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# Development of High Frequency Low Weight Power Magnetics for Aerospace Power Systems

Gene E. Schwarze  
*Lewis Research Center  
Cleveland, Ohio*

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# DEVELOPMENT OF HIGH FREQUENCY LOW WEIGHT POWER MAGNETICS FOR AEROSPACE POWER SYSTEMS

Gene E. Schwarze  
National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135

## ABSTRACT

A dominant design consideration in the development of space-type power magnetic devices is the application of reliable thermal control methods in order to prevent device failure due to excessive temperature rises and hot spot temperatures in critical areas. The resultant design must also yield low weight, high efficiency, high reliability and maintainability, and long life. A transformer weight equation is developed to show that the weight is directly proportional to the 3/4th power of the kVA rating and inversely proportional to the 3/4th power of the product of the variables  $f$ ,  $B_m$ ,  $J_s$ ,  $\alpha$ ,  $(FF)$ , and  $(SF)_c$ . A family of curves, obtained when the normalized specific weight is plotted as a function of the transformer's kVA rating with frequency as the parameter, show insignificant weight savings for frequencies above 50 kHz. The weight savings and high efficiency that results by going to high frequency and unique thermal control techniques is demonstrated by the development of a 25 kVA, 20 kHz space type transformer under Lewis' power magnetics technology program. Earlier work included heat pipe cooled inductors and transformers in the 3 kVA range. Present work in the area of power rotary transformers is also discussed.

## INTRODUCTION

The power circuits in future high power space systems will in many cases require the use of power transformers. The power transformer, whether fixed or rotary, provides the means to transfer power at source voltage levels to load voltage requirements. The requirement for isolation between source and load is inherently provided by the power transformer.

In the space environment, rejection of the transformer's core and winding losses must be accomplished almost solely by conductive heat transfer to a radiator. The development of thermal control methods which eliminate potential hot spots and also give predictable core and winding temperature rises thus becomes a dominant consideration in the design strategy of space-type power magnetics. The resultant design must also be such that the device has low specific

weight, high efficiency, high reliability and long life.

Over the past decade, the NASA Lewis Research Center has been actively engaged in developing the technology of lightweight, high efficiency and high reliability power magnetic devices for aerospace power systems. The characterization and testing of these magnetic power components through technology development programs is a prerequisite for consideration of the component's use in future aerospace power systems.

One of the first magnetic devices developed was a conduction cooled high voltage transformer for the cathode/collector power supply of the 200 watt TWT used on the Communications Technology Satellite (1). This 500 VA, 11.3 kV output transformer operated at 10 kHz at an efficiency greater than 98 percent and weighed 0.82 kg for a specific weight of 1.6 kg/kVA.

Another magnetic device development was a conduction cooled 2.3 kVA, 10 kHz transformer for a 30-cm ion thruster power supply (2,3). This 1.1 kV output transformer has an efficiency of 98.6 percent, a weight of 1.8 kg and a specific weight of 0.78 kg/kVA.

A heat pipe cooled transformer having identical electrical specifications of the above conduction cooled transformer has an efficiency of 98.2 percent, a weight of 1.2 kg, and a specific weight of 0.52 kg/kVA, (4,5). A significant difference between these electrically identical transformers is that the conduction cooled transformer has a temperature rise of 41° C while the heat pipe cooled transformer has a temperature rise of only 20° C. Thus, the heat pipe transformer would have a higher rating than 2.3 kVA and a lower specific weight than 0.52 kg/kVA if it were operated at the same temperature rise as the conduction cooled transformer.

The specific weight and efficiency of power magnetic components is of primary concern to space power systems' designers. In this paper a transformer weight analysis is performed and the results are used to plot a family of curves of normalized specific weight versus the kVA-rating. The paper also describes a recent addition to low weight, high efficiency power magnetics

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technology which was the development of a conduction cooled 20 kHz, 25-kVA, 200 V input and 1500 V output, continuous duty, single phase transformer (6,7). Rotary power transformers for photovoltaic space power systems are also briefly addressed.

#### WEIGHT ANALYSIS

The weights of the magnetic devices in space power supplies are generally the greatest percentage of the total weight. Thus, every effort must be made to reduce the magnetics weight and still achieve high efficiency, high reliability and permissible temperature rises in the core and windings. The design variables which affect the weight will now be investigated by means of the following weight analysis.

The kVA rating of a single phase transformer is

$$\text{kVA} = I_s V_s \times 10^{-3} = N_s I_s \left( \frac{V_s}{N_s} \right) \times 10^{-3} \quad (1)$$

The secondary RMS current density  $J_s$  is by definition

$$J_s = \frac{I_s}{b_s} \quad \text{A/m}^2 \quad (2)$$

The substitution of Eq. (2) into Eq. (1) gives

$$\text{kVA} = N_s b_s J_s \left( \frac{V_s}{N_s} \right) \times 10^{-3} \quad (3)$$

The window area required for the primary and secondary turns is

$$A_w = \left( \frac{N_p b_p + N_s b_s}{\alpha} \right) \quad \text{m}^2 \quad (4)$$

If it is assumed that  $N_p b_p = N_s b_s$  then Eq. (4) can be written as

$$N_p b_p = N_s b_s = \frac{\alpha A_w}{2} \quad \text{m}^2 \quad (5)$$

By the use of this last result, Eq. (3) then becomes

$$\text{kVA} = \frac{\alpha A_w J_s}{2} \left( \frac{V_s}{N_s} \right) \times 10^{-3} \quad (6)$$

Equation (6) can be written in the form

$$A_w = \frac{2(\text{kVA}) \times 10^3}{\alpha J_s \left( \frac{V_s}{N_s} \right)} \quad \text{m}^2 \quad (7)$$

From this last equation it should be noted that for a specified kVA rating, the window area decreases for increases in  $\alpha$ ,  $J_s$ , and  $(V_s/N_s)$ . High voltage transformers will have small values of  $\alpha$  and thus it is seen that they will require larger window areas for the same kVA rating since more electrical insulation is required. The limit to which  $J_s$  can be increased is dependent on the maximum allowable temperature rise of the windings.

If it is assumed that the voltage drops due to the primary and secondary winding impedances are negligible respectively to the primary input and secondary output voltages, then by means of Faraday's Law we can write

$$\frac{V_p}{N_p} = \frac{V_s}{N_s} = 4(\text{FF}) B_m f (\text{SF})_c A_c \quad \text{V/turn} \quad (8)$$

Solving Eq. (8) for  $A_c$  gives

$$A_c = \frac{\left( \frac{V_s}{N_s} \right)}{4(\text{FF}) (\text{SF})_c B_m f} \quad \text{m}^2 \quad (9)$$

A comparison of Eq. (9) with Eq. (7) shows that for a specified kVA rating that as  $(V_s/N_s)$  increases, then the window area decreases but the core cross-sectional area increases. Since the weight and size of a transformer are dependent on  $A_w$  and  $A_c$ , it would appear that increasing or decreasing  $(V_s/N_s)$  does not contribute to any weight savings. An increase in  $A_c$  causes an increase in core weight, generally an increase in the mean-length of turn of the primary and secondary winding; and thus an increase in winding weight. A decrease in  $A_w$  results in reduced core weight, reduced mean-turn lengths and hence reduced winding weight.

The substitution of Eq. (8) into Eq. (6) gives

$$\text{kVA} = 2 \alpha (\text{SF})_c (\text{FF}) J_s B_m f A_c A_w \times 10^{-3} \quad (10)$$

The total transformer weight,  $W_T$ , includes the weight of the windings,  $W_w$ , the weight of the magnetic core,  $W_c$ , and

the weight of the mechanical structural elements, insulation, and cooling hardware,  $W_x$ . The total weight is then defined as

$$W_T = W_W + W_C + W_x \quad \text{kg} \quad (11)$$

The dimensions of the core and windings can all be expressed in terms of a basic linear dimension,  $d$ , and dimensionless scaling constants,  $a_1, a_2, a_3, \dots, a_n$ . That is, all the linear dimensions of the core and windings can be normalized with respect to a particular linear dimension of either the core or winding. This normalized or reference dimension is then the basic linear dimension  $d$ , and the ratio of a particular core or winding dimension to the basic dimension is the scaling constant for that dimension.

For example, the basic dimension could be the length of the core window. The window area would then be

$$A_W = (d)(a_1 d) = a_1 d^2 \quad \text{m}^2 \quad (12)$$

where  $a_1$  is the scaling constant of the width of the window and  $a_1 d$  is the width.

The weights of the core and windings can thus be written in terms of the basic dimension and the appropriate scaling constants along with the density of the core or winding. For the winding conductor,

$$W_W = D_W(U_p + U_s) \quad \text{kg} \quad (13)$$

where

$$U_p = b_p l_p = b_p N_p (\text{MLT})_p = \frac{\alpha A_W (\text{MLT})_p}{2} \quad \text{m}^3 \quad (14)$$

$$U_s = b_s l_s = b_s N_s (\text{MLT})_s = \frac{\alpha A_W (\text{MLT})_s}{2} \quad \text{m}^3 \quad (15)$$

The substitution of Eqs. (14) and (15) into Eq. (13) gives

$$W_W = \frac{\alpha D_W A_W}{2} \left[ (\text{MLT})_p + (\text{MLT})_s \right] \quad \text{kg} \quad (16)$$

Let

$$(\text{MLT})_p = a_2 d \quad \text{m} \quad (17)$$

$$(\text{MLT})_s = a_3 d \quad \text{m} \quad (18)$$

Now by means of Eqs. (12), (17), and (18) Eq. (16) becomes,

$$W_W = k_W D_W d^3 \quad \text{kg} \quad (19)$$

where

$$k_W = \alpha a_1 (a_2 + a_3)$$

For the magnetic core,

$$W_C = D_C A_C \bar{T}_C \quad \text{kg} \quad (20)$$

where the geometrical cross-sectional area of the core  $A_C$  is given by

$$A_C = a_4 a_5 d^2 \quad \text{m}^2 \quad (21)$$

and where the core path length,  $\bar{T}_C$ , is given by

$$\bar{T}_C = a_6 d \quad \text{m} \quad (22)$$

The substitution of Eqs. (21) and (22) into Eq. (20) gives

$$W_C = k_C D_C d^3 \quad \text{kg} \quad (23)$$

where

$$k_C = a_4 a_5 a_6$$

The weight  $W_x$  can be represented as

$$W_x = \left( \frac{W_x}{W_T} \right) W_T = k_x W_T \quad \text{kg} \quad (24)$$

where

$$k_x = \left( \frac{W_x}{W_T} \right) < 1$$

The substitution of Eqs. (19), (23), and (24) into Eq. (11) gives,

$$W_T = k_T D_W d^3 \quad \text{kg} \quad (25)$$

where

$$k_T = \left[ \frac{k_W + (D_C/D_W) k_C}{(1 - k_x)} \right]$$

The substitution of Eqs. (12) and (21) into Eq. (10) gives

$$kVA = k_V \alpha (FF)(SF)_C J_S B_m f d^4 \times 10^{-3} \quad (26)$$

where

$$k_V = 2 a_1 a_4 a_5$$

Solving Eq. (26) for  $d$  and substituting this result into Eq. (25) gives

$$d = \left[ \frac{kVA \times 10^3}{k_V \alpha (FF)(SF)_C J_S B_m f} \right]^{1/4} \text{ m} \quad (27)$$

$$W_T = k_R D_w \left[ \frac{kVA \times 10^3}{\alpha (FF)(SF)_C J_S B_m f} \right]^{3/4} \text{ kg} \quad (28)$$

where

$$k_R = \left( \frac{k_T}{k_V^{3/4}} \right)$$

Equation (28) provides the means to examine the variables which affect the total transformer weight. The first significant thing to note is that the weight is not a linear function of the kVA rating but rather the weight varies as the 3/4th power of the kVA rating. This fact leads to the conclusion that as the kVA rating increases, then the specific weight should decrease, i.e., the higher the kVA-rating, the lower the specific weight.

To reduce the weight of a transformer with a specified kVA rating requires that the denominator of the right member of Eq. (28) increases. An examination of each design variable in this denominator and its upper limit will now be investigated.

(1) The conductor space factor,  $\alpha$ , is a fraction and thus its limit is one. In reality though  $\alpha$  can only approach about half its upper limit since the insulating and cooling systems of the windings determine the value of this design variable. In general, as the voltage rating increases, then  $\alpha$  decreases.

(2) The stacking factor,  $(SF)_C$ , of the magnetic core is also a fraction and its upper limit is one. The upper limit is approached by increasing the lamination thickness but this leads to higher specific core losses. For this variable then a trade-off must be made between transformer efficiency and weight.

(3) The form factor,  $(FF)$ , is fixed once the voltage waveform is selected. It should be noted though that a sine wave voltage transformer having a form factor of 1.11 will yield a lower weight transformer

than a square wave voltage transformer having unity form factor.

(4) An increase in the current density,  $J_S$ , will cause an increase in the winding losses since the winding losses are proportional to the square of the current density. The upper limit to which  $J_S$  can be increased is determined by the allowable temperature rise of the windings. The use of high thermal conductivity insulating materials, multiple thermal paths for the winding and core loss heat rejection, and minimum thermal interfaces and joints all promote reduction in temperature rise and thus allow for increases in  $J_S$ .

(5) The upper limit of the magnetic flux density,  $B_m$ , is its saturation value, which is dependant on the choice of magnetic material used for the core. The specific core loss of a magnetic material is a non-linear function of  $B_m$  and increases as  $B_m$  increases. Thus, increases in  $B_m$  result in core loss increases and thus changes in this variable likewise require a weight versus efficiency trade-off.

(6) The frequency upper limit in a sense is unbounded and thus increases in this variable provide the largest weight savings. However, the specific core loss, also a function of the frequency, increases as the frequency increases. In order to have manageable core losses at high frequencies it is required that the magnetic flux density be decreased. Thus, decreases in  $W_T$  achieved by increases in  $f$  can be offset to a certain extent by the necessary decreases in  $B_m$ . Also, as the frequency increases, the ac winding resistance increases due to skin and proximity effects and thus causes increased winding losses.

From this weight analysis it is seen that savings in weight can be achieved by increases in several design variables, most notably the frequency but that these savings in weight can be at the expense of the transformer's efficiency. However, by proper choice of the variables involved, it is possible to achieve a transformer that has both a very low weight and a very high efficiency.

From Eq. (28) the normalized specific weight is defined as,

$$(W_T/k_R)/(kVA) = \frac{D_w}{(kVA)^{1/4}} \left[ \frac{1 \times 10^3}{\alpha (SF)_C (FF) J_S B_m f} \right]^{3/4} \text{ kg/kVA} \quad (29)$$

In Fig. 1 a family of curves of normalized specific weight plotted against the kVA rating are drawn for specified values of  $J_S$ ,  $\alpha$ ,  $(FF)$ ,  $D_w$ , and  $(SF)_C$ . Each

curve of the family represents a given frequency and for this frequency a value of  $B_m$  is selected so as to avoid excessive specific core losses. The curves clearly illustrate that for a given frequency, the normalized specific weight decreases as the kVA-rating increases. Also, as the frequency is increased, the normalized specific weight decreases but the rate of decrease diminishes as the frequency increases.

A comparison of the 20 kHz and 50 kHz curves shows that minimal weight savings are realized by going to 50 kHz. Thus, beyond 50 kHz the weight savings become insignificant.

An identical family of curves can be obtained for different specified values of  $J_s$ ,  $\alpha$ , (FF),  $D_w$  and  $(SF)_c$ . For example, if only  $J_s$  is changed, then increases in  $J_s$  cause a downward shift of the curves while decreases in  $J_s$  cause an upward shift of the curves.

#### 25-kVA SPACE-TYPE TRANSFORMER

The significant weight and size reductions which can be achieved by going to high frequency operation and unique thermal control techniques is clearly demonstrated by the transformer shown in Fig. 2. This 25 kVA, 20 kHz, 200 V input and 1500 V output, conduction cooled, continuous duty, single phase transformer was developed under Lewis' power magnetics technology program. This transformer will be described in some detail because of its importance to the space station, which has power levels consistent with 25 kVA modules.

The electrical power loss of this 25 kVA transformer is 196 watts for an efficiency of 99.2 percent. Its weight is 3.2 kg (7 lb) for a specific weight of 0.13 kg/kVA (0.28 lb/kVA). A comparable 25 kVA, 60 Hz commercial power transformer weighs about 180 kg (400 lb) for a specific weight of 7.3 kg/kVA (16 lb/kVA). In Fig. 3 a comparison of the 25 kVA, 20 kHz space-type transformer and a commercial 25 kVA, 60 Hz commercial power transformer are shown.

Table I gives a breakdown of the transformer's loss. From the table it should be noted that the losses are fairly evenly distributed between the primary and secondary winding losses and the core loss. Table II gives a weight breakdown of the transformer's major elements. It is significant to note that the sum of the weights of the structural, and cooling components, insulators, and mechanical fasteners comprise just over 50 percent of the total weight.

The mechanical design of the transformer was based on the premise that it would be mounted on a constant temperature surface. Figure 4 shows the mechanical structure of the transformer. The principle elements of this structure are the baseplate, the core clamps, and the coil mounting plates and core supports which attach to the base plate. Aluminum was used to fabricate these structural components since it has features that combine good thermal conductivity, lightweight, and ease of fabrication. The transformer's mechanical structure not only provides the required mechanical support for the core and windings but it also provides, almost more importantly, the multithermal paths for the conduction cooling of the windings and core.

Figure 5 shows a coil plate assembly along with the location of the primary and secondary terminals, the magnetic core, and other structural members. The core arrangement is of the shell-type. Supermalloy C cores with 0.025 mm (0.001 in) thick wound tape material were used for the magnetic cores. Four sets of core mounting supports and clamps encompassing the exposed portions of the magnetic core hold the core in a fixed position. An insulated core tube fits over the center leg of the core and this tube passes through the center diameter hole in all of the coil support plates. The insulation on the underside of the exterior core legs was removed in order to provide more intimate thermal contact between the cores and the core support surfaces. An insulated pressure plate is placed between the core clamp and the upper surface of the exterior core legs. Top mounted screws in the core clamps are adjusted to apply pressure to this insulated plate and the exterior core legs. This arrangement of the core clamps and supports thus provides the core's mechanical support and the thermal paths to transmit the core losses to the baseplate.

Prewound pie or pancake single layer coils are bonded to coil mounting plates with a thin insulating film placed between coil and plate. Each pie coil's  $I^2R$  losses are uniformly transmitted directly to its mounting plate which conducts the heat directly to the heat sink baseplate. A primary coil is mounted to one face of the mounting plate and a secondary coil to the opposite face. This arrangement leads to very good magnetic coupling and, hence, low leakage inductance. The equivalent leakage inductance measured at the secondary winding with the primary winding shorted was 57  $\mu\text{H}$  so that the calculated equivalent leakage inductance referred to the primary is 1.0  $\mu\text{H}$ . The metal mounting plates also

provide a natural electrostatic shield between the windings. In Figs. 4 and 5 it should be noted that each mounting plate is slit from its top edge to its center hole to prevent the plate from acting as a shorted turn.

The eight individual primary pie coils are connected in parallel while the eight secondary pie coils are connected in series. The turns ratio of the secondary to primary turns is 7.5 and the volts per turn is 16.7 V/turn.

Segmented hollow copper spacers are used to construct both the primary and secondary bus bar assemblies. To reduce the size and weight of the primary bus-bar assembly, the external primary connections are made to both ends of the primary terminal assemblies.

The transformer was tested under short circuit conditions at 60 Hz. The primary winding was short-circuited and the impedance voltage applied to the secondary. Under these conditions full power rated current flowed through the windings. For this test the transformer was instrumented with 16 thermocouples to identify hot spot temperatures and also to obtain a temperature profile of the windings. The maximum temperature rise of the coils was 45° C.

Even though the leakage inductance of this transformer is very low, at 20 kHz under short circuit conditions the leakage reactance becomes the predominant term in the impedance so that the phase angle approaches 90° and the power factor approaches zero. Limited success was achieved in conducting 20 kHz short-circuit tests since the amplifier used could not cope with this type of load.

To conduct full load high frequency complex waveform tests will require special test circuits and specially designed linear power amplifiers. Presently under development at NASA Lewis is a 25 kVA solid state amplifier with variable output frequency and gain and capable of operating into low power factor loads.

#### ROTARY TRANSFORMER

Future high power spacecraft such as the space station will require the transfer of large quantities of power across a rotating interface. Slip rings and roll rings are potential candidates as the rotary power transfer device but the rotary transformer is also a strong candidate since it is contactless and thus offers the desirable characteristics of high reliability, long life-

time, and low noise. The rotary transformer becomes an even more attractive candidate if an ac distribution system is used.

Low power rotary transformers in the range of 1 kVA and operating frequencies up to 20 kHz have been developed (8 to 11). Design studies have been conducted for a 20 kHz rotary transformer with an axial gap geometry (12) and a radial gap geometry (13) for 25 to 100 kVA levels. Present studies include the design characterization of various rotary power transformer geometrical configurations and how these characteristics affect the design of high frequency and high power inverters. The fabrication of a 25 kVA, 20 kHz rotary power transformer for proof of concept tests and device characterization will begin in the near future.

#### CONCLUSION

The transformer weight equation shows that the weight is directly proportional to the 3/4th power of the kVA rating and inversely proportional to the 3/4 power of the product of the variables  $f$ ,  $B_m$ ,  $J_s$ ,  $\alpha$ ,  $(FF)$ , and  $(SF)_c$ . The weight equation is also used to define the normalized specific weight. The family of curves, obtained when the normalized specific weight is plotted as a function of the transformer's kVA rating with frequency as the parameter, shows insignificant weight savings for frequencies above 50 kHz.

The weight savings and high efficiency that can be achieved by going to high frequency and unique thermal control techniques were demonstrated by the development of a 25 kVA space-type transformer developed under Lewis' power magnetics technology program. Power magnetics technology will continue to be developed in the 100 kVA range for the near term and the 1-MVA range for the longer term. Anticipated additional NASA technology to be developed includes both high temperature (300° to 500° C) and radiation resistant power magnetics. The magnetic technology developed should be applicable to both photovoltaic and future high power rotating space-power systems.

#### SYMBOLS

$A_c$	geometrical cross-sectional area of magnetic core, $m^2$
$A_w$	core window area, $m^2$
$a_1, a_2, \dots, a_6$	scaling constants, dimensionless

$B_m$	maximum magnetic flux density, T
$b_p, b_s$	primary and secondary conductor wire cross-sectional area, respectively, $m^2$
$D_c$	core density, $kg/m^3$
$D_w$	winding conductor material density, $kg/m^3$
$d$	basic or reference linear dimension, m
FF	form factor; the ratio of RMS to average voltage, dimensionless
$f$	frequency, Hz
$I_s$	secondary RMS current, A
$J_s$	secondary RMS current density, $A/m^2$
$k_c, k_R, k_T,$ $k_V, k_W, k_X$	constants defined in text
$\bar{T}_c$	mean path length of magnetic core, m
$l_p, l_s$	primary and secondary winding conductor lengths, respectively, m
$(MLT)_p, (MLT)_s$	primary and secondary winding mean length of turn, respectively, m
$N_p, N_s$	number of primary and secondary turns, respectively, dimensionless
$(SF)_c$	core stacking factor; fraction of core volume filled with magnetic material, dimensionless
$U_p, U_s$	primary and secondary winding conductor volume, respectively, $m^3$
$V_p, V_s$	primary and secondary RMS voltage, respectively, V
$W_c$	core weight, kg
$W_w$	winding weight, kg
$W_T$	total transformer weight, kg
$W_x$	weight of transformer's mechanical structure, insulation, and cooling hardware, kg
$\alpha$	window space factor; fraction of window filled with bare wire conductor, dimensionless

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TABLE I. - 25 kVA TRANSFORMER LOSS  
AND EFFICIENCY

<u>Description</u>	<u>Loss</u> W.	<u>Percent of total</u> percent
Pri. Wdg $I^2R$	74	37.8
Sec. Wdg $I^2R$	62	31.6
Total $I^2R$	136	69.4
Core Loss	60	30.6

Total transformer Loss - 196 watts.  
Total transformer efficiency - 99.2 percent

TABLE II. - 25 kVA TRANSFORMER WEIGHT BREAKDOWN

<u>Description</u>	<u>Weight</u> kg (lb)	<u>Percent total weight</u> percent
Magnetic core	0.70 (1.53)	22.0
Coils and bus bar assembly	0.87 (1.92)	27.6
Structural components	1.14 (2.50)	36.0
Insulators	0.21 (0.47)	6.8
Mechanical fasteners	0.24 (0.53)	7.6
Total weight	<u>3.16 (6.95)</u>	<u>100</u>

Specific weight - 0.13 kg/kVA (0.28 lb/kVA).  
Specific power - 7.92 kVA/kg (3.6 kVA/lb).

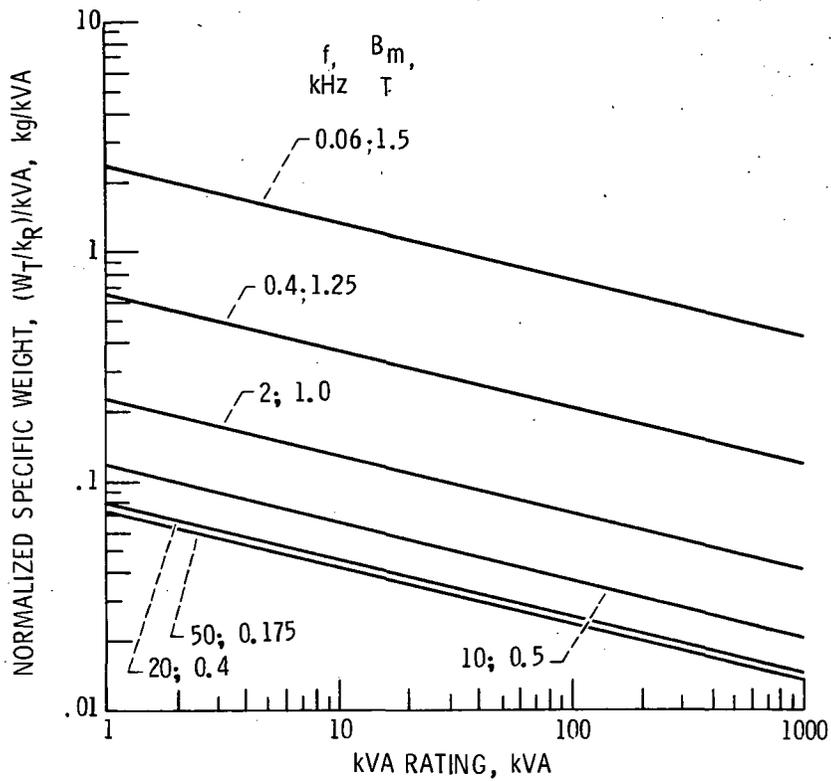


Figure 1. - Normalized specific weight as a function of transformer kVA rating.  $\alpha = 0.25$ ;  $J_S = 2.63 \times 10^6 \text{ A/m}^2$ ;  $(SF)_C = 0.9$ ;  $(F.F) = 1.11$ ;  $D_W = 8.89 \times 10^3 \text{ kg/m}^3$ .

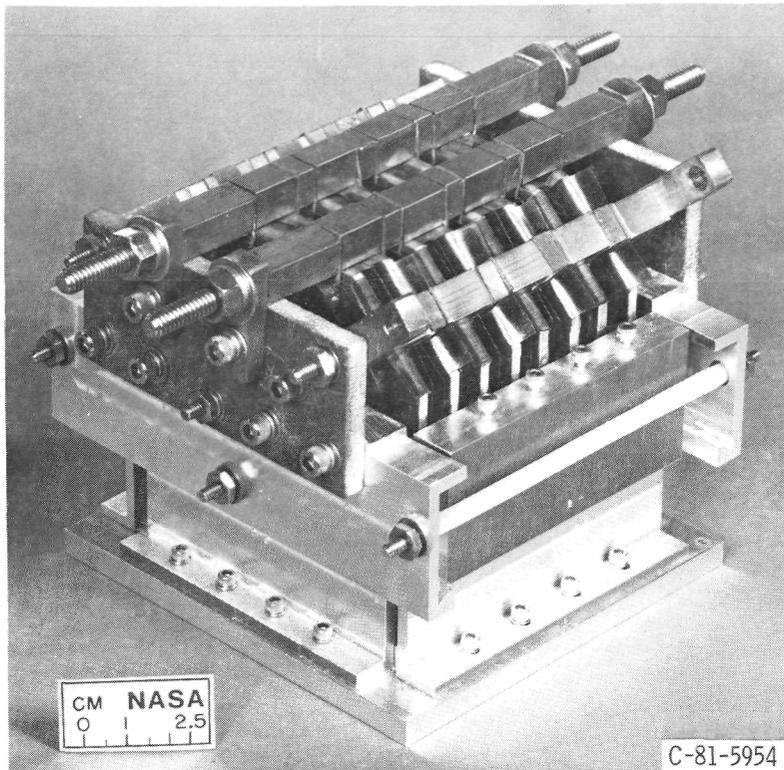
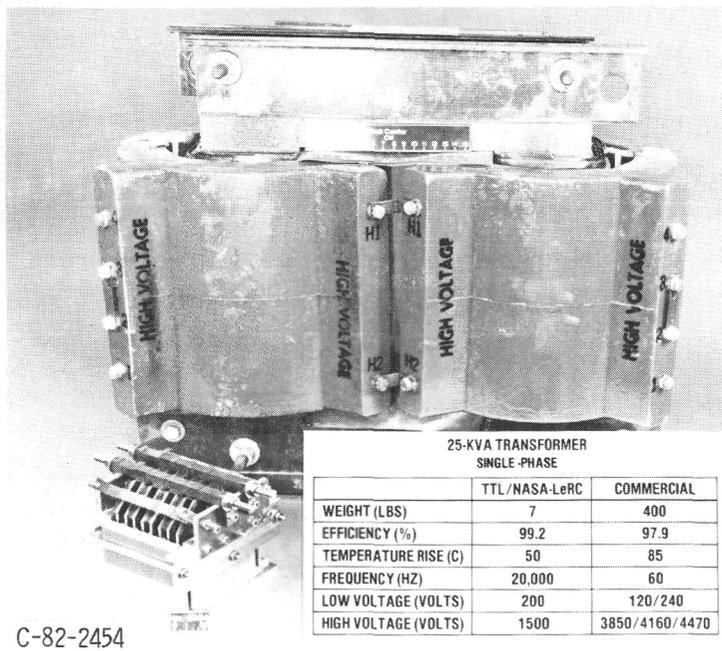


Figure 2. - 25 kVA, 20 kHz transformer.



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Figure 3. - Comparison of space and commercial 25 kVA single-phase transformers.

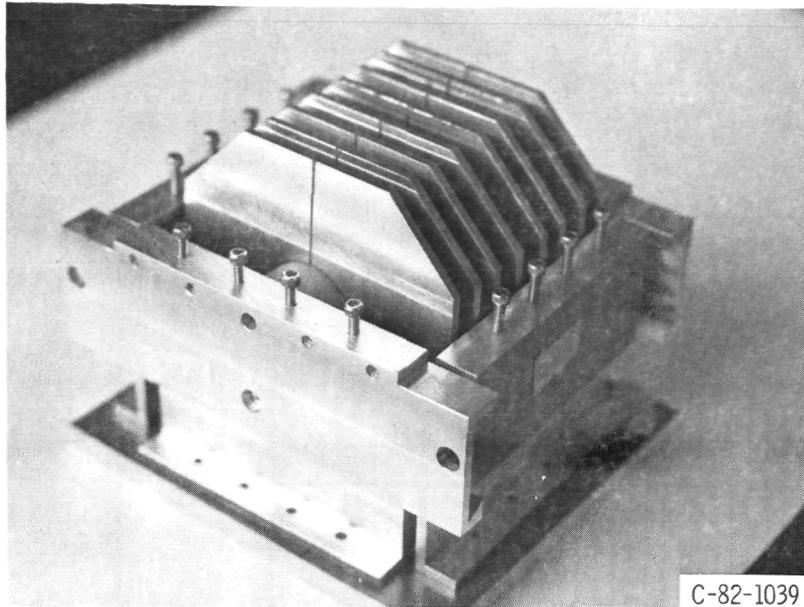


Figure 4. - Mechanical structure of 25 kVA, 20 kHz transformer.

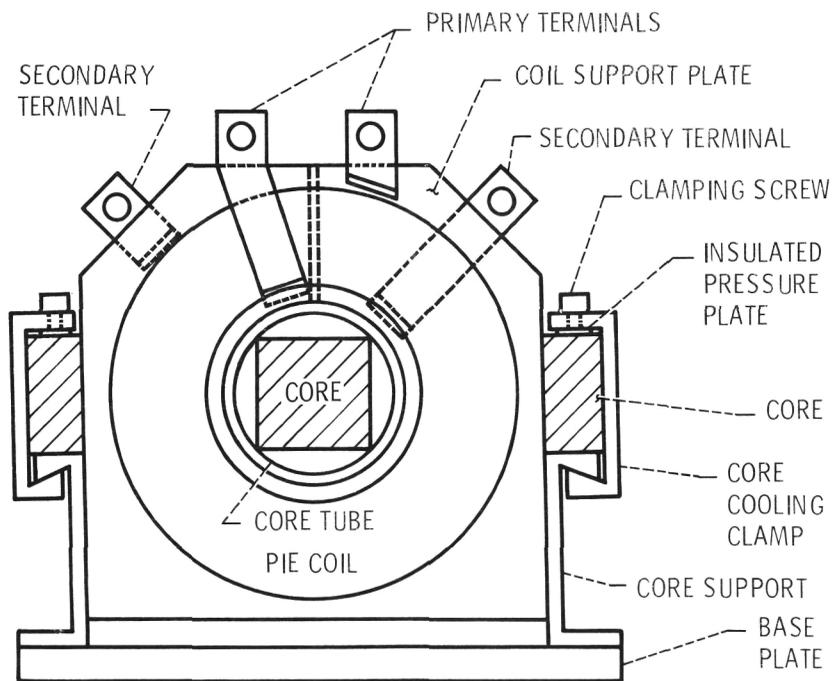


Figure 5. - Coil plate assembly for 25 kVA, 20 kHz transformer.

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16. Abstract A dominant design consideration in the development of space-type power magnetic devices is the application of reliable thermal control methods in order to prevent device failure due to excessive temperature rises and hot spot temperatures in critical areas. The resultant design must also yield low weight, high efficiency, high reliability and maintainability, and long life. A transformer weight equation is developed to show that the weight is directly proportional to the 3/4th power of the kVA rating and inversely proportional to the 3/4th power of the product of the variables $f$ , $B_m$ , $J_s$ , $\alpha$ , $(FF)$ , and $(SF)_c$ . A family of curves, obtained when the normalized specific weight is plotted as a function of the transformer's kVA rating with frequency as the parameter, show insignificant weight savings for frequencies above 50 kHz. The weight savings and high efficiency that results by going to high frequency and unique thermal control techniques is demonstrated by the development of a 25 kVA, 20 kHz space type transformer under Lewis' power magnetics technology program. Earlier work included heat pipe cooled inductors and transformers in the 3 kVA range. Present work in the area of power rotary transformers is also discussed.					
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