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TOROIDAL TRANSFORMER DESIGN PROGRAM  
WITH APPLICATION TO INVERTER CIRCUITRY

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16. Abstract <p>Estimates of temperature, weight, efficiency, regulation, and final dimensions are included in the output of this computer program for the design of transformers for use in the basic parallel inverter. The program, written in FORTRAN IV, selects a tape wound toroidal magnetic core and, taking temperature, materials, core geometry, skin depth, and ohmic losses into account, chooses the appropriate wire sizes and number of turns for the center tapped primary and single secondary coils. Using the program, 2- and 4-kilovolt-ampere transformers are designed for frequencies from 200 to 3200 Hz and the efficiency of a basic transistor inverter is estimated.</p>					
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# TOROIDAL TRANSFORMER DESIGN PROGRAM WITH APPLICATION TO INVERTER CIRCUITRY

by James A. Dayton, Jr.

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## SUMMARY

Users of this program are relieved of most computational details, while maintaining control over most engineering decisions, in the design of toroidal transformers for use in parallel inverter circuitry.

The information supplied to the computer is the input voltage, input current, output voltage, frequency of operation, desired fill factor, maximum  $I^2R$  loss in a coil, maximum magnetic flux density, density of the magnetic material, specific core loss, specific apparent excitation power, ambient temperature, desired current density in the windings, and relative resistance and density of the wire if a metal other than copper is used.

The computer output consists of the input and output currents and voltages, excitation current, core identification number, core weight, core loss, approximate regulation, total losses, efficiency, total mass, fill factor, ambient and operating temperatures, final height, diameter, and surface area, frequency, power lost per unit surface area, and, for each coil, the number of turns, size of wire, number of parallel windings, resistance, power dissipated, and mass.

The program contains information on 90 sizes of magnetic cores, equally divided into two groups, and 48 sizes of wire. If this selection is inadequate, the program prints out an appropriate error symbol.

The program is applied to the design of 2- and 4-kilovolt-ampere transformers and, over a range of frequency from 200 to 3200 hertz, a class of transformers of nearly equal efficiency is designed. The variation in characteristics of transformers wound on heavy and light cores is also examined.

Pre-execution time on the IBM 7094 is less than 0.5 minute and execution time is approximately 0.0011 minute per transformer.

## INTRODUCTION

Electrical power requirements in spacecraft are frequently met by the use of inverter circuits that turn direct into alternating current. In most inverter circuits, the transformer is the heaviest component and usually accounts for a significant fraction of the power loss. Therefore, careful attention to transformer design can have an important effect on system weight and efficiency, but, because transformer calculations tend to be tedious and time consuming, a detailed analysis of the effects of various parameters can be a formidable task.

To meet this challenge, computer technology was first applied to transformer design by Williams, Abetti, and Magnusson (ref. 1) in 1953. Numerous authors have treated the subject since then; much of this work being summarized in a monograph by Kusko and Wroblewski (ref. 2) in 1969. A computer program for design of toroidal transformers with tape wound cores was written by Hopper (ref. 3) in 1969. However, this earlier work simply determines the core and wire sizes and the number of turns per winding; it does not take skin depth or core weight and reluctance into account, nor does it compute transformer weight, efficiency, operating temperature, and regulation.

The program developed in this report includes these effects and performs the computations required in the transformer design. However, the number of specifications that must be supplied by the user allows for considerable flexibility and for the exercise of engineering judgement. Furthermore, the speed of the program makes it possible to run a great many cases, economically determining the effect of various parameter changes.

The transformers considered here have a center tapped primary coil surrounded by a single secondary coil on a tape wound toroidal core, as shown in figure 1. The program contains the specifications of 90 toroid sizes, equally divided into two groups, and 48 round wire sizes. The user determines the magnetic core and wire materials to be used. The rationale behind the division of the magnetic core library into heavy or low-gain cores and light or high-gain cores is discussed in detail in appendix A. The power

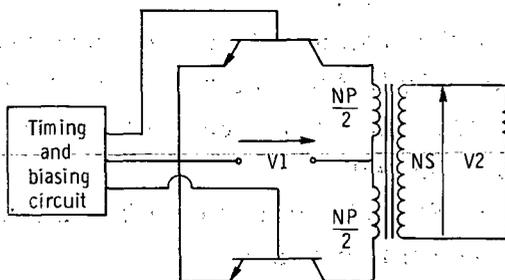


Figure 1. - Circuit diagram of basic parallel inverter.

ratings of transformers that can be designed by this program depend on the materials used and the frequency of operation but in general extend from a few volt-amperes to the low kilovolt-ampere range. To design systems for power levels higher than a few kilovolt-amperes, either data on larger cores may be placed in the program library or the system may be made up of several modules.

Taking into consideration such parameters as the desired current density, desired fill factor, the ohmic power consumption, skin depth, and ambient temperature, the program produces a statement of the physical description of the transformer and computes its weight, efficiency, regulation, and operating temperature.

The model used for the estimation of operating temperature is that of a transformer suspended in a vacuum from leads that cannot conduct heat. The only mechanism of heat loss is radiation from the entire outer surface to a sink at a constant ambient temperature.

Two numerical examples, a 2.0 and a 4.0 kilovolt-ampere transformer, are contained in this report. A detailed analysis is made of the variation in mass, efficiency, and operating temperature functions of the frequency, current density, fill factor, and materials. An estimate of the performance of inverters using these transformers is illustrated by including the effect of frequency on the efficiency of typical transistors for this power level.

## SYMBOLS

A	program indicator, if $A = 0$ the metal used in the transformer coil is copper, if another metal is used $A = 1.0$
AC	cross sectional core area, $\text{cm}^2$
AD	inside diameter of toroid after primary winding is applied, in.
AWT	wire cross sectional area including insulation, cir. mils
BD	inside diameter of toroid after secondary winding is applied, in.
BMAX	specified magnetic flux density, G
BUSED	actual magnetic flux density, G
CMPA	inverse current density, (cir. mils/A)
CORWAT	mass of magnetic core, kg
CU	symbol indicating to program when copper wire is to be used; $CU = 1.0$ if copper is used, if another metal is used $CU = 0$
CUREX	excitation current, A

CUR1	current delivered to transformer by source, A
CUR2	current delivered by transformer to load, A
DENSITY	density of core material, (lb/in. <sup>3</sup> )
DITC	inside diameter of core box, (in.)
e <sub>1</sub>	instantaneous voltage supplied by source, V
EFISH	transformer efficiency
F	frequency, Hz
FF	desired fill factor
FHTT	height of wound toroid, cm
FIL1	fraction of core window area filled by primary winding
FIL2	fraction of core window area filled by secondary winding
FILF	fraction of core window area filled by both windings
FOD	outer diameter of transformer, cm
HTT	height of core box, in.
I <sub>B</sub>	transistor base drive current, A
I <sub>CR</sub>	reverse collector current, A
I <sub>SAT</sub>	transistor saturation current, A
NP	number of turns in primary winding
NS	number of turns in secondary winding
ODT	outside diameter of core box, in.
OPM	ohms per 1000 ft at 20° C
PCUMAX	maximum ohmic losses allowed in the secondary or one half of the primary winding, W
PCU1	ohmic losses in primary winding, W
PCU2	ohmic losses in secondary winding, W
PLOSS	total transformer losses, W
R'	relative reluctance of core, cm <sup>-1</sup>
R1	primary resistance, ohm
R2	secondary resistance, ohm
RDENS	density of substitute coil material relative to copper

REGUL	final transformer regulation
RRES	resistance of substitute coil material relative to copper
SKND	skin depth, m
SURFT	total surface area of transformer, $\text{cm}^2$
T	transformer operating temperature, $^{\circ}\text{C}$
TAMB	ambient temperature, $^{\circ}\text{C}$
TAPEV	voltage rating of insulating tape in volts/mil
TEMCOR	temperature coefficient of resistance for substitute material, $^{\circ}\text{C}^{-1}$
$t_f$	transistor switching fall time, sec
$t_r$	transistor switching rise time, sec
V1	primary voltage, V
V2	desired secondary voltage, V
V2FL	full load output voltage delivered, V
V2O	no load output voltage, V
$V_{BE}$	transistor base-emitter voltage, V
$V_{SAT}$	transistor saturation voltage, V
VAPP	specific exciting apparent power, (VA/lb)
WA	core box window area, cir. mils
WAC	core window area, cross sectional area product, $\text{cm}^2$ -cir. mils
WACO	minimum core window area, cross sectional area product, $\text{cm}^2 \times$ cir. mils
WATPP	specific core loss, watts/lb
WRAP1	number of parallel primary conductors
WRAP2	number of parallel secondary conductors
XLONG1	length of primary winding, in.
XLONG2	length of secondary winding, in.
$\epsilon$	thermal emissivity, dimensionless
$\mu$	permeability, henrys/m
$\varphi$	magnetic flux, We
$\sigma$	electrical conductivity, ohm/m

## PREPARATION OF THE DATA

The user must first decide which set of magnetic core data to use. The two sets, labeled "heavy" and "light," produce transformers of somewhat different characteristics and are discussed in more detail in appendix A.

Next, a set of data cards specifying the transformers to be designed must be prepared. These cards are read into the machine on a Namelist format with a class name of "IN." To design a transformer, the computer must be given values for V1, V2, CUR1, F, FF, PCUMAX, BMAX, DENSITY, TAPEV, WATPP, VAPP, TAMB, CU, A, RRES, and CMPA. If a metal other than copper is used in the windings the resistivity relative to copper at 20<sup>0</sup> C, RRES, must be computed and placed in the input statement along with the temperature coefficient of resistivity at 20<sup>0</sup> C, TEMCOR, and the density relative to copper, RDENS. If copper is used RRES must be specified as 1.0.

The first word of the data statement for each transformer is \$IN which is begun in column two. After this the rest of the data are written in the form V1 = 32.0, V2 = 2000.0, etc. The data need not be in the same order as in the Namelist declaration, and data that are unchanged from the previous data statement need not be repeated. The statement is ended by typing \$ after the last data specification. A detailed explanation of the Namelist declaration is presented by Organick (ref. 4).

The program, including core and wire libraries and a sample data input, is included in appendix B.

## DESCRIPTION OF THE PROGRAM

The first step in the computation is to determine the number of parallel conductors WRAP1 and the wire size that will be required to make up the primary coil. The specified inverse current density CMPA is used to determine the wire size and WRAP1 on the first iteration, but, if ohmic losses exceed PCUMAX, current density is reduced and the computation repeated. Since only half of the primary winding is used at one time, CMPA is halved in making this computation.

Next, the wire diameter is compared with the skin depth SKND at the specified frequency. Skin depth is computed for the winding material at 20<sup>0</sup> C using the relation

$$SKND = (\pi \sigma F \mu)^{-1/2} \quad (1)$$

The wire diameter is held to no more than 1.5 skin depths so that current density in the wire is approximately uniform at the operating frequency (ref. 5). When a smaller diameter wire size must be chosen to compensate for skin depth, the number of parallel

conductors in the coil is appropriately increased. No provision is made to correct skin depth for temperature rises that occur during transformer operation.

If the DC source feeding the inverter is considered a perfect voltage generator and the inverter transistors can be taken as perfect switches, the primary voltage  $V_1$  is alternately applied to each half of the primary winding for one half of a cycle. Thus the primary winding may be represented as a single winding of one half the number of turns and driven by a perfect square wave generator  $e_1$ . The voltage relation at the primary terminals is then

$$e_1 = \frac{NP}{2} \frac{d\phi}{dt} \quad (2)$$

During a half cycle of operation this equation may be written

$$V_1 = 2NP \times B_{MAX} \times F \times AC \times 10^{-8} \quad (3)$$

where  $AC$  is the effective core cross sectional area, and  $B_{MAX}$  is the maximum magnetic flux density in the core.

The user must specify the approximate fraction  $FF$  of the window area of the core that will be filled with the windings. Since the primary and secondary windings will take up about the same cross section, a second equation involving  $NP$  may be written:

$$NP \times AWT \times WRAP_1 = \frac{WA \times FF}{2} \quad (4)$$

where  $AWT$ , the total wire cross section area, and  $WA$ , the window area, must be in the same units.

Combining equations (3) and (4) results in an expression for the window-area, core-area product:

$$WA \times AC = WACO = \frac{V_1 \times AWT \times WRAP_1 \times 10^8}{F \times B_{MAX} \times FF} \quad (5)$$

The computer then sorts through the cores in its library, which are arranged in order of increasing  $WAC$ , and selects for use in the transformer the first core having a  $WA-AC$  product ( $WAC$ ) greater than  $WACO$ . In each library only one core is listed at any value of  $WAC$ , so that the choice is unambiguous.

The number of primary turns are then computed using equation (3) and appropriately rounded off so that  $NP$  is an even whole number. This value of  $NP$  is then substi-

tuted into equation (3) to obtain BUSED, the actual magnetic flux density. BUSED will be approximately equal to BMAX unless NP is very small, say, 2 or 4. The data on specific apparent power and core loss are subsequently multiplied by the ratio BUSED/BMAX to approximate linearly the variation in B.

Using NP the fraction of the core window area filled by the primary winding FIL1 is computed:

$$FIL1 = \frac{NP \times WRAP1 \times AWT}{WA} \quad (6)$$

When a load of unity power factor is assumed and leakage inductance is neglected, the number of turns needed in the secondary NS may be computed. First, the resistance R1 is computed from the known diameter and composition of the wire, the ambient temperature, and the length of the winding XLONG1, which is estimated as

$$XLONG1 = NP \left[ 2HTT + ODT + DITC \left( 1 - 2\sqrt{1 - FIL1} \right) \right] \quad (7)$$

$$R1 = \frac{OPM \times XLONG1 (CU + A \times RRES) [1.0 + (CU \times 0.00393 + A \times TEMCOR)] (TAMB - 20.0)}{24000.0 \times WRAP1} \quad (8)$$

After computing the primary resistance, FIL1 is increased to allow for insulating tape between the primary and secondary windings and then checked to be no greater than  $0.64 \times FF$ , otherwise the core having the next larger WAC is chosen.

After determining that the primary coil dissipation does not exceed twice PCUMAX, the number of turns needed in the secondary is computed,

$$NS = \frac{NP \times V2}{2(V1 - 2CURI \times R1)} \quad (9)$$

and rounded off to the next largest whole number.

The mass of the core CORWAT is computed, and the excitation current CUREX is found:

$$CUREX = \frac{VAPP \times CORWAT \times BUSED}{(VI \times BMAX)} \quad (10)$$

No provision is made for variations in CUREX or PIRON due to changes in core temperature. As it will be shown later, this simplification is a good one for most of

the cores treated in this report.

The secondary current CUR2 is computed for a load of unity power factor, neglecting leakage inductance and the phase lag between CUR1 and CUREX.

$$\text{CUR2} = \frac{\text{NP} \times (\text{CUR1} - \text{CUREX})}{2\text{NS}} \quad (11)$$

The process of choosing a wire size and the number of parallel conductors is then repeated for the secondary coil. The fill factor FIL2 is computed and allowance made for insulating tape between layers. The next larger core is chosen if the sum of FIL1 and FIL2 is greater than 1.28 times FF.

The length of wire in the secondary coil XLONG2 is calculated using the formula

$$\text{XLONG2} = \text{NS} \times [2\text{HTT} + \text{ODT} + 3\text{DITC} - 2(\text{AD} + \text{BD})] \quad (12)$$

where

$$\text{AD} = \text{DITC} \sqrt{1 - \text{FIL1}} \quad (13)$$

and

$$\text{BD} = \text{DITC} \sqrt{1 - \text{FIL1} - \text{FIL2}} \quad (14)$$

The resistance R2 at ambient temperature and secondary power dissipation PCU2 are then computed.

The outside surface area SURFT of the wound toroid is calculated as if it were a smooth surface:

$$\text{SURFT} = 6.45\pi \left[ (\text{ODT} + \text{DITC} - \text{BD})(\text{HTT} + \text{DITC} - \text{BD}) + \frac{1}{2} (\text{ODT} + \text{DITC} - \text{BD})^2 - \frac{\text{BD}^2}{2} \right] \quad (15)$$

Since the transformer would be operating in the vacuum of space, only radiation is considered as a mechanism for heat transfer. The temperature of operation T is, therefore, estimated by the equation

$$T = \left[ \frac{\text{PCU1} + \text{PCU2} + \text{PIRON}}{5.67 \times 10^{-8} \epsilon \text{SURFT}} + (\text{TAMB} + 273)^4 \right]^{1/4} - 273 \quad (16)$$

where the relative emissivity  $\epsilon$  is taken to be 0.95 for most transformer materials (ref. 6).

The temperature calculated from equation (16) must be recognized as an estimate only. The assumption is made that the entire outside surface of the toroid, that is, all but the inside surface of the hole, is free to radiate to a sink of constant temperature TAMB. What fraction of the surface is actually free to radiate depends on the placement of the transformer in the vehicle, and the temperature will rise if the effective radiating surface or emissivity is reduced. Furthermore, this estimate of temperature does not consider temperature gradients within the transformer; this effect will be examined later. On the other hand, equation (16) implies that no provision is made for cooling the transformer by conduction. If the temperature so calculated is considered excessive for the materials being used, then some allowance must be made for cooling the transformer; in this sense equation (16) estimates an upper limit of operating temperature.

Using the estimated operating temperature from equation (16), the program then recomputes all of the resistances and power dissipations and temperature until on successive iterations the total power loss in the transformer has changed by less than 1 percent, which corresponds to a temperature change of less than 0.25 percent.

Having completed the temperature iteration, it is necessary to determine if the desired full-load output voltage V2 will be delivered. For this purpose the full-load output voltage must be estimated using the expression,

$$V2FL = \frac{2NS(V1 - CUR1 \times R1)}{NP} - CUR2 \times R2 \quad (17)$$

If V2FL is less than V2, a new value of NS is computed as

$$NS = \frac{(V2 + CUR2 \times R2)NP}{2(V1 - CUR1 \times R1)} \quad (18)$$

The program then corrects CUR2, using the new NS, and recomputes the temperature and secondary voltage until a transformer design with V2FL greater than V2 is achieved.

At this point the program has finished in its design calculations and sets about computing those quantities specified for the output statement. The weight of the windings are calculated using the length, mass per unit length, and number of parallel windings for each coil. The mass of the insulation on the wire is neglected. Efficiency is taken as

$$EFISH = 100 \left[ 1 - \frac{PLOSS}{V1 \times CUR1} \right] \quad (19)$$

The final fill factor FILF is simply

$$\text{FILF} = \text{FIL1} + \text{FIL2} \quad (20)$$

The regulation REGUL of the transformer is defined as the percent voltage drop from no load to full load of unity power factor, neglecting leakage inductance and the phase lag of excitation current:

$$\text{REGUL} = 100 \frac{(\text{V20} - \text{V2FL})}{\text{V2FL}} \% \quad (21)$$

where V20, the no-load output voltage is given by

$$\text{V20} = 2\text{NS} \frac{(\text{V1} - \text{CUREX} \times \text{R1})}{\text{NP}} \quad (22)$$

The outer diameter FOD and the height FHTT of the wound toroid are calculated:

$$\text{FOD} = 2.54(\text{ODT} + \text{DITC} - \text{BD}) \quad (23)$$

$$\text{FHTT} = 2.54(\text{HTT} + \text{DITC} - \text{BD}) \quad (24)$$

For this application it was of interest to vary some of the input quantities over a wide range to determine the changes of some transformer parameters. To assist in this work, a computer program was written to plot curves of some of these results. Owing to individual differences in curve plotting equipment, this part of the program was considered to be of less general interest and is not discussed here, but may be obtained from the author.

## TRANSFORMER DESIGN

The computer program was applied to the design of transformers for inverters of 2.0 (125 A, 16 V/2000 V) and 4.0 kilovolt-amperes (125 A, 32 V/2000 V) capacity. A presentation of the results of this design will serve to illustrate the use of the program.

When the ohmic power consumption restriction is removed by making PCUMAX a large fraction of the output power, the transformer design will be determined primarily by the materials used, the frequency, and the inverse current density in the windings, which permits an examination of the effect of these parameters on the transformer oper-

TABLE I. - EFFECT OF CURRENT

[2 kVA (16/2000 V); frequency, 800 Hz; ambient

Type of core	Inverse current density, CMPA	Primary coil characteristics								Secondary coil			
		Current delivered by transformer to load, CUR2, A	Excitation current, CUREX, A	Number of turns, NP	Wire gauge, IAWG1	Number of parallel windings, WRAP1	Resistance, R1, mΩ	Ohmic losses, PCU1, W	Mass of primary coil, CUWAT1, kg	Number of turns, NS	Wire gauge, IAWG2	Number of parallel windings, WRAP2	
Heavy	3125	0.948	6.16	10	8	12	0.228	3.6	1.352	627	15	1	
	2500	.946	6.16	10	↓	10	.272	4.2	1.099	628	16	↓	
	2000	.946	6.16	10	↓	8	.338	5.3	.858	628	17	↓	
	1600	.947	5.90	8	↓	6	.416	6.5	.575	503	18	↓	
	1270	.956	4.52	10	↓	5	.537	8.4	.526	630	19	↓	
	1000	.955	4.52	10	8	4	.673	10.5	.413	631	20	1	
	800	.965	2.70	16	8	3	1.09	17.1	.381	1014	21	↓	
	640	.961	2.64	14	9	3	1.47	22.9	.307	891	22	↓	
	512	.959	2.44	16	8	2	1.71	26.7	.247	1022	23	↓	
	410	.931	1.17	42	9	2	4.58	71.6	.384	2794	24	↓	
	328	.942	1.64	20	10	2	3.59	56.1	.181	1309	25	↓	
	Light	3125	0.954	5.30	12	8	12	0.260	4.1	1.578	753	15	1
		2500	.954	5.30	12	↓	10	.309	4.8	1.278	753	16	↓
		2000	.962	4.11	14	↓	8	.425	6.6	1.136	880	17	↓
		1600	.959	4.28	12	↓	6	.509	7.9	.741	755	18	↓
1270		.967	2.88	20	↓	5	.773	12.1	.800	1263	19	↓	
1000		.965	2.88	20	8	4	.962	15.0	.618	1266	20	1	
800		.964	2.46	↓	8	3	1.30	20.3	.454	1271	21	↓	
640		.963	2.05	↓	9	3	1.68	26.2	.355	1277	22	↓	
512		.958	2.05	↓	8	2	2.04	31.8	.292	1283	23	↓	
410		.890	.770	72	9	2	7.51	117.3	.600	5026	24	↓	
328		.892	.875	54	10	2	7.63	119.3	.361	3759	25	↓	

DENSITY ON TRANSFORMER DESIGN

temperature, 127° C; copper windings; Supermendur core.]

characteristics			Core characteristics			Overall transformer characteristics							
Resistance, R2, Ω	Ohmic losses, PCU2, W	Mass of secondary coil, CUWAT2, kg	Serial number, ICORNO	Mass of core iron, CORWAT, kg	Core loss, W	Final regulation, REGUL, percent	Total losses, PLOSS, W	Efficiency, EFISH, percent	Total weight, TOTWAT, kgm	Final fill factor, FILF	Temperature, T, °C	Full-load output voltage delivered, V2FL, V	Actual magnetic-flux density, T
2.30	2.1	1.847	237	1.773	86.3	0.278	91.9	95.41	4.973	0.563	210.9	2000.7	1.62
2.75	2.5	1.359	237	1.773	86.3	.333	93.0	95.35	4.231	.460	219.7	2002.7	1.62
3.29	2.9	1.009	237	1.773	86.3	.408	94.5	95.28	3.640	.368	228.6	2001.2	1.62
3.71	3.3	.689	235	1.510	82.7	.486	92.5	95.38	2.774	.426	243.8	2002.0	1.82
5.21	4.8	.622	234	1.300	63.3	.656	76.4	96.18	2.449	.513	234.0	2002.6	1.62
6.34	5.8	.469	234	1.300	63.3	.814	79.6	96.02	2.182	.412	244.6	2002.5	1.62
10.8	10.0	.503	232	.690	37.7	1.37	64.8	96.76	1.574	.513	239.8	2000.3	1.82
13.6	12.5	.378	231	.709	37.0	1.80	72.5	96.38	1.394	.477	262.2	2000.2	1.73
17.0	15.6	.295	230	.624	34.1	2.15	76.5	96.18	1.166	.449	273.2	2000.4	1.82
56.5	48.9	.562	228	.315	16.4	6.40	136.9	93.15	1.261	.475	316.2	2000.0	1.74
37.0	32.9	.222	227	.420	23.0	4.64	111.9	94.40	.823	.505	341.6	2000.8	1.82
2.71	2.5	2.230	138	1.527	74.3	0.324	80.8	95.96	5.335	0.570	200.6	2001.3	1.62
3.22	2.9	1.624	138	1.527	74.3	.386	82.0	95.90	4.429	.466	209.7	2000.0	1.62
4.56	4.2	1.468	137	1.103	57.5	.542	68.4	96.58	3.708	.516	205.7	2000.4	1.74
4.92	4.5	.963	136	1.231	59.9	.622	72.4	96.38	2.936	.508	219.0	2000.6	1.62
8.56	8.0	1.078	135	.736	40.3	1.01	60.3	96.98	2.613	.468	209.5	2000.3	1.82
10.1	9.4	.786	135	.736	40.3	1.23	64.7	96.76	2.139	.376	222.9	2000.6	1.82
13.0	12.1	.613	134	.630	34.5	1.64	66.9	96.66	1.698	.433	237.1	2000.4	1.82
16.9	15.7	.477	133	.525	28.8	2.13	70.6	96.47	1.357	.514	256.1	2000.1	1.82
20.8	19.1	.359	133	.525	28.8	2.60	79.7	96.02	1.177	.424	277.0	2000.2	1.82
114.1	90.3	1.083	131	.199	10.8	11.6	218.4	89.08	1.882	.550	342.8	2001.3	1.80
104.5	83.1	.588	130	.227	12.2	11.2	214.6	89.27	1.176	.516	379.5	2001.6	1.80

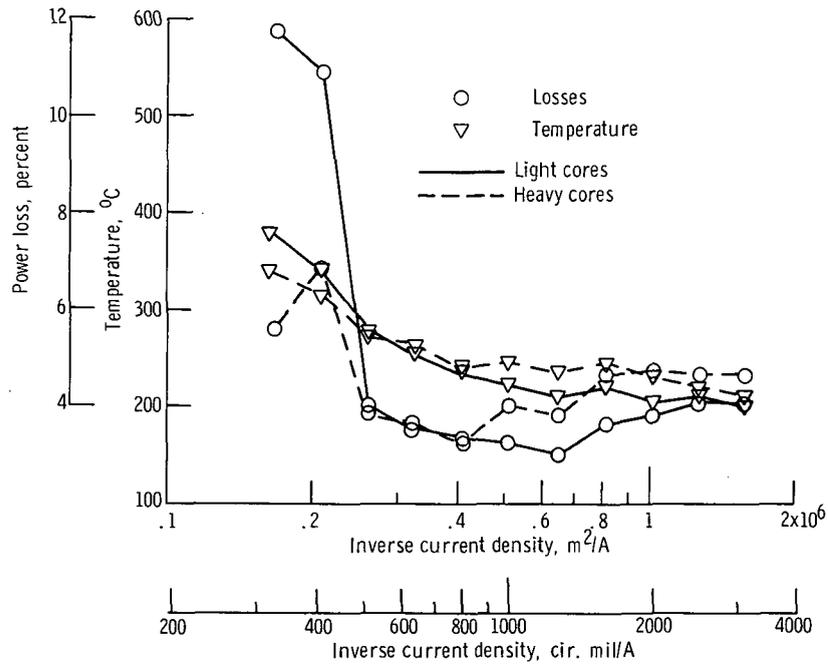


Figure 2. - Variation of power loss and temperature with changes in current density. Copper coils, Supermendur core; frequency, 800 hertz, volt-ampere, 2 kilovolt-amperes (16/2000 V); ambient temperature, 127° C; fill factor, 0.5.

ating conditions. A typical variation of power loss and temperature in a 2.0-kilovolt-ampere transformer at 800 hertz and at an ambient temperature of 127° C with variations in the inverse current density is presented in figure 2. Data on specific core loss in this computation were obtained from Frost, McVay, and Pavlovic (ref. 7) for a 2-mil Supermendur (ref. 8) tape at 250° C and 1.8 tesla, excited by a square wave of current. The effect of adding insulating tape is not included. Much greater detail of the transformer designs in the center portion of figure 2 is presented in table I. At low current densities (high CMPA), where ohmic losses are less important, the transformers wound on the heavy cores have greater losses and run hotter than those on light cores. However, as current density increases, the copper losses increase rapidly in the higher-resistance coils needed to drive the higher-reluctance, light magnetic cores causing them to operate at a higher temperature and lower efficiency.

It should be particularly noted in figure 2 that the transformer designs reach broad minima in losses, indicating that by varying the current density in the windings a most efficient design can be found for given frequency, power input, materials, and heavy or light core. At a given frequency the highest efficiency design is generally not achieved at the same current density for light and heavy cores. A comparison of the weight, power loss, and operating temperature of the most efficient 2-kilovolt-ampere transformers wound on light and heavy cores is given in figure 3 as a function of frequency. The light-core transformers are more efficient in all but one case and operate at lower

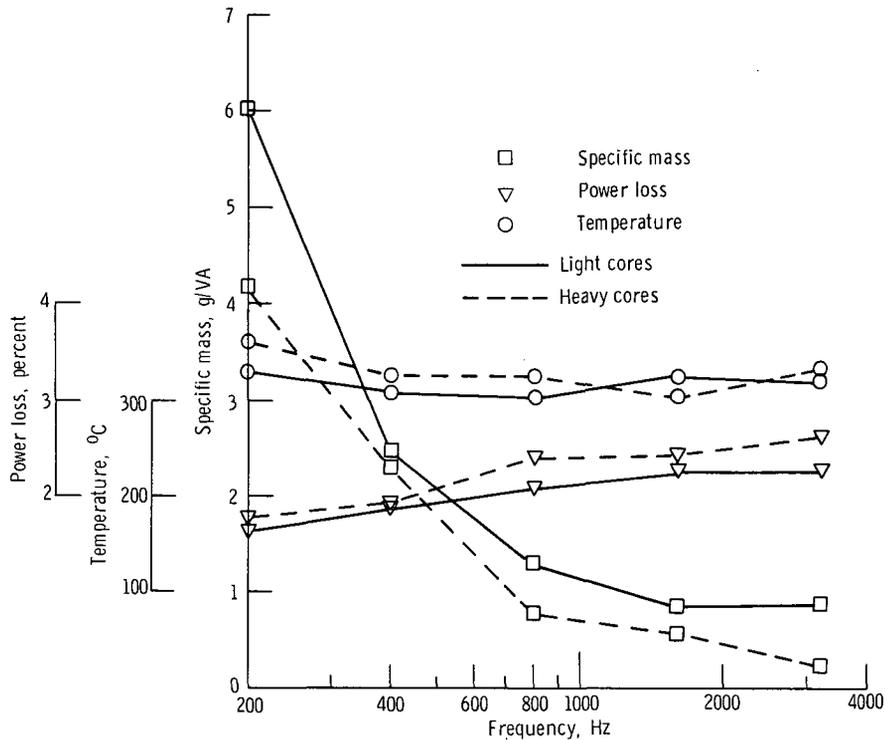


Figure 3. - Properties of the most efficient transformer designs. Copper coils; Supermendur core; volt-ampere, 2 kilovolt-amperes (16/2000 V); ambient temperature, 127° C; fill factor, 0.5.

temperatures than do the low-gain core transformers, but they weigh more than 50 per cent as much at some frequencies. In the one case at 1600 hertz where the heavy core transformer is more efficient, core 228, chosen by the program, is one that is on the borderline between heavy and light cores, having a diameter ratio of 0.714. The interrelation of efficiency, weight, and temperature as a function of frequency is evident in figure 3. The total power loss for these most efficient designs varies relatively little, but temperature rises and weight falls for increasing frequency. Efficiency varies between 96.71 and 96.98 percent for the highest efficiency transformers.

For transformers wound on heavy and light cores with aluminum wire, the light cores produce transformers somewhat more efficient and heavier than the heavy core. However, the differential in weight is not as great as when copper wire is used.

The most efficient transformer is not necessarily the optimum design for every application as illustrated in figure 4 where the most efficient transformers are compared with the "next best," usually a transformer one or more steps lower in inverse current density and sometimes wound on a heavy, rather than a light core. At a penalty of a few tenths of a percent in efficiency, a reduction of 50 percent or more in weight can be achieved by using the next best, an important consideration in space and aeronautical applications. Table II contains a detailed description of the most efficient and next best

TABLE II. - COPPER-WOUND

Transformer, kVA	Rating	Fre- quency, Hz	Inverse current density, CMPA  (c)	Primary coil characteristics								Secondary coil		
				Current delivered by trans- former to load, CUR2, A	Excita- tion current, CUREX, A	Number of turns, NP	Wire gauge, IAWG1	Number of parallel windings, WRAP1	Resist- ance, R1, mΩ	Ohmic losses, PCU1, W	Mass of primary coil, CUWAT1, kg	Number of turns, NS	Wire gauge, IAWG2	Number of parallel windings, WRAP2
2 <sup>a</sup>	Most efficient	200	<sup>d</sup> 2500L	0.963	3.23	28	3	3	0.838	13.1	3.519	1771	16	1 ↓
		400	1600L	.965	2.85	22	5	3	.909	14.2	1.427	1392	18	
		800	1270L	.967	2.88	20	8	5	.773	12.1	.800	1263	19	
		1600	800H	.965	2.73	20	11	6	.985	15.4	.339	1267	21	
		3200	1600L	.964	3.80	18	14	25	.385	6.0	.592	1132	18	
	Next best	200	1270H	0.957	3.29	20	4	2	1.282	20.0	1.409	1272	19	1 ↓
		400	1000L	.962	2.02	28	5	2	1.701	26.6	1.137	1790	20	
		800	800H	.965	2.70	16	8	3	1.094	17.1	.381	1014	21	
		1600	512H	.963	2.44	14	11	4	1.354	21.2	.188	891	23	
		3200	512H	.964	2.89	14	14	8	1.014	15.8	.134	887	23	
4 <sup>b</sup>	Most efficient	200	<sup>d</sup> 2000H	1.93	2.79	34	2	2	1.54	24.0	4.387	1074	14	1 ↓
		400	1600L	1.94	2.20	34	5	3	1.76	27.5	2.704	1075	15	
		800	1000L	1.94	2.05	28	8	4	1.81	28.3	1.136	886	17	
		1600	1270L	1.94	3.18	20	11	10	.850	13.3	.799	629	16	
		3200	640L	1.94	2.08	28	14	10	1.75	27.4	.375	886	19	
	Next best	200	1270H	1.93	1.96	42	4	2	2.89	45.1	3.129	1338	16	1 ↓
		400	1000H	1.94	2.09	32	5	2	2.33	36.4	1.515	1016	17	
		800	800L	1.94	2.33	22	8	3	2.01	31.4	.673	697	18	
		1600	512L	1.94	2.27	20	11	4	2.20	34.4	.292	634	20	
		3200	512H	1.93	2.89	14	14	8	1.53	23.9	.186	442	20	

<sup>a</sup>16/2000 V.

<sup>b</sup>32/2000 V.

<sup>c</sup>L and H denote light and heavy cores, respectively.

<sup>d</sup>Not a maximum of efficiency.

TRANSFORMERS

characteristics			Core characteristics			Overall transformer characteristics							
Resistance, R2, Ω	Ohmic losses, PCU2, W	Mass of secondary coil, CUWAT2, kg	Serial number, ICORNO	Mass of core iron, CORWAT, kg	Core loss, W	Final regulation, REGUL, percent	Total losses, PLOSS, W	Efficiency, EFISH, percent	Total weight, TOTWAT, kg	Final fill factor, FILF	Temperature, T, °C	Full-load output voltage delivered, V2FL, V	Actual magnetic-flux density, T
9.05	8.4	5.07	145	3.468	44.3	1.08	65.7	96.71	12.058	0.535	165.5	2002.0	1.74
9.44	8.8	1.982	138	1.527	38.7	1.16	61.7	96.92	4.94	.530	188.6	2001.2	1.77
8.56	8.0	1.078	135	.736	40.3	1.01	60.3	96.98	2.613	.468	209.5	2000.3	1.82
10.5	9.8	.487	228	.315	35.2	1.27	60.4	96.98	1.14	.421	243.0	2001.5	1.82
4.94	4.6	.949	131	.199	53.3	.53	63.9	96.81	1.74	.506	228.0	2001.6	1.80
12.76	11.7	1.672	241	3.362	45.1	1.60	76.8	96.16	6.444	0.468	192.2	2002.6	1.82
18.69	17.3	1.498	137	1.103	27.5	2.24	71.3	96.43	3.74	.527	207.3	2000.6	1.74
10.76	10.0	.503	232	.690	37.7	1.37	64.8	96.76	1.574	.513	239.8	2000.3	1.82
13.95	12.9	.234	224	.296	31.4	1.73	65.5	96.72	.718	.548	290.8	2001.6	1.74
10.94	10.2	.176	219	.158	40.6	1.31	66.6	96.67	.468	.468	313.6	2000.8	1.74
4.12	15.4	5.625	245	6.042	76.2	0.99	115.6	97.11	16.064	0.525	181.3	2001.5	1.72
4.53	17.1	3.752	143	2.430	59.8	1.12	104.3	97.39	8.885	.520	197.7	2000.8	1.72
4.89	18.5	1.480	137	1.103	57.5	1.18	104.3	97.39	3.719	.518	234.8	2001.3	1.74
2.32	8.7	1.073	135	.736	82.2	.55	104.1	97.40	2.607	.463	250.9	2001.6	1.82
5.25	19.8	.554	130	.227	58.3	1.19	105.5	97.36	1.156	.497	295.7	2001.0	1.74
7.78	29.0	4.028	243	4.20	53.6	1.88	127.8	96.81	11.360	0.528	198.5	2000.8	1.74
6.15	23.0	1.919	239	2.276	56.6	1.50	116.1	97.10	5.709	.497	220.0	2001.6	1.74
4.81	18.0	.865	136	1.231	65.3	1.24	114.8	97.13	2.769	.468	259.2	2002.4	1.77
5.50	20.6	.354	133	.525	58.7	1.39	113.7	97.16	1.171	.416	316.5	2000.7	1.82
3.80	14.2	.225	225	.315	81.1	.96	119.3	97.02	.727	.458	363.0	2001.1	1.74

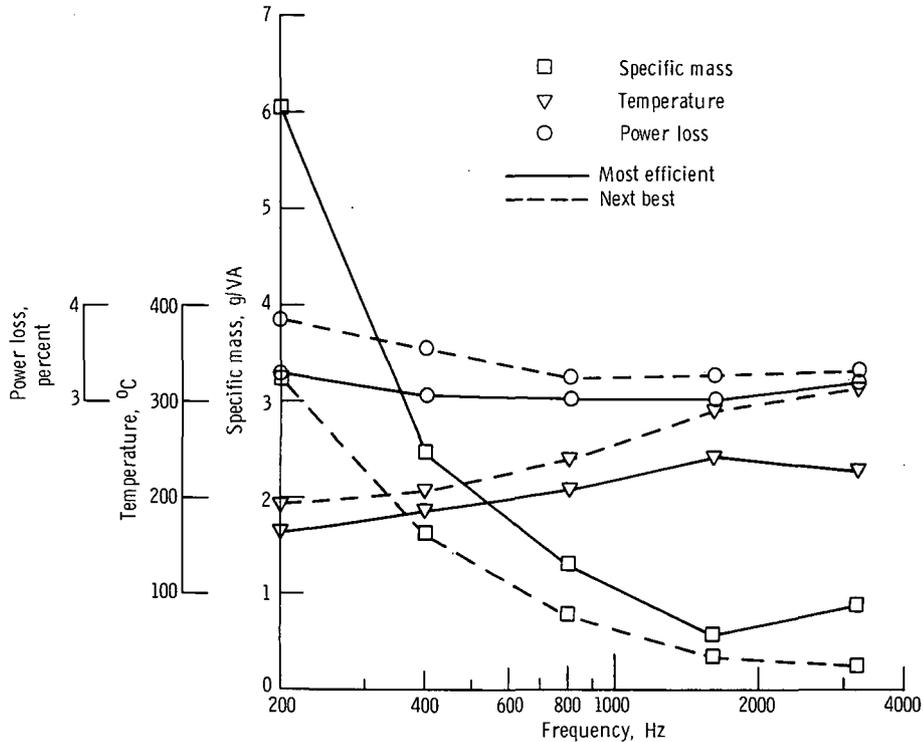


Figure 4. - Comparison of most efficient with next best copper-wound 2-kilovolt-ampere (16/2000 V) transformer designs. Supermendur core; ambient temperature, 127° C; fill factor, 0.5.

designs at 2 and 4 kilovolt-amperes for transformers wound with copper wire.

In general, a greater reduction in weight, but at the penalty of a correspondingly greater reduction in efficiency, can be achieved by winding the transformer with aluminum rather than copper wire. Figure 5 compares the most efficient copper wound designs with the most efficient aluminum wound transformers. A reduction in efficiency of about a half percent and a reduction in weight of 50 percent result from the substitution of aluminum, but operating temperature is virtually the same.

Similar comparisons of most efficient to next best and of most efficient copper to most efficient aluminum are made for a 4-kilovolt-ampere system in figures 6 and 7, respectively.

There is no provision in the program for the correction of core loss and excitation current due to changes in the core temperature. The data used in this computation indicate negligible changes for the temperature range from 25° to 250° C, which covers 75 percent of the cases in table II.

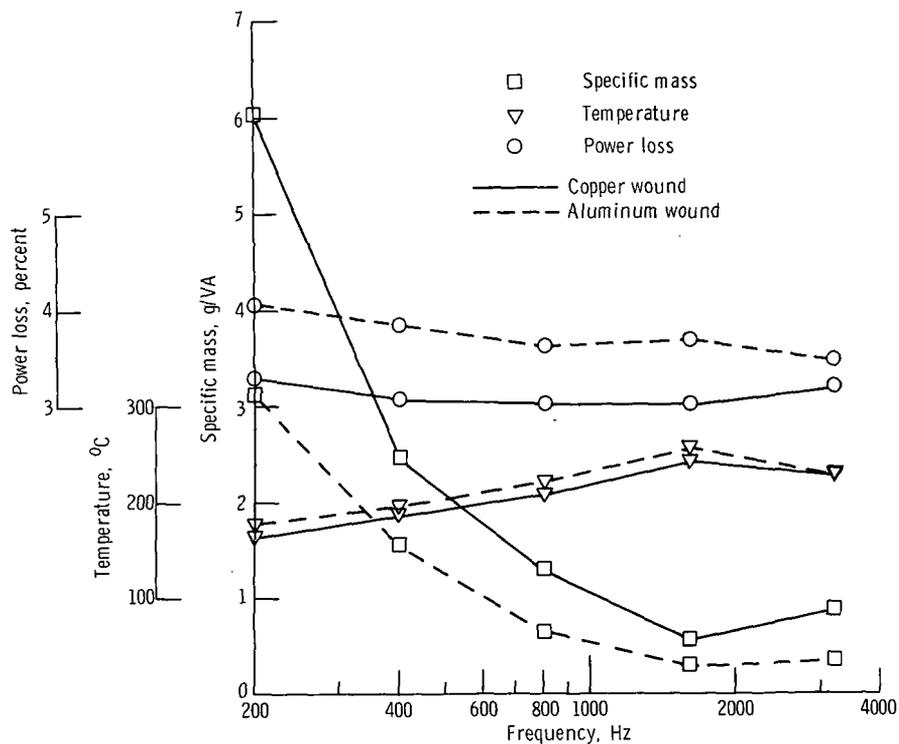


Figure 5. - Comparison of most efficient copper- and aluminum-wound 2-kilovolt-ampere (16/2000 V) transformers. Supermendur cores; ambient temperature, 127° C; fill factor, 0.5.

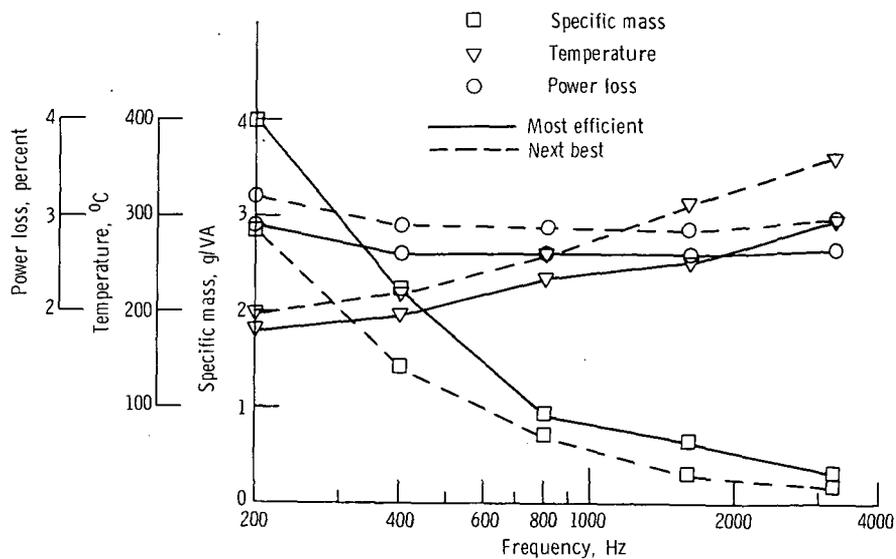


Figure 6. - Comparison of most efficient with next best copper-wound, 4-kilovolt-ampere (32/2000 V) transformer designs. Supermendur core; ambient temperature, 127° C; fill factor, 0.5.

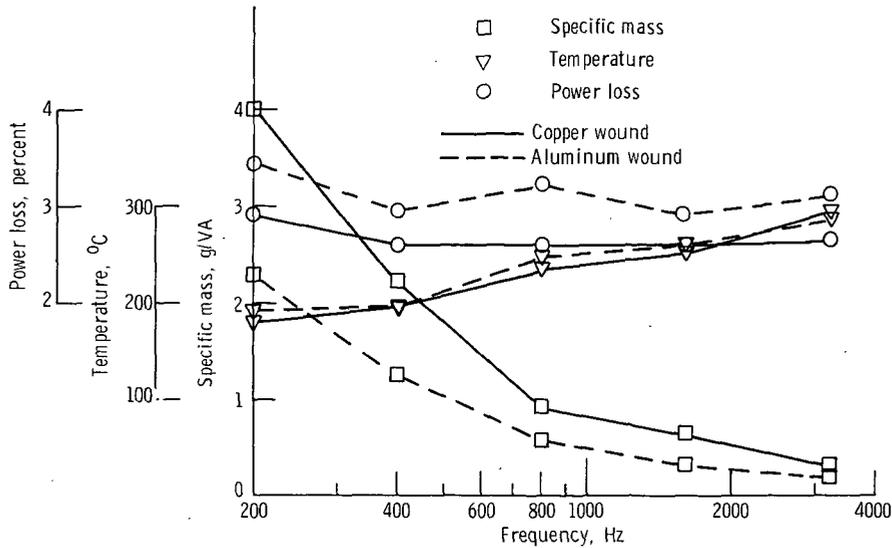


Figure 7. - Comparison of most efficient copper- and aluminum-wound 4-kilovolt-ampere (32/2000 V) transformers. Supermendcor core; ambient temperature, 127° C; fill factor, 0.5.

An estimate of the increase in core losses for temperatures in excess of 250° C may be made from the data published by Keuser et al (ref. 9). For 363° C, the highest temperature design in table II, the core losses may be underestimated by approximately 25 percent. At the other high temperatures the estimated core loss errors are 316° and 313° C, 12 percent; and 295° and 290° C, 6 percent.

An estimate of the temperature change across the transformer windings may be made by assuming a parallel plane model. For the highest temperature case in table II the temperature change between the surface of the transformer and the surface of the core would be less than 7° C. Temperature variations within the core may be calculated using an expression derived by Carslaw and Jaeger (ref. 10). For the same case the hottest point within the core is 3° C above the core surface temperature. Therefore, the hottest point in the core would be approximately 10° C above the surface temperature, an increase in the rise above ambient only 4 percent greater than at the surface.

The variation in the properties of the most efficient designs for a change in nominal fill factor from 0.5 to 0.2 are illustrated in figure 8. The transformers with an FF of 0.2 are approximately 1 percent lower in efficiency, run somewhat hotter, and in all but one case are lighter.

The program allows for the application of insulating tape between primary and secondary windings and between layers within the secondary. For the same core and current density this results in a heavier, less efficient transformer since the secondary coil must be longer to accommodate the added bulk of the tape. However, the resulting increase in surface area permits the transformer to operate at a lower temperature.

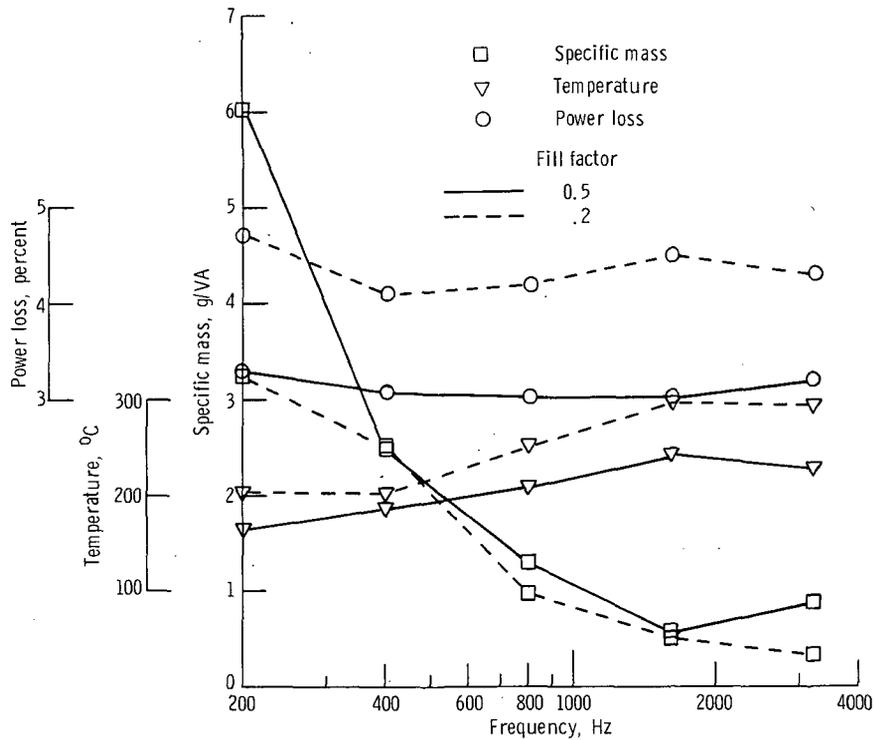


Figure 8. - Comparisons of most efficient designs with nominal fill factors of 0.5 and 0.2 for 2-kilovolt-ampere (16/2000) transformers. Supermendur core; copper coils; ambient temperature, 127° C.

The result of adding tape at a thickness of 150 V/mil to the 2-kilovolt-ampere transformer design is represented in figure 9 as a comparison of the most efficient designs with and without tape. It can be seen that the most efficient designs with tape are slightly less efficient and heavier, while operating at a lower temperature. This reduction in temperature tends to lower resistance, somewhat offsetting the increase in resistance due to increased conductor length. The weight of the tape is not included in the estimate of transformer mass.

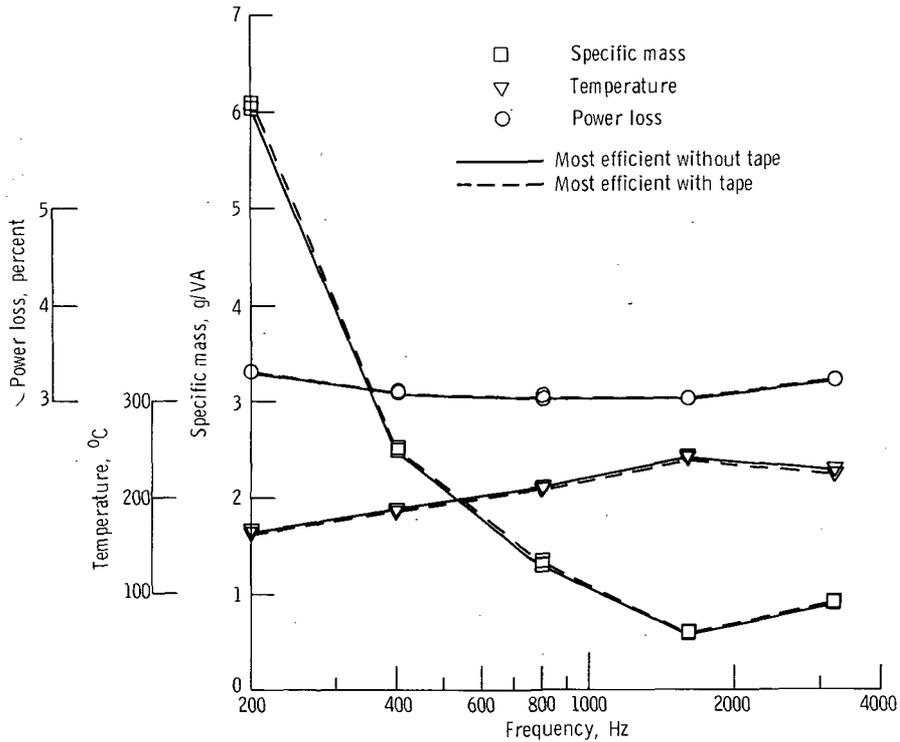


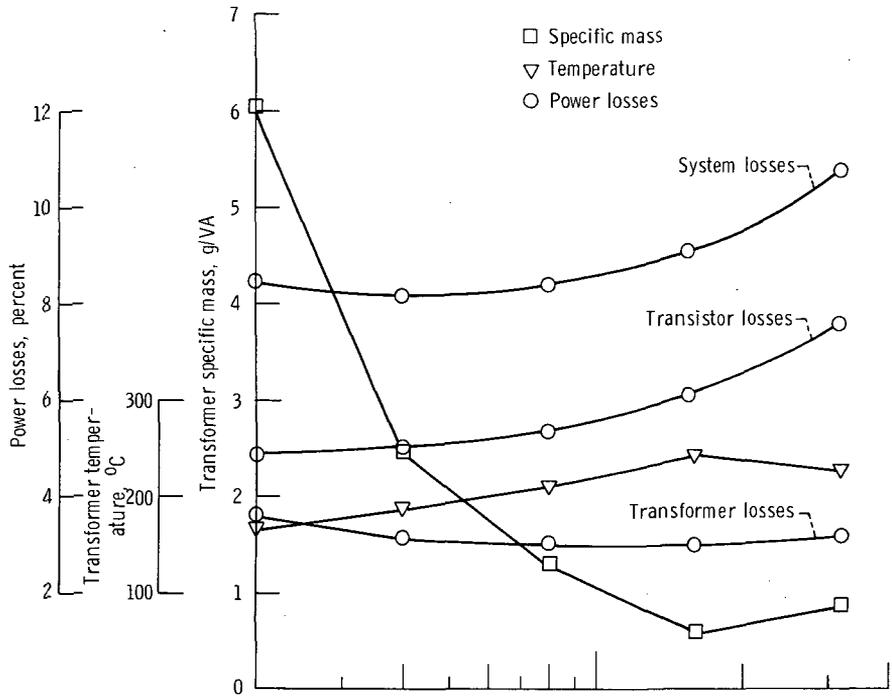
Figure 9. - Effect of adding tape between primary and secondary windings and between layers in secondary winding for 2-kilovolt-ampere, copper-wound transformers. Supermendur core; ambient temperature, 127° C; fill factor, 0.5.

## INVERTER EFFICIENCY

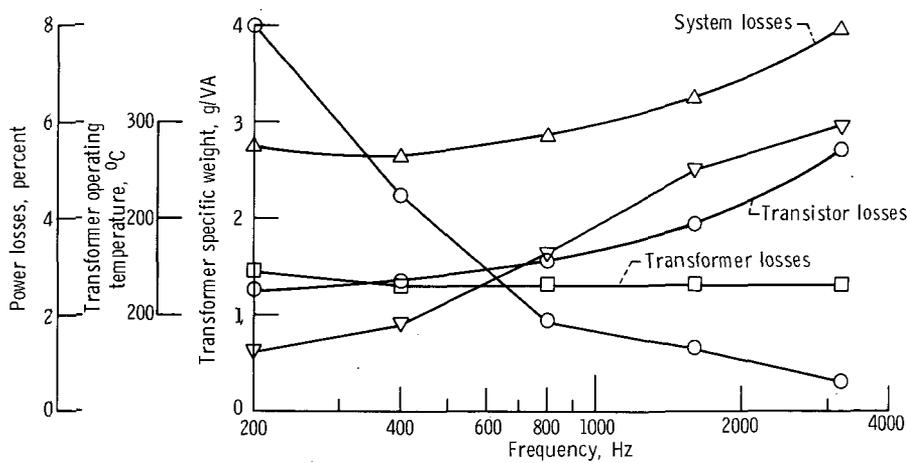
The transformer designs discussed have been incorporated into the analysis of a simple inverter circuit by combining the computed transformer characteristics with estimates of transistor parameters based on manufacturers data. The transistor losses  $P_t$  are computed approximately using the equation (ref. 11):

$$P_t = (I_{SAT}V_{SAT} + 2I_{CR}V_1) \left[ 1 - F(t_r + t_f) \right] + 0.667V_1I_{SAT}F(t_r + t_f) + I_B V_{BE} \quad (25)$$

For purposes of this calculation the 1401-0425 transistor is used with  $I_{SAT} = 125$  amperes,  $V_{SAT} = 0.7$  volts,  $I_{CR} = 10$  milliamperes,  $V_1 = 16$  or 32 volts,  $t_r + t_f = 15$  microseconds,  $I_B = 5$  amperes, and  $V_{BE} = 0.95$  volts. When the transistor and transformer losses are combined, it can be seen in figure 10(a) that the basic dissipation in the simple 2-kilovolt-ampere inverter remains under 8.6 percent up to 1.0 kilohertz before switching losses in the transistors become a major factor. For the 32-volt, 4-kilovolt-ampere system shown in figure 10(b), losses remain under 6 percent to about 1.0 kilohertz.



(a) 2-kilovolt-ampere transformers.



(b) 4-kilovolt-ampere transformers.

Figure 10. - Inverter system properties for most efficient, copper-wound transformers with Supermendur cores. Ambient temperature, 127° C.

The losses in the circuit that provides the base drive for the transistors, whether it be a saturable transformer or an external function generator, are not considered in these estimates. However, this circuit must supply only 4 percent of the current at 3 to 6 percent of the voltage that the power transistors handle so that even if it is only 50 percent efficient it would increase losses by only 0.24 or 0.12 percent in the 16- or 32-volt systems, respectively.

In a typical complete inverter system (ref. 12) additional reductions in efficiency of approximately 5 percent have been experienced because of losses in the regulation and filter circuits.

## CONCLUSIONS

The computer program described here carries out the necessary calculations for the design of toroidal transformers made with tape wound cores and standard round wire. Any magnetic material may be used in the core, and any round metal wire may be used in the coil. The transformer has a single secondary coil and a center tapped primary. The output of the program contains considerable detail about the specifications and operating parameters of the transformer. Running time on the IBM 7094 is approximately 0.0011 minute per transformer.

When the program is employed in the design of transformers for 2.0- and 4.0-kilovolt-ampere inverters, it is found that over a range of frequencies from 200 to 3200 hertz, the efficiency of the most efficient transformer at each frequency varies by only a few tenths of a percent. Transformer weight drops nearly linearly with frequency, and temperature rises with increasing frequency, but at much less than a linear rate.

Savings in transformer weight are illustrated by using either the "next best" rather than the most efficient design, by winding the transformer with aluminum rather than copper wire, and by the use of heavier, lower-reluctance magnetic cores. Each of these savings in weight is generally accompanied by a lowering in efficiency and an increase in operating temperature, however.

Application of the most efficient transformer designs to inverter systems using 1401-025 transistors indicates a basic loss at 1000 hertz for the 16-volt, 2-kilovolt-ampere system of 8.6 percent and for the 32-volt, 4-kilovolt-ampere system, 6.0 percent.

These calculations indicate that the most efficient transformers will operate at temperatures  $40^{\circ}$  to  $170^{\circ}$  C, in excess of the ambient of  $127^{\circ}$  C. In calculating temperature it is assumed that the entire outside surface of the transformer will be free to radiate and that the emissivity is 0.95. If, for example, only 50 percent of the surface is able to radiate, then the temperature estimates need be revised upward by approximately

19 percent. Furthermore, the temperature is only an estimate and does not take into account the presence of hot spots. However, these temperatures still do not approach the upper limits of available magnetic materials and insulation (ref. 13). Furthermore, no provision has been made in the computation of temperature for any heat transfer due to conduction through mounting brackets or a heat sink or to convection if the transformer is not to be operated in a vacuum.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, March 29, 1972,  
112-27.

## APPENDIX A

### HEAVY AND LIGHT MAGNETIC CORES

Two physical properties of magnetic cores, mass and reluctance, appear to have a strong influence on the operation of transformers in which they are used. A heavier piece of magnetic material will generally result in a transformer with greater losses at higher frequencies or lower current densities where iron losses become predominant. Two magnetic cores may have the same or nearly the same window-area core-area product and yet be quite different in mass, the heavier generally being more compact or squat, usually having a lower ratio of inside to outside diameter. However, the heavier core will tend to have a lower relative reluctance magnetic path where relative reluctance  $R'$  is defined:

$$R' = \pi \frac{(ODI + DII)}{(2AC)} \quad (26)$$

Because of the higher reluctance usually associated with the lighter cores, transformers made with them must generally have more turns and, therefore, heavier coils, which leads to the result that transformers made with the lighter cores tend to be heavier.

Therefore, if magnetic cores are simply arranged in order of increasing WAC, as done previously (ref. 3), the resulting transformer designs will vary erratically in mass, efficiency, and temperature.

AIEE Standard No. 430 (IEEE Standard No. 104, ref. 14), published in 1958, recommends 21 tape wound toroidal magnetic cores and separates them into two groups; high-gain cores, distinguished by having a ratio of inside to outside diameter greater than 0.70, and low-gain cores, which have a diameter ratio less than 0.70. Today, a typical manufacturer's catalog may describe hundreds of cores, and it is an aid in designing an optimum transformer to have a large number of cores from which to choose.

For the cores recommended by the AIEE standard, the diameter ratio distinction is clear cut in terms of weight being greater and reluctance less for low-gain cores, but only 15 of the recommended cores are within the range of WAC considered here. The cores presently available come in a much larger variety of heights and diameters so that a simple delineator such as the diameter ratio cannot adequately separate the data into two distinct groups unless a great many cores are eliminated. The magnetic cores used in the program are available from a variety of manufacturers, in most cases as catalog items. They have been separated somewhat arbitrarily into two groups of 45 each, called light (high-gain), numbered 101 to 145, and heavy (low-gain) cores, numbered 201

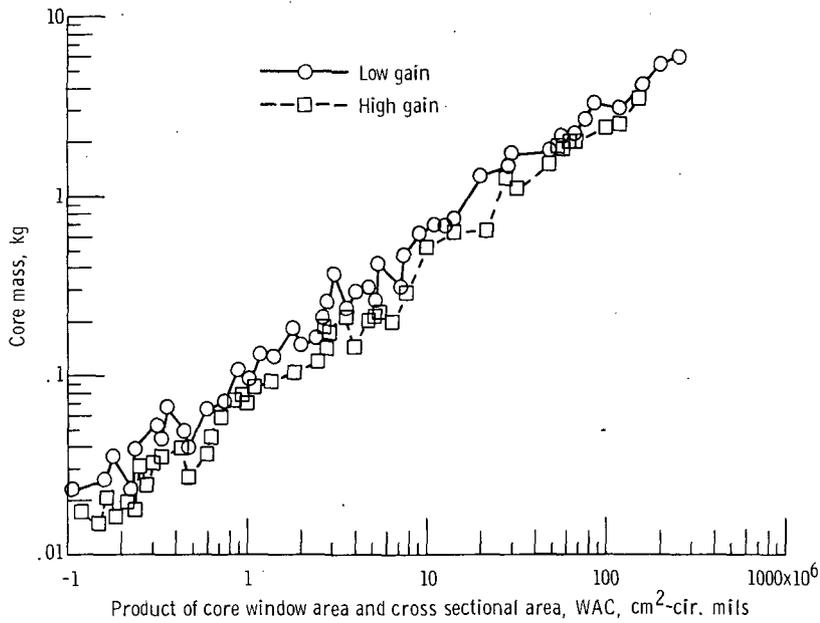


Figure 11. - Variation of core mass.

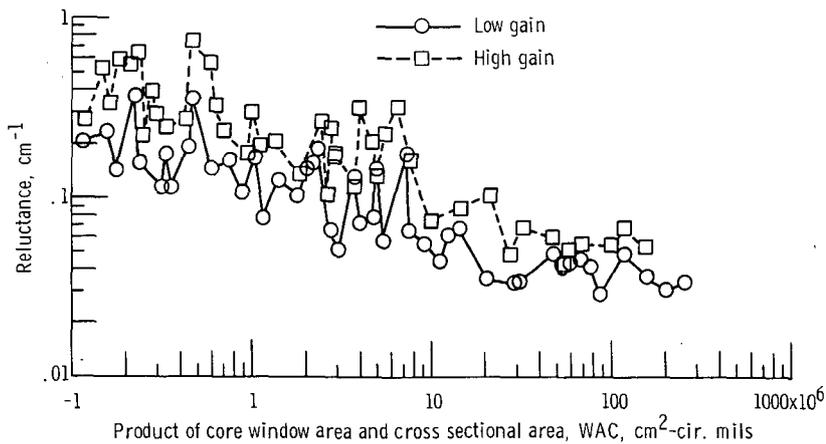


Figure 12. - Variation of core reluctance.

to 245. The distinction between them is that the heavy cores are more massive for approximately the same WAC and usually have smaller ratios of inside to outside diameter. The plot of core mass against WAC shown in figure 11 with 2.0-mil Supermendur as the magnetic material illustrates the greater mass of the low-gain cores, while also indicating that the distinction is not clear cut in every case.

A consequence of this new designation is that core numbers 109, 133, and 136, which were classified by AIEE as low-gain, are included here in the light or high-gain listing and that core numbers 204 and 228, classified high-gain by AIEE, are heavy or low-gain in this listing.

The squat shape of the heavy cores causes them to have a smaller relative reluctance in all but two cases as seen in figure 12.

The user may produce a deck of core data cards with any specifications or manufacturer's data desired, following the format used here. If a deck of other than 45 cores is required, the appropriate do loop and iteration limit statements should be altered accordingly.

# APPENDIX B

## PROGRAM LISTING

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C THIS PROGRAM DESIGNS TOROIDAL TRANSFORMERS FOR THE INTERMEDIATE
C POWER RANGE
C ICRNO IS THE CORE SERIAL NUMBER
C DITC IS THE INSIDE DIAMETER OF THE CORE BOX IN INCHES
C ODT IS THE OUTSIDE DIAMETER OF THE CORE BOX IN INCHES
C HTT IS THE HEIGHT OF THE CORE BOX IN INCHES
C WA IS THE WINDOW AREA IN CIR. MILS.*1.0E6
C AC IS THE EFFECTIVE CORE CROSS SECTIONAL AREA IN CM SQUARED
C WAC IS THE PRODUCT OF WA AND AC
C DII IS THE INSIDE DIAMETER OF THE CORE IRON IN INCHES
C ODI IS THE OUTSIDE DIAMETER OF THE CORE IRON IN INCHES
C HTI IS THE HEIGHT OF THE CORE IRON IN INCHES
C DIMENSION ICRNO(45),DITC(45),ODT(45),HTT(45),WA(45),AC(45),
1WAC(45),DII(45),ODI(45),HTI(45)
C IAWG IS THE STANDARD WIRE GAUGE NUMBER
C WACU IS THE AREA OF THE CONDUCTING PORTION OF THE WIRE IN CIR.
C MILS.
C DIC IS THE DIAMETER OF THE CONDUCTING PORTION OF WIRE IN INCHES
C AWT IS THE TOTAL WIRE AREA IN CIR. MILS.
C AWT IS THE TOTAL WIRE AREA IN C.M.
C OPM IS THE WIRE RESISTANCE IN OHMS/1000.0 FT FOR COPPER
C CUPPM IS THE WIRE WEIGHT IN POUNDS/1000.0 FT FOR COPPER
C DIMENSION IAWG(48), WACU(48),DIC(48),AWT(48),OPM(48),CUPPM(48)
C DATA (IAWG(I),I=1,48)/-3,-2,-1,0,1,2,3,4,5,6,7,8,9,10,11,12,
113,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,
134,35,36,37,38,39,40,41,42,43,44/
C DATA (WACU(I),I=1,48)/211600.0,167800.0,133100.0,105600.0,83690.0,
166360.0,52620.0,41740.0,33090.0,26240.0,20820.0,16510.0,13090.0,
110380.0,8230.0,6530.0,5180.0,4110.0,3260.0,2580.0,2050.0,
11620.0,1290.0,1020.0,812.0,640.0,511.0,404.0,320.0,253.0,202.0,
1159.0,128.0,100.0,79.2,64.0,50.4,39.7,31.4,25.0,20.2,16.0,
112.2,9.61,7.84,6.25,4.84,4.0/
C DATA (DIC(I),I=1,48)/0.46,0.4096,0.3648,0.3249,0.2893,0.2576,
10.2294,0.2043,0.1819,0.162,0.1443,0.1285,0.1144,0.1019,0.0907,
10.0808,0.072,0.0641,0.0571,0.0508,0.0453,0.0403,0.0359,0.032,
10.0285,0.0253,0.0226,0.0201,0.0179,0.0159,0.0142,0.0126,0.0113,
10.01,0.0089,0.008,0.0071,0.0063,0.0056,0.005,0.0045,0.004,
10.0035,0.0031,0.0028,0.0025,0.0022,0.002/
C DATA (AWT(I),I=1,48)/220712.0,175393.0,139428.0,110889.0,88209.0,
170172.0,55838.0,44016.0,35044.0,27922.0,22231.0,17742.0,
114137.0,11257.0,8987.0,7174.0,5730.0,4651.0,3709.0,2970.0,
12381.0,1910.0,1529.0,1232.0,986.0,790.0,640.0,515.0,412.0,331.0,
1269.0,216.0,177.0,142.0,117.0,96.0,77.0,61.0,49.0,40.0,32.0,
126.0,20.0,16.0,13.0,10.0,8.0,7.0/
C DATA (OPM(I),I=1,48)/0.04901,0.06182,0.07793,0.09825,0.1239,
10.1503,0.1971,0.2485,0.3134,0.3952,0.4981,0.6281,0.7925,
10.9988,1.26,1.59,2.0,2.52,3.18,4.02,5.05,6.39,8.05,10.1,12.8,
116.2,20.3,25.7,32.4,41.0,51.4,65.3,81.2,104.0,131.0,162.0,
1206.0,261.0,331.0,415.0,512.0,648.0,847.0,1080.0,1320.0,
1160.0,2140.0,2590.0/
C DATA (CUPPM(I),I=1,48)/640.5,507.8,402.8,319.5,253.3,200.9,

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1159.3.126.3.100.2.79.44.63.03.49.98.39.62.31.43.24.9.19.8.15.7,  
112.4.9.87.7.81.6.21.4.92.3.9.3.1.2.46.1.94.1.55.1.22.0.97,  
10.765.0.610.0.481.0.367.0.303.0.240.0.194.0.153.0.12.0.0949,  
10.0757.0.0613.0.0484.0.0371.0.0291.0.0237.0.0189.0.0147.0.0121/

C V1 IS THE INPUT VOLTAGE IN VOLTS  
C V2 IS THE OUTPUT VOLTAGE IN VOLTS  
C CUR1 IS THE INPUT CURRENT IN AMPS  
C F IS THE OPERATING FREQUENCY IN HERTZ  
C PCUMAX IS THE MAXIMUM POWER CONSUMPTION ALLOWED PER COIL IN WATTS  
C BMAX IS THE SPECIFIED MAGNETIC FLUX DENSITY IN GAUSS  
C DENSTY IS THE DENSITY OF THE CORE IRON IN POUNDS/CUBIC INCH  
C TAPEV IS THE RATED VOLTAGE PER MIL FOR INSULATING TAPE  
C WATPP IS THE CORE LOSS IN WATTS PER POUND  
C VAPP IS THE APPARENT CORE POWER IN VOLT-AMPERES PER POUND  
C TAMB IS THE AMBIENT TEMPERATURE IN DEGREES CENTIGRADE  
C CU EQUALS 1.0 IF THE COILS ARE COPPER, EQUALS 0.0 IF ANOTHER  
C CONDUCTOR IS USED  
C A EQUALS 0.0 IF THE COILS ARE COPPER, EQUALS 1.0 IF ANOTHER  
C CONDUCTOR IS USED  
C RDENS IS THE DENSITY OF AN ALTERNATE CONDUCTOR, RELATIVE TO COPPER  
C RRES IS THE RESISTANCE OF AN ALTERNATE CONDUCTOR, RELATIVE TO  
C COPPER  
C TEMCOR IS THE TEMPERATURE COEFFICIENT OF RESISTANCE OF ALTERNATE  
C CONDUCTOR IN OHMS PER DEGREE CENTRIGRADE AT 20.0 C  
C CMPA SPECIFIES THE DESIRED INVERSE CURRENT DENSITY IN CIR. MILS.  
C PER AMP  
C NAMELIST/IN/V1, V2, CUR1, F, PCUMAX, BMAX, DENSTY, TAPEV, WATPP,  
C IVAPP, TAMB, FF, CU, A, RDENS, RRES, TEMCOR, CMPA/OUT/V1, V2, CUR1,  
C ICUR2, CUREX, NP, IAWG1, NWRAP1, R1, PCU1, CUWAT1, FF, IAWG2, NS,  
C INWRAP2, R2, PCU2, CUWAT2, XLONG1, XLONG2, ICORN, CORWAT, PIRON,  
C IREGUL, PLUS, EFISH, TOTWAT, FILE, TAMB, T, FOD, FHIT, F, SURFT,  
C IV2FL, WATTPA, CMPA, CU, A, BUSED/TROBLE/ISORCE/CORDTA/ICORNO,  
C 1DITC, OCT, HTT, WA, AC, WAC, DII, ODI, HTI  
C CUR2 IS THE OUTPUT CURRENT IN AMPS  
C CUREX IS THE EXCITATION CURRENT IN AMPS  
C NP IS THE NUMBER OF PRIMARY TURNS  
C IAWG1 IS THE WIRE GAUGE CHOSEN FOR THE PRIMARY COIL  
C IAWG2 IS THE WIRE GAUGE CHOSEN FOR THE SECONDARY COIL  
C NS IS THE NUMBER OF SECONDARY TURNS  
C WRAP1 IS THE NUMBER OF PARALLEL WINDINGS IN THE PRIMARY  
C WRAP2 IS THE NUMBER OF PARALLEL WINDINGS IN THE SECONDARY  
C R1 IS THE PRIMARY RESISTANCE IN OHMS  
C R2 IS THE SECONDARY RESISTANCE IN OHMS  
C PCU1 IS THE POWER DISSIPATED IN THE PRIMARY IN WATTS  
C PCU2 IS THE POWER DISSIPATED IN THE SECONDARY IN WATTS  
C CUWAT1 IS THE MASS OF THE PRIMARY COIL IN KILOGRAMS  
C CUWAT2 IS THE MASS OF THE SECONDARY COIL IN KILOGRAMS  
C CORWAT IS THE MASS OF THE CORE IRON IN KILOGRAMS  
C PIRON IS THE CORE LOSS IN WATTS  
C REGUL IS THE REGULATION IN PER CENT  
C PLUS IS THE TOTAL TRANSFORMER LOSS IN WATTS  
C EFISH IS THE TRANSFORMER EFFICIENCY IN PER CENT  
C TOTWAT IS THE TOTAL WEIGHT OF THE TRANSFORMER  
C FILE IS THE FINAL FILL FACTOR  
C FOD IS THE FINAL OUTSIDE DIAMETER IN CM  
C FHIT IS THE FINAL HEIGHT IN CM  
C T IS THE OPERATING TEMPERATURE IN DEGREES CENTIGRADE  
C SURFT IS THE FINAL SURFACE AREA IN SQUARE CM  
C WATTPA IS THE RATIO OF LOSSES TO SURFACE AREA

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C      BUSED IS THE ACTUAL MAGNETIC FLUX DENSITY IN GAUSS
C      ISORCE INDICATES THE POINT COMPUTATION WAS TERMINATED WHEN PROGRAM
C      CANNOT DESIGN TRANSFORMER ACCORDING TO SPECIFICATIONS
C      EXPLANATION OF ISORCE INDICATORS
C      ISORCE=1. INSUFFICIENT LIST OF WIRE SIZES FOR PRIMARY AT START
C      ISORCE=2 OR 3. INSUFFICIENT LIST OF WIRE SIZES TO ALLOW FOR SKIN
C      EFFECT CORRECTION ON PRIMARY COIL
C      ISORCE=4. INSUFFICIENT LIST OF CORES AT START
C      ISORCE=5. LIST OF CORES INSUFFICIENT TO ALLOW DESIRED FIL1
C      ISORCE=6. INSUFFICIENT LIST OF WIRE SIZES FOR SECONDARY AT START
C      ISORCE=7 OR 8. INSUFFICIENT LIST OF WIRE SIZES TO ALLOW FOR SKIN
C      EFFECT CORRECTION ON SECONDARY COIL
C      ISORCE=9. LIST OF CORES INSUFFICIENT TO ALLOW DESIRED FIL2
1  FORMAT (1I4,6F6.3,2F7.3,1F8.3)
    READ(5,1) (ICUKND(I),DII(I),ODI(I),HTI(I),DITC(I),ODT(I),HTT(I),
    1WA(I),AC(I),WAC(I),I=1,45)
4  READ(5,IN)
    CUX1=CUR1
5  WRAP1 = 0.5*CUX1*CMPA/211600.0 + 1.0
    NWRAP1=IFIX(WRAP1)
    WACUP=(0.625*CMPA*CUX1)/FLOAT(NWRAP1)
    I=1
    DO 10 I=1,48
      IF (WACUP-WACU(I))10,10,9
9  NW=I
    GO TO 11
10 CONTINUE
    ISORCE=1
    WRITE(6,TROBLE)
    WRITE(6,IN)
    GO TO 4
11 SKND= 2.5984*(CU+A*SQRT(RRES))/SQRT(F)
    NSK = IFIX(WACU(NW)/(1.0E6*(1.5*SKND)**2))
    IF (NSK.GT.5) GO TO 15
    NWRAP1=NWRAP1*(NSK+1)
    WRAP1=FLOAT(NWRAP1)
    IF (NSK-1)20,13,14
13 NW=NW+3
    IF (NW.LT.49) GO TO 20
    ISORCE=2
    WRITE(6,TROBLE)
    WRITE(6,IN)
    GO TO 4
14 NW=NW+NSK+3
    IF (NW.LT.49) GO TO 20
    ISORCE = 2
    WRITE(6,TROBLE)
    WRITE(6,IN)
    GO TO 4
15 DO 17 I=1,48
    IF (1.5*SKND-DIC(I)) 17,16,16
16 NW = I
    GO TO 18
17 CONTINUE
    ISORCE = 3
    WRITE (6,TROBLE)
    WRITE(6,IN)
    GO TO 4

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18 NWRAP1=IFIX(0.5*CUX1*CMPA/WACU(NW) + 1.0)
   WRAP1 = FLOAT(NWRAP1)
20 WACG=100.0*V1*AWT(NW)*WRAP1/(F*FF*BMAX)
   J=1
21 DO 23 J=1,45
   IF (WACG-WAC(J))22,22,23
22 NC=J
   GO TO 30
23 CONTINUE
   ISORCE=4
   WRITE(6,TRUBLE)
   WRITE(6,IN)
   GO TO 4
30 NP=2*(IFIX(V1*0.25E8/(F*AC(NC)*BMAX)+0.8))
   PN=FLOAT(NP)
   BUSED=V1*1.0E8/(2.0*PN*F*AC(NC))
40 FILL=PN*WRAP1*AWT(NW)/(WA(NC)*1.E6)
   AD=DITC(NC)*SQRT(1.0-FILL)
   TAPEXP=FLOAT(IFIX((V1+V2)/TAPEV))
   AD=AD-TAPEXP/500.0
   FILL = 1.0-AD**2/DITC(NC)**2
   FF1=0.64*FF
   IF (FILL.GT.FF1) GO TO 41
   GO TO 50
41 NC=NC+1
   IF (NC.LT.46) GO TO 30
   ISORCE=5
   WRITE(6,TRUBLE)
   WRITE(6,IN)
   GO TO 4
50 XLONG1=PN*(2.0*HTT(NC)+ODT(NC)+DITC(NC)*(1.0-2.0*SQRT(1.0-FILL)))
54 R01 = OPM(NW)*XLONG1*(CU+A*RRRES)/(24000.0*WRAP1)
   R1= R01*(1.0+(CU*0.00393+A*TEMCOR)*(TAMB-20.0))
55 PCU1=R1*CUR1**2
56 IF (PCU1-2.0*PCUMAX) 60,60,57
57 CUX1=1.1*CUX1
   GO TO 5
60 SN = 0.5*PN*V2/(V1-2.0*CUR1*R1)
   NS=IFIX(SN)+1
   SN=FLOAT(NS)
   CURWAT = 3.14159*HTI(NC)*DENSTY*(ODI(NC)**2-DII(NC)**2)/4.0
   CUREX=VAPP*CURWAT*BUSED/(V1*BMAX)
   CUR2=PN*0.5*(CUR1-CUREX)/SN
   CUX2=CUR2
61 NWRAP2 = IFIX(CUX2*CMPA/211600.0 + 1.0)
62 WRAP2 = FLOAT(NWRAP2)
   WACUS= 1.25*CMPA*CUX2/FLOAT(NWRAP2)
63 M=1
   DO 70 M=1,48
   IF (WACUS-WACU(M))70,70,64
64 MW=M
   GO TO 80
70 CONTINUE
   ISORCE=6
   WRITE(6,TRUBLE)
   WRITE(6,IN)
   GO TO 4

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80 MSK = IFIX(WACU(MW)/(1.0E6*(1.5*SKND)**2))
   NWRAP2=NWRAP2*(MSK+1)
   WRAP2=FLD(NT(NWRAP2))
   IF (MSK.GT.5) GO TO 85
   IF (MSK-1)90.83.84
83 MW=MW+3
   IF (MW.LT.49) GO TO 90
   ISORCE=7
   WRITE(6,TROBLE)
   WRITE(6,IN)
   GO TO 4
84 MW=MW+MSK+3
   IF (MW.LT.49) GO TO 90
   ISORCE=7
   WRITE(6,TROBLE)
   WRITE(6,IN)
   GO TO 4
85 DO 87 I=1,48
   IF (1.5*SKND-DIC(I)) 87,86,86
86 MW = I
   GO TO 88
87 CONTINUE
   ISORCE=8
   WRITE(6,TROBLE)
   WRITE(6,IN)
   GO TO 4
88 NWRAP2=IFIX(CUX2*CMPA/WACU(MW)+1.0)
   WRAP2=FLD(NT(NWRAP2))
90 FIL2=SN*WRAP2*AWT(MW)/(WA(NC)*1.E6)
   BD = DITC(NC)*SQRT(1.0-FIL1-FIL2)
   TAPEXS=FLD(NT(IFIX(V2/TAPEV)))
   BD=BD-TAPEXS/500.0
   FILE = 1.0 - BD**2/DITC(NC)**2
   FFF=1.28*FF
   IF (FILE.GT.FFF) GO TO 91
   GO TO 100
91 NC=NC+1
   IF (NC.LT.46) GO TO 30
   ISORCE=9
   WRITE(6,TROBLE)
   WRITE(6,IN)
   GO TO 4
100 PIRON=WATPP*CURWAT*BUSED/BMAX
   C=0.5*(DITC(NC)-AD)
   B=0.5*(AD-BD)
111 XLONG2=SN*(2.0*HTT(NC)+8.0*C+4.0*B+ODT(NC)-DITC(NC))
112 KQ2 = OPM(MW)*XLONG2*(CU+A*KRES)/(12000.*WRAP2)
   K2 = KQ2*(1.0+(CU*0.00393+A*TEMCOR)*(TAMB-20.0))
   PCU2=K2*CUR2**2
   IF (PCU2-PCUMAX)120,120,113
113 CUX2=1.1*CUX2
   GO TO 61
120 SURF1 = 3.14159*(ODT(NC)+DITC(NC)-BD)*(HTT(NC) +2.0*C +2.0*B)
   SURF2=3.14159*((ODT(NC)+2.0*C+2.0*B)**2-BD**2)/2.0
   SURFT = (SURF1 + SURF2)*2.54**2.54
   PLUSS=PCU1+PCU2+PIRON
121 PLAST=PLOSS
   WATPPA=PLUSS/SURFT
   T = (WATPPA/(0.95*5.67E-12) + (TAMB + 273.0)**4)**0.25 - 273.0

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123 R1= R01*(1.0+(CU*0.00393+A*TEMCOR)*(T-20.0))
    PCU1=R1*CUR1**2
    IF (PCU1-PCUMAX)125,125,57
125 R2 = R02*(1.0+(CU*0.00393+A*TEMCOR)*(T-20.0))
    PCU2=R2*CUR2**2
    IF (PCU2-PCUMAX) 130,130,113
130 PLOSS=PCU1+PCU2+PIRON
    IF (PLOSS-1.01*PLAST) 131,131,121
131 V2FL = 2.0*(V1-CUR1*R1)*SN/PN-CUR2*R2
    IF (V2FL .GT. V2) GO TO 140
    SN = 0.5*(V2+CUR2*R2)*PN/(V1-CUR1*R1)
    NS = FIX(SN) + 1
    SN = FLOAT(NS)
    CUR2=PN*0.5*(CUR1-CUREX)/SN
    GO TO 90
140 ICORN = ICORND(NC)
    V20 = (V1 - CUREX*R1)*2.0*SN/PN
    KEGUL = 100.0*(V20-V2FL)/V2FL
    IAWG1=IAWG(NW)
    IAWG2=IAWG(MW)
    CUWAT1= XLONG1*WRAP1*(CU+A*RDENS)*CUPPM(NW)/(12000.0*2.205)
    CUWAT2= XLONG2*WRAP2*(CU+A*RDENS)*CUPPM(MW)/(12000.0*2.205)
    CORWAT = CORWAT/2.205
    FISH=100.0*(1.0-PLOSS/(V1*CUR1))
    TOTWAT = (CORWAT+CUWAT1+CUWAT2)
    FOD = (ODT(NC) + 2.0*C + 2.0*B)*2.54
    FHTT = (HTT(NC) + 2.0*C + 2.0*B)*2.54
    WRITE(6,OUT)
    GO TO 4
END

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SDATA

C THE NEXT 45 CARDS CONTAIN THE DATA FOR THE HEAVY CORES

201	0.625	1.125	0.250	0.545	1.205	0.345	0.308	0.343	0.106
202	0.750	1.250	0.250	0.670	1.330	0.345	0.462	0.343	0.158
203	0.650	1.150	0.375	0.575	1.225	0.470	0.348	0.514	0.179
204	1.000	1.375	0.250	0.915	1.460	0.345	0.865	0.257	0.222
205	0.750	1.250	0.375	0.665	1.335	0.470	0.462	0.514	0.237
206	0.750	1.250	0.500	0.670	1.335	0.605	0.462	0.686	0.317
207	0.875	1.375	0.375	0.790	1.460	0.470	0.648	0.514	0.333
208	0.750	1.500	0.375	0.665	1.585	0.480	0.462	0.771	0.356
209	1.000	1.500	0.375	0.915	1.585	0.470	0.865	0.514	0.445
210	1.250	1.750	0.250	1.160	1.840	0.350	1.369	0.343	0.470
211	1.000	1.500	0.500	0.915	1.585	0.605	0.865	0.686	0.593
212	1.125	1.625	0.500	1.035	1.715	0.610	1.092	0.686	0.749
213	1.000	1.750	0.500	0.905	1.845	0.615	0.865	1.028	0.889
214	1.250	2.000	0.375	1.160	2.090	0.480	1.369	0.771	1.055
215	1.000	1.500	1.000	0.915	1.585	1.105	0.865	1.371	1.186
216	1.250	2.000	0.500	1.150	2.110	0.615	1.369	1.028	1.407
217	1.250	2.250	0.500	1.150	2.350	0.620	1.369	1.371	1.814
218	1.500	2.250	0.500	1.400	2.350	0.615	1.960	1.028	2.015
219	1.625	2.375	0.500	1.520	2.480	0.620	2.326	1.028	2.391
220	1.500	2.500	0.500	1.380	2.610	0.620	1.960	1.371	2.687
221	1.250	2.000	1.000	1.150	2.110	1.115	1.369	2.057	2.816
222	1.250	2.250	1.000	1.150	2.350	1.115	1.369	2.742	3.093
223	1.750	2.750	0.500	1.640	2.860	0.620	2.723	1.371	3.733
224	1.500	2.250	1.000	1.395	2.350	1.115	1.960	2.057	4.032
225	1.625	2.375	1.000	1.520	2.480	1.115	2.326	2.057	4.785
226	2.000	3.000	0.500	1.880	3.120	0.625	3.610	1.371	4.949
227	1.500	2.500	1.000	1.380	2.620	1.115	1.960	2.742	5.374

228	2.500	3.500	0.500	2.380	3.620	0.635	5.530	1.371	7.335
229	1.750	2.750	1.000	1.640	2.860	1.120	2.723	2.742	7.466
230	1.750	3.000	1.000	1.630	3.120	1.120	2.723	3.428	9.221
231	1.750	2.750	1.500	1.630	2.865	1.635	2.723	4.113	11.200
232	2.000	3.250	1.000	1.880	3.370	1.120	3.610	3.428	12.375
233	2.250	3.500	1.000	2.130	3.620	1.130	4.252	3.428	14.576
234	2.000	3.500	1.500	1.870	3.630	1.660	3.610	6.170	20.281
235	2.250	3.500	2.000	2.120	3.630	2.190	4.252	6.855	29.147
236	2.250	4.000	1.500	2.110	4.140	1.660	4.252	7.198	30.606
237	3.000	4.500	1.500	2.850	4.650	1.670	7.913	6.170	48.823
238	3.000	4.750	1.500	2.845	4.905	1.690	7.913	7.198	56.915
239	3.250	5.000	1.500	3.090	5.160	1.695	9.376	7.198	67.488
240	3.250	5.250	1.500	3.085	5.415	1.700	9.376	8.226	77.127
241	3.000	5.000	2.000	2.840	5.160	2.195	7.913	10.968	86.724
242	4.000	6.000	1.500	3.825	6.175	1.705	14.561	8.226	119.764
243	4.000	6.000	2.000	3.825	6.175	2.205	14.531	10.968	159.376
244	4.000	6.500	2.000	3.815	6.685	2.210	14.531	13.711	199.235
245	4.500	7.000	2.000	4.310	7.190	2.215	18.602	13.711	255.052

C THE NEXT 45 CARDS CONTAIN THE DATA FOR THE LIGHT CORES

101	0.750	1.000	0.375	0.670	1.080	0.470	0.462	0.257	0.119
102	1.000	1.250	0.250	0.915	1.335	0.345	0.865	0.171	0.148
103	0.875	1.250	0.250	0.790	1.335	0.345	0.648	0.257	0.167
104	1.125	1.375	0.250	1.045	1.455	0.345	1.092	0.171	0.187
105	1.125	1.500	0.188	1.045	1.580	0.280	1.113	0.193	0.215
106	1.250	1.500	0.250	1.170	1.580	0.345	1.369	0.171	0.234
107	0.875	1.250	0.375	0.790	1.335	0.470	0.648	0.386	0.250
108	1.125	1.375	0.375	1.045	1.455	0.470	1.092	0.257	0.281
109	1.000	1.500	0.250	0.915	1.585	0.345	0.865	0.343	0.297
110	1.000	1.375	0.375	0.915	1.460	0.470	0.865	0.386	0.334
111	1.125	1.500	0.375	1.040	1.585	0.470	1.113	0.386	0.430
112	1.625	2.000	0.188	1.510	2.115	0.285	2.418	0.193	0.467
113	1.625	2.000	0.250	1.510	2.115	0.350	2.326	0.257	0.598
114	1.375	1.750	0.375	1.285	1.840	0.475	1.626	0.386	0.628
115	1.250	1.750	0.375	1.160	1.840	0.475	1.369	0.514	0.704
116	1.250	1.750	0.500	1.160	1.840	0.610	1.369	0.686	0.939
117	1.500	2.000	0.375	1.405	2.095	0.475	1.960	0.514	1.007
118	1.375	1.875	0.500	1.285	1.965	0.615	1.626	0.686	1.115
119	1.500	2.000	0.500	1.400	2.100	0.615	1.960	0.686	1.345
120	1.750	2.250	0.500	1.650	2.350	0.620	2.723	0.686	1.868
121	2.000	2.500	0.500	1.895	2.605	0.620	3.610	0.686	2.476
122	1.500	2.000	1.000	1.395	2.105	1.110	1.960	1.371	2.687
123	2.000	2.750	0.375	1.890	2.860	0.495	3.610	0.771	2.783
124	1.750	2.500	0.500	1.645	2.605	0.620	2.789	1.028	2.867
125	1.875	2.625	0.500	1.765	2.735	0.620	2.846	1.028	2.926
126	1.750	2.250	1.000	1.645	2.355	1.115	2.723	1.371	3.733
127	2.500	3.000	0.500	2.390	3.110	0.620	5.760	0.686	3.951
128	2.250	3.000	0.500	2.130	3.120	0.620	4.623	1.028	4.752
129	2.000	2.500	1.000	1.880	2.620	1.115	3.610	1.371	4.949
130	2.500	3.250	0.500	2.380	3.370	0.625	5.350	1.028	5.495
131	3.000	3.750	0.375	2.870	3.880	0.515	8.410	0.771	6.484
132	2.500	3.000	1.000	2.390	3.110	1.120	5.350	1.371	7.734
133	2.000	3.000	1.000	1.880	3.120	1.120	3.610	2.742	9.899
134	2.500	3.500	1.000	2.380	3.620	1.135	5.350	2.742	14.670
135	3.000	4.000	1.000	2.870	4.130	1.145	7.913	2.742	21.697
136	2.500	3.750	1.500	2.360	3.890	1.660	5.350	5.142	27.510
137	3.000	4.000	1.500	2.860	4.140	1.660	7.913	4.113	32.546
138	3.250	4.500	1.500	3.100	4.650	1.670	9.376	5.142	48.211
139	3.000	4.250	2.000	2.855	4.395	2.195	7.913	6.855	54.244
140	3.250	4.750	1.500	3.100	4.905	1.690	9.382	6.170	57.887

141	3.250	4.500	2.000	3.100	4.650	2.200	9.376	6.855	64.437
142	3.500	5.000	1.500	3.340	5.160	1.695	10.969	6.170	67.679
143	4.000	5.250	2.000	3.835	5.415	2.205	14.539	6.855	99.665
144	4.500	6.000	1.500	4.325	6.175	1.695	19.184	6.170	118.365
145	4.500	6.500	1.500	4.315	6.685	1.710	18.593	8.226	152.946

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SIN V1=16.0,V2=2000.0,CURL=125.0,F=200.0,PCUMAX=40.0,BMAX=18000.0,  
 DENSITY=0.295,WATPP=6.00,VAPP=7.00,TAMB=127.0, RRES =1.0,  
 CU=1.0,A=0.0,CMPA=3125.0,FF=0.5,TAPEV=150.0

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