stainless Steel, Inconel
- Heat Pipe Aluminum, Titanium, Stainless Steel, Inconel

The thermal expansion coefficients and thermal conductivities for these materials, up to 100^{o}C are:

		Thermal Expansion (Per ^{o}C)	Thermal Conductivity BTU hr/ft^{2}/^{o}F/in
MN 60 Ferrite		11.5×10^{-6}	43.5
Inconel	702	12.1×10^{-6}	81.0
	722	12.1×10^{-6}	102.0
	X 750	12.6×10^{-6}	83.0
Aluminum 6061		23.4×10^{-6}	1070
Stainless Steel	302	17.3×10^{-6}	113.0
	305	16.5×10^{-6}	113.0
	309	14.9×10^{-6}	108.0
	310	14.4×10^{-6}	98.0
Titanium 6Al-4V		9.0×10^{-6}	50.0

Figure 3.6 shows the possible combinations of materials and epoxy bond thicknesses. It appears that the best approach consists of using an Inconel housing and Inconel heat pipes. Another approach would be the use of stainless steel housing and heat pipes. The Inconel system provides a better match of thermal conductivity to the ferrite than a stainless steel system. Figure 3.7 , Housing,

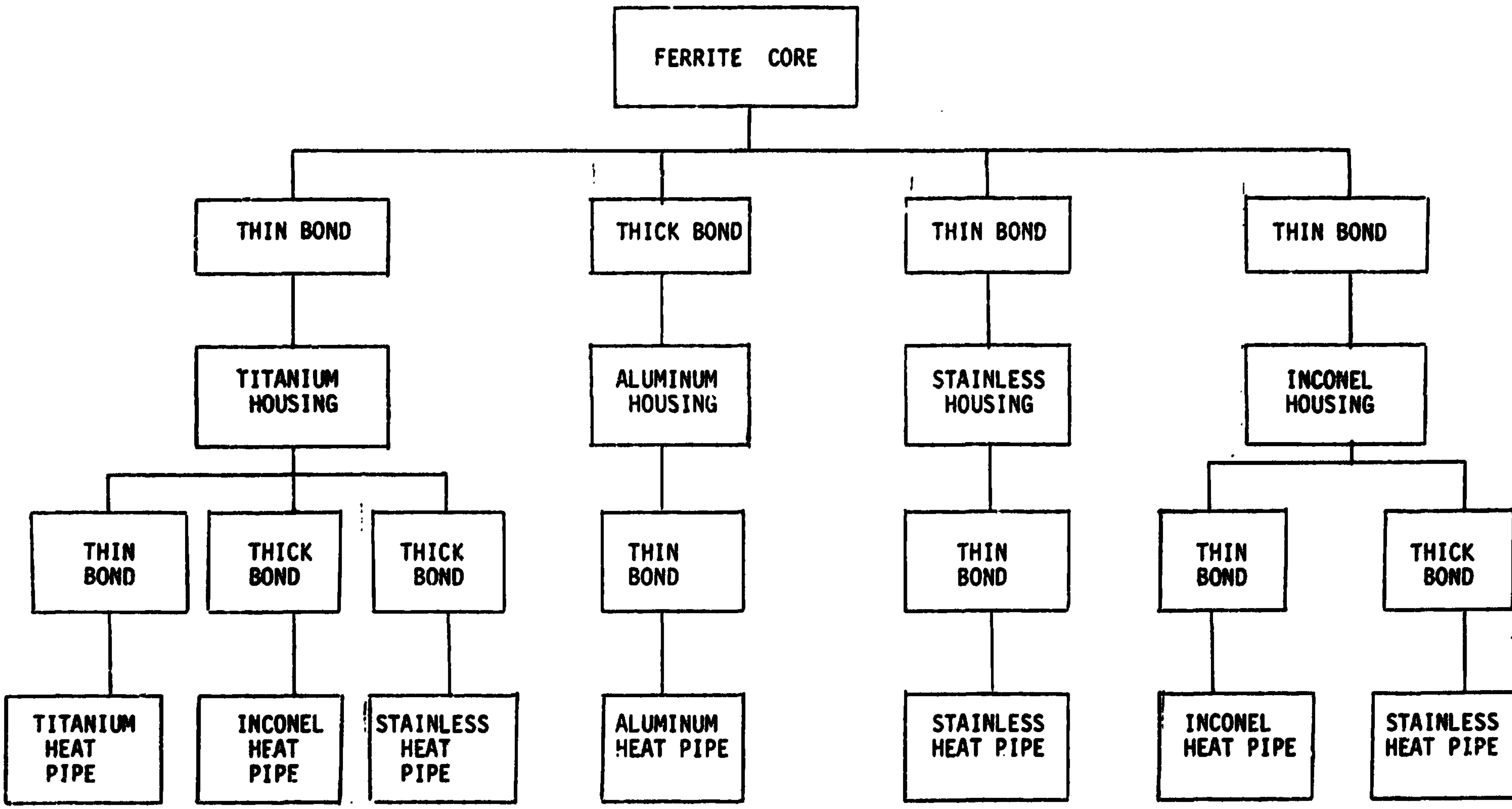
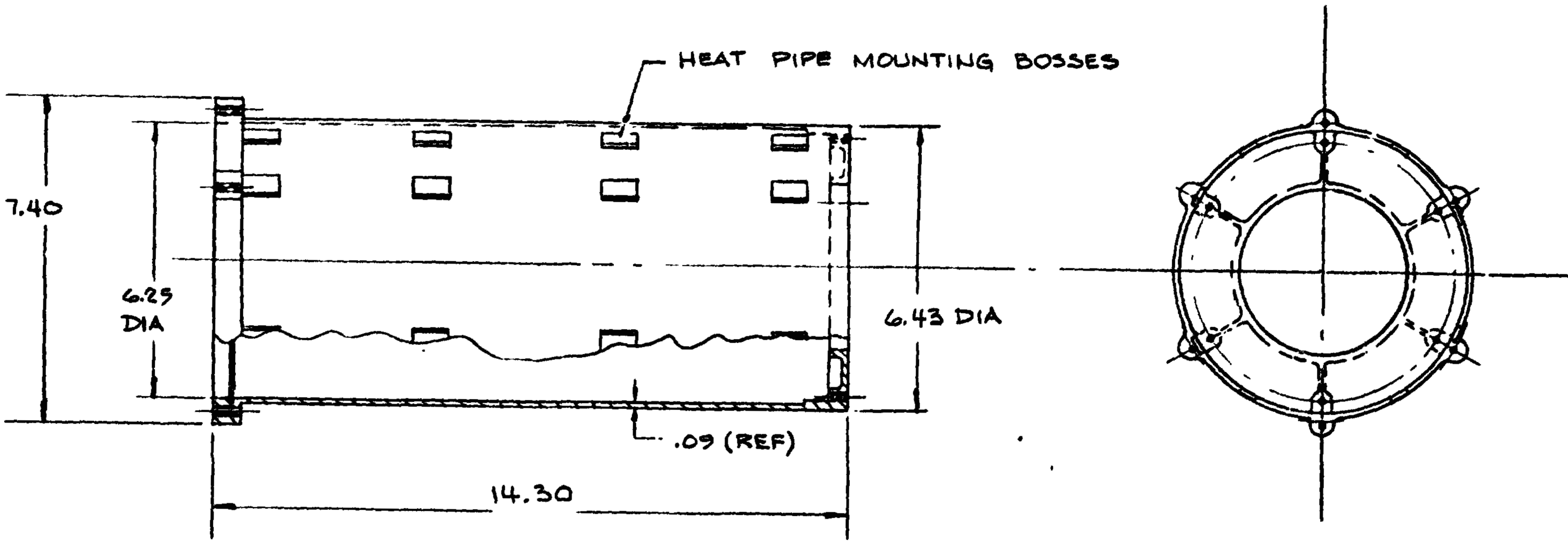


Figure 3.6 Rotary Transformer Material Combinations



HOUSING , MATERIAL: INCONEL 722

FIGURE 3.7

could be used with either Inconel or stainless steel material. A concern is the ready availability of Inconel of the requisite size for the housing, and of Inconel heat pipes. If it is found that the procurement of Inconel parts presents serious problems, a viable alternative would be the utilization of stainless steel. The preferred grades of Inconel and stainless steel from the aspects of thermal expansion and thermal conductivity are: Inconel 722 or 702; or 310 stainless steel.

The major disadvantages of Inconel, in addition to availability, are its density, difficulty of fabrication and poor thermal conductivity; however, it does permit the use of an unfilled epoxy.

Another aspect of consideration was that the use of titanium or aluminum heat pipes in conjunction with methanol, the preferred heat pipe fluid, was not recommended by vendors because of material compatibility problems.

3.1.5 ADHESIVES

Epoxy adhesives are used in the rotary transformer to bond various parts together and to function as a heat conducting joint between the parts. Their proper performance is vital to the operation of the rotary transformer. Should there be a failure in their heat conducting capabilities, the temperature gradient across the joints would become high causing the transformer temperatures to become excessive.

Two types of adhesives were considered for use in the rotary transformer unfilled epoxy adhesives and filled epoxy adhesives. Filled epoxies were considered because of their higher thermal conductivity than the unfilled. There are two types of filled epoxies: electrically insulating and electrically conductive. Electrically insulating epoxies are typically filled with alumina while conducting epoxies are filled with silver. Although the silver filled are some highly conductive than the alumina, their bond strength was poorer and were not recommended for the rotary transformer. Unfilled epoxy adhesives have higher bond strength than the filled epoxy but have lower thermal conductivities. Another aspect is that filled epoxies necessitate a bond line thickness of at least .010" because of the inherent size of the filler particles. Unfilled epoxies can have substantially thinner bonds.

Discussions were held with a number of vendors to obtain their recommendations for epoxies. These vendors included Emerson & Cumming, Canton, Mass.; Furane Products Division, M&T Chemicals, Inc., Los Angeles, Calif.; and, Aremco Products, Ossining, New York. Based on these discussions, two Emerson & Cumming adhesives, Eccobond 285 and Eccobond 45, were selected for the rotary transformer. Eccobond 285 is an alumina filled epoxy while Eccobond 45 is unfilled.

The following is a summary of the characteristics of the candidate adhesives for use in the rotary transformer:

	ECCOBOND 285 ALUMINA FILLED EPOXY	ECCOBOND 45 UNFILLED EPOXY
Shear Bond Strength (psi)	2100	3100
Flexibility	Rigid	Adjustable
Thermal Conductivity ($BTU/hr/ft^2/^oF/in$)	10.4	2.5
Thermal Expansion Coefficient ($10^6/^oC$)	15	30
Dielectric Strength (volts/mil)	420	400
Service Temperature (^oC max)	177	121

The adhesives will be used in the rotary transformer as follows:

	ADHESIVE
Primary	
Core to Shaft	Eccobond 285 (Filled)
Winding	Eccobond 45 (Unfilled)
Bobbin to Core	Eccobond 285 (Filled)
Heat Pipes to Shaft	Eccobond 285 (Filled)
Leads to Shaft	Eccobond 285 (Filled)

Secondary	Adhesive
Core to Housing	Eccobond 45 (Unfilled)
Winding	Eccobond 45 (Unfilled)
Winding to Core	Eccobond 285 (Filled)
Heat Pipes to Housing	Eccobond 45 (Unfilled)
Magnet Shunt to Bobbin	Eccobond 45 (Unfilled)

Further study might show that other adhesives would be more applicable to the rotary transformer because of more desirable and better shear strength, thermal conductivity, temperature or fabrication characteristics. However, those selected should perform as required.

The following table shows the shear stress as a function of epoxy thickness for Eccobond 45, an unfilled epoxy. It can be seen that the use of an Inconel housing with the ferrite core results in the thinnest epoxy bondline. If a filled epoxy were used, the comparable thickness would be greater because of its higher shear modulus and lower shear strength

PARTS	EPOXY THICKNESS (INCHES)	EPOXY SHEAR STRESS (PSI)
Ferrite Core/Inconel Housing	.006	3000
	.012	1500
Ferrite Core/310 Stainless Housing	.029	3000
	.058	1500
Ferrite Core/Titanium Housing	.025	3000
	.050	1500
Titanium Housing/Stainless Heat Pipe	.42	3000
	.84	1500

3.2 THERMAL DESIGN

The thermal design of the rotary transformer is of great importance because it defines the overall size and weight of the Rotary Power Transfer Device. Heat is generated in the transformer windings and in the cores. The magnitude of these losses are controllable: decreasing the current density in the windings and decreasing the flux density in the cores will reduce the losses, but at the expense of size and weight. There are two temperature limits associated with the rotary transformer: winding temperature and core temperature. The winding temperature is life-limited, the higher the temperature, the shorter the life. As discussed in Section 3.1.2, Windings, the 5 year life requirement will be attained if the winding temperature is kept below 138°C, while a 145°C winding temperature will have a life of 2.3 years. The core temperature is limited to 125°C by the flux carrying capability of the ferrite core material. Higher core temperatures than 125°C result in lower effective permeability which increases the magnetizing current which, in turn, increases the losses and, thus, the core temperature is increased further.

The heat rejection system consists of heat pipes attached to the rotary transformer primary and secondary which transfer heat to thermal radiators. Heat generated in the cores and windings is transferred by conduction to the heat pipes. The heat pipes would normally be stainless steel with methanol being the working fluid. However, because the shaft and housing are fabricated from Inconel and because of thermal expansion considerations, Inconel appears to be a better heat pipe material. Although Inconel has not been used as a heat pipe material, there does not appear to be any inherent reason why they could not be fabricated and used with the methanol working fluid.

The primary and secondary losses in the rotary transformer are 680 watts and 668 watts, respectively. Four heat pipes having a diameter of 1/2 inch have sufficient capacity to remove these losses. Placing four 1/2 inch diameter heat pipes in the shaft, see Figure 3.8, Shaft, will remove the primary losses quite satisfactorily. However, if four 1/2 inch heat pipes are placed on the secondary housing, a problem arises because of a significant circumferential thermal gradient. This results from the fact that the four heat pipes are widely spaced around the housing, being approximately 5 inches from each other. In addition, the thermal conductivity of the ferrite cores and the Inconel housing is relatively low.

The large circumferential spacing, coupled with a poor circumferential conductivity, can produce local hot spots in the winding and core. Increasing the number of heat pipes from four to eight does reduce the gradient, but not to acceptable levels of temperature. However, by using four curved heat pipes, each 3 inches wide, see Figure 3.9, Secondary Heat Pipe, 60% of the housing surface is covered and the circumferential temperature gradient is practically eliminated. Discussions were held with personnel of McDonnel Douglas, St. Louis, and they indicated that, although it has not been done, there were no fundamental problems in fabricating the required curved heat pipes from Inconel.

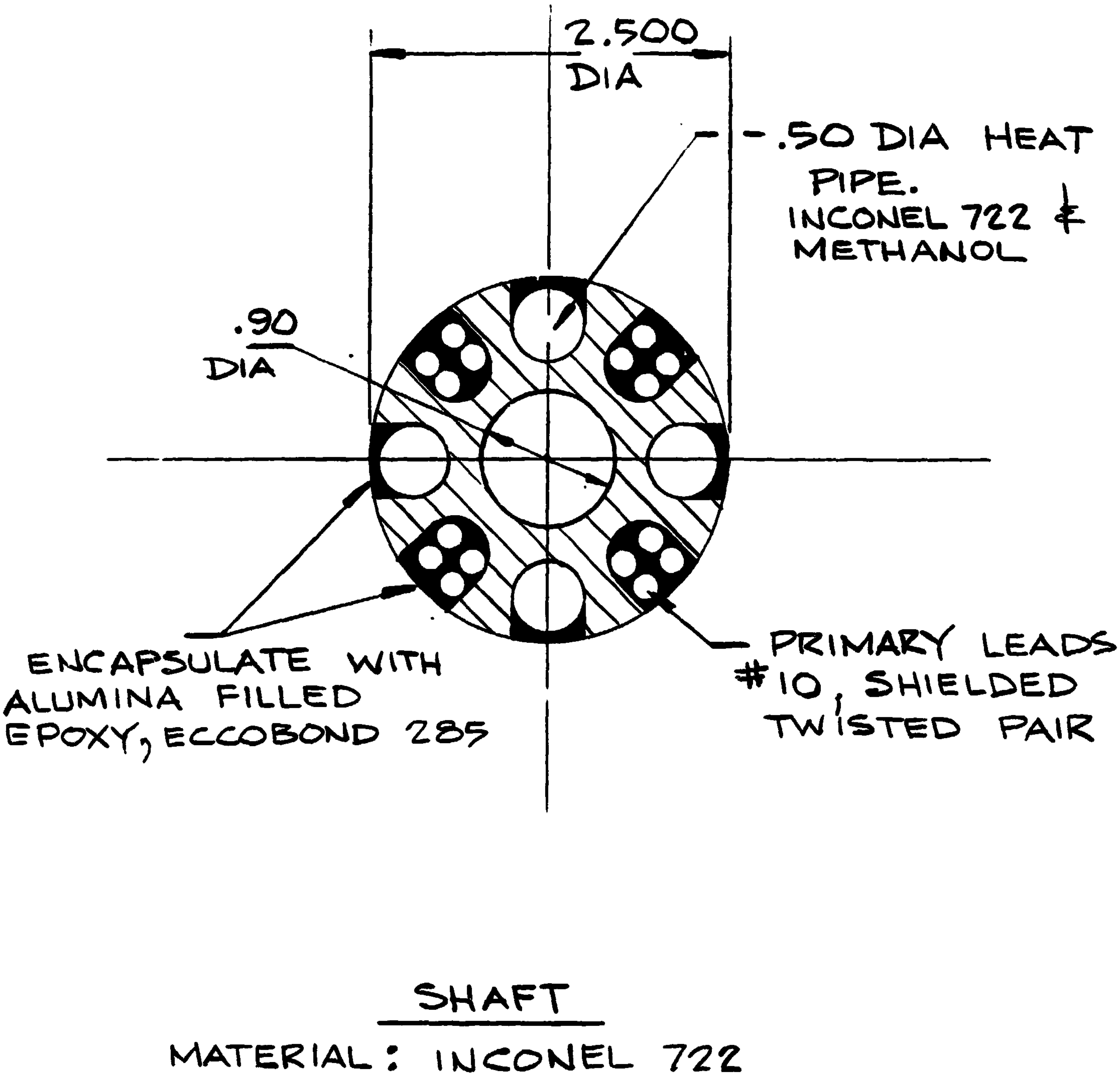
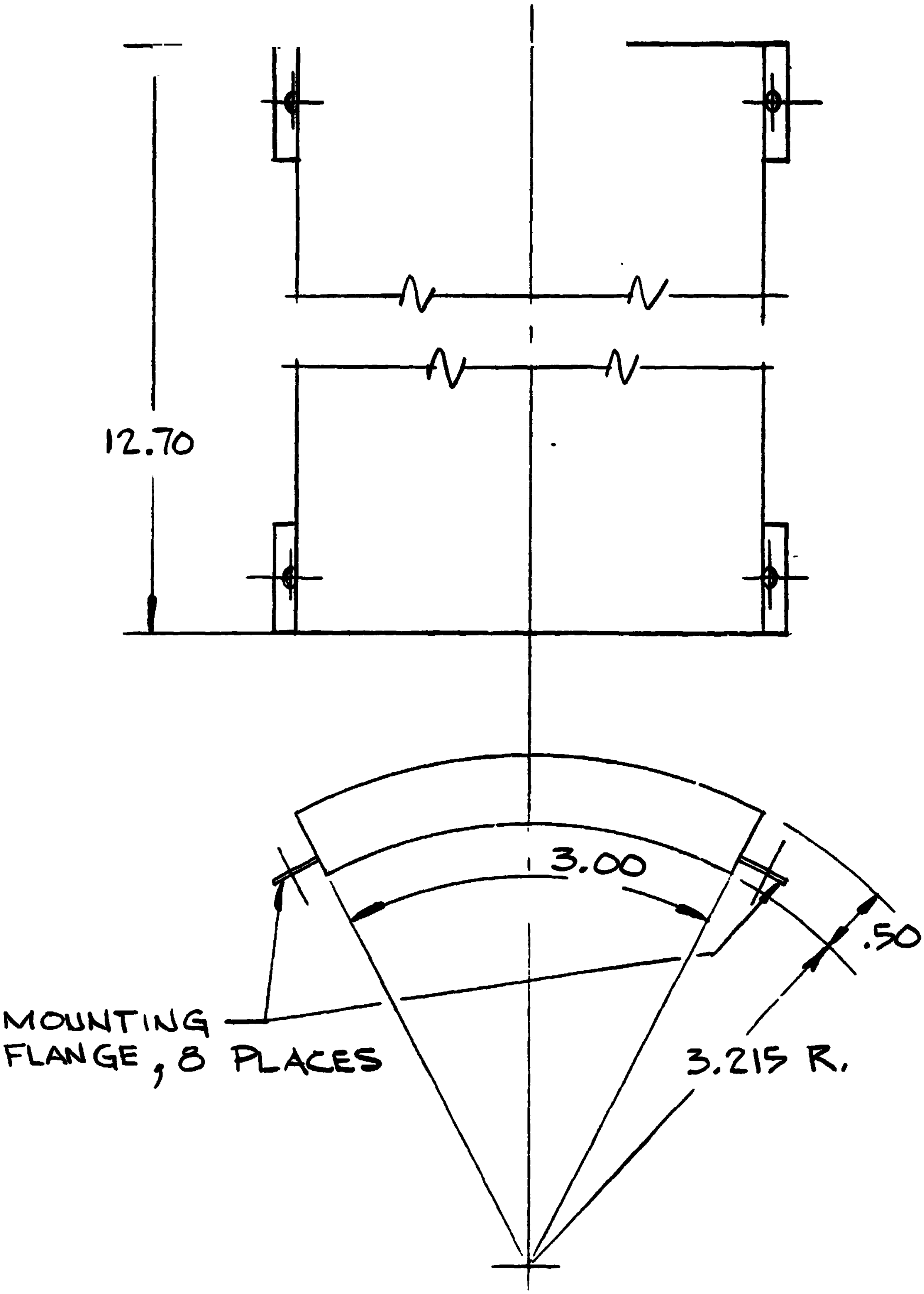

2.500
DIA
.50 DIA HEAT
PIPE.
INCONEL 722 &
METHANOL
.90
DIA
ENCAPSULATE WITH
ALUMINA FILLED
EPOXY, ECCOBOND 285
PRIMARY LEADS
#10, SHIELDED
TWISTED PAIR
SHAFT
MATERIAL: INCONEL 722

FIGURE 3.8



SECONDARY HEAT PIPE - 4 REQUIRED
MATERIAL:- INCONEL 722/METHANOL

FIGURE 3.9

The temperatures of the rotary transformer primary and secondary cores and windings were calculated. This was done based on a 60°C radiator temperature and an 80°C radiator temperature. The 60°C radiator temperature will result in lower rotary transformer temperatures, but will be larger and heavier than an 80°C core.

The thermal conductivities of the materials used in the rotary transformer, as well as some alternative ones, are as follows:

		$BTU/hr/ft^2/^oF/in$
MN 60 Ferrite		43.5 *
Inconel	722	102 *
	702	81
Bobbin,	Melamine glass	2.4 *
	Textolite	1.8
Winding		60 *
Epoxy	Eccobond 45	2.5 *
	Eccobond 285	10 *

* Used in Rotary Transformer

The temperatures of the primary and secondary cores and windings were::

	Primary			Secondary	
	60°C Radiator	80°C Radiator		60°C Radiator	80°C Radiator
Core (22 watts)	95°C	115°C	Core (37 watts)	96°C	116°C
Winding (148 watts)	118°C	138°C	Winding (130 watts)	110°C	130°C

The thermal calculations show that the primary and secondary core temperatures are both below the 125°C maximum with either 60°C or 80°C radiators. The primary winding temperature is higher than the secondary winding temperature. If an 80°C radiator is used with the primary, its temperature, 138°C, will result in an estimated winding life of 5 years which is specified.

The sources of largest temperature gradients in the rotary transformer were as follows:

Primary:	Bobbin, Ferrite Core
Secondary:	Winding, Winding to Core Epoxy Bond

Consideration should be given to the thermal radiators since they will contribute to the overall weight of the rotary power transfer device. Table 3.4 gives the radiator size and weight based on two different base temperatures, 60°C and 80°C.

Table 3.6. Thermal Radiators

	60°C Base		80°C Base	
	Size (ft^2) ($33\ ft^2/KW$)	Weight (lbs) (5.9 lbs/KW)	Size (ft^2) ($26\ ft^2/KW$)	Weight (lbs) (4.8 lbs./KW)
Primary (680 watts)	22.4	4.0	17.7	3.3
Secondary (668 watts)	22.3	3.9	17.4	3.2
TOTAL	44.7	7.9 (3.6 Kg)	35.1	6.5 (3.0 Kg)
Power Conditioning Electronics (2000 watts)	66	11.8 (5.4 Kg)	52	9.6 (4.4 Kg)
Overall Total	101.7	19.7 (9.0 Kg)	87.1	16.1 (7.4 Kg)

3.3 DRIVE MECHANISM

A solar array drive mechanism developed by General Electric is applicable for use as the drive on the Rotary Power Transfer Device. This solar array drive is space qualified and has been flown successfully on a number of spacecraft including Nimbus, ERTS and BSE. The major parts of the solar array drive are the stepper motor, harmonic drive speed reducer, spur gear set and wrap spring clutches. The drive contains two completely redundant unidirectional drives interconnected by two wrap spring clutches which permit either or both drives to be energized with a resultant output torque of 20 ft. lbs. and 40 ft. lbs., respectively. Rotational speeds between one revolution per day to one revolution every 90 minutes can be achieved.

The stepper motor is a brushless permanent magnet DC stepper motor having a two phase winding and a 1.8° step angle. The stepper motor was selected because of its reliability and simplicity of construction. It contains no brushes or commutators or rubbing mechanical parts.

The harmonic drive produces a speed reduction of 100:1; it is simple, having only three major parts: the circular spline, the flexspline and the wave generator. The 100:1 ratio avoids excessively fine teeth and is the upper limit recommended by the manufacturer. The materials used in the harmonic drive are 321 and 17-4 PH CRES.

The spur gear set has a 6.05:1 gear ratio. It consists of a 19-tooth pinion and a 115-tooth output gear having a 20 diametrical pitch, 20 degree pressure angle, and class 12 gears. The pinion material is nitrided steel and the output gear is hard anodized 7075 -T6 aluminum. The dissimilarity of the materials prevents cold welding should there be a lubrication failure and a breakdown of the metallic coatings.

The assembly is dry lubricated. The only exception is a small quantity of Krytox grease in the harmonic drive. The bearings, wrap spring clutch and sput gear sets are all lubricated with bonded moly disulfide films.

The drive characteristics are as follows:

Motor

1 revolution per day	1 watt
1 revolution per 90 minutes	4 watts
Weight	6.6 lbs.

Electronics

5 vdc and 28 vdc available

Power	1 watt
Weight	1 lb.

Autonomous power supply

Power	10 watts
Weight	10 lbs.

4.0 RESULTS

The Rotary Power Transfer Device is a feasible technique for transferring power in the 100 KW to 200 KW regime across a rotating spacecraft interface. The rotary transformer does not necessitate materials or techniques which are not currently available. The rotary transformer was designed conservatively; a design optimization and a materials study could result in weight and size reduction. A reduction in weight could be achieved if, for example, titanium or aluminum could be used instead of Inconel for the shaft and housing. Also, a more detailed thermal analysis could show how the transformer could be made smaller with no increase in core or winding temperatures.

A listing of the characteristics of the Rotary Power Transfer Device is summarized, both at the component and system levels. This summarization covers weight, size, losses and efficiency. In order to provide figures of merit that will permit analysis and comparison, a tabulation of weight/power ratios is given for the power transfer device from the component and assembly levels to the complete system.

4.1 WEIGHT

A weight breakdown was made for the Rotary Power Transfer Device and the results are given below.

Rotary Transformer

The power transfer device consists of 4 - 25 KW transformer modules. The weight of a single 25 KW module and of the four modules is as follows:

25 KW Rotary Transformer Module

	Primary (lbs)	Secondary (lbs)	Total (lbs)
Copper	1.1	1.8	2.9
Core	2.1	3.3	5.4
Epoxy, Shunt	1.0	1.3	2.3
Miscellaneous	.5	.5	1.0
Total	4.7	6.9	11.6 (5.3 Kg)

100 KW Rotary Transformer, 4 - 25 KW Modules

Primary	18.8 lbs.
Secondary	27.6 lbs.
Total	46.4 lbs. (21.1 Kg)

Mechanical Parts

The weight of the mechanical parts which includes housing, shaft, heat pipes, etc., for this device is:

Housing	8.4 lbs.	
Shaft	11.8 lbs.	
Leads	2.0 lbs.	
End Mounts	7.0 lbs.	
Heat Pipes	8.6 lbs.	
Bearings	.7 lbs.	
Hardware	2.0 lbs.	
Misc.	3.0 lbs.	
Total	43.5 lbs.	(19.7 Kg)

Drive Mechanism

The weight of the drive mechanism and its associated control is:

Mechanism	6.6 lbs.
Control	
5 & 28 volts provided	1 lb
Autonomous	10 lbs.
Total 5 & 28 volts provided	7.6 lbs (3.5 Kg)

Radiators

The weight of radiators required for the rotary transformer losses is

60° C Base	7.9 lbs. (3.6 Kg)
80° C Base	6.5 lbs. (3.0 Kg)

The 80° C base radiators appear satisfactory from the aspect of transformer temperatures.

Power Conditioning

The weight of power conditioning electronics is estimated as being:

25 KW module	19 lbs. (8.6 Kg)
100 KW	76 lbs. (34.5 Kg)

The radiator weights for 100 KW are:

60°C Base	11.8 lbs. (5.4 Kg)
80° C Base	9.6 lbs. (4.4 Kg)

A 60° C base radiator was selected for the power conditioning.

100 KW Rotary Power Transfer Device

	Component (Lbs.)	Cumulative Total -(Lbs.)
Rotary Transformer	46.4 (21.1 kg)	
Housing, Shaft, Heat Pipes,etc.	43.5 (19.7 kg)	
Rotary Transformer Assembly		89.9 (40.8 kg)
Radiators (80° C Base)	6.5 (3.0 kg)	96.4 (43.8 kg)
Drive	7.6 (3.4 kg)	104.0 (47.2 kg)
Power Conditioning Electronics	76.0 (34.5 kg)	
Radiator (60° C Base)	11.8 (5.4 kg)	
Rotary Power Transfer Device		191.8 (87.1 kg)

4.2 SIZE

	Diameter (Inches)	Length (Inches)
Rotary Transformer		
25 KW Module	6.25	2.9
100 KW Assembly	7.43	14.3
Rotary Power Transfer Device	7.43	16.25
Overall Envelope	8.25" x 10.40" x 16.25" Long	

4.3 LOSSES, POWER and EFFICIENCY

Rotary Transformer

Losses, Watts

25 KW Transformer Module

	Primary	Secondary	Total
Copper	148	130	278
Core	22	37	59
Total	170	167	337

100 KW Rotary Transformer, 4 - 25 KW Modules

Primary	680 watts
Secondary	668 watts
Total	1348 watts

Efficiency 98.6%

Mechanism

Power

5 volts and 28 volts provided	5 watts
Autonomous	15 watts

Power Conditioning

Losses

25 KW Module	500 watts
100 KW	2000 watts

Power Conditioning - continued

Efficiency 98%

Overall System 100 KW

Rotary Transformer, Power Conditioning and Drive Loss 3353 watts

Efficiency 98.6%

4.4 WEIGHT/POWER RATIOS 100 KW

	Lbs. (Kg)	KW/LB	KW/Kg	Kg/KW
Rotary Transformer	46.4 (21.1 Kg)	2.2	4.7	.21
Rotary Transformer Assembly	89.9 (40.8 Kg)	1.1	2.5	.41
Rotary Transformer Assembly and Radiators	96.4 (43.8 Kg)	1.04	2.3	.44
Rotary Transformer Assembly, Radiators & Drive	104.0 (47.2 Kg)	.96	2.1	.47
Power Conditioning Electronics Radiator	76.0 (34.5 Kg) 11.8 (5.4 Kg)	1.32	2.9	.35
Rotary Power Transfer Device	191.8 (87.1 Kg)	.52	1.1	.87

5.0 CONCLUSIONS

The following conclusions can be made based on the Design Study, Task II.

1. The rotary transformer is a feasible power transfer device.
2. The concentric cylinder is easier to implement than the parallel plate approach.
3. The parallel plate configuration is a viable alternative to the concentric cylinder.
4. The Rotary Power Transfer Device has an envelope of 8.25" x 10.40" x 16.25"; and a weight of 190.8 lbs (86.6 Kg) without radiators, and 209.1 lbs. (94.9 lbs.) with radiators.
5. The rotary transformer assembly, made up of 4-25 KW modules, is 6.43 " diameter, 14.3 " long; weighs 41.5 lbs. (18.8 Kg), without heat pipes; and 50.1 lbs (22.7 Kg) with heat pipes.
6. The power conditioning electronics is based on a Schwarz resonant circuit and weighs 76 lbs.
7. The overall efficiency of the 100 KW Rotary Power Transfer Device is 96.6%, the rotary transformer is 98.6%, and the power conditioning is 98.0%
8. Trade-off studies in the magnetic, electrical, mechanical and thermal design could result in a significant size and weight reduction.
9. The use of ferrite imposes temperature limitations on the cores.

10. Differential thermal expansion indicates the use of Inconel for housing, shaft and heat pipes.

11. Poor thermal conductivities of Inconel and ferrite necessitate the use of curved heat pipes to prevent hot spots.

12. Unfilled epoxies result in a better thermal and mechanical design than filled epoxies because of better shear strength and thinner bond-lines.

13. The drive will be provided by a qualified solar array drive mechanism.

APPENDIX

Design Formulas

Flux Density

$$B = \frac{E_s}{4fNA} \times 10^8$$

B = flux density, gauss

E_s = square wave equivalent of input voltages, volts

f = frequency, Hz

N = number of turns in primary.

A = cross section area, cm^2

$$E_s = \frac{\int_{t_1}^{t_2} e\,dt}{\int_{t_1}^{t_2} dt}$$

Winding Area

$$A_w = \frac{Nas}{FF}$$

A_w winding area, coil only, in^2 (Does not include area required for bobbin, insulation, connections)

N = number of turns

a = area of insulated strand, in^2

s = number of strands

FF = coil fill factor, approximately .6

Resistance

$$R_{dc} = \rho \frac{N\, MLT}{A} \quad \text{, primary or secondary}$$

R_{dc} = dc resistance, ohms

N = number of turns, primary or secondary

MLT = mean length of turn, inches

A = cross-section area of turn, in^2

ρ = electrical resistivity, at operating temperature, ohm in/in^2

$$\frac{R_{ac}}{R_{dc}} = 1 + q^2 \left(\frac{D}{9} - \frac{17}{3790} D^2 \quad . \; . \; . \right) - \frac{D}{45} + \frac{D^2}{900} \quad . \; . \; .$$

R_{ac} = ac resistance of winding

$$D = \left[\frac{h^2 fw}{8.23S} \right]^2$$

h = height of rectangular conductor, inches

f = frequency, hz

w = width of conductors in slot

s = total width of slot

q = number of conductors in height (radially)

For the rotary transformer, this equation can be simplified to

$$\frac{R_{ac}}{R_{dc}} = 1 + q^2 \; \frac{D}{9}$$

Inductances

Primary

$$L_p = 1.257 \times 10^{-8} N^2 MLT_p \left[\frac{d_{1p}}{3w} + \frac{d_{2p}}{w} \right]$$

Secondary

$$L_s = 1.257 \times 10^{-8} N^2 MLT_s \left[\frac{d_{1s}}{3w} + \frac{d_{2s}}{w} + \frac{\mu d_s}{w} \right]$$

where

L_p = primary inductance, henries

N = number of turns, primary

MLT_p = mean length of turn, primary, cm

d_{1p} = depth of primary slot occuplied by winding, cm

d_{2p} = depth of primary sloth not occupied by winding, cm

w = width of sloth, cm

MLT_s = mean length of turn, secondary

d_{1s} = depth of secondary slot occupied by winding, cm

d_{2s} = depth of secondary slot not occupied by winding, cm

d_s = depth of shunt, cm

μ = permeability of shunt

Air Gap

$$L_g = 1.257 \times 10^{-8} N^2 \frac{A_g}{2\ell_g}$$

L_g = air gap inductance, henries

A_g = area of gap, cm^2

ℓ_g = length of gap, cm

Inductances (continued)

Magnetizing

$$L_m = \frac{L_g}{K_s}$$

L_m = magnetizing inductance, henries

k_s = saturation factor

$$= \frac{\text{ampere turns for magnetic circuit}}{\text{ampere turns for air gap}}$$

TASK III

RECOMMENDATIONS AND TESTING REQUIREMENTS

TASK III

RECOMMENDATIONS AND TESTING REQUIREMENTS

1.0 INTRODUCTION

As part of Task III, Recommendations and Testing Requirements, the following subjects were covered:

1. Baseline Slip Ring
2. Testing
3. New Technology or Components
4. Recommendations

The baseline slip ring involved the determination of the characteristics of a conventional brush-type slip ring that the same requirements as the power transfer device, and comparing it with the power transfer device. In testing, some of the problems and possible solutions associated with the performance and life test aspects are reviewed, and the faci'.ty and instrumentation requirements are delineated. New technologies or components cover developments necessary for the ratory transformer and power conditioning electronics. Recommendations are given for future effort for the power transfer device.

2.0 BASE LINE SLIP RING

In order to obtain an idea of the comparative characteristics, Polyscientific Corp., Blackburg, VA. provided an estimate of a slip ring which would be applicable to transferring 100 KW electrical power in 25 KW modules. Polyscientific has broad experience in the design of power slip rings for spacecraft applications.

A summary of the Polyscientific slip ring design is as follows (see Appendix):

Power	100 KW 4-25 KW Modules
Voltage	400 VDC
Current	62.5 Amps Per Module 250 Amps, Total
Life	5 Years
Rings	
Number	8, Total 4 Positive, 4 Negative
Material	Coin Silver (9 Ag-10 Cu) or Hard Silver Electrodeposit
Brushes	
Number	8 Per Ring
Current Density	62.5 Amps/in^2, Normal 150 Amps/in^2, Emergency
Material	Silver, Molydisulfide and Graphite
Contact Drop	.090 Volts
Drive Torque	8 in-lbs.
Power Loss	45 Watts
Size	
Length	11 Inches
Outside Diameter	5.5 Inches
Weight	13 Lbs (5 Kg)

A comparison of the weight and losses of the slip ring with cumulative assembly build-ups of the Rotary Power Transfer Device is shown in Table 1. As would be expected, the rotary transfer device is heavier and has greater losses than a brush-type slip ring. However, only compairson between should be done at the system level and consider the overall effects on the spacecraft of the weight and power characteristics. The study by General Dynamics of power managment for multi-100 KW applications shows that the use of a rotary transformer results in net advantages at the spacecraft level.

Table 1.

Comparison of 100 KW Rotary Power Transfer

Device & Slip Ring

	Diameter (Inches)	Length (Inches)	Volume (In^3)	Weight (Lbs)	Power Loss (Watts)
Rotary Transformer	6.25	12.8	393	46.4	1348
Rotary Transformer Assembly	7.43	14.3	620	89.9	-
Rotary Transformer Assembly & Radiators	-	-	-	96.4	-
Rotary Transformer Assembly Radiators & Drive	8.4" x 10.4" x 16.75" Envelopes (Not Including Radiators)			104.0	1353
Power Conditioning Electronics				76.0	2000
Rotary Power Transfer Device				191.8	3353
Slip Ring	11.0	5.5	261	13	45

3.0 TESTING

Testing of the Rotary Power Transfer Device presents a challenge because of the uniquness of the device, the high power and high frequency involved. The power transfer device basically consists of power conditioning electronics to change dc power to 20 KHz ac and a 100 KW rotary transformer; also, heat pipes are used to remove the heat from the rotary transformer and a drive mechanism to provide rotation capability for the transformer. In order to obtain fullest understanding of the performance of the power transfer device, the characteristics of the power conditioning electronics and rotary transformer should be determined, first, individually, and then together. The test program is not showed as being particularly difficult; however, detailed planning will be required.

The tests on the rotary transformer should include the following:

- Electrical Parameters
  - Resistance & Inductance
- Loss Characteristics
  - Copper Loss & Core Loss
- Load Test
  - Efficiency
  - Regulation
  - Temperature
- Dielectric Test
  - Insulation Resistance
  - Dielectric Strength
- Electromagnetic Interference
- Torque

In addition, the rotary transformer tests should be tested with the power conditioning electronics to provide overall characteristics. These tests would cover:

Loss Characteristics

Load Test

Electromegnetic Interference

A technique that could be considered for the load tests on the rotary transformer alone would be the "back-to-back" method. This consists of using two similar transformers and loading one on the other and with the only power required being that to supply the losses. The primaries of the transformers are connected parallel to the supply; the secondaries are connected in series opposition. Load current is circulated through the windings by introducing comparatively small, low-voltage ac power from a second supply. This technique could be used since there are 4-25 KW transformer modules in the power transfer device. The back-to-back method appears very promising because it reduces the power required per test so that special high power test facilities are not necessary. However, a careful review and check-out of this procedure is necessary to establish its validity in this application which includes both a rotary transformer and power conditioning electronics.

Getting electrical power to the rotating primary winding during test can be achieved several ways:

1. Allow the input leads to wind up and then reversing the direction of the motor drive to unwind them.
2. Use conventional slip rings.

The first approach appears more promising since it does not entail the procurement of high power slip rings for vacuum operation.

3.1 FACILITIES

The major facilities required for testing the Rotary Power Transfer Device include the following:

Power
- 120 KW 440 Volts dc

Power Control Equipment
- Circuit Breakers
- Switches
- Load Banks

Thermal Vacuum Chamber

Electromagnetic Interference

Dielectric Test

The major facility requirement for testing the rotary power transfer device is the power required: 100 KW, 440 volts dc. This is a high power, however, it is available; for example, the General Electric High Power Laboratory in Philadelphia, Pa., has a capacity of 7500 amps at 700 volts dc, which is in excess of the requirements of the power transfer device. However, it would be appropriate to determine if the back-to-back test method or other test techniques could be used so that this power requirement could be alleviated and permitting more flexibility in testing.

3.2 INSTRUMENTATION

The instrumentation necessary to test the Rotary Power Transfer Device would include:

DC	Voltage	500 Volts
	Current	65 & 250 Amps
	Power	25 & 100 KW
AC	Voltage	1000 Volts
	Current	25 & 100 Amps
	Power	25 & 100 KW

EMI
Temperature
Torque
Impedance Bridge
Oscilloscopes
Recorders

3.3 LIFE TESTING

Life testing of the Rotary Power Transfer Device does not appear to present any unique problems. The life test should be run in thermal vacuum with full load on the rotary transformer under rotational conditions. The Rotary Power Transfer Device would be fully instrumented to record input and output power characteristics and temperatures. Controls would be provided to shut down if rotary transformer temperatures become excessive or if the power parameters become anomolous. A life test should be preceeded by tests which would simulate launch environments. Consideration should be given to an accelerated life test. This is not difficult on mechanical components which can be run a higher speeds to demonstrate life capability. The life of electrical components is temperature limited, however, a temperature over 125°C on the rotary transformer cores will result in a degradation of performance while at the excessive temperatures. A test technique would have to be evaluated for performing valid accelerated life test on the rotary transformer.

Full load characteristics on the transformer can be achieved by using the back-to-back method. An alternative method would be to run the transformer with the secondary short-circuited producing full load current in both the primary and secondary. However, since under short circuit with low input voltage, the core loss and magnetizing current are low, the input current would have to be increased somewhat so that copper losses would be equal to the normal full load copper losses plus core losses.

4.0 NEW TECHNOLOGIES OR COMPONENTS

No new technologies or components are required to fabricate and test the rotary transformer. This can be done within the present state of the art. There are some areas that might necessitate some further investigation. If further investigation is not undertaken, the rotary transformer still could be built. The areas for further study and the alternatives are as follows:

Component	Area of Investigation	Alternatives
Heat Pipes	Fabrication of Curved Inconel heat pipes.	(a) Additional circular heat pipes. (b) Flat heat pipes.
Windings	Coil Connections.	Increased transformer length.
Magnetic Shunt	Attainment of Permeability.	(a) External trimming inductance. (b) Increased transformer size.

The primary area of concern in the rotary transformer would be the magnetic shunt. There is no fundamental concern that a magnetic shunt of the proper magnetic characteristics can be attained; however, some development work would be required.

In the power conditioning area there could be some component development desirable. The resonant converter requires low loss high voltage capacitors and a prototype would be useful to determine loss characteristics, corona susceptibility and operational life. Either large capacity FET power switches should be developed; or, as an alternative, circuit arrangements for large scale paralleling of current technology devices should be investigated in order to take advantage of the reduced switching losses that can be obtained by using such high speed devices. Other facets of power conditioning design which should be addressed are carona and the thermal problems resulting from the high power involved.

5.0 RECOMMENDATIONS

This study has shown that the rotary transformer using a resonant converter is a feasible approach for transferring power in the 100 KW regime across a rotating spacecraft interface. It is recommended that a number of topics be pursued in more detail; these are:

1. Perform design study of parallel plate rotary transformer and compare with concentric cylinder approach.

2. Investigate ferrite core materials, epoxy adhesives, magnetic shunt and heat pipes for rotary transformer.

3. Investigate low-loss high-voltage capacitors, FET power switches, circuit paralleling, corona and thermal aspects of power conditioning electronics.

4. Fabricate and test a 10 KW rotary transformer and power conditioning electronics.

APPENDIX

Slip Ring Capsule Assembly For Transferring 100 KW of Power in Space

Summary

A slip ring capsule assembly may be used to reliably and efficiently transfer 100 KW of power in space. This can be accomplished by using flight proven designs and materials.

Background

As part of NASA contract NAS3-22266 on power management technology, General Electric Space Systems asked that Poly-Scientific evaluate the feasibility of producing a slip ring capsule assembly that would transfer 100KW of power for 5 years. The capsule would operate in space and turn one to sixteen revolutions per day. To assist in their analyses, GE suggested that the capsule be designed in 25KW sections.

Design

For purposes of this analysis a slip ring capsule with no bore has been assumed. A section was taken to be a pair of rings (positive and negative) and associated brushes. Poly-Scientific, following a GE suggestion, has assumed that the operating voltage would be 400 VDC, thus each 25KW section would be required to carry 62.5A. The 100 KW capsule would have four positive rings at one end of the capsule and four negative rings at the other. The overall capsule would be cylindrical in shape, approximately 11 inches (280 mm) long and 5.5 inches (140 mm) in diameter. The average ring pitch would be about 1 1/8 inches (29 mm). Extra distance would be provided between high and low voltage contacts.

Each of the rings would have eight brushes that would operate at 62.5 amperes/in^2 (.10 MA/m^2). The brushes could carry more than 150 amperes/in^2 (.23 MA/m^2) under emergency conditions. P-S has tested (1) this brush material for 2 years at 100 amperes/in^2 (.16 MA/m^2). At the 62.5 ampere/ in^2 current density, the contact drop would be approximately 0 090 volts (3). Thus, the total power lost in the 100KW capsule due o positive and negative contact drop would be approximately 45 watts (250A X 0.090V X 2).

Based on a brush coefficient of friction of 0.2, the capsule torque would be approximately 8 in-lbs (0.9 Nm) The torque of the bearings would be negligible compared to the contact torque. Thus, each 25KW section will contribute about 2 in-lbs (.2 Nm).

The contact materials would be silver alloys. The ring material could be either coin silver (90 Ag - 10Cu) or a hard silver electro-deposit. The brush material would be a composite of silver, molybdenum disulfide and graphite. Silver alloy rings and silver/molybdenum-disulfide/graphite brushes have been used successfully on many space programs.

Most of the composite materials listed on the attached list of space slip rings and Poly-twists are silver/molybdenum-disulfide/graphite composites.

The weight of the 100KW slip ring capsule is estimated to be 13 lbs (5 Kg).

One must be aware that 400VDC is above the minimum breakdown voltage of the Paschen curve. This should present no problems unless the slip ring assembly is to be operated at a local internal pressure greater than 10^{-3} torr. If operation above 10^{-3} torr is required, the voltage should be less than 200 VDC to prevent harmful electrical discharges.

In five years of operation at 16 revolutions per day the brush wear will be very slight (less than 0.0004 inches). This is based on a wear rate of 2×10^{-9} inches of brush wear per inch of ring travel (1). The actual wear rate is expected to be much less then 2×10^{-9} (e.g., 10^{-10}) after the initial wear-in period.

The production of a 100KW slip ring assembly is well within the capability of Poly-Scientific (2).

Stephen R. Cole
Senior Engineer
8/26/80

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SPACE SLIP RINGS & POLY-TWISTS
PRELIMINARY POLY-SCIENTIFIC DATA

P/N	Application	Customer	Type	Mat'l	Use	Notes
FK1806,7	Nimbus Sad	TRW	Sep P	Au/Au	F	
D1836	Tiros	BBRC	Cap	Au/Au	F	
BQ1946	Not Defined		Cap	Comp	F	
ET2010	OSD	BBRC	Cap	Au/Au	F	
EW2063	Apollo Ant	Dalmo Victor	Cap	Comp	F	
FL2076	INT IV A	HAC	Sep	Comp	F	
BN2098	Mars Probe	GE	Cap	Comp	F	
D2142	Nimbus S.A.	Bendix	Cap	Comp	T	Qual, no flight
DP2165	Study	NASA	Cap	Comp	T	
ET2189	Scoop	BBRC	Cap	Au/Au	F	
D2253	Skylab	Bendix	Cap P	Au/Au	T	Gnd.Em., NASA
FK2334	Viking	TRW	SW	Comp	F	
HC2361	Viking	Itek	PT	Tape	F	
ET2366	Atm Exp	BBRC	PT	Tape	F	
ET2374	Atm Exp	BBRC	Cap	Au/Au	F	
FL2391	OSO	HAC	Cap	Au/Au(comp)	F	
AS2431	Dom Sat	RCA	Sep	Comp	F	
ET2445	CTS	BBRC	Cap	Au/Au	F	
FK2450	FLT SAT COM	BBRC	Sep P	Au/Au	F	
FK2470	Solar Array	TRW	Cap	Comp	T	
D2494	CMG	Bendix	Cap	Au/Au	?	
ET2604	Not Defined	BBRC	Cap	Au/Au	?	
DQ2614	Not Defined	LMSD	SW	Au/Au	F	
DQ2615	Solar Array	LMSD	Cap	Comp	F	
DP2616	C.M.G.	NASA	Cap	*	TBF	
FL2617	Not Defined	HAC	Sep SR	Comp	?	
D2634	ELMS	Bendix	Cap	Comp	-	
AS2646	TEL SAT	RCA	Cap	Au/Au	F	
JP2650	OTS	HSD	Sep	Comp	T	
BN2655	BSE	GE	Cap	Comp	TBF 3/78	
JQ2662	Mars/Jup/Sat	Johns Hop.	PT	Tape	F	
ET2687	GPS	BBRC	Cap	Comp	F 2/78	
F2728	TAMS	Sperry	PT	Tape	TBF	
F2729	TAMS	Sperry	PT	Tape	TBF	
DP2736	Weather Satellite	NASA	PT	Tape	F	
AC2737	Not Defined	-	Cap	Comp	F	
DQ2769	Sea Sat.	LMSD	Cap	Comp	F	
ET2793	P78-2	BBRC	Cap	Au/Au	F	
DW2794	Shuttle	Martin	Sep P	Comp	TBF	
F2796	Not Defined	Sperry	Sep	Au/Au	T	
HG2799	Shuttle	Spar	Cap	Comp	TBF	
KR2812	Shuttle	ITT	Sep	Comp	TBF	
ET2816	SAGE	BBRC	PT	Tape	F	
KU2832	INT V	FACC	Sep	Comp	F	
DQ2835	Test	LMSD	Cap	Comp	T	
FK2857	TDRSS	TRW	Sep	Au/Au	F	
LE2897	Not Defined	Vought Corp.	Cap	Au/Au	TBF	

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FL2907	SBS; ANIK-C,D	Hughes	Sep	Comp	F
CV2929	Space Shuttle	MDAC	Cap	Au/Au	TBF
AS2940	Not Defined	RCA	Cap	Au/Au	F
FL2963	SBS; ANIK-C,D	Hughes	Sep	Comp	TBF
JQ2972	GALILEO	Johns Hop.	PT	Tape	TBF
KU3005	INSAT I	FACC	Sep	Comp.	TBF
FL3039	LEASAT	Hughes	Sep	Comp.	TBF
ET3040	P-80 Sat.	Ball Bros.	PT	Tape	TBF
A3053	HOE	Honeywell	PT	Tape	TBF
AS3068	SATCOM	RCA	Cap	Au/Au	TBF
ET3113	PAM (Space Shuttle)	Ball Bros.	Cap	Au/Au	TBF
BD3115	ERBE	Barnes	PT	Tape	TBF
FK3135	ERBE	TRW	PT	Tape	TBF

Sep-Separate
P-Pancake
PT-Poly-twist
SW-Switch
Cap-Capsule

Au/Au-Gold alloy rings & brushes
Comp-Composite brush
Tape-No contacts, tape conducts
*Composite on power ckt.
Au/Au-inner signal ckt.

F-Flown
TBF-To be flown
T-Test

(7/30/80)

PART IV

CONCLUSIONS

PART IV

CONCLUSIONS

Based on this Preliminary Design Development Study, the following conclusions can be made:

1. A rotary transformer is a feasible device for transferring 100 KW power across a rotating spacecraft interface; no basic difficiulities are forseen in transferring power up to 1 MW.

2. The concentric cylinder (axial air-gap) is the preferred transformer configuration.

3. There is no obvious advantage for using either resonant or non-resonant (square wave) circuitry for the power conditioning electronics.

4. There is no advantage to for the power conditioning to operate above 20 KHz; however, the rotary transformer would be smaller at higher frequencies.

5. A rotary transformer will be larger and heavier than a brush-type slip ring.

6. Power requirements for testing can be reduced by using the back to back transformer test technique.

7. A model 10 KW, 20 KHz rotary transformer and power conditioning electronics wuold demonstrate the rotary power transfer concept.

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