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INTERNATIONAL AIRPORT
LOS ANGELES 9, CALIFORNIA

POWER CONVERSION AND GENERATION STUDY

PROGRESS REPORT - SECOND QUARTER

(July 15, 1963 to October 15, 1963)

Contract AF33(657)-11049

AERONAUTICAL SYSTEMS DIVISION

PREPARED BY

ENERGY CONVERSION GROUP

APPROVED BY

R C Stuber

for J. J. PIERRO, PRINCIPAL SCIENTIST
AVIONIC SCIENCES

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DATE	REV. BY	PAGES AFFECTED	REMARKS

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF TABLES

1.0 PREFACE

This report is the second of several Quarterly Progress Reports of Aeronautical Systems Division's Study Contract AF33(657)-11049, dated April 15, 1963. The contract involves a study of power generation and conversion techniques for supplying high-frequency electric power for an electric propulsion engine. Study details conform to Exhibit "A" (revised) of the Work Statement dated 29 August 1962, and modified by supplemental agreement dated 21 May 1963.

Data and information in this report represents study effort expended during the July 15 to October 15, 1963 reporting period.

2.0 SUMMARY AND RECOMMENDATIONS

Analytic investigations are proceeding ahead of schedule. 800 KC design concepts have been analyzed in this second quarter of study in order that weight versus frequency and efficiency versus frequency data for the three converter frequency levels might be presented at the earliest date possible. Analysis of three converter concepts, previously formulated in the first three-month study period, has continued throughout the second three-month period. These concepts are (1) a motor-generator unit, (2) a static (tube) unit and (3) a static (transistor) unit. Each of these converter concepts is discussed in a separate section of this report which also includes the parametric data developed during this reporting period.

Figure 2.1-1 summarizes the three converter system concepts (1Ø and 3Ø) on a lbs/KW (without cooling) versus frequency basis. The weight advantage of the static (transistor) converter concept (both 1Ø and 3Ø) over the other two concepts at each of the three conversion frequencies is quite evident. The motor-generator concept is competitive with the transistor unit in weight only at the 50 KC level (within the design objective) but gets decidedly heavier at the 200 KC frequency level. It has not been considered at the 800 KC frequency level because of the extreme number of poles and/or high rotor speed required for such a converter device. The weight of the static (tube) converter is heavy, but fairly independent of the frequency conversion level for the 50 to 800 KC range.

Figure 2.1-2 summarizes in a similar fashion the efficiency versus frequency for the three converter concepts. The static (transistor) converter is the most efficient of the three concepts with the static (tube) converter being the least efficient. To be noted is the fact

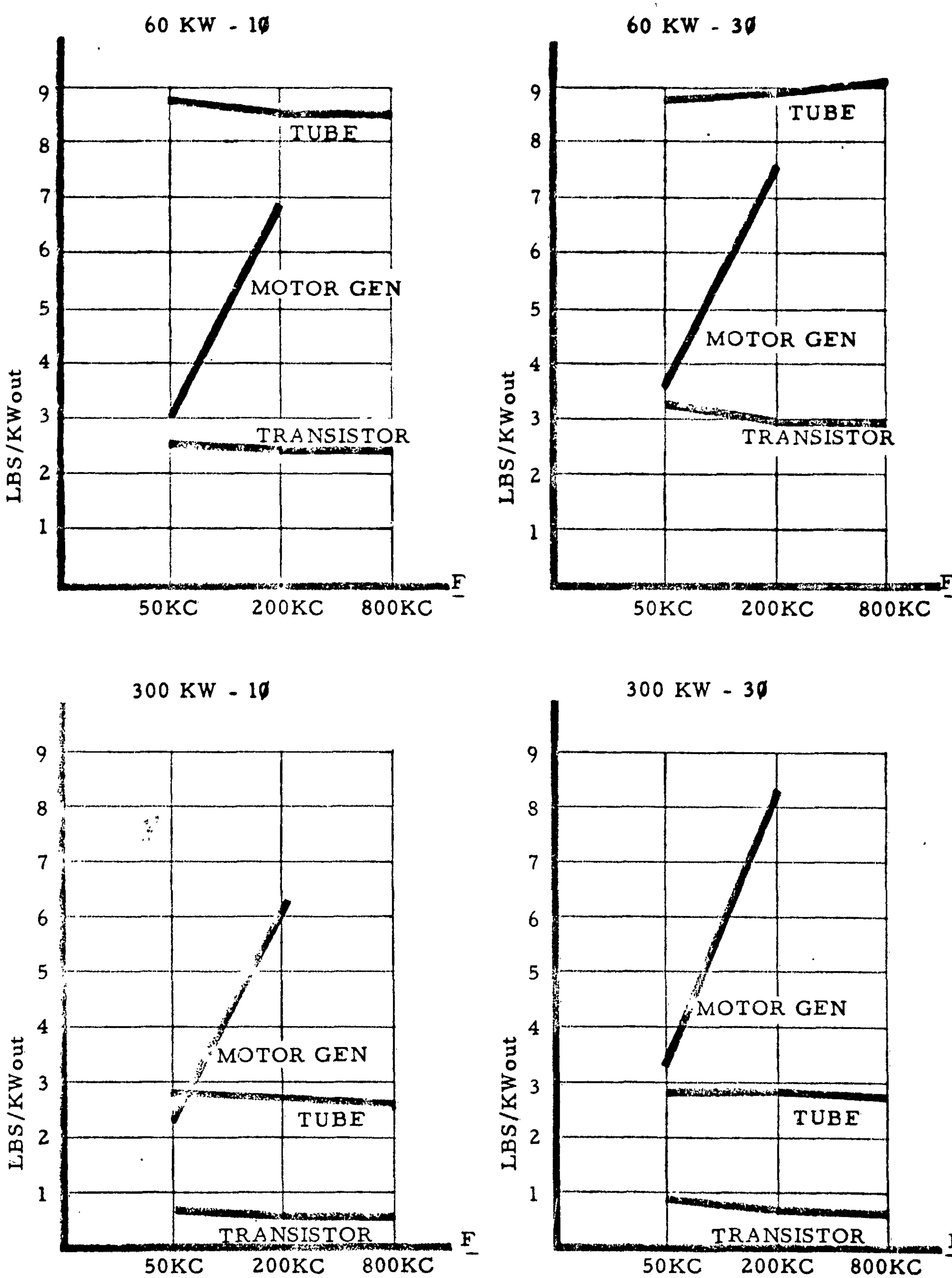


Figure 2.1-1 Comparison of Weight vs Frequency for Converters

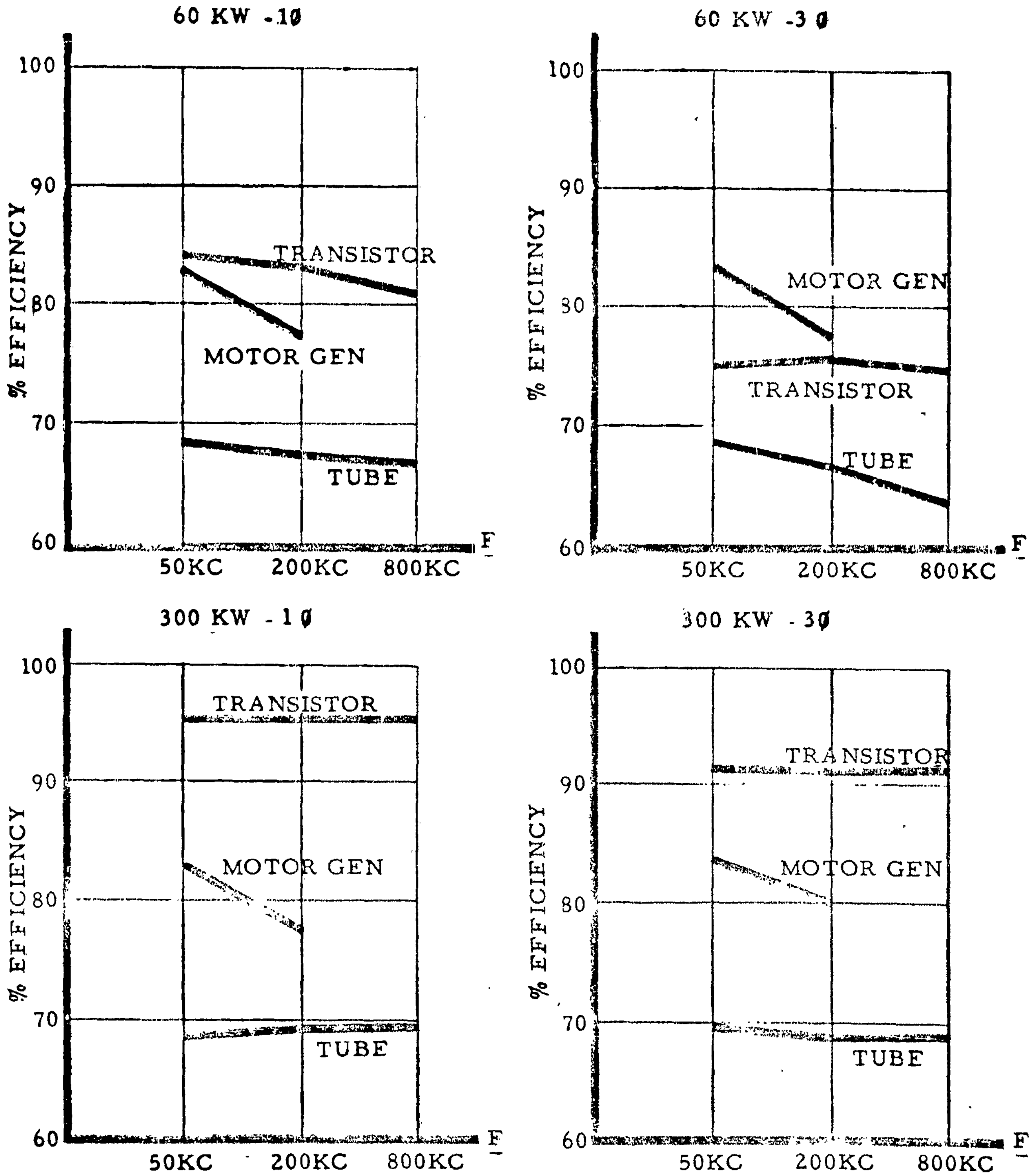


Figure 2.1-2 Comparison of Efficiency vs. Frequency for 60 KW & 300 KW Converter

that the efficiency of the 300 KW static (transistor) unit exceeds the design objective of 90%. Unit dimensions, component weights and losses, and other required data are summarized in the separate converter design sections.

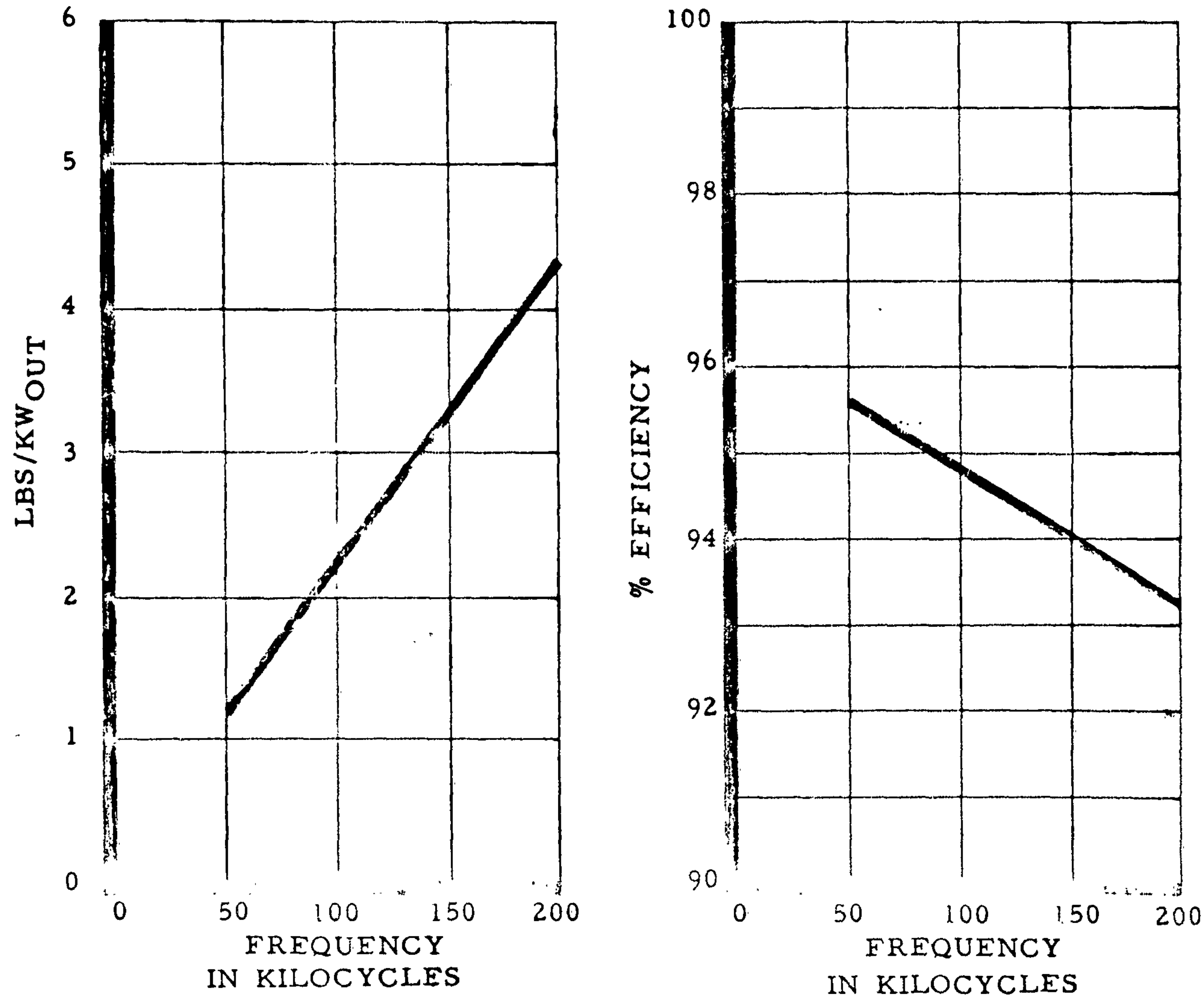
Figure 2.1-3 summarizes high-frequency generator weight and efficiency versus frequency. Efficiencies are higher and weights lower for the 50 KC unit than for the 200 KC unit.

Figure 2.1-4 is part of the thermal analysis work accomplished during the second three-month period and shows the weight of the cooling system (radiator, pumps, fluid, and piping) in lbs/KW of heat radiated necessary to maintain different system operating temperatures. Total system weight versus temperature results for the three converter systems are compared in Figures 2.1-5 and 2.1-6.

A more complete picture of the effect of cooling system requirements on total system weight is given in each of the individual system sections of this report. Curves showing the total system weight/KW as a function of temperature for each frequency range are included.

No experimental effort has been performed in the first six months of the study. It is felt that experiments need to be performed in two areas to verify basic design assumptions. These two areas in which experiments are being proposed under a separate letter are:

1. Determination of core loss data at the 50 to 800 KC frequency level. Only a limited amount of information presently exists concerning the magnitude of losses at these frequency levels and at greater than room temperatures. The data presented in a later section is a collection of loss data from several sources. Information is lacking for the 800 KC range and thought not to be too accurate at the 100 to 200 KC level. Since transformer weight is a major portion of the system



NOTE: Curves are based on data of Table 3.2.1-1

Figure 2.1-3 Comparison of Weight and Efficiency vs. Frequency for High Frequency Generator

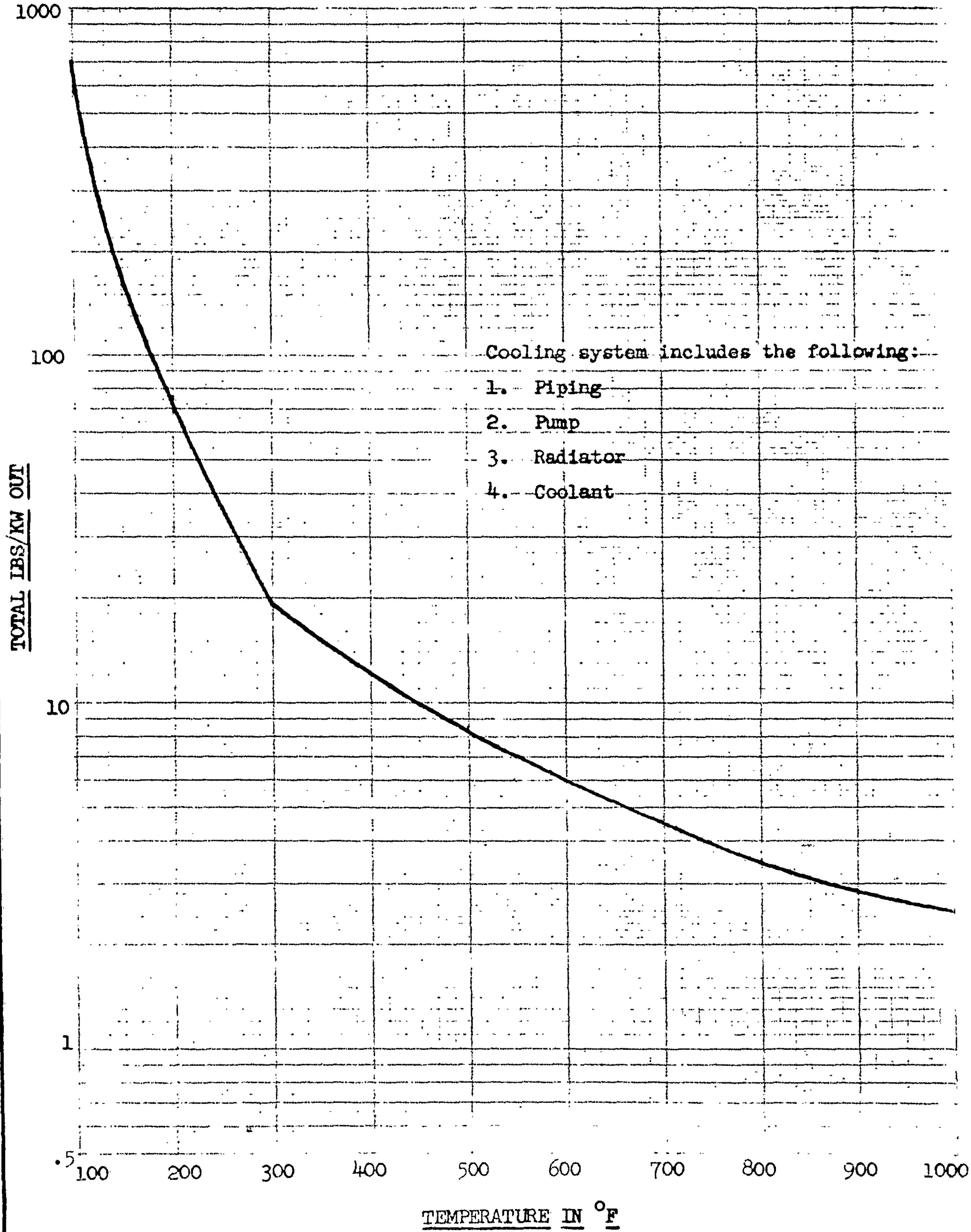


Figure 2.1-4 Analysis of Cooling System Weight vs System Operating Temperature

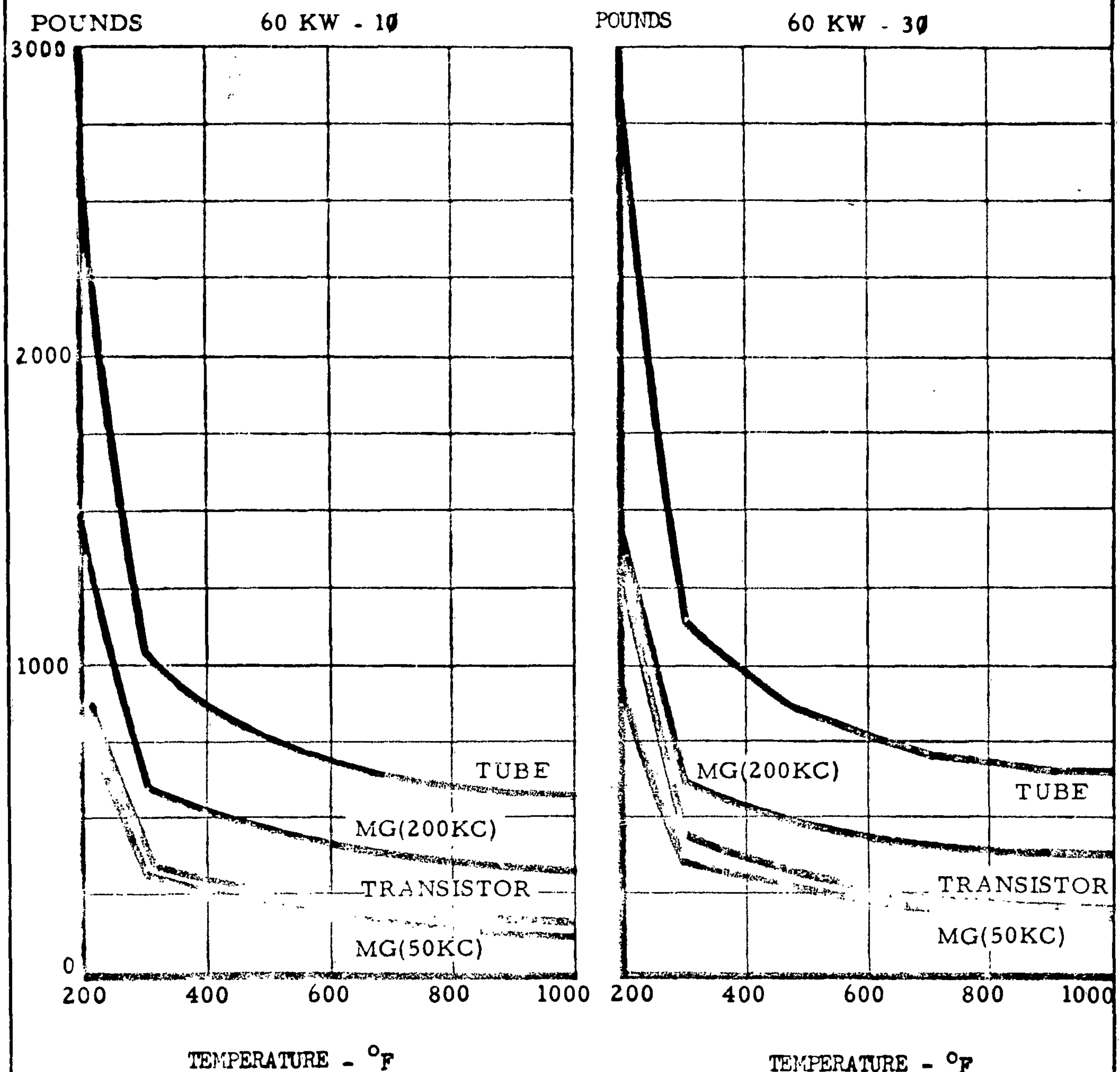


Figure 2.1-5 Analysis of System Weight vs. Temperature for 60 KW Converter

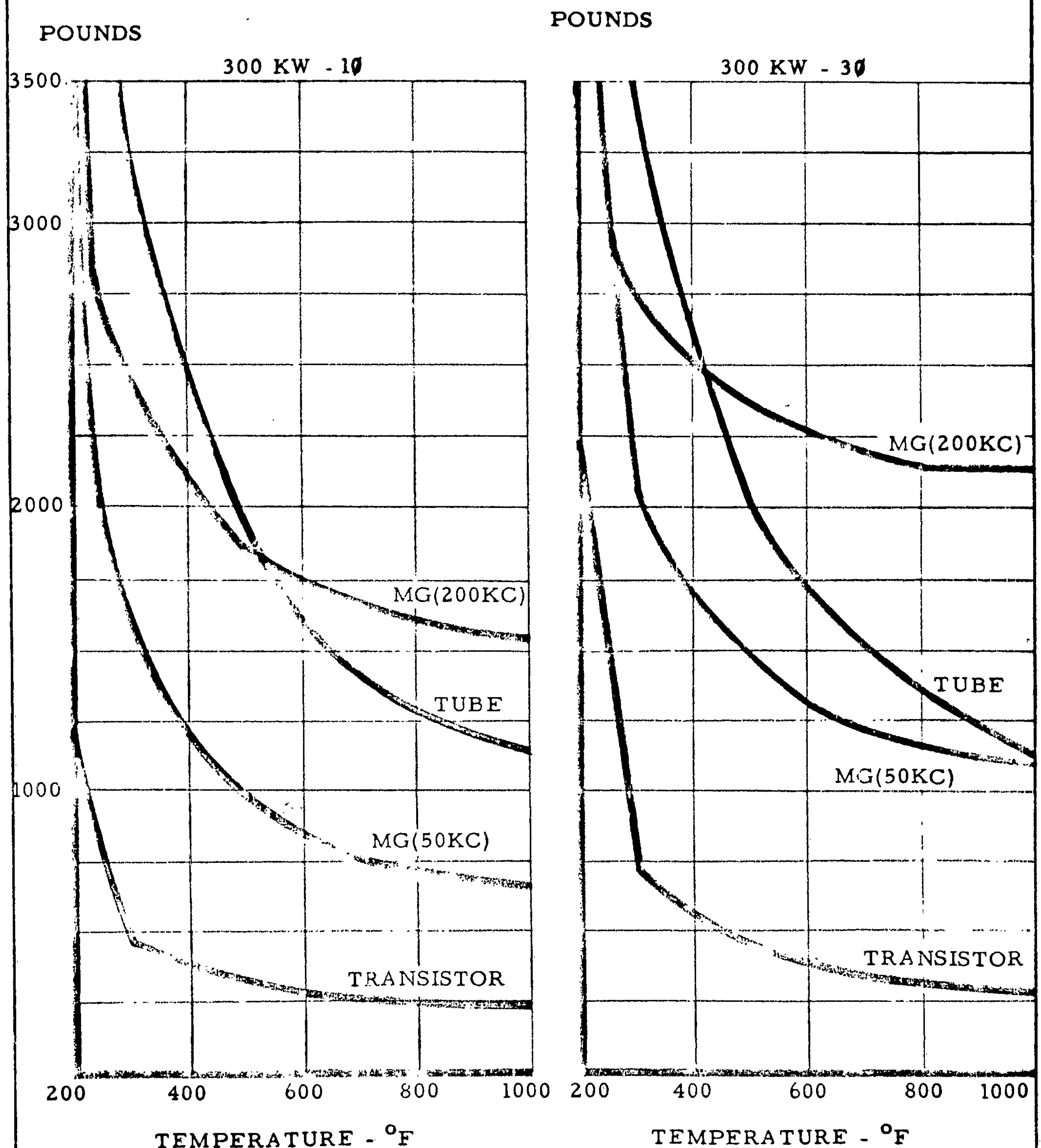


Figure 2.1-6 Analysis of System Weight vs. Temperature for 300 KW Converter

weight for a static (transistor) converter and static (tube) converter, losses in the core significantly affect the system weight and also the system cooling requirements.

2. Verification of the response of power transistors in series and in parallel in a high power chopper circuit. The success of the power chopper circuit is dependent upon how well transistors in parallel share currents equally and this aspect of the converter designs needs experimental analysis.

Recommendations for the remaining portion of the study program are:

1. Concentration of major portion of the design effort on the static (transistor) type of converter.
2. Performance of experiments to determine magnitude of magnetic material losses when used in transformer cores at high frequencies (50 to 800 KC) This would include testing of 10 to 15 small core samples (4 or 5 different types of materials) in core configurations and also in typical reduced-size transformer configurations.
3. Performance of experiments using a limited number of power transistors (10 to 15) in a power chopper circuit to determine the response of these devices in parallel operation.
4. Continued design effort to determine parametric data for the 100 KC high-frequency generator and a refinement of 50 KC and 200 KC data. This will include environment and thermal studies.
5. Summation of material, environment and reliability study information.
6. Completion and submittal of preliminary final report for ASD approval.

3.0 SECOND QUARTER PROGRESS

Second quarter progress has included the following analytic efforts:

1. Conceptual converter designs of the following types:
   a. 60 KW, 1Ø, 50 and 200 KC motor-generator sets.
   b. 60 KW, 1Ø, 50 and 800 KC static (tube) converter units.
   c. 60 KW, 1Ø, 50 and 800 KC static (transistor) converter units.
   d. 300 KW, 1Ø, 50 and 200 KC motor-generator sets.
   e. 300 KW, 1Ø, 50 and 800 KC static (tube) converter units.
   f. 300 KW, 1Ø, 50 and 800 KC static (transistor) converter units.
   g. 60 KW, 3Ø, 50 and 200 KC motor-generator sets.
   h. 60 KW, 3Ø, 50, 200 and 800 KC static (tube) converter units.
   i. 60 KW, 3Ø, 50, 200 and 800 KC static (transistor) converter units.
   j. 300 KW, 1Ø, 50 KC generator for 24,000 RPM turbine drive.
2. Further analysis of the original 60 and 300 KW, 1Ø, 200 KC converter and high-frequency generator designs.
3. Related studies in the following areas:
   a. Materials
   b. Cooling system design
4. Preparation of parametric data, mechanical details, and schematics of the above items for use in this report.

3.1.1 MOTOR-GENERATOR DESIGNS

3.1 CONCEPTUAL CONVERTER DESIGNS

3.1.1 MOTOR GENERATOR

A. A 60 KW UNIT

The design of a motor-generator type of 60 KW converter has been based on:

Input - 60 KW, 1 KC, 43.6/75.8 Volts, 3Ø

Output - 10,100 Volts, 50 - 800 KC, 1Ø and 3Ø

Figure 3.1.1-1 illustrates a particular converter concept in which a solid-rotor type of generator is used to generate high-frequency, high-voltage power. The input frequency of 1 KC for the 60 KW converter requirement gives an operating speed of 30,000 RPM for a 4-pole motor to drive the generator. This speed has been selected for the preliminary design speed.

Parametric data on weight, volume, losses, and efficiency for both 1Ø and 3Ø 60 KW converter designs for several frequencies are tabulated in Tables 3.1.1-1, 3.1.1-2 and 3.2.1-3. The effort to date has been concentrated on single-phase 50 and 200 KC designs, and on a 50 KC three-phase design. Due to the number of poles required in an 800 KC design, the motor-generator concept has not been considered for the 800 KC requirement.

Figure 3.1.1-2 shows mechanical details for a 60 KW, 1Ø, 50 KC unit and Figure 3.1.1-3 shows details of the 200 KC unit.

Since a three-phase generator requires three times as many stator slots as does a single-phase generator, a larger size stator is required for the three-phase generator in order to accommodate the number of slots. In order to limit the rotor stress to the design valve of 60,000 psi, it

NA 63-755-2

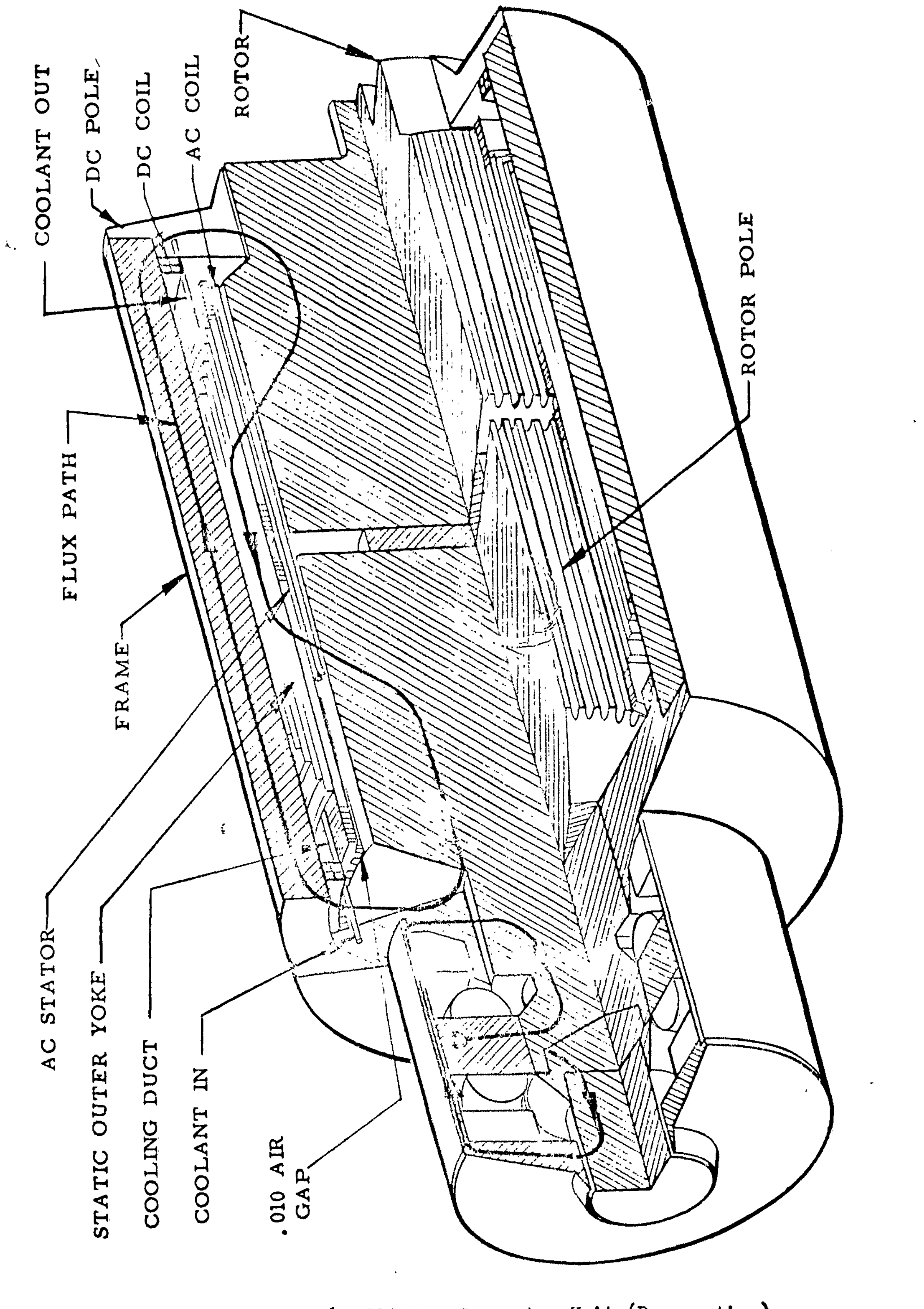


Figure 3.1.1-1 60 KW Motor-Generator Unit (Perspective)

TABLE 3.1.1-1

SUMMARY OF 60 KW MOTOR-GENERATOR PARAMETRIC DATA

1Ø	50 KC	200 KC	800 KC
WEIGHT (lbs)	150	320	--
KW RAD (LOSSES)	10.1	13.5	--
KW OUT	49.9	46.5	--
EFFICIENCY (%)	83.1	77.5	--
LENGTH (inches)	11.5	17.8	--
DIAMETER (inches)	10	12.5	--
VOLUME (cu. ft.)	.52	1.3	--
LBS/KW RAD	13.9	23.7	--
LBS/KW OUT	3.0	6.8	--

3Ø	50 KC	200 KC	800 KC
WEIGHT (lbs)	176	350	--
KW RAD (LOSSES)	10.1	13.8	--
KW OUT	49.9	46.2	--
EFFICIENCY (%)	83.2	77	--
LENGTH (inches)	15.8	22	--
DIAMETER (inches)	9.8	12	--
VOLUME (cu. ft.)	.65	1.4	--
LBS/KW RAD	17.4	25.4	--
LBS/KW OUT	3.5	7.6	--

NOTE: Values do not include cooling system weights.

TABLE 3.1.1-2

60 KW MOTOR-GENERATOR 1Ø DESIGN DATA

CONFIGURATION	50 KC	200 KC
OPERATING SPEED	30,000 RPM	30,000 RPM
WEIGHT (LBS.)		
Motor	60	60
Generator	70	240
Controls	10	10
Cooling (Structure)	5	5
Bearings	5	5
Total (Pounds)	150	320
STATOR LAMINATIONS (.0005")	HYMU 80	HYMU 80
GENERATOR LOSSES (WATTS)		
Stator Iron	1480	1610
Stator I^2R	760	920
Field I^2R	940	3920
Windage (2PSIA)	145	1510
Stray Load 1%	600	600
Total (Watts)	3925	8560
GENERATOR EFFICIENCY %	94	87.5
MOTOR EFFICIENCY %	88.5	88.5
CONVERTER EFFICIENCY %	83.1	77.5
OTHER DATA		
Avg. Stator Tooth Flux Density		
In Kilolines/Sq. Inch.	29.8	15.8
In Gauss	4610	2440
Stator Conductor Current Density		
In Amperes/Square Inch	6400	6400
Field Conductor Current Density		
In Amperes/Square Inch	3500	3500
Conductors	28 Ni-Clad Cu	28 Ni-Clad Cu
Curie Temperature °F	932°F	860°F

TABLES 3.1.1-3

60 KW MOTOR-GENERATOR DESIGN DATA (3Ø)

CONFIGURATION	50 KC 3Ø	200 KC 3Ø
OPERATING SPEED	30,000 RPM	30,000 RPM
WEIGHT (LBS.)		
Motor	60	60
Generator	96	270
Controls	10	10
Cooling (Structure)	5	5
Bearings	5	5
Total (Pounds)	176	350
STATOR LAMINATIONS (.0005")	HYMU 80	HYMU 80
GENERATOR LOSSES (WATTS)		
Stator Iron	595	1975
Stator I^2R	1435	1600
Field I^2R	658	3900
Windage (2PSIA)	265	1700
Stray Load 1%	600	600
Total (Watts)	3553	9775
GENERATOR EFFICIENCY %	94.1	83
MOTOR EFFICIENCY %	88.5	88.5
CONVERTER EFFICIENCY %	83.2	77
OTHER DATA		
Avg. Stator Tooth Flux Density		
In Kilolines/Sq. Inch	21.5	15.8
In Gauss	3330	2440
Stator Conductor Current Density		
In Ampere/Square Inch	4200	6400
Field Conductor Current Density		
In Ampere/Square Inch	3500	3500
Conductors	28 Ni-Clad Cu.	28 Ni-Clad Cu.
Curie Temperature °F	932°F	860°F

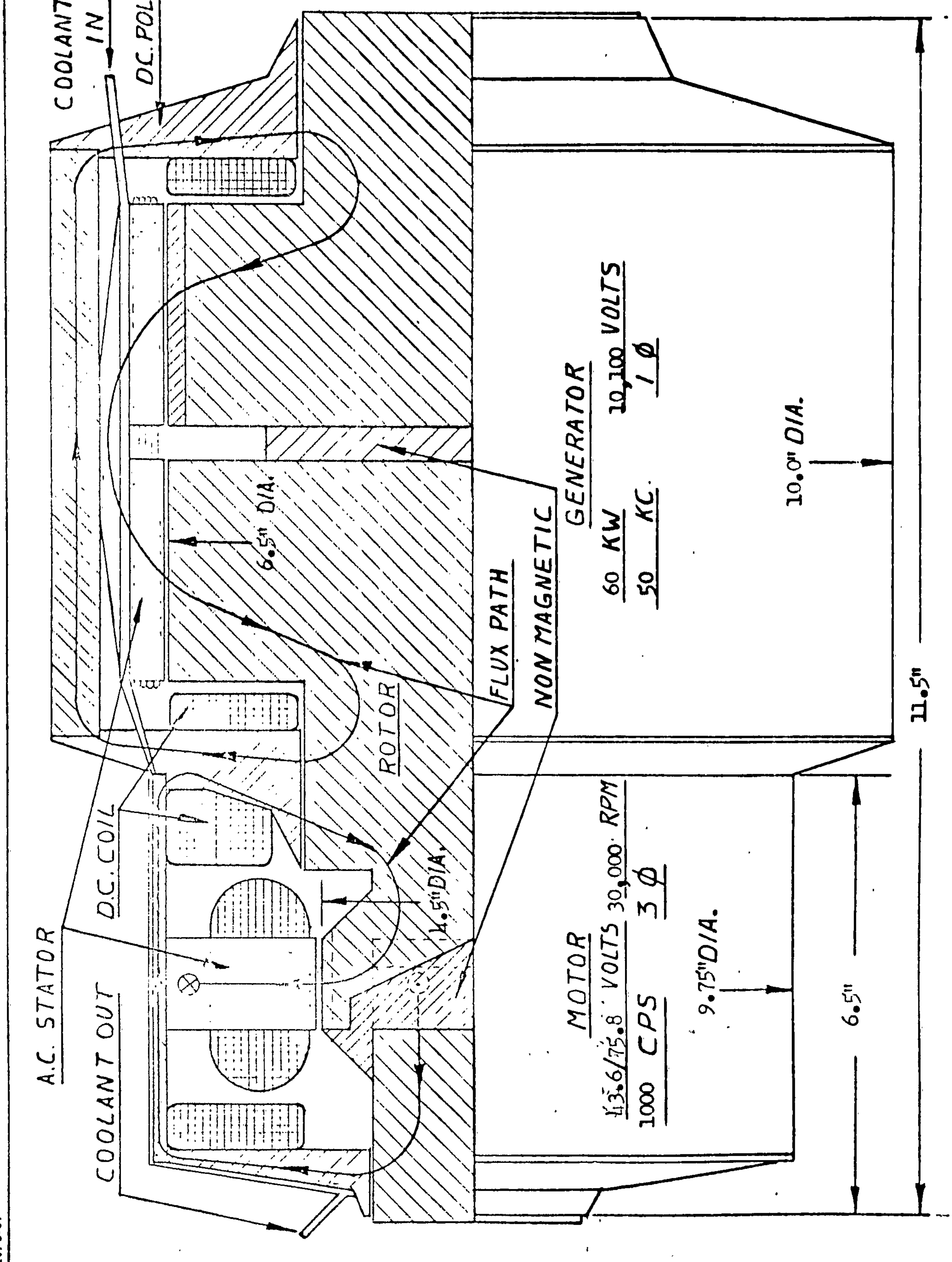


Figure 3.1.1-2 Preliminary Mechanical Design of 60 KW
1 Ø, 50 KC Motor-Generator

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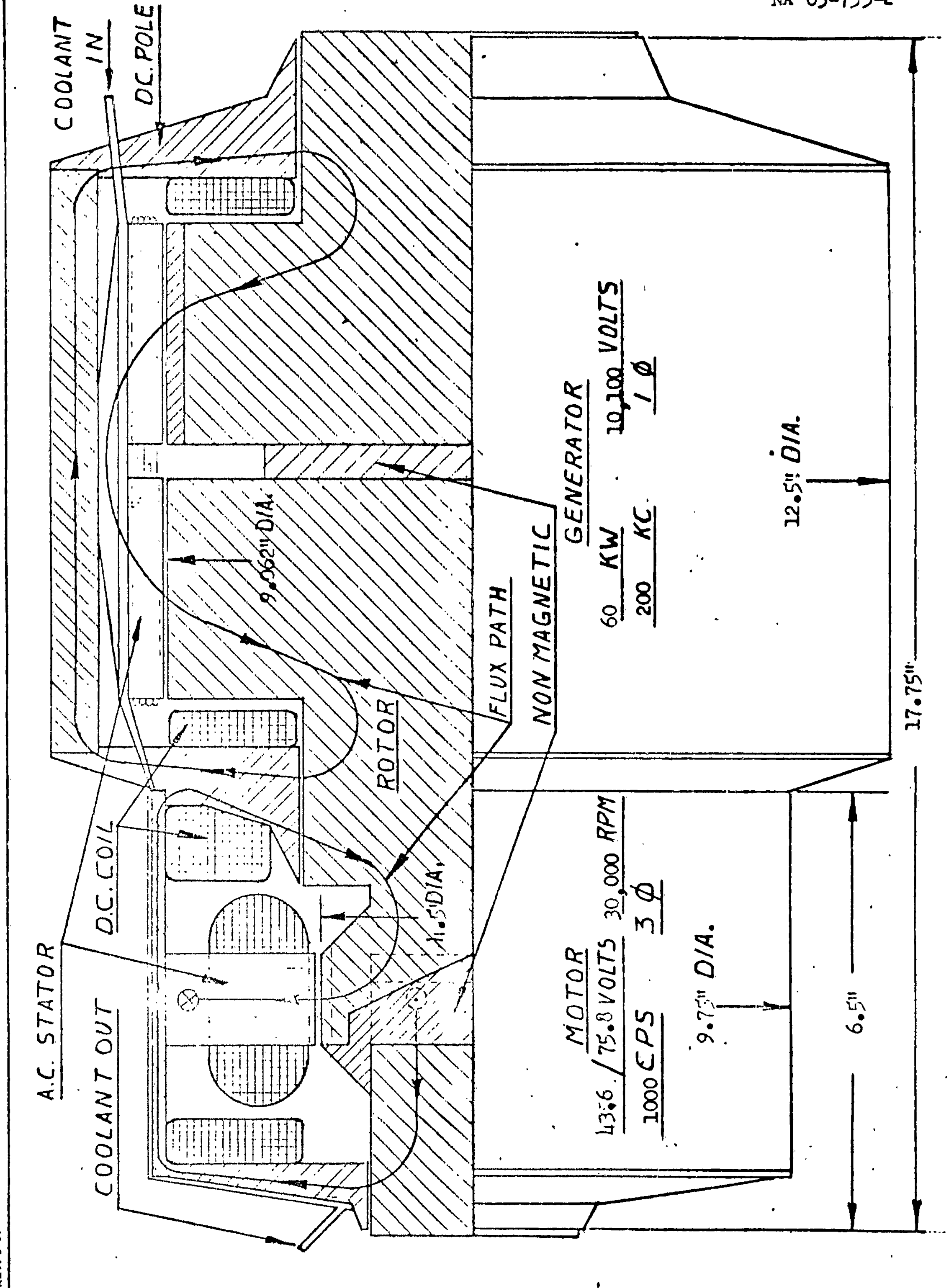

Figure 3.1.1-3 Preliminary Mechanical Design of 60 KW 1 Ø, 200 KC Motor-Generator

is necessary to construct the three-phase generator using a common shaft with three rotor sections on it. There are three separate stators in the design, and the poles of the rotor sections are displaced from each other by 120 electrical degrees. In effect, the three-phase output is achieved by installing three single-phase generators in a common frame with their voltage outputs in parallel, and their phase displacement such as to achieve three-phase power at the output terminals. This concept is illustrated in Figure 3.1.1-4.

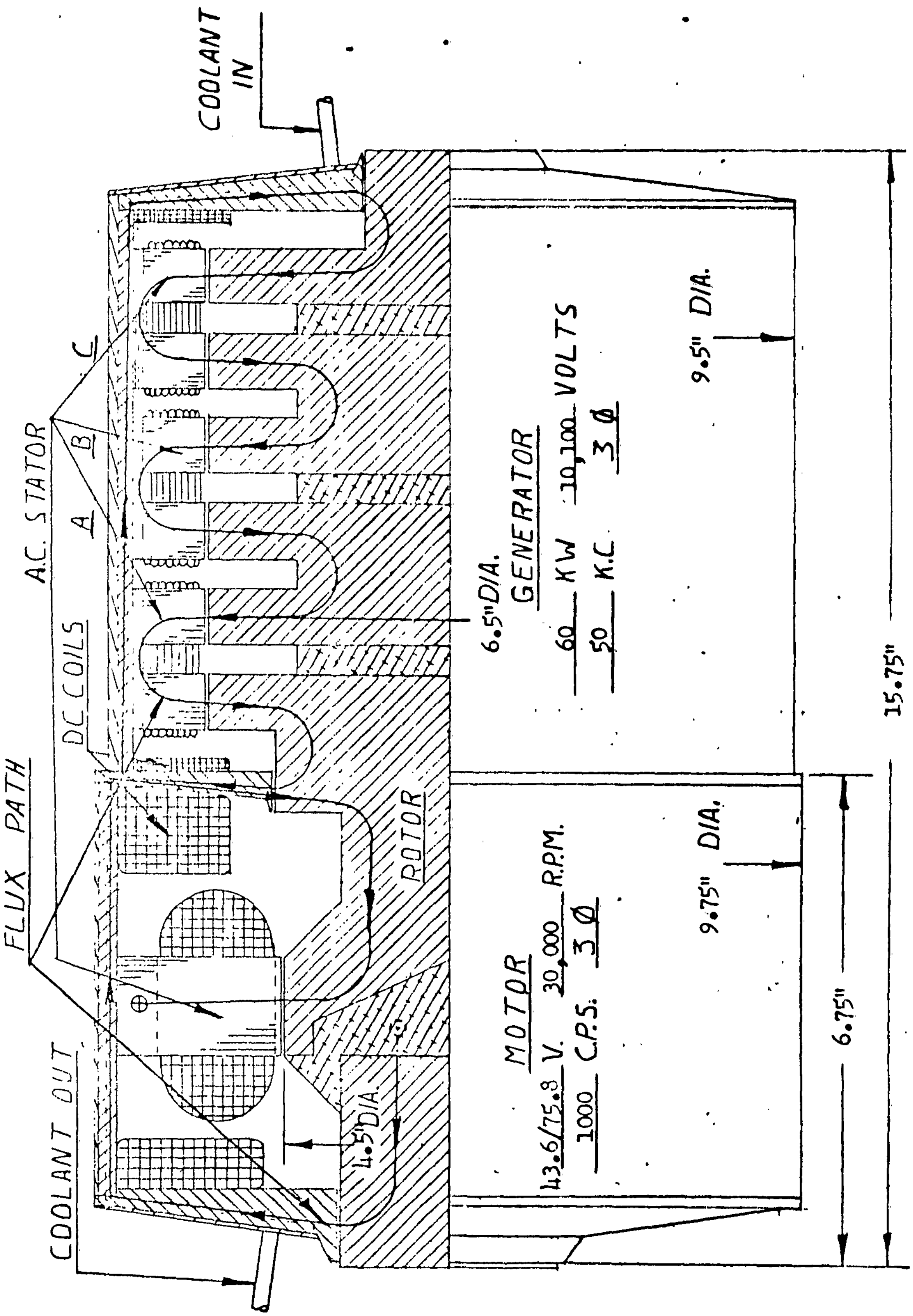

Figure 3.1.1-4 Preliminary Mechanical Design of 60 KW, 3 Ø, 50 KC Motor-Generator

B. A 300 KW UNIT

Design details of a motor generator type of converter unit to meet the 300 KW power conversion requirements of the Work Statement are similar to those of the 60 KW unit as shown in Figure 3.1.1-1. The basic difference other than power handling level is in a different input which is listed as follows:

Input - 300 KW, 3200 CPS, 120/208V, 3Ø

Output - 50 - 200 KC, 10,100 V, 1Ø and 3Ø

As in the case of the 60 KW design a motor-generator unit was not considered for the 800 KC requirement because of the extreme number of poles required for such a unit.

The motor for driving each of the generators is a 120 volt, 3200 CPS, 3Ø synchronous solid-rotor type, turning at 24,000 RPM. Parametric data for a 300 KW converter (1Ø and 3Ø) is summarized in Tables 3.1.1-4. Additional information is shown in Tables 3.1.1-5 and 3.1.1-6.

Mechanical details of 50 KC and 200 KC, 1Ø converters are shown in Figures 3.1.1-5 and 3.1.1-6. Figure 3.1.1-7 shows a 3Ø, 50 KC unit in which three separate generator sections are mounted on a common shaft. The three rotor and stator sections are displaced from each other by 120 electrical degrees to produce a three-phase voltage output.

TABLE 3.1.1-4

SUMMARY OF 300 KW MOTOR-GENERATOR PARAMETRIC DATA

1∅	50 KC	200 KC	800 KC
WEIGHT (lbs)	540	1500	--
KW RAD (LOSSES)	49.5	52.8	--
KW OUT	250.5	247.2	--
EFFICIENCY (%)	83.5	82.4	--
LENGTH (inches)	13.5	35.6	--
DIAMETER (inches)	16.0	17.8	--
VOLUME (cu. ft.)	1.6	5.3	--
LBS/KW RAD	10.9	28.4	--
LBS/KW OUT	2.2	6.0	--

3∅	50 KC	200 KC	800 KC
WEIGHT (lbs)	801	2000	--
KW RAD (LOSSES)	48.6	60	--
KW OUT	251.4	240	--
EFFICIENCY (%)	83.8	80	--
LENGTH (inches)	26.5	70	--
DIAMETER (inches)	11	14	--
VOLUME (cu. ft.)	1.5	6.2	--
LBS/KW RAD	16.5	33.3	--
LBS/KW OUT	3.2	8.3	--

NOTE: Values do not include cooling system weights.

TABLE 3.1.1-5

300 KW MOTOR-GENERATOR DESIGN DATA (1Ø)

CONFIGURATION	50 KC 1Ø	200 KC 1Ø
OPERATING SPEED	24,000 RPM	24,000 RPM
WEIGHT (LBS.)		
Motor	175	175
Generator	340	1300
Controls	11	11
Cooling (Structure)	7	7
Bearings	7	7
Total (Pounds)	540	1500
STATOR LAMINATIONS (.0005")	HYMU 80	HYMU 80
GENERATOR LOSSES (WATTS)		
Stator Iron	10900	5600
Stator I^2R	2370	6430
Field I^2R	1285	3640
Windage (2PSIA)	633	4650
Stray Load 1%	3000	3000
Total (Watts)	18188	23320
GENERATOR EFFICIENCY %	94.4	93.2
MOTOR EFFICIENCY %	88.5	88.5
CONVERTER EFFICIENCY %	83.5	82.4
OTHER DATA		
Avg. Stator Tooth Flux Density	29.8	15.8
In Kilolines/Square Inch		
In Gauss	4,460	2,440
Stator Conductor Current Density	6,400	6,400
In Amperes/Square Inch		
Field Conductor Current Density		
In Amperes/Square Inch	3,500	3,500
Conductors	28 Ni-Clad Cu	28 Ni-Clad Cu.
Curie Temperature °F	932	932

TABLE 3.1.1-6

300 KW MOTOR-GENERATOR DESIGN DATA (3Ø)

CONFIGURATION	50 KC 3Ø	200 KC 3Ø
OPERATING SPEED	24,000 RPM	24,000 RPM
WEIGHT (LBS.)		
Motor	175	175
Generator	601	1800
Controls	11	11
Cooling (Structure)	7	7
Bearings	7	7
Total (Pounds)	801	2000
STATOR LAMINATIONS (.0005")	HYMU 80	HYMU 80
GENERATOR LOSSES (WATTS)		
Stator Iron	4020	12655
Stator I^2R	6520	6800
Field I^2R	1240	1250
Windage	1295	1295
Stray Load 1%	3000	3000
Total (Watts	16075	25000
GENERATOR EFFICIENCY %	94.6	91.6
MOTOR EFFICIENCY %	88.5	88.5
CONVERTER EFFICIENCY %	83.8	80
OTHER DATA		
Avg. Stator Tooth Flux Density In Kilolines/Sq. Inch	21.21	15.8
In Gauss	3300	2440
Stator Conductor Current Density in Amperes/Sq. Inch	6400	6400
Field Conductor Current Density In Amperes/Square Inch	3500	3500
Conductors	28 Ni-Clad Cu.	28 Ni-Clad Cu.
Curie Temperature °F	932°F	932°F

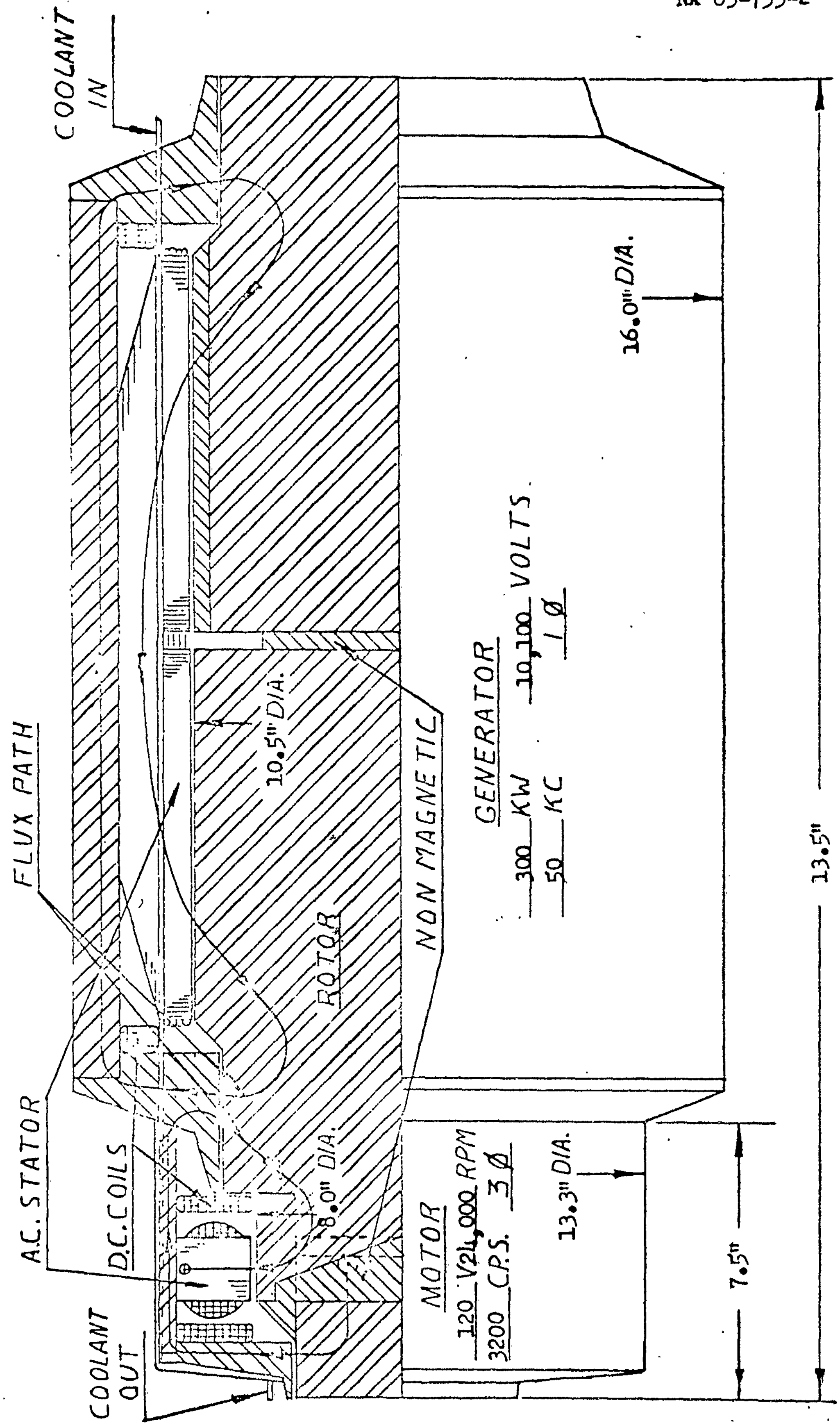

Figure 3.1.1-5 Preliminary Mechanical Design of 300 KW, 1 Ø, 50 KC Motor-Generator

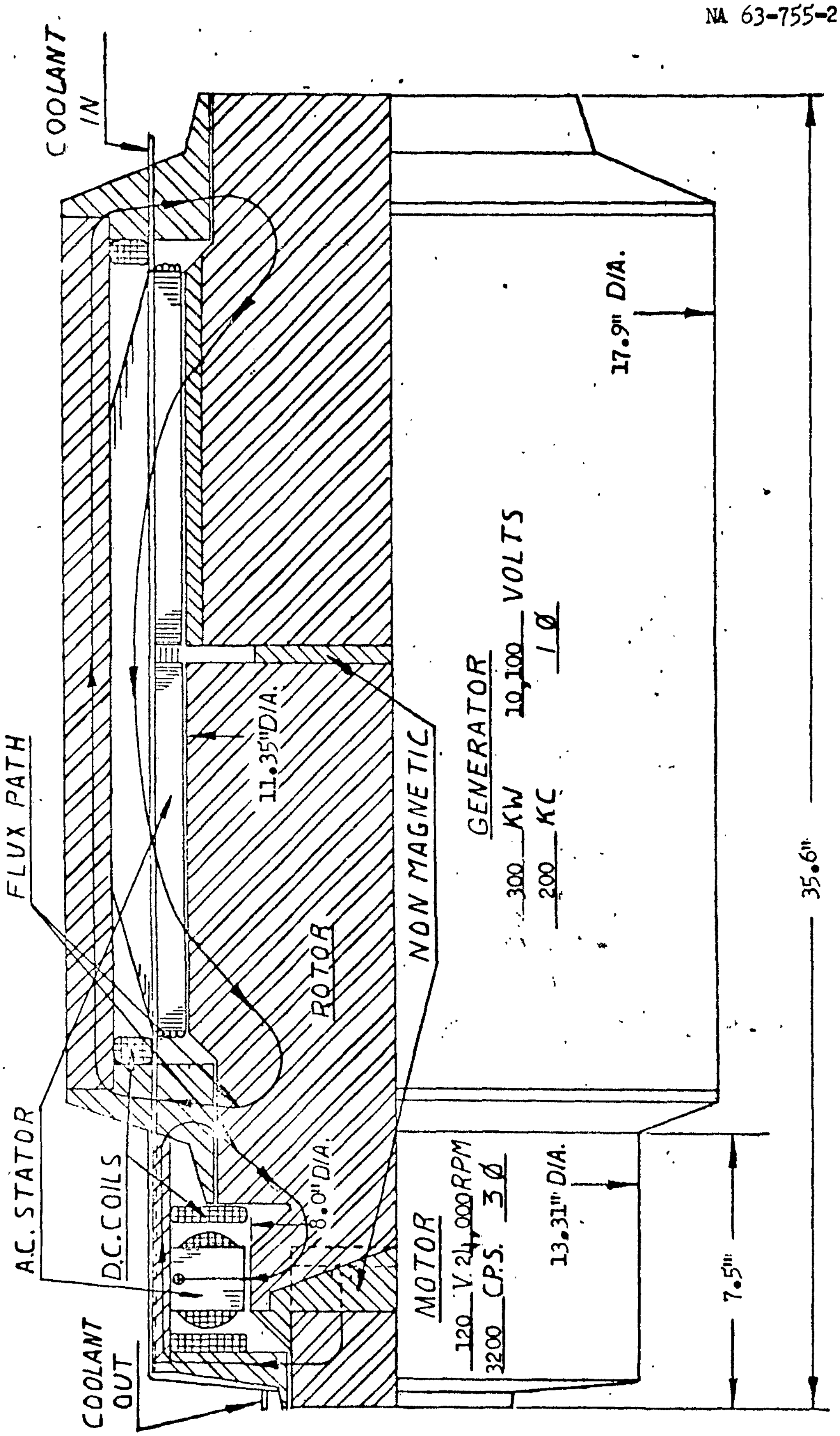

Figure 3.1.1-6 Preliminary Mechanical Design of 300 KW 1 Ø, 200 KC Motor-Generator

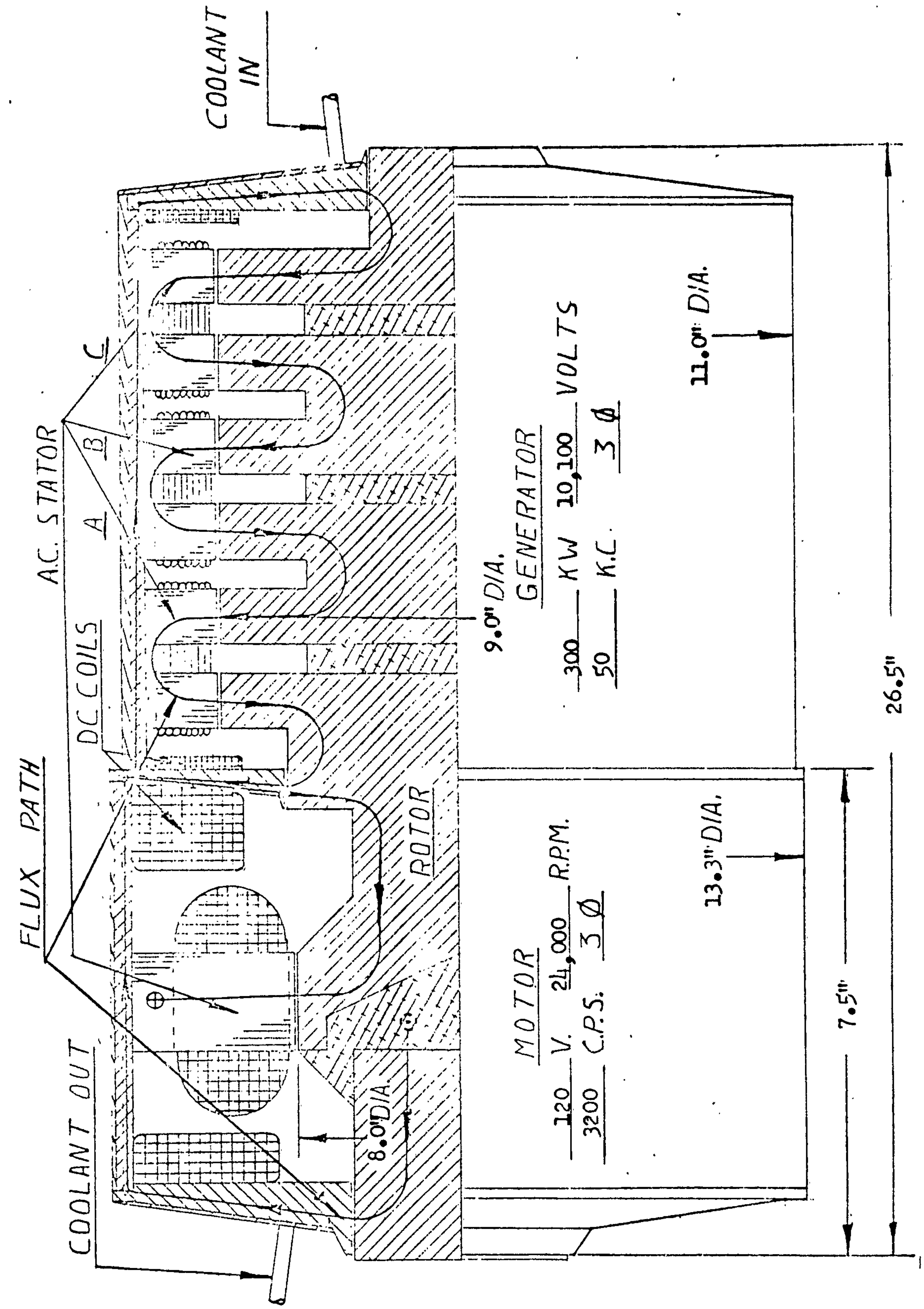

Figure 3.1.1-7 Preliminary Mechanical Design of 300 KW, 3 Ø, 50 KC Motor-Generator

C. THERMAL DESIGN

The cooling system of the motor-generator unit is made up of thin parallel tubing located in the stator yoke. The parallel tubes converge into a collection ring at each end. Heat is removed from the stator by means of conduction to the coolant which is pumped through the system and to the radiators for dissipation to space.

Motor-generator units are capable of operating at temperatures above 1000°F. However, most of the designs considered here are based on coolant temperatures in the 500°F to 800°F range. Figure 3.1.1-8 shows the effect of system motor generator on system weight for a 60 KW unit and Figure 3.1.1-9 shows the same type of data for a 300 KW unit. Computed efficiences in the summary tables are based on loss calculations for HYMU 80 materials of lamination thicknesses listed.

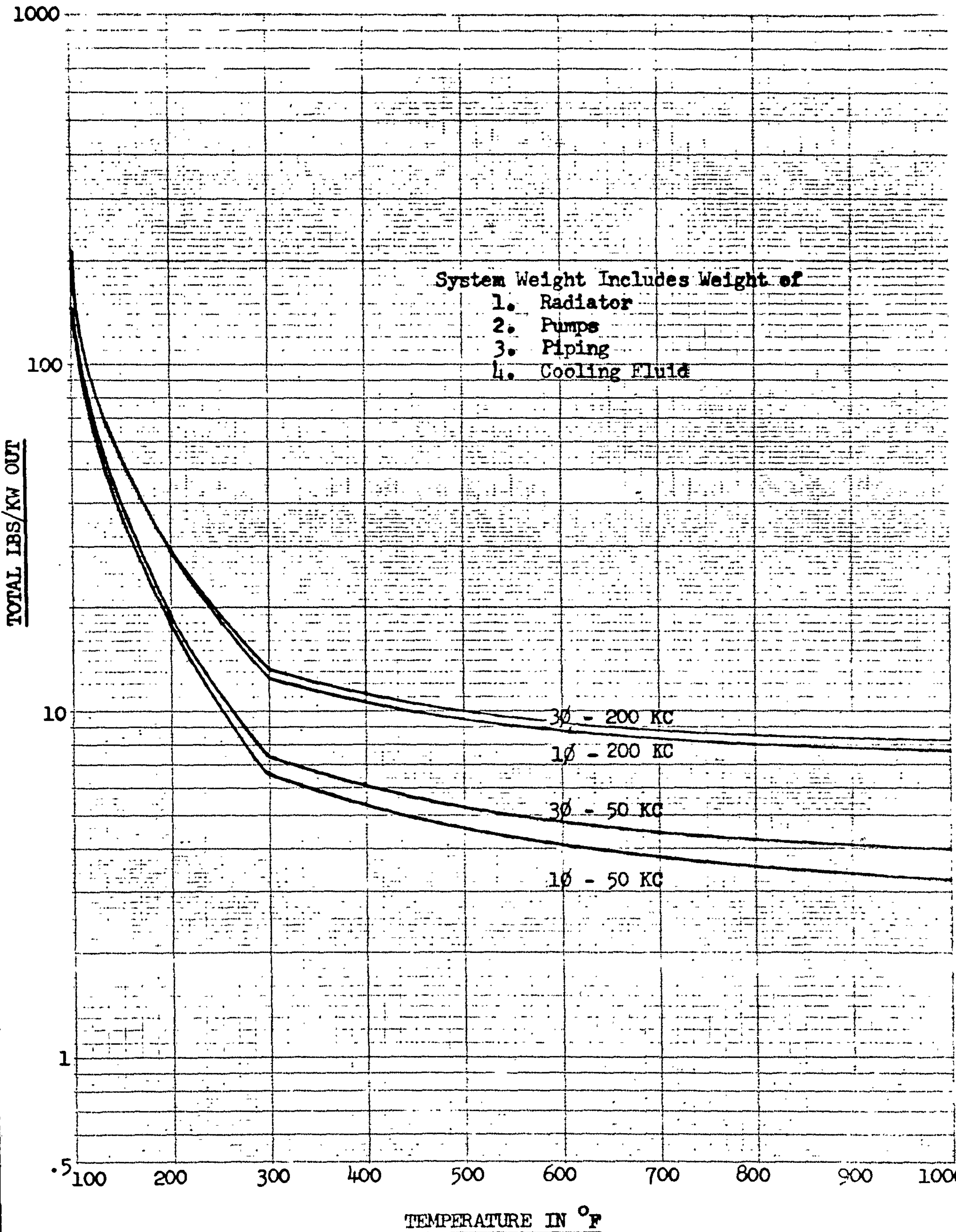

Figure 3.1.1-8 Analysis of System Weight vs Temperature for 60 KW Motor Generator

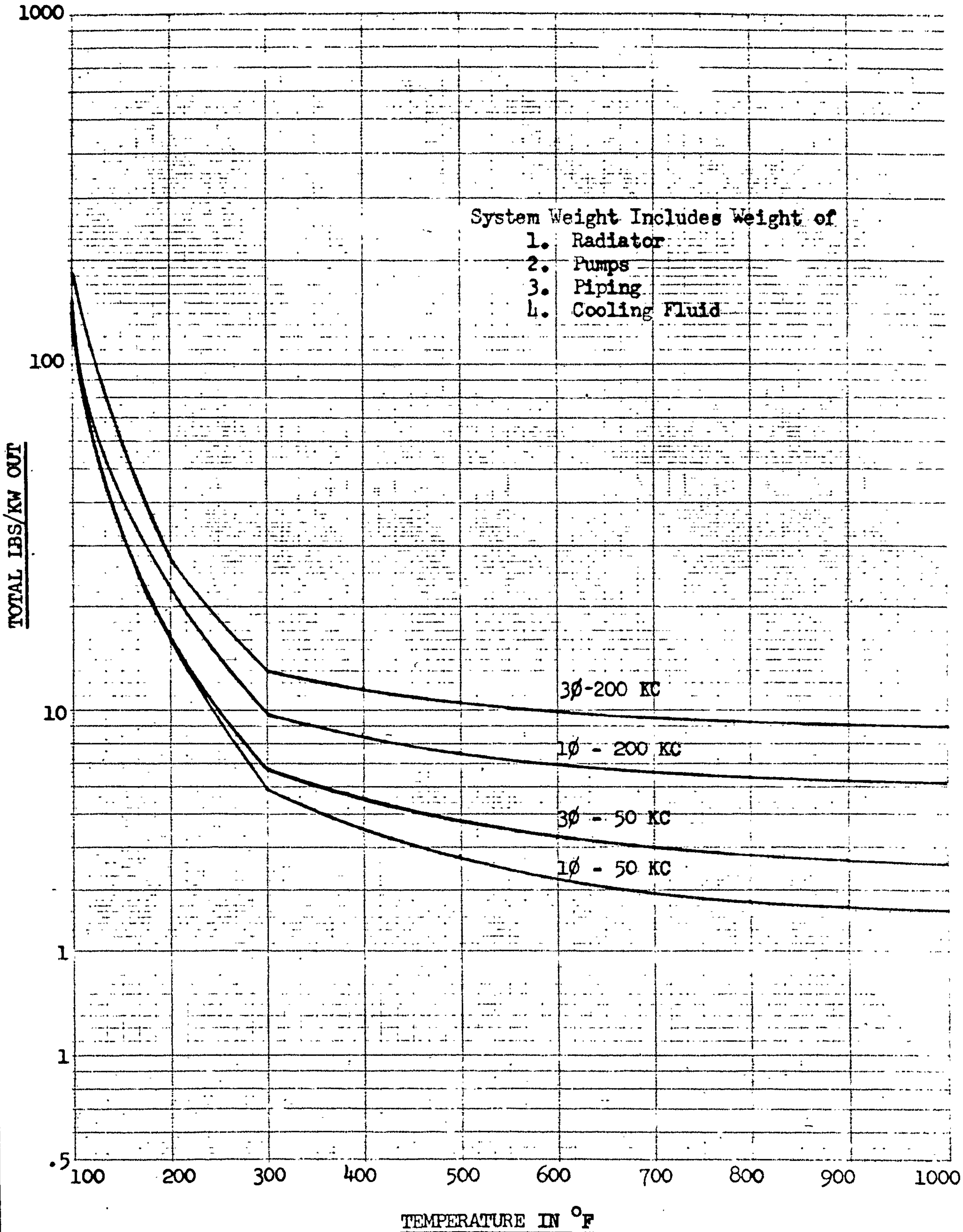

Figure 3.1.1-9 Analysis of System Weight vs Temperature for 300 KW Motor Generator

3.1.2 STATIC (TUBE) CONVERTER DESIGNS

3.1.2 STATIC (TUBE) CONVERTER DESIGNS

A. A 60 KW UNIT

One design concept for a 60 KW (input) static converter unit to meet the high-frequency, high-voltage requirements of the Work Statement involves use of a vacuum tube type of r-f generator. A particular single-phase concept is shown in Figure 3.1.2-1. The system is fairly simple and involves use of a ceramic type power oscillator tube operating in Class C mode to generate 50 - 800 KC output in a resonant tank circuit. Transfer of high-frequency, high-voltage power to the single-phase load can be accomplished through a matching transformer. Weights, volumes, and efficiencies are shown in Tables 3.1.2-1 and 3.1.2-2 for a single-phase concept.

The high-voltage plate power for the oscillator tube is furnished by a typical series three-phase (quadrature operation) power supply composed of a high-voltage plate transformer, three thyratrons and three diodes. The D-C output from the power supply is filtered and applied to the oscillator tube plate through two r-f chokes (L1 & L2) which also serve as r-f isolators. Control of the grid circuit of the gas thyratrons (T1, T2, & T3) is provided by a phase-shifter technique which allows adjustment of the plate voltage and current to the oscillator. The net result is a means of varying the power output to the load.

A three-phase concept is shown in Figure 3.1.2-2. As can be seen from the figure, the three-phase concept involves a phase shifting of the output from a typical single-phase output into a composite three-phase output. This is done by a capacitive and resistive network.

TABLE 3.1.2-1

SUMMARY OF 60 KW STATIC (TUBE) CONVERTER PARAMETRIC DATA

1Ø	50 KC	200 KC	800 KC
WEIGHT (lbs)	358	347	345
KW RAD (LOSSES)	18.9	19.5	19.9
KW OUT	41.2	40.5	40.1
EFFICIENCY (%)	68.6	67.5	66.9
LENGTH (inches)	26	26	26
WIDTH (inches)	19	19	19
HEIGHT (inches)	38	38	38
VOLUME (cu. ft.)	10.9	10.9	10.9
LBS/KW RAD	18.9	17.7	17.2
LBS/KW OUT	8.7	8.5	8.5

3Ø	50 KC	200 KC	800 KC
WEIGHT (lbs)	363	353	349
KW RAD (LOSSES)	18.8	20.0	21.8
KW OUT	41.2	39.9	38.2
EFFICIENCY (%)	68.7	66.6	63.7
LENGTH (inches)	34	34	34
WIDTH (inches)	23	23	23
HEIGHT (inches)	39	39	39
VOLUME (cu. ft.)	17.7	17.7	17.7
LBS/KW RAD	19.3	17.8	16.0
LBS/KW OUT	8.8	8.9	9.1

NOTE: VALUES DO NOT INCLUDE COOLING SYSTEM WEIGHT

NA-63-755-2

TABLE 3.1.2-2

PRELIMINARY COMPONENT LIST FOR A 60 KW STATIC CONVERTER (TUBE) (1Ø)

NO.	COMPONENTS	50 KC WT	50 KC LOSSES	200 KC WT	200 KC LOSSES	800 KC WT	800 KC LOSSES
	POWER SUPPLY (HIGH VOLTAGE)						
1	High Voltage Transformer (X7) 1 KC, 3Ø, 60 KW	114	640	114	640	114	640
1	Magnetic Switch	10	100	10	100	10	100
3	Filament Transformers (X1, X2 & X3)	9	6	9	6	9	6
3	Filament Transformers (X4, X5 & X6)	8	12	8	12	8	12
3	Thyratrons (T1, T2, & T3)	3	1800	3	1800	3	1800
3	Diodes (T4, T5 & T6)	3	378	3	378	3	378
	OSCILLATOR SECTION						
1	Oscillator Tube (T7) 80% x 56 KW	45	11,200	45	11,200	45	11,200
1	Filament Transformer (X9)	5	105	5	105	5	105
1	Phase Shifter	15	100	15	100	15	100
2	Filter Choke (L1 & L2)	9	3200	9	3200	9	3200
1	Filter Capacitor (C1)	3	--	3	--	3	--
2	Coupling Capacitors (C2 & C3)	4	120	4	120	4	120
2	Neutralizing Capacitors (C4 & C5)	1	--	1	--	1	--
1	Tank Coil Capacitor (Ct)	2	60	2	60	2	60
5	Resistors (R1, R2, R3, R4, R5)	2	--	2	--	2	--
1	Tank Coil	2	100	3	100	3	100
	OUTPUT SECTION						
1	Matching Transformer (X8) 60 KW, 1Ø	17	1030	6	1650	4	2050
	MISCELLANEOUS						
-	Mounting structure	80	--	80	--	80	--
-	Cooling Ducts	5	--	5	--	5	--
-	Controls	10	--	10	--	10	--
-	Wire and Hardware	10	--	10	--	10	--
	TOTALS	358#	18851 Watts	347#	19471 Watts	345#	19871 Watts

FORM 10-G-1 REV. 6-41

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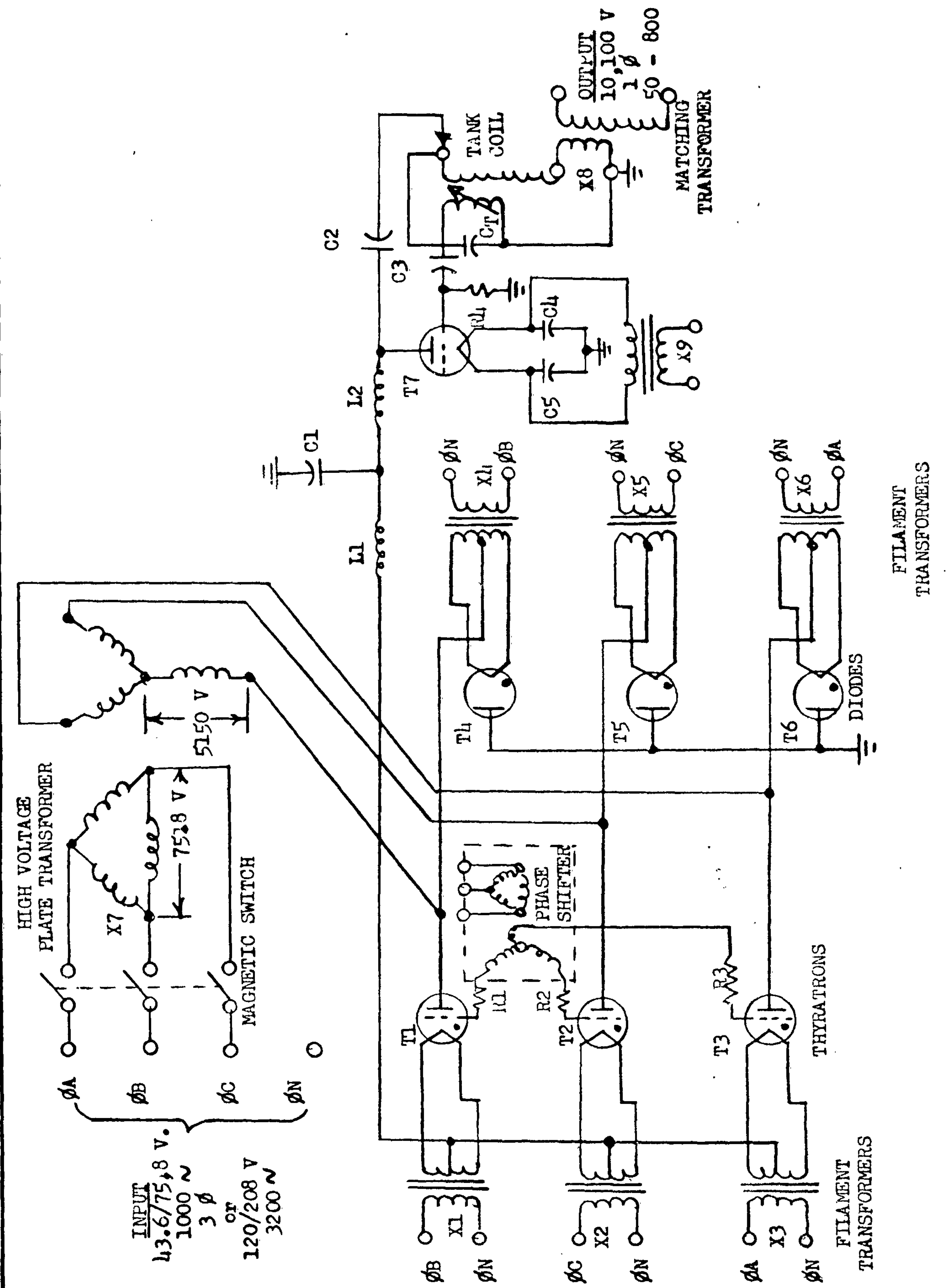

FIGURE 3.1.2-1
Preliminary Schematic of Static (Tube) Converter (1Ø)

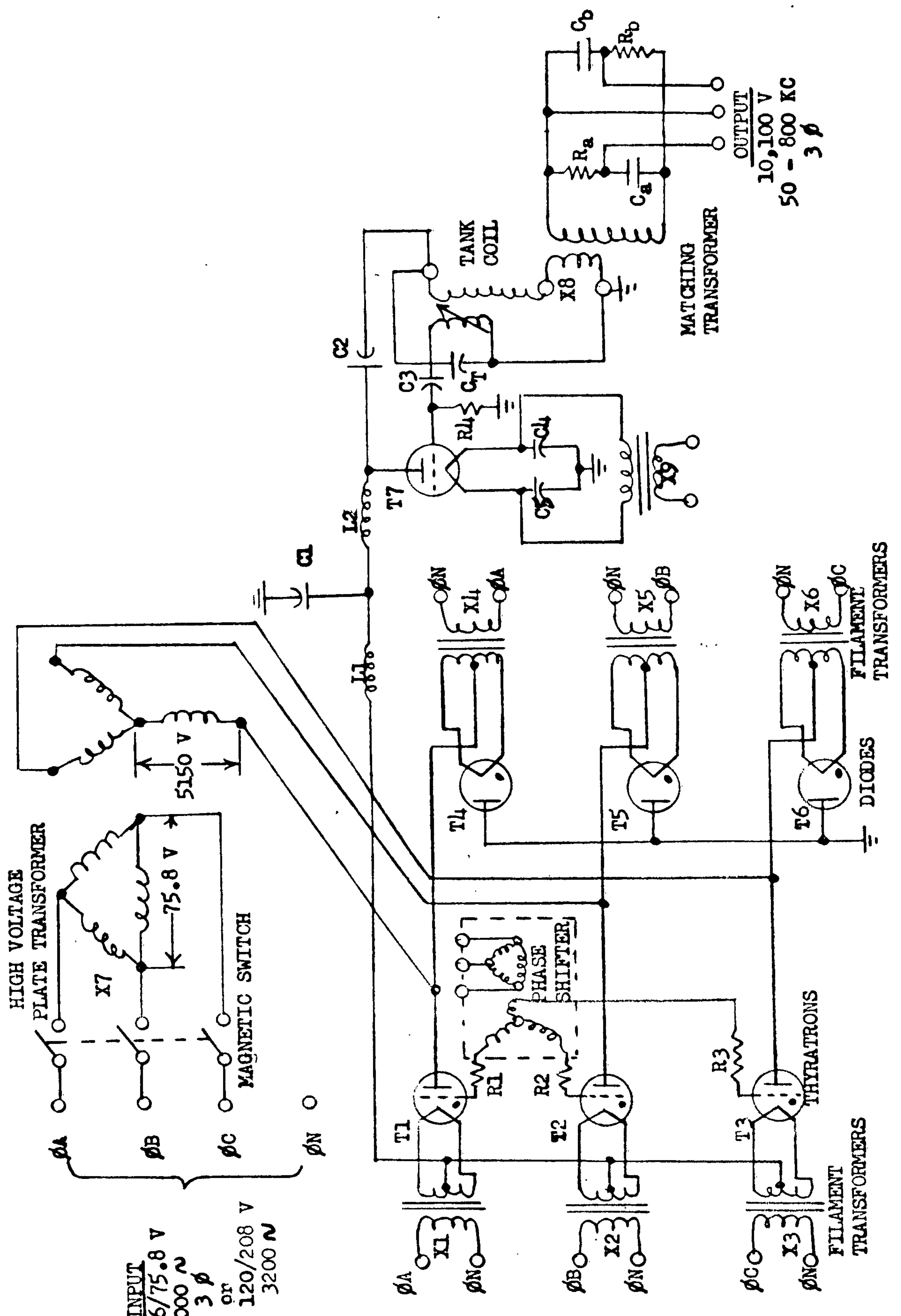

Figure 3.1.2-2
Preliminary Schematic of Static (Tube) Converter (3∅)

Ø A of the output waveform is derived directly from the inverted waveform (+ 180 degrees) of the transformer secondary. Ø B is shifted -60 degrees electrically and Ø C is shifted + 60 degrees electrically. The three outputs then form a composite three-phase voltage for use in the load. Power consumed in the phase-shifting capacitors and resistances is fairly low because of the low-current, high-voltage output requirement.

Weights, volumes, and efficiencies for a three-phase converter are summarized in Table 3.1.2-3. To be noted is the fact that weights and volumes for the three-phase unit are not much greater than those for the single-phase unit.

NA-63-755-2

TABLE 3.1.2-3

PRELIMINARY COMPONENT LIST FOR A 60 KW STATIC (TUBE) CONVERTER (3Ø)

		50 KC		200 KC		800 KC	
NO.	COMPONENT	WT	LOSSES	WT	LOSSES	WT	LOSSES
	POWER SUPPLY (HIGH VOLTAGE)						
1	High Voltage Transformer (X7) 1 KC, 3Ø, 60 KW	114	640	114	640	114	640
1	Magnetic Switch	10	100	100	100	10	100
3	Filament Transformer (X1, X2 & X3)	9	6	9	6	9	6
3	Filament Transformer (X4, X5, X6)	8	12	8	12	8	12
3	Thyratrons (T1, T2 & T3)	3	1800	3	1800	3	1800
3	Diodes (T4, T5 & T6)	3	380	3	380	3	380
	OSCILLATOR SECTION						
1	Oscillator Tube (T7) 80% x 56 KW	45	11,200	45	11,200	45	11,200
1	Filament Transformer (X9)	5	100	5	100	5	100
1	Phase Shifter	15	100	15	100	15	100
2	Filter Choke (L1 & 12)	9	3200	9	3200	9	3200
1	Filter Capacitor (C1)	3	--	3	--	3	--
2	Coupling Capacitors (C2 & C3)	4	120	4	120	4	120
2	Neutralizing Capacitors (C4 & C5)	1	--	1	--	1	--
1	Tank Coil Capacitor (CT)						
5	Resistors	2	--	2	--	2	--
1	Tank Coil	3	100	3	100	3	100
	OUTPUT SECTION						
1	Matching Transformer	17	907	7	2180	3	3920
2	Resistors	1	10	1	10	1	8
2	Capacitors	4	25	4	25	4	25
	MISCELLANEOUS						
--	Mounting Structure	80	--	80	--	80	--
--	Cooling Ducts	5	--	5	--	5	--
--	Controls	10	--	10	--	10	--
--	Wire and Hardware	10	--	10	--	10	--
	TOTALS	363 #	18,760 Watts	353#	20,033 Watts	349#	21,773 Watts

FORM 16-6-1 REV. 6-41

B. A 300 KW UNIT

The design of a single-phase 300 KW (input) static (tube) converter unit is based on the same schematic (Figure 3.1.2-1) as the 60 KW unit with a higher power input level being the major difference. Power input to this converter unit is also at a different voltage and frequency - 120/208 volts at 3200 cps rather than the 43.6/75.8 volts at 1000 cps of the 60 KW unit. Weights, volumes, and efficiencies for a 300 KW unit are summarized in Tables 3.1.2-4 and 3.1.2-5.

A three-phase concept is shown in Figure 3.1.2-2. This concept also involves use of the single-phase concept with the addition of a phase-shifting network composed of resistors and capacitors. At the present time we are not sure of the power-handling capabilities of this phase-shifting network at the 300 KW level. It appears feasible because of the fact that the power is at a high-voltage, low-current level and I^2R losses should not be too great.

Output to the load is from a 3Ø transformer. Control of the output power is through the individual grid circuits of each of the thyratrons of the power supply section where voltage and plate current to the oscillator can be raised or lowered. Components of a 300 KW, 3Ø system plus weights, volumes, and efficiencies are summarized in Table 3.1.2-6 for each of three frequencies.

TABLE 3.1.2-4

SUMMARY OF 300 KW STATIC (TUBE) CONVERTER PARAMETRIC DATA

1Ø	50 KC	200 KC	800 KC
WEIGHT (lbs)	577	555	549
KW RAD (LOSSES)	91.2	92.6	91.4
KW OUT	208.8	207.4	208.6
EFFICIENCY (%)	69.6	69.1	69.5
LENGTH (inches)	26	26	26
WIDTH (inches)	19	19	19
HEIGHT (inches)	38	38	38
VOLUME (cu. ft.)	10.9	10.9	10.9
LBS/KW RAD	6.3	6.0	6.0
LBS/KW OUT	2.8	2.7	2.6

3Ø	50 KC	200 KC	800 KC
WEIGHT (lbs)	592	573	562
KW RAD (LOSSES)	91.5	94.3	94.1
KW OUT	208.6	205.7	205.9
EFFICIENCY (%)	69.5	68.6	68.7
LENGTH (inches)	34	34	34
WIDTH (inches)	23	23	23
HEIGHT (inches)	38	38	38
VOLUME (cu. ft.)	17.2	17.2	17.2
LBS/KW RAD	6.5	6.1	6.0
LBS/KW OUT	2.8	2.8	2.7

NOTE: Weight figures do not include cooling system weight

NA-63-755-2

TABLE 3.1.2-5

PRELIMINARY COMPONENT LIST FOR A 300 KW STATIC (TUBE) CONVERTER (1Ø)

NO.	COMPONENT	50 KC WT	50 KC LOSSES	200 KC WT	200 KC LOSSES	800 KC WT	800 KC LOSSES
	POWER SUPPLY (HIGH VOLTAGE)						
1	Plate Transformer X7 3.2 KC, 3Ø, 300 KW	99	8350	99	8350	99	8350
1	Magnetic Swtich	30	200	30	200	30	200
3	Filament Transformer	15	48	15	48	15	48
3	Filament Transformer	12	18	12	18	12	18
3	Thyratrons	12	14,000	12	14,000	12	14,000
3	Diodes	6	495	6	495	6	495
	OSCILLATOR SECTION						
1	Oscillator Tube 80% x 290 KW	140	58,000	140	58,000	140	58,000
1	Filament Transformer	12	240	12	240	12	240
1	Phase Shifter	15	200	15	200	15	200
2	Filter Choke	35	7,100	35	7,100	35	7,100
1	Filter Capacitor	4	--	4	--	4	--
2	Coupling Capacitor	4	600	4	600	4	600
2	Neutralizing Capacitor	2	--	2	--	2	--
1	Tank Coil Capacitor	2	300	2	300	2	300
	Resistors	2	--	2	--	2	--
1	Tank Coil	10	250	10	250	10	250
	OUTPUT SECTION						
1	Matching Transformer (X8) 1Ø, 300 KW	36	1377	14	2796	86	1638
	MISCELLANEOUS						
-	Mounting Structure	90	--	90	--	90	--
-	Cooling Ducts	21	--	20	--	20	--
-	Controls	10	--	10	--	10	--
-	Wire and Hardware	20	--	20	--	20	--
	TOTALS	577#	91,178 Watts	555#	92,597 Watts	549#	91,439 Watts

FORM 10-6-1 REV. 8-41

NA-63-755-2

TABLE 3.1.2-6

PRELIMINARY COMPONENT LIST FOR A 300 KW STATIC (TUBE) CONVERTER (3Ø)

NO.	COMPONENT	50 KC WT	50 KC LOSSES	200 KC WT	200 KC LOSSES	800 KC WT	800 KC LOSSES
	POWER SUPPLY (HIGH VOLTAGE)						
1	Plate Voltage Transformer	99	8350	99	8350	99	8350
1	Magnetic Swtich	30	200	30	200	30	200
3	Filament Transformer	15	48	15	48	15	48
3	Filament Transformer	12	18	12	18	12	18
3	Thyratrons	12	14,000	12	14,000	12	14,000
3	Diodes	6	495	6	495	6	495
	OSCILLATOR SECTION						
1	Oscillator Tube	140	58,000	140	58,000	140	58,000
1	Filament Transformer	12	240	12	240	12	240
1	Phase Shifter	15	200	15	200	15	200
2	Filter Choke	35	7,100	35	7,100	35	7,100
1	Filter Capacitor	4	--	4	--	4	--
2	Coupling Capacitor	4	600	4	600	4	600
2	Neutralizing Capacitor	2	--	2	--	2	--
1	Tank Coil Capacitor	2	300	2	300	2	300
	Resistors	2	--	2	--	2	--
1	Tank Coil	10	250	10	250	10	250
	OUTPUT SECTION						
1	Matching Transformer	38	1460	19	4240	7	3920
2	Resistors	4	100	4	150	5	200
2	Capacitors	4	120	4	120	4	120
	MISCELLANEOUS						
--	Mounting Structure	90	--	90	--	90	--
--	Cooling Ducts	21	--	21	--	21	--
--	Controls	15	--	15	--	15	--
--	Wire and Hardware	20	--	20	--	20	--
	TOTALS	592 #	91,481 Watts	573#	94,311 Watts	562#	94,041 Watts

C. THERMAL DESIGN

Most triode tubes operating in Class C mode are up to 80% efficient and such efficiency is assumed in this converter unit. Ceramic-type tubes with exceptionally low driving power are being developed and some have capabilities up to 400°F maximum.

Figures 3.1.2-3 and 3.1.2-4 show the total lbs/KW out for both single-phase and three-phase converter, 60 KW and 300 KW, at 50 KC, 200 KC, and 800 KC frequency levels. The plotted curve indicates the system weight incurred at various temperature levels. Since the tube system is limited by temperature, the system operating point, as far as system weight is concerned, is at the maximum tube operating temperature (400°F).

Design of the cooling system considers internal cooling ducts for each tube (or coolant jacket) and use of rugged ceramic tube types. Cold-plate shelving for cooling all the other components is also considered in addition to internal cooling ducts for each of the transformers. The possibility of using a liquid bath cooling technique, enclosing all the gas tubes and maintaining a common operating temperature has been considered.

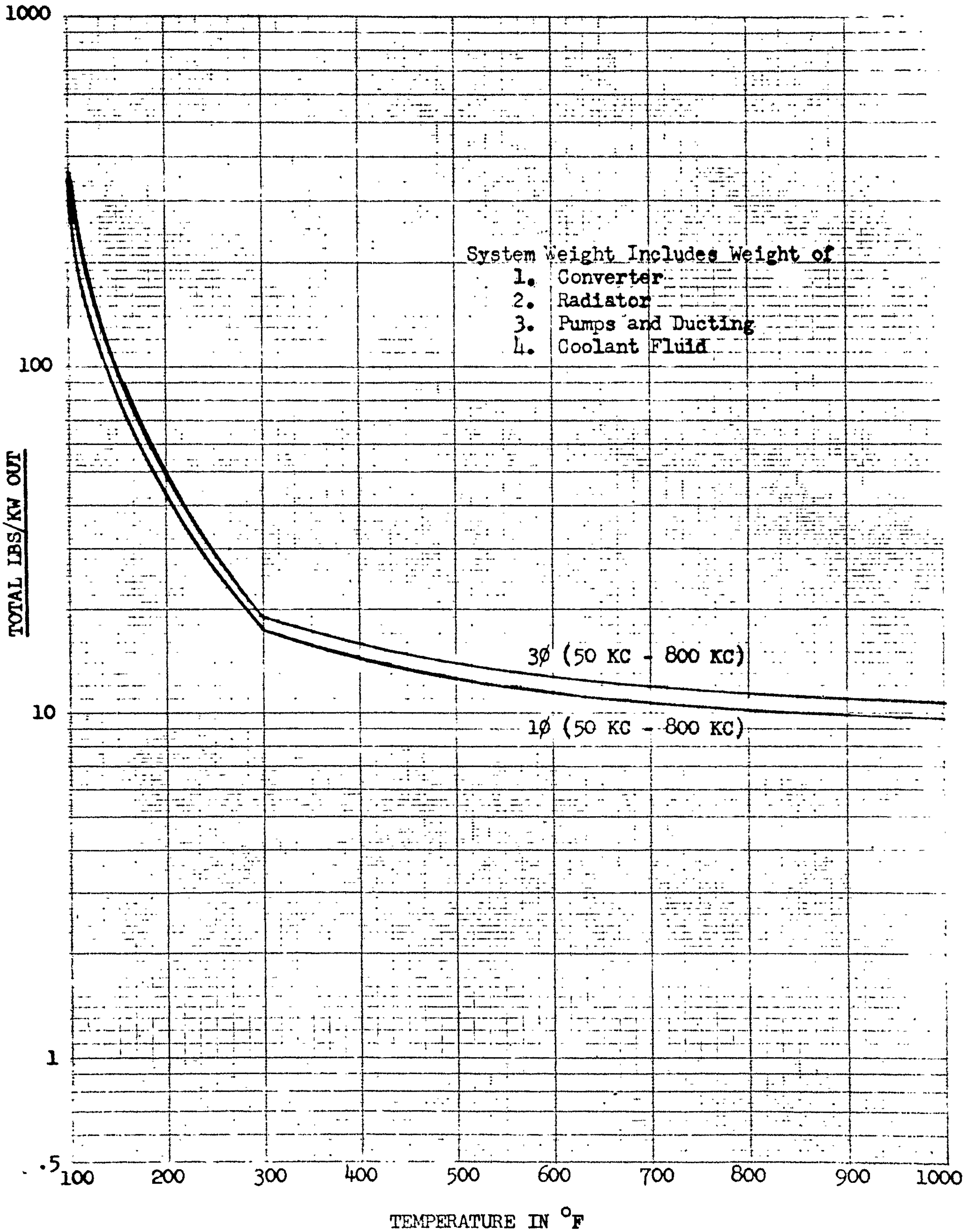

Figure 3.1.2-3 Analysis of System Weight vs Temperature for 60 KW Static (Tube) Converter

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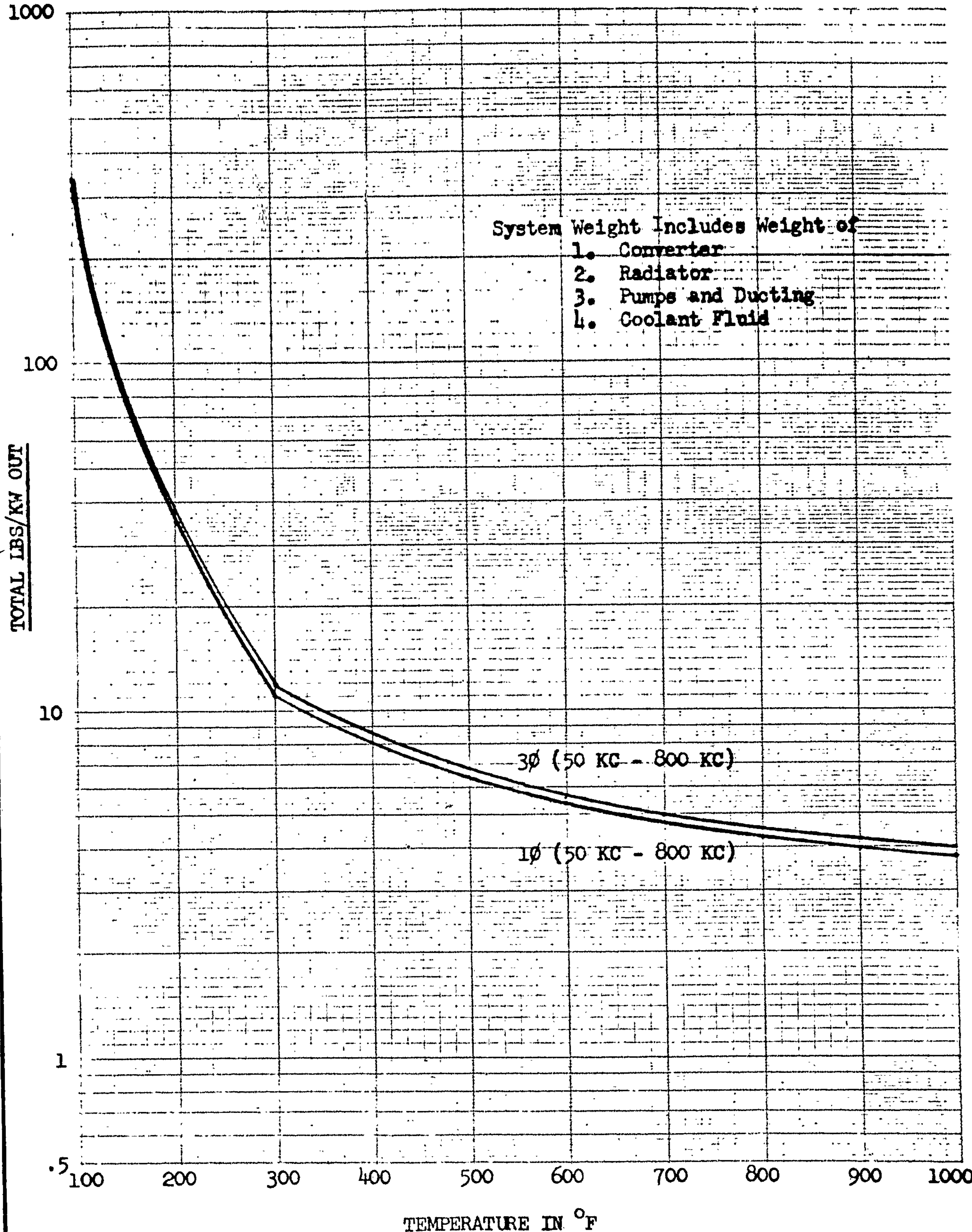

Figure 3.1.2-4 Analysis of System Weight vs Temperature for 300 KW Static (Tube) Converter

D. MECHANICAL DESIGN

The static (tube) converter unit can be packaged in an aluminum container for partial protection from a radiation environment, for mechanical support, for limited protection from meteriod damage, and to serve as a heat sink. Typical structural design for a 60 KW, 3Ø, 50 KC unit is shown in Figure 3.1.2-5 A through D, and is based on maximum system reliability, minimum weight, and minimum volume. Weight dimensions and volume data is shown in Tables 3.1.2-1 and 3.1.2-4.

Each tube will be mounted on its own filament transformer for compactness and to make use of the transformer as a partial heat sink. Tube cooling will be by integral cooling ducts for the oscillators and cooling fluid jackets for the diodes and thyratrons. Optimum cooling for each of the transformers will be gained by mounting them back to back on a common cold plate with coolant ducts carrying fluid through each transformer.

Packaging for this concept is not too flexible because of the tube volumes and shapes. Tube outlines used in the design layout are of conventional units and are expected to become smaller in the future as advances are made in the state-of-art. Packaging is dependent to a great degree on the generator configuration and also the load configuration. Only a preliminary concept can be considered until more information is available on these parts of the total system. Components in a tube system are not as susceptible to radiation damage as semiconductor components and shielding is not too much of a problem.

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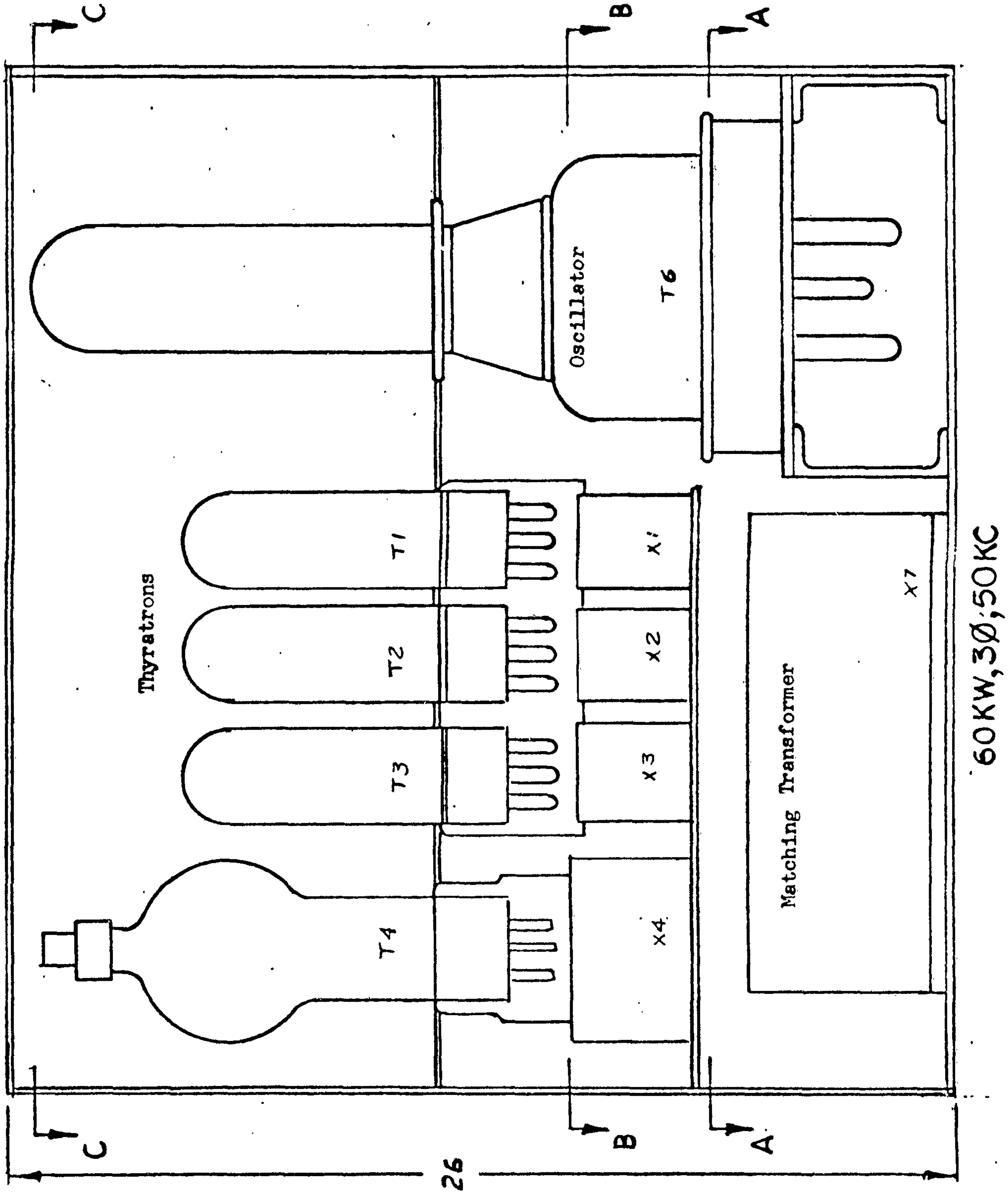

Figure 3.1.2-5A - 60 KW, 3Ø, 50 KC Static Converter

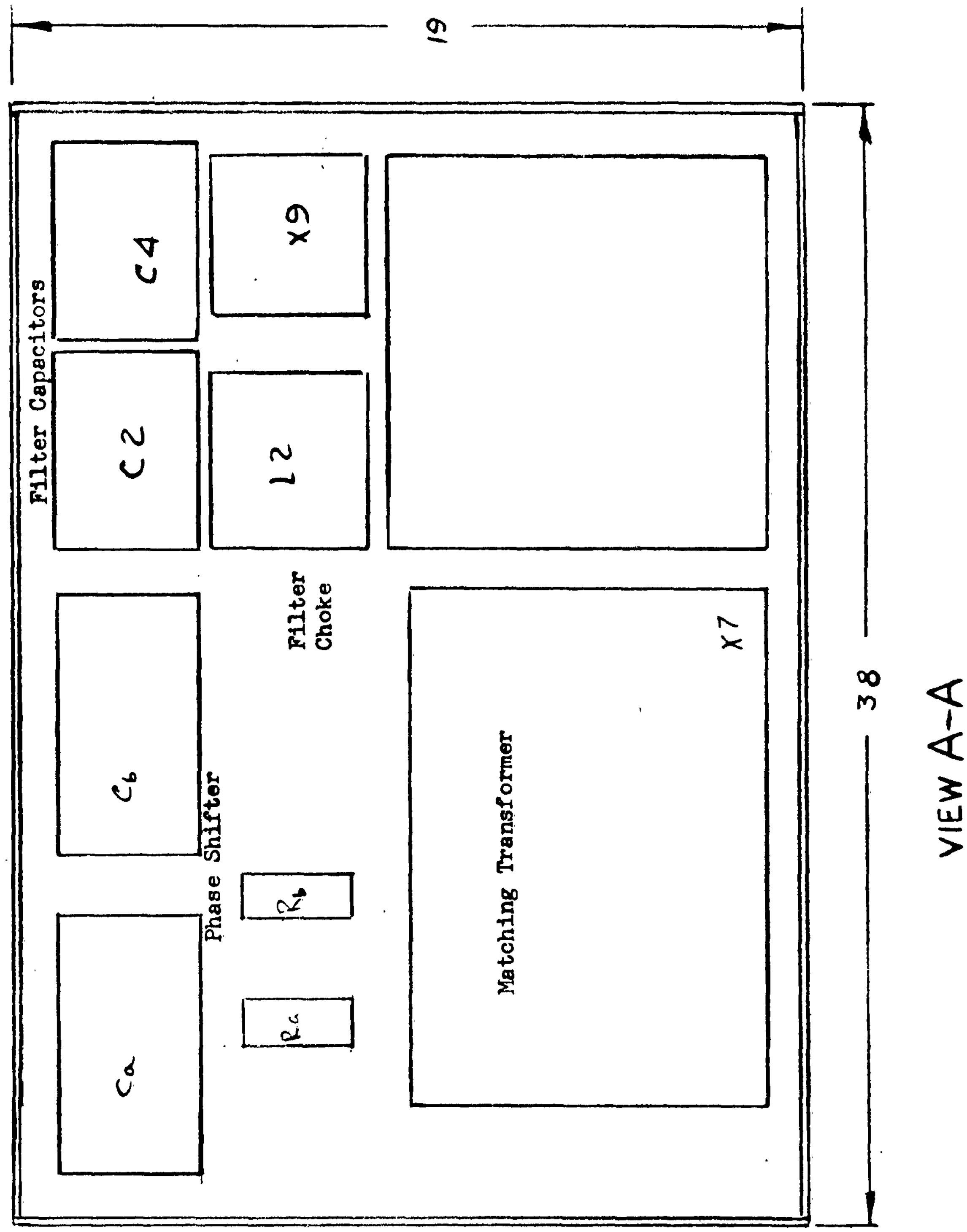

Figure 3.1.2-5B - Section View of 60 KW, 3Ø 50 KC Static Converter

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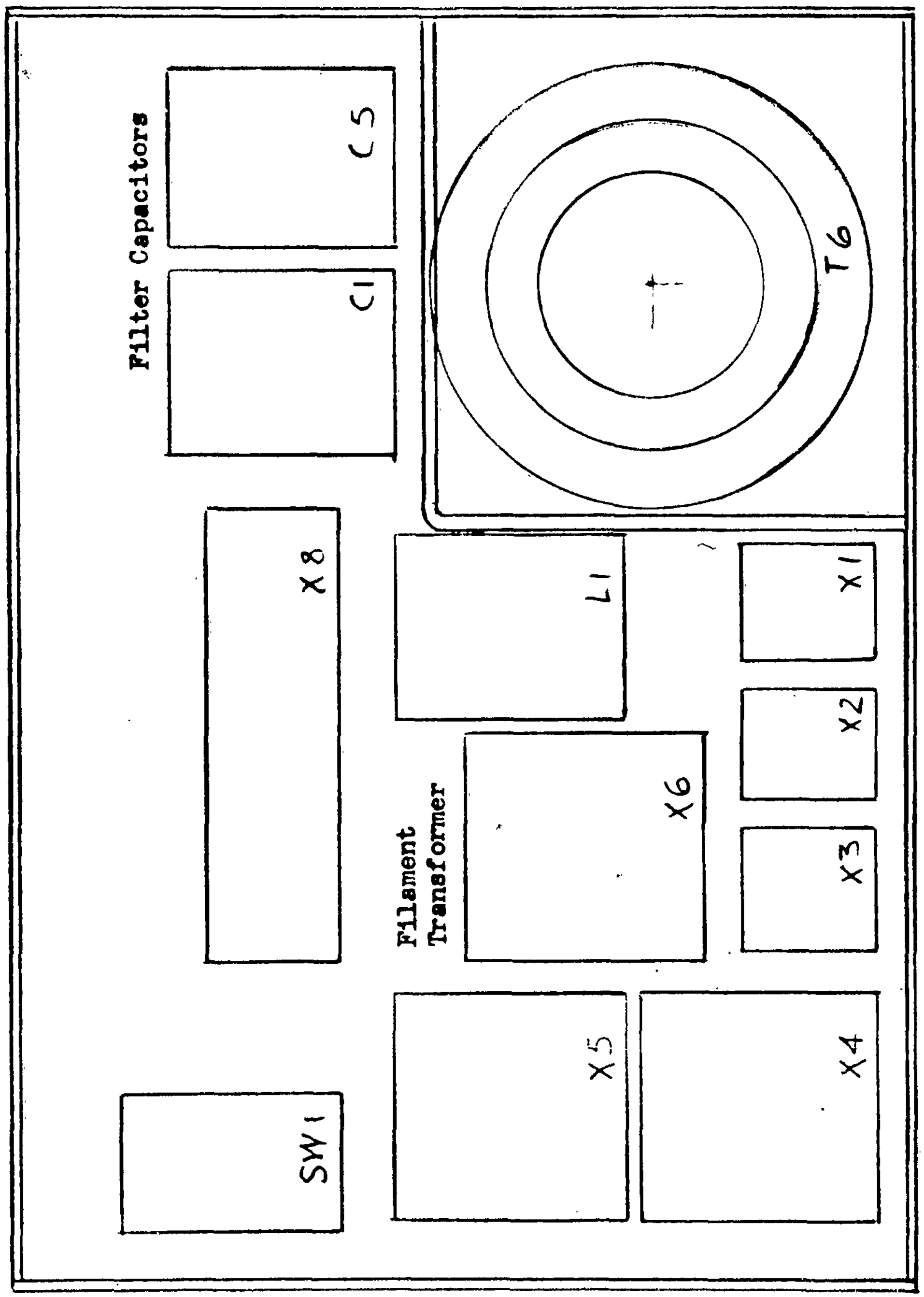
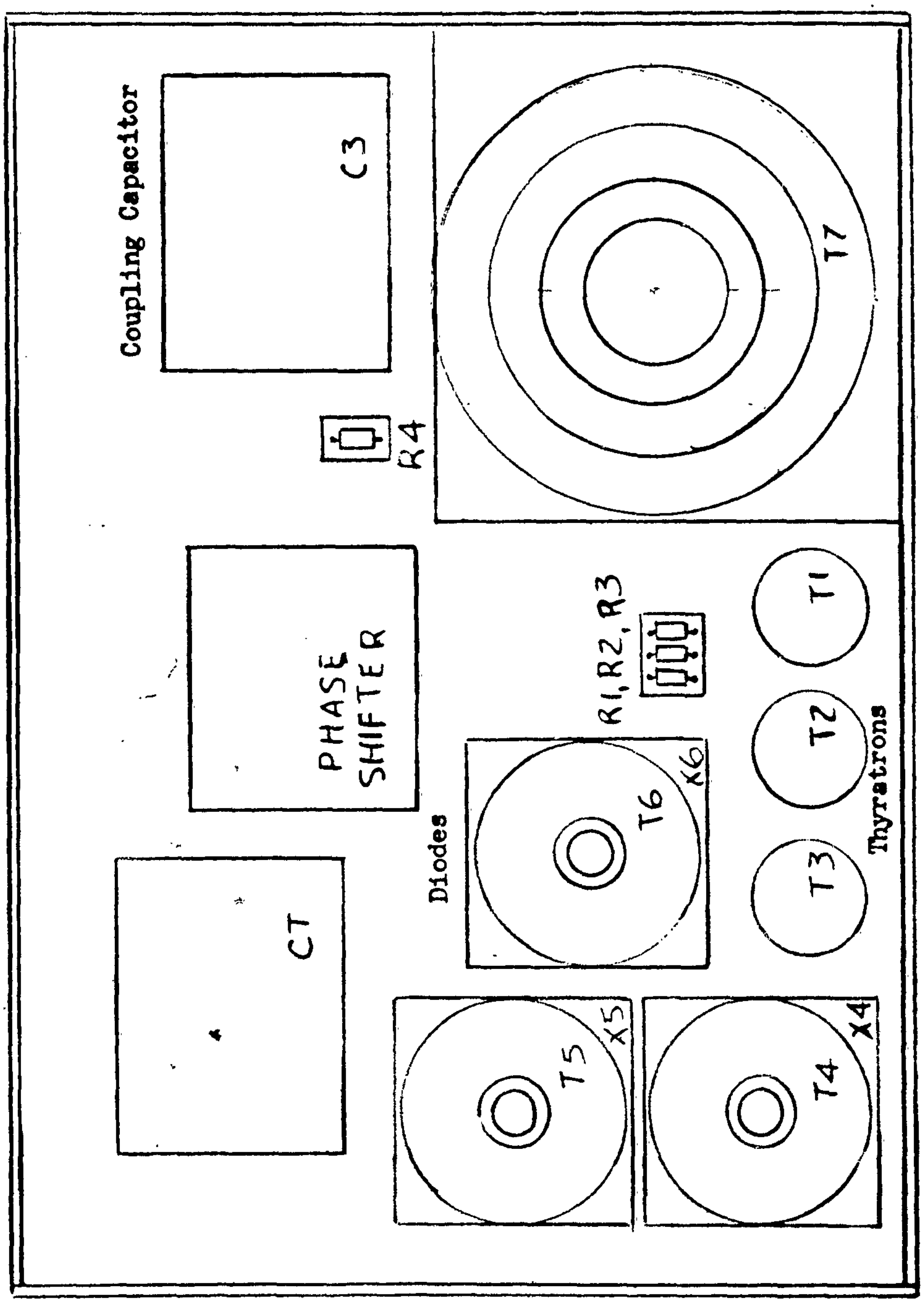


VIEW B-B

Figure 3.1.2-5C - Section View of 60 KW, 3Ø 50 KC Static Converter



VIEW C-C

Figure 3.1.2-5D - Section View of 60 KW, 3∅, 50 KC Static Converter

3.1.3 STATIC (TRANSISTOR) CONVERTER DESIGNS

3.1.3 STATIC (TRANSISTOR) CONVERTER DESIGNS

A. A 60 KW UNIT

A transistorized 60 KW power converter is illustrated in Figure 3.1.3-1 and shown schematically in Figure 3.1.3-2. Parametric data is summarized in Tables 3.1.3-1 and 3.1.3-2.

The 43.6/75.8, 3Ø, 1000 cycle power is applied at the input terminals and is converted to a pulsating D-C by diodes CR1 - CR6. Filter choke L1 and filter capacitors C3 and C6 smooth the rectified A-C. This filtered D-C is then applied through output transformer T2 to the collectors of the power switching transistors Q3, Q5, Q7, Q9, Q10, and Q11. The switching rate of the power transistors is determined by the precision square wave oscillator Q1 and Q2. The output from the square wave oscillator is applied to the impedance matching transistor Q4. The output from Q4 is amplified by the driver transistors Q6 and Q8 and is applied to the power switching transistors. Transformer T1, filter choke L2 and filter capacitors C7 and C8 form the low-voltage power supply which furnishes the power for the square-wave oscillator and the driver transistors. Reference diode CR13 provides a regulated voltage for the oscillator.

The selection of transistors for the power switching section will depend on future current capabilities of power transistors. Serious limitation of present-day semiconductor devices is in operating temperature (100°C). However, new materials, including gallium arsenide, are being developed which should raise their operating temperature capability in the future to 400°C.

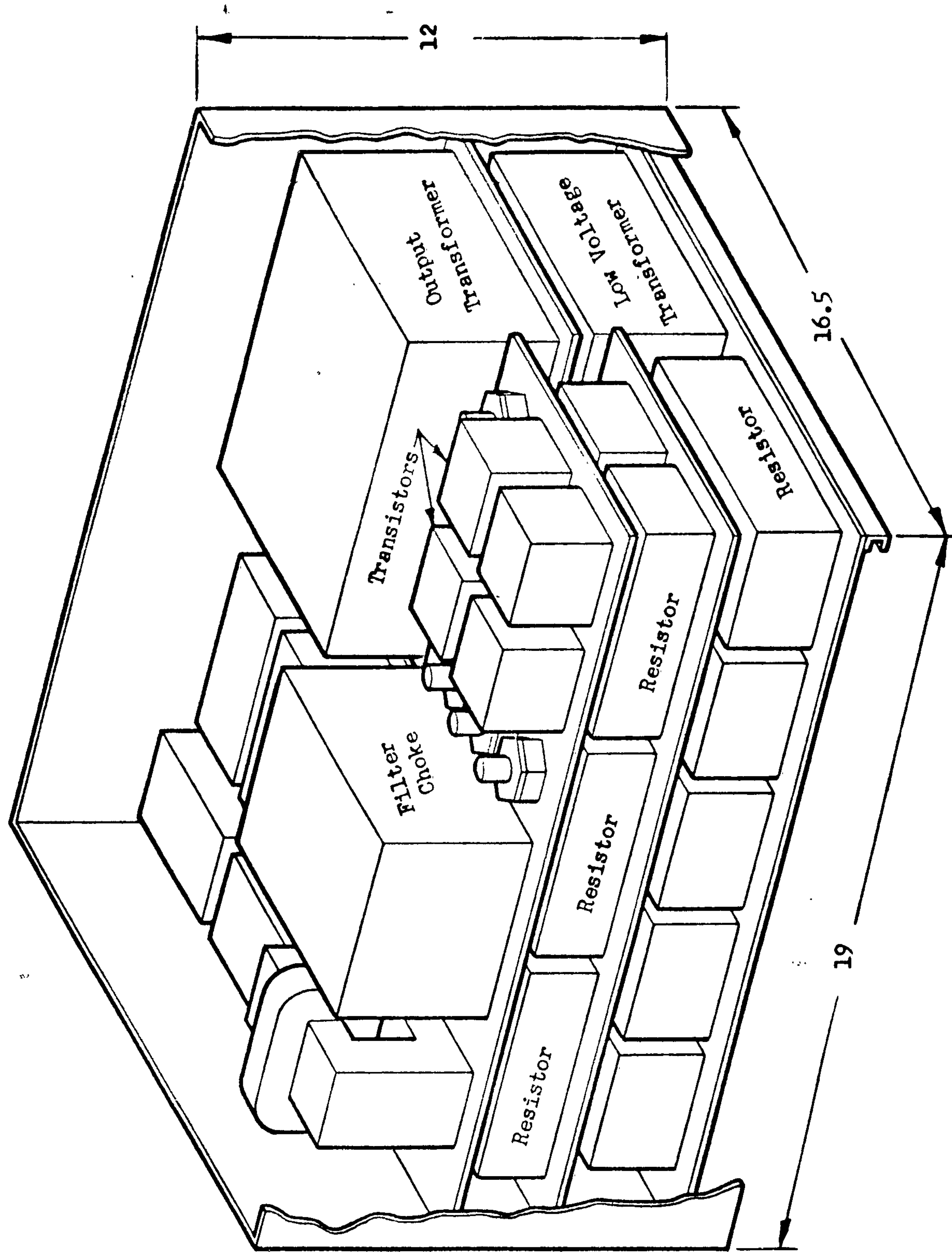


Figure 3.1.3-1 60 KW Static (Transistor) Converter (Perspective)

TABLE 3.1.3-1

SUMMARY OF 60 KW STATIC (TRANSISTOR) CONVERTER PARAMETRIC DATA

1Ø	50 KC	200 KC	800 KC
WEIGHT (lbs)	152	147	144
KW RAD (LOSSES)	9.4	10.1	11.4
KW OUT	50.7	49.9	48.6
EFFICIENCY (%)	84.4	83.2	81.1
LENGTH (inches)	19	14.	19.
WIDTH (inches)	16.5	16.5	16.5
HEIGHT (inches)	12	12	12
VOLUME (cu. ft.)	2.2	2.2	2.2
LBS/KW RAD	16.2	14.5	12.7
LBS/KW OUT	3.0	3.0	3.0

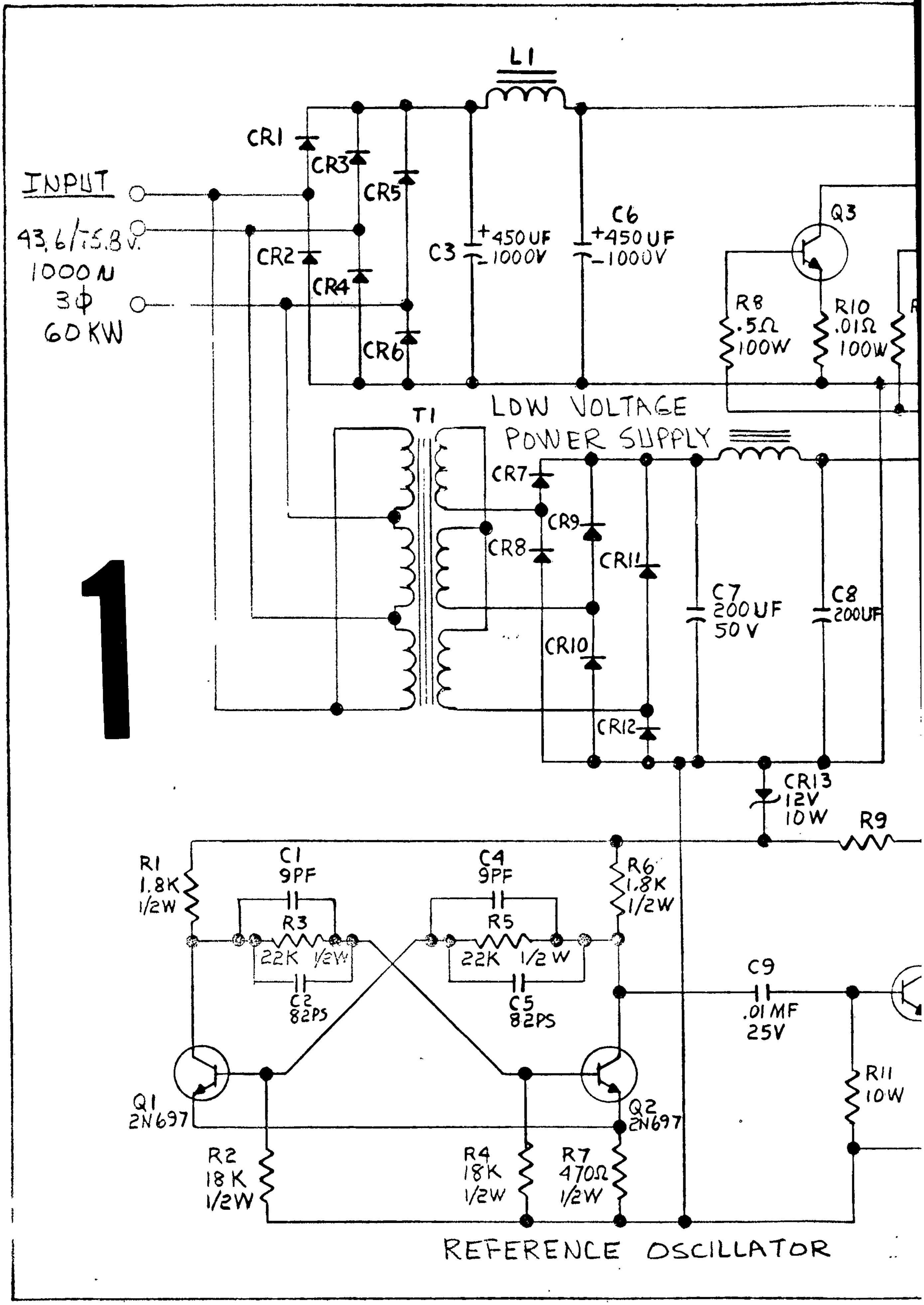
3Ø	50 KC	200 KC	800 KC
WEIGHT (lbs)	195	178	175
KW RAD (LOSSES)	14.9	14.6	14.9
KW OUT	45.1	45.5	45.0
EFFICIENCY (%)	75.2	75.8	75.0
LENGTH (inches)	20	20	20
WIDTH (inches)	20	20	20
HEIGHT (inches)	15.5	15.5	15.5
VOLUME (cu. ft.)	3.5	3.5	3.5
LBS/KW RAD	13.2	12.2	11.7
LBS/KW OUT	4.3	3.9	3.9

NOTE: Values do not include cooling system weights.

TABLE 3.1.3-2

PRELIMINARY COMPONENT LIST FOR A 60 KW STATIC (TRANSISTOR) CONVERTER (1Ø)

NO.	COMPONENTS	50 KC WT	50 KC LOSSES	200 KC WT	200 KC LOSSES	800 KC WT	800 KC LOSSES
	POWER SUPPLY (LOW VOLTAGE)						
6	Rectifier, semiconductor	3.0	1440	3.0	1440	3.0	1440
1	Transformer, low voltage (T1)	11.7	207	11.7	207	11.7	207
2	Capacitor, filter	2.0	1.0	2.0	1.0	2.0	1.0
1	Filter Choke (L2)	15.85	64.8	15.85	64.8	15.85	64.8
1	Diode, zener reference (CR13)	.1	2.0	.1	2.0	.1	2.0
1	Resistor	.2	10.0	.2	10.0	.2	10.0
	POWER SUPPLY (HIGH VOLTAGE)						
6	Rectifier, semiconductor	3.0	1440	3.0	1440	3.0	1440
2	Capacitor, filter	.5	--	.5	--	.5	--
1	Filter Choke (L1)	18.0	3520	18.0	3520	18.0	3520
	OSCILLATOR SECTION						
2	Transistor, low power (Q1, Q2)	1.0	2.0	1.0	2.0	1.0	2.0
7	Resistor	1.5	350	1.5	350	1.5	350
5	Capacitor	1.25	---	1.25	--	1.25	---
	WAVE SHAPER AND DRIVER						
1	Transistor, power (Q8)	.5	60	.5	60	.5	60
1	Transistor, med power (Q6)	.1	5	.1	5	.1	5
1	Transistor, low power (Q4)	.05	.2	.05	.2	.05	.2
2	Resistor	.1	20	.1	20	.1	20
3	Resistor, power	.2	300	.2	300	.2	300
	OUTPUT SECTION						
6	Transistor, power	3.0	360	3.0	360	3.0	360
6	Resistor, power	1.75	600	1.75	600	1.75	600
6	Resistor, base drive	1.3	300	1.3	300	1.3	300
1	Transformer, output (T2)	13.0	680	8.09	1400	4.8	2675
	MISCELLANEOUS						
-	Mounting plate and Enclosure	40.8	---	40.8	---	40.8	---
-	Cooling ducts	3.0	---	3.0	---	3.0	---
-	Controls	10.0	---	10.0	---	10.0	---
-	Wire and Hardware	20.0	---	20.0	---	20.0	---
	TOTALS	151.9#	9362 Watts	146.9#	10,082 Watts	143.7#	11,357 Watts



L1
CR1
CR3
CR5
INPUT
43.6/75.8V.
1000 N
3Φ
60 KW
CR2
CR4
CR6
C3
+450UF
1000V
C6
+450UF
1000V
Q3
R8
.5Ω
100W
R10
.01Ω
100W
LOW VOLTAGE
POWER SUPPLY
T1
CR7
CR9
CR8
CR11
C7
200UF
50V
C8
200UF
CR10
CR12
CR13
12V
10W
R9
R1
1.8K
1/2W
C1
9PF
R3
22K 1/2W
C2
82PS
C4
9PF
R5
22K 1/2 W
C5
82PS
R6
1.8K
1/2W
C9
.01 MF
25V
Q1
2N697
Q2
2N697
R11
10W
R2
18 K
1/2W
R4
18K
1/2W
R7
470Ω
1/2W
REFERENCE OSCILLATOR

1

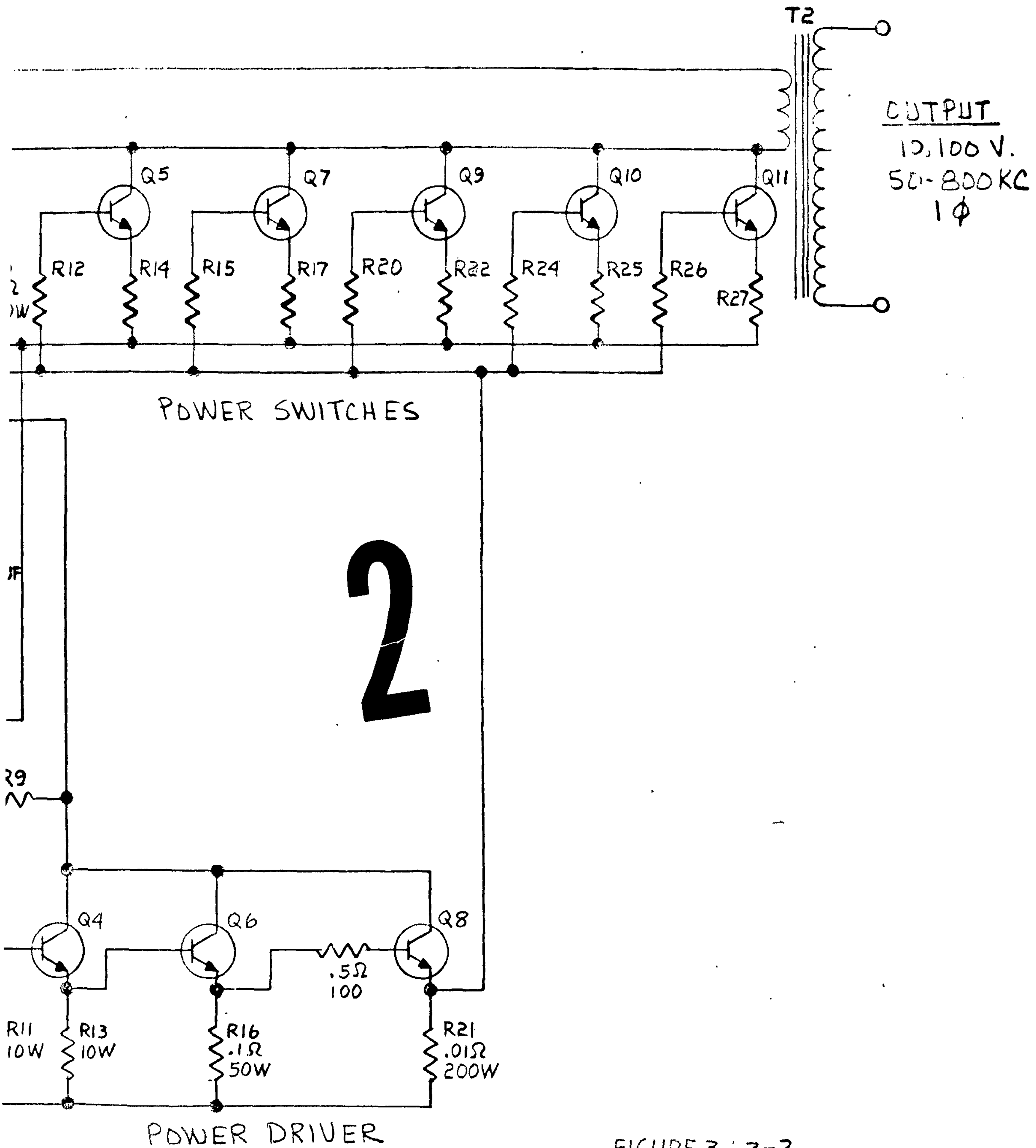


FIGURE 3. .3-2
PRELIMINARY SCHEMATIC OF 60 KW, 1φ, STATIC (TRANSISTOR) CONVERTER

If the power switching circuit was designed using state-of-the-art transistors, it would consist of 100 transistors. In order to compensate for the voltage limit of most power devices, two transistors would have to be used in series. Most devices are presently limited to 20 amperes of current and this would require 50 pairs of transistors in parallel for the 60 KW unit.

A three-phase converter is shown schematically in Figure 3.1.3-3 with parametric data included in Tables 3.1.3-1 and 3.1.3-3. 120/208 volt, 3Ø, 1000 cps power is applied at the input terminal and is converted to a pulsating DC voltage by the power diodes CRI-CR6. This DC voltage is then filtered by filter choke L1 and filter capacitors C_1 and C_2. This filtered DC is now applied directly to power transistors Q19 through Q60.

The switching rate of the power transistors is determined by the three-phase sine wave oscillator. The ØA output from the oscillator is applied to the impedance matching transistor Q7. The output from Q7 is applied to the Schmitt trigger (square wave forming circuit) Q8 and Q9. The output from Q9 is then applied to the emitter follower Q61 which feeds transformer T2 and powers the push-pull driver Q13 and Q14.

The output from the push-pull driver is then applied through transformer T5 to drive the power transistors. The same pattern is followed with ØB and ØC. The final output is taken from three-phase output transformer T8.

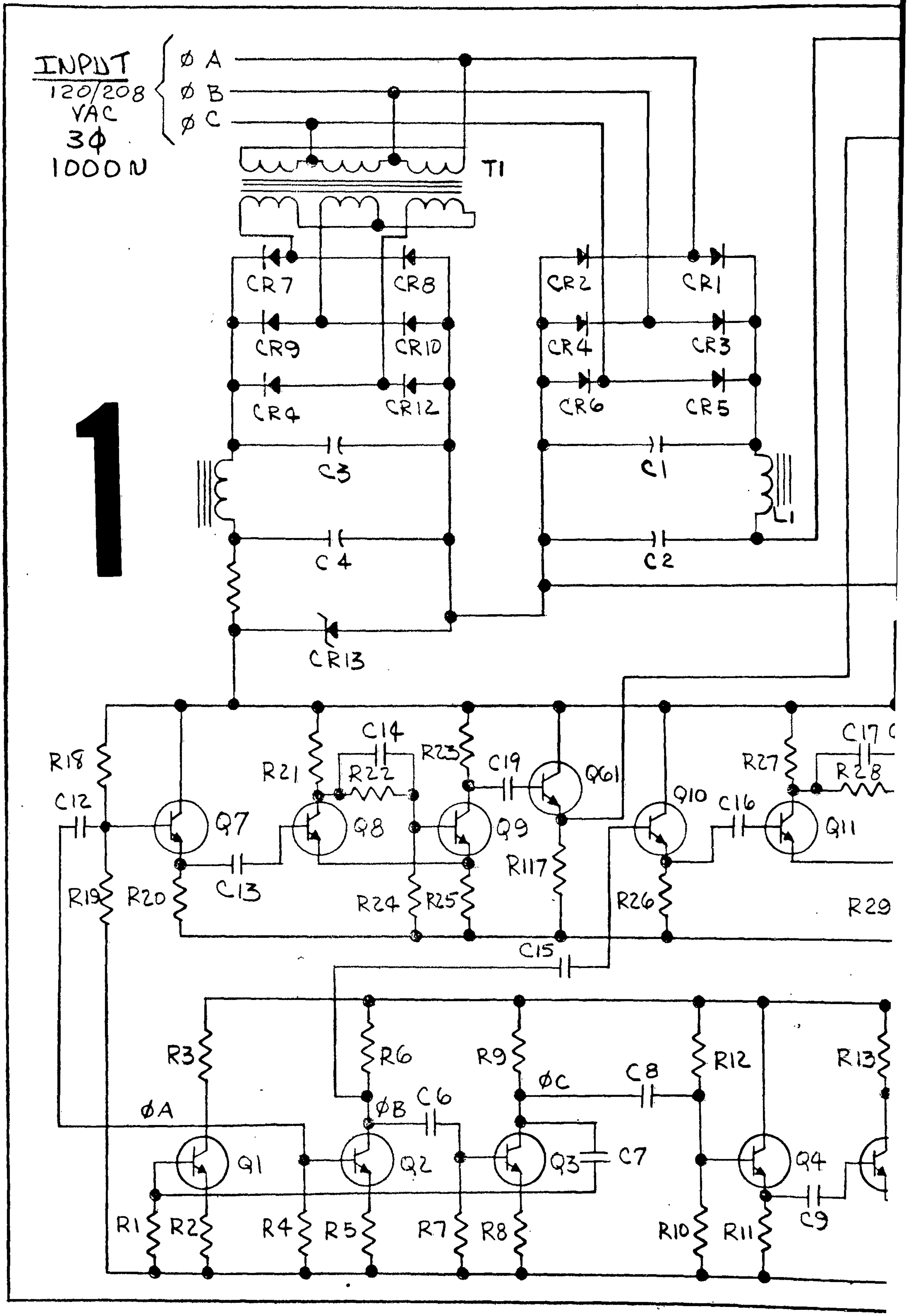
TABLE 3.1.3-3

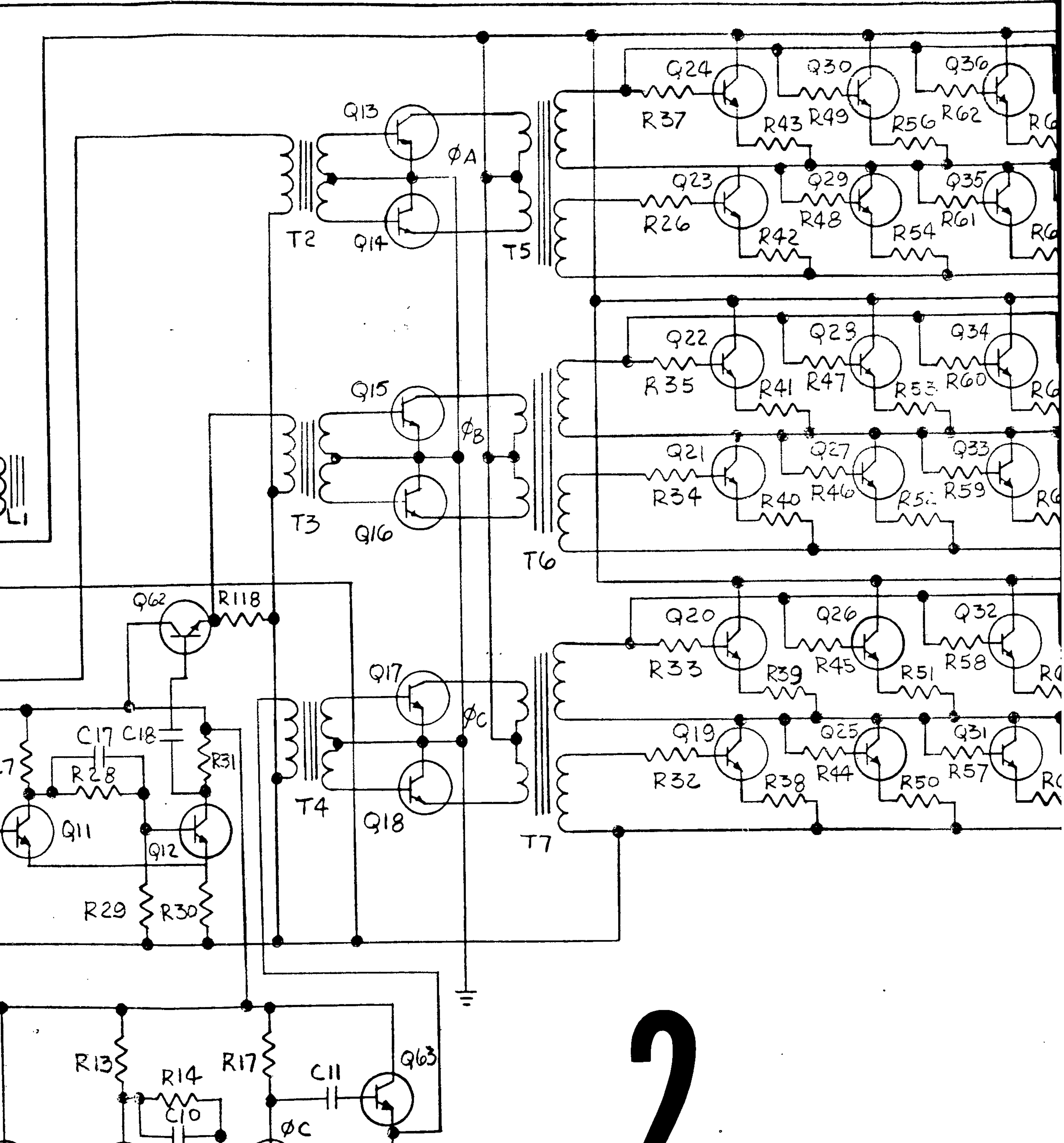
PRELIMINARY COMPONENT LIST FOR A 60 KW STATIC (TRANSISTOR) CONVERTER (3Ø)

NO.	COMPONENTS	50 KC WT	50 KC LOSSES (Watts)	200 KC WT	200 KC LOSSES (Watts)	800 KC WT	800 KC LOSSES (Watts)
	POWER SUPPLY (LOW VOLTAGE)						
2	Capacitor, filter	2.0	2.0	2.0	2.0	2.0	2.0
1	Filter Choke	10.0	1000	10.0	1000	10.0	1000
1	Diode, zener reference	.1	1.0	.1	1.0	.1	1.0
1	Resistor	.2	10.0	.2	10.0	.2	10.0
6	Rectifier, semiconductor	1.5	344	1.5	344	1.5	344
1	Transformer	18.0	429.5	18.0	429.5	18.0	429.5
	POWER SUPPLY (HIGH VOLTAGE)						
6	Rectifier, semiconductor	3.0	2004	3.0	2004	3.0	2004
2	Capacitor, filter	.5	--	.5	--	.5	--
1	Filter Choke (L2)	31.0	200	31.0	200	31.0	200
	OSCILLATOR SECTION						
3	Transistor	1.5	30.0	1.5	30.0	1.5	30.0
3	Capacitor	.75	--	.75	--	.75	--
3	Resistor, base drive	.6	6.0	.6	6.0	.6	6.0
6	Resistor	.6	6.0	.6	6.0	.6	6.0
	WAVE SHAPER AND DRIVER						
4	Transistor, low power	.3	1.5	.3	1.5	.3	1.5
15	Capacitor	4.0	---	4.0	---	4.0	---
6	Resistor (10W)	.75	60.0	.75	60.0	.75	0.0
4	Transistor, med power	.75	20.0	.75	20.0	.75	60.0
4	Transistor, high power	1.0	30.0	1.0	30.0	1.0	30.0
26	Resistor (1W)	.5	26.0	.5	26.0	.5	26.0
	OUTPUT SECTION						
24	Transistor, power	8	5280	8	5280	8	5280
24	Resistor, emitter	6	2400	6	2400	6	2400
1	Transformer, output	19	1019.6	6.7	968	5	1645
3	Transformer, push-pull driver	5.95	615	.94	300	.18	68
3	Transformer, driver	.36	30	.36	30	.36	30
24	Resistor, base drive	4	1200	4	1200	4	1200
3	Transistor	1	193.8	1	193.8	1	193.8
	MISCELLANEOUS						
--	Mounting plate and Enclosure	40.8	---	40.8	---	40.8	---
--	Cooling Ducts	3.0	---	3.0	---	3.0	---
--	Controls	10.0	---	10.0	---	10.0	---
--	Wire and Hardware	20.0	---	20.0	---	20.0	---
	TOTALS	195.2#	14,908	177.9#	14,542	175.4#	14,987

FORM 18-G-1 REV. 8-61

1

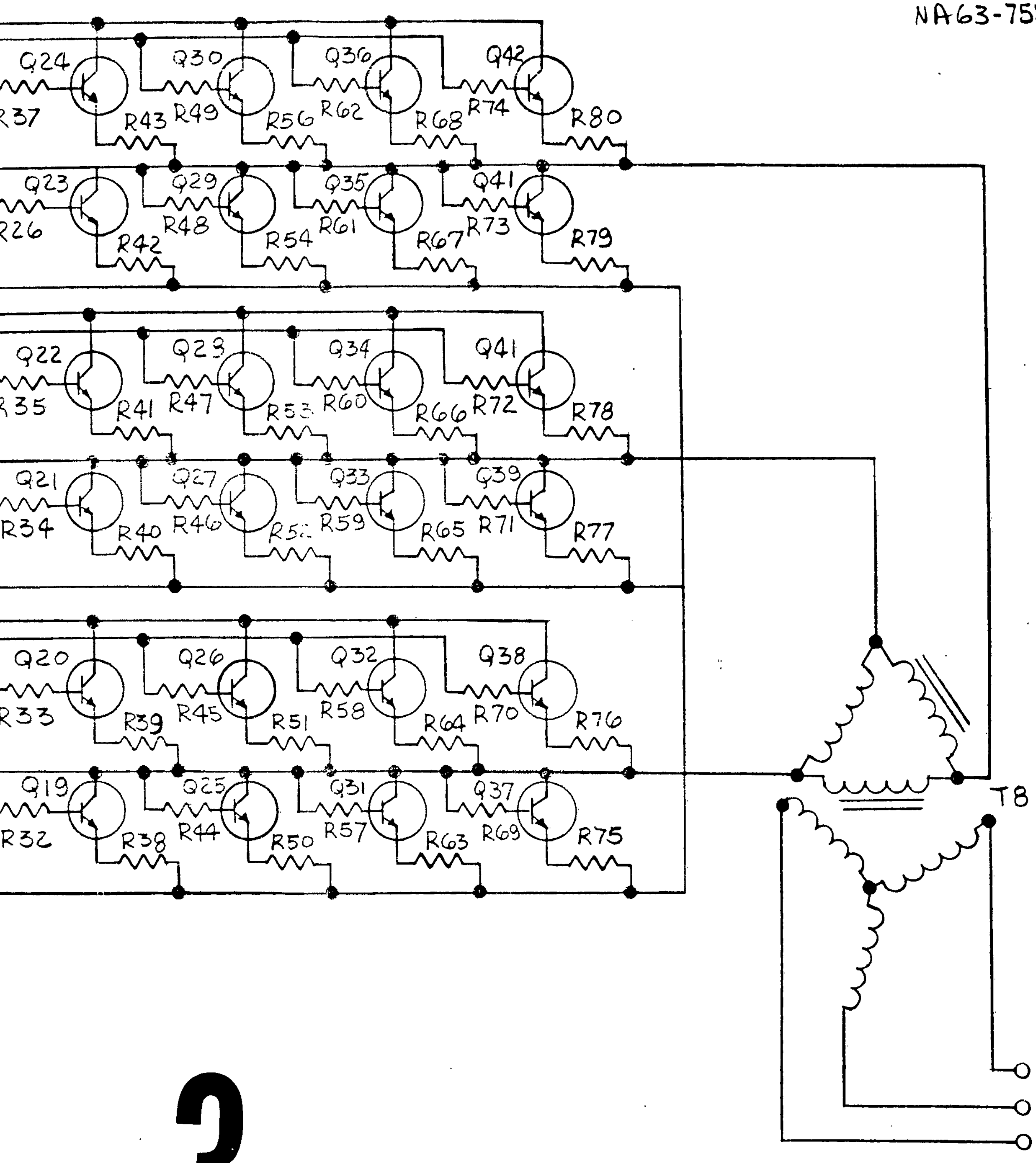

INPUT
120/208 VAC
3Φ
1000N
Φ A
Φ B
Φ C
T1
CR7
CR8
CR9
CR10
CR4
CR12
CR2
CR1
CR4
CR3
CR6
CR5
C3
C4
C1
C2
L1
CR13
C14
R18
R21
R22
R23
C19
Q61
C17
R27
R28
C12
Q7
Q8
Q9
Q10
C16
Q11
C13
R117
R19
R20
R24
R25
R26
R29
C15
R3
R6
R9
R12
R13
ΦC
C8
ΦA
ΦB
C6
Q1
Q2
Q3
C7
Q4
R1
R2
R4
R5
R7
R8
R10
R11
C9



2

FIGURE 3
PRELIMIN
3Φ STA

NA63-755-2



3

FIGURE 3.1.3-3
PRELIMINARY SCHEMATIC OF 60KW
3Ø STATIC (TRANSISTOR) CONVERTER

B. A 300 KW UNIT

A transistorized power converter for delivering single-phase, high frequency power is shown schematically in Figure 3.1.3-4. Data is summarized in Tables 3.1.3-4 and 3.1.3-5. The operation of the circuit is identical to that of the 60 KW unit. The 300 KW input is 120/208 volt, 3ø, 3200 cps power rather than the 43.6/75.8 volt, 1000 cps power for the 60 KW unit. The filtered DC from the rectifier section is applied to one side of the output transformer T2. The other side of the output transformer is connected in series with this parallel group of power transistors which switch the DC voltage at a 50-800 K cps rate thru the primary winding of T2. The output from the secondary winding of T2 is then stepped up to a value of 10,100 volts AC for the load.

The switching rate of the power transistors is determined by the precision square-wave oscillator. The output from the oscillator is fed to the driver transistors Q8 and Q10 through the impedance matching emitter-follower transistor Q4. The driver transistors and oscillator are powered by the low voltage power supply.

A three-phase design for the 300 KW (input) unit is shown in Figure 3.1.3-5 and is almost identical to the 3ø, 60 KW unit. Major difference is in the number of power transistors in the power switch section. Summarized data for this design is shown in Tables 3.1.3-4 and 3.1.3-6.

TABLE 3.1.3-4

SUMMARY OF 300 KW STATIC (TRANSISTOR) CONVERTER PARAMETRIC DATA

1Ø	50 KC	200 KC	800 KC
WEIGHT (lbs)	203	175	167
KW RAD (LOSSES)	13.9	13.7	13.9
KW OUT	286.2	286.3	286.2
EFFICIENCY (%)	95.4	95.4	95.4
LENGTH (inches)	24	24	20
WIDTH (inches)	19	19	19
HEIGHT (inches)	11.5	12	11.5
VOLUME (cu. ft.)	3.0	3.2	2.5
LBS/KW RAD	14.7	14.2	12.8
LBS/KW OUT	.71	.61	.58

3Ø	50 KC	200 KC	800 KC
WEIGHT (lbs)	265	206	194
KW RAD (LOSSES)	25.9	26.2	26.0
KW OUT	274.1	273.8	273.9
EFFICIENCY (%)	91.4	91.3	91.3
LENGTH (inches)	24.5	24.5	24.5
WIDTH (inches)	22.5	22.5	22.5
HEIGHT (inches)	18	18	18
VOLUME (cu. ft.)	5.7	5.7	5.7
LBS/KW RAD	10.3	7.9	7.4
LBS/KW OUT	.97	.75	.70

NOTE: Values do not include cooling system weights.

NA-63-755-2

TABLE 3.1.3-5

PRELIMINARY COMPONENT LIST FOR A 300 KW STATIC (TRANSISTOR) CONVERTER (1Ø)

		50 KC		200 KC		800 KC	
NO.	COMPONENTS	WT	LOSSES	WT	LOSSES	WT	LOSSES
	POWER SUPPLY (LOW POWER)						
6	Rectifier, semiconductor	3.0	1440	3.0	1440	3.0	1440
1	Transformer, low voltage (T1)	18.0	430	18.0	430	18.0	430
2	Capacitor, filter	2.0	1.0	2.0	1.0	2.0	1.0
1	Filter Choke (L2)	31.0	200	31.0	200	31.0	200
1	Diode, zener reference (CR13)	.1	2.0	.1	2.0	.1	2.0
1	Resistor	.2	10.0	.2	10.0	.2	10.0
	POWER SUPPLY (HIGH VOLTAGE)						
6	Rectifier, semiconductor	3.0	1440	3.0	1440	3.0	1440
2	Capacitor, filter	.5	--	.5	--	.5	--
1	Filter Choke (L1)	10.0	1000	10.0	1000	10.0	1000
	OSCILLATOR SECTION						
2	Transistor, low power (Q1, Q2)	1.0	2.0	1.0	2.0	1.0	2.0
7	Resistor	1.5	350	1.5	350	1.5	350
5	Capacitor	1.25	---	1.25	---	1.25	---
	WAVE SHAPER AND DRIVER						
2	Transistor, power (Q8, Q10)	.5	60	.5	60	.5	60
1	Transistor, med power (Q6)	.1	5	.1	5	.1	5
1	Transistor, low power (Q4)	.05	.2	.05	.2	.05	.2
2	Resistor	.1	30	.1	20	.1	20
5	Resistor, power	.5	500	.5	500	.5	500
	OUTPUT SECTION						
10	Transistor, power	2.5	2300	2.5	2300	2.5	2300
10	Resistor, power	2.0	1000	2.0	1000	2.0	1000
10	Resistor, base drive	1.3	500	1.3	500	1.3	500
1	Transformer, output (T2)	50.7	4622	22.8	4472	14.36	4622
	MISCELLANEOUS						
--	Mounting plate and enclosure	40.8	--	40.8	--	40.8	--
--	Cooling ducts	3.0	--	3.0	--	3.0	--
--	Controls	10.0	--	10.0	--	10.0	--
--	Wire and Hardware	20.0	--	20.0	--	20.0	--
	TOTALS	203.1#	13,882 Watts	175.2#	13732.2 Watts	166.8#	13,882 Watts

FORM 10-G-1 REV. 8-61

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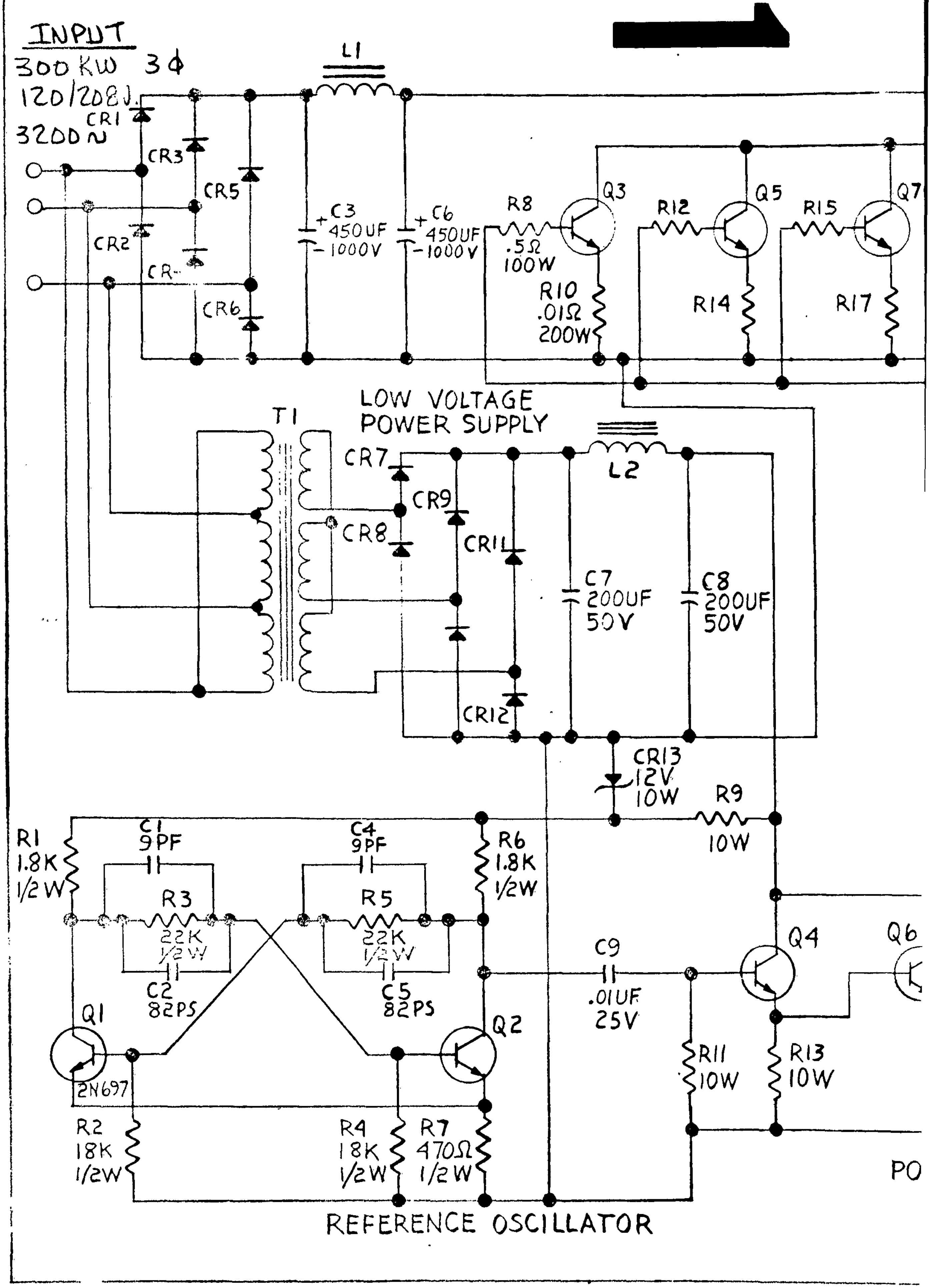


INPUT
300 KW 3φ
120/208V
3200 ~
CR1
CR3
CR5
CR2
CR-
CR6
L1
C3 450UF 1000V
C6 450UF 1000V
R8 .5Ω 100W
R10 .01Ω 200W
Q3
R12
Q5
R14
R15
Q7
R17
LOW VOLTAGE POWER SUPPLY
T1
CR7
CR9
CR8
CR11
L2
C7 200UF 50V
C8 200UF 50V
CR12
CR13 12V 10W
R9 10W
R1 1.8K 1/2W
C1 9PF
R3 22K 1/2W
C2 82PS
C4 9PF
R5 22K 1/2W
C5 82PS
R6 1.8K 1/2W
C9 .01UF 25V
Q4
Q6
Q1
2N697
Q2
R2 18K 1/2W
R4 18K 1/2W
R7 470Ω 1/2W
R11 10W
R13 10W
PO
REFERENCE OSCILLATOR

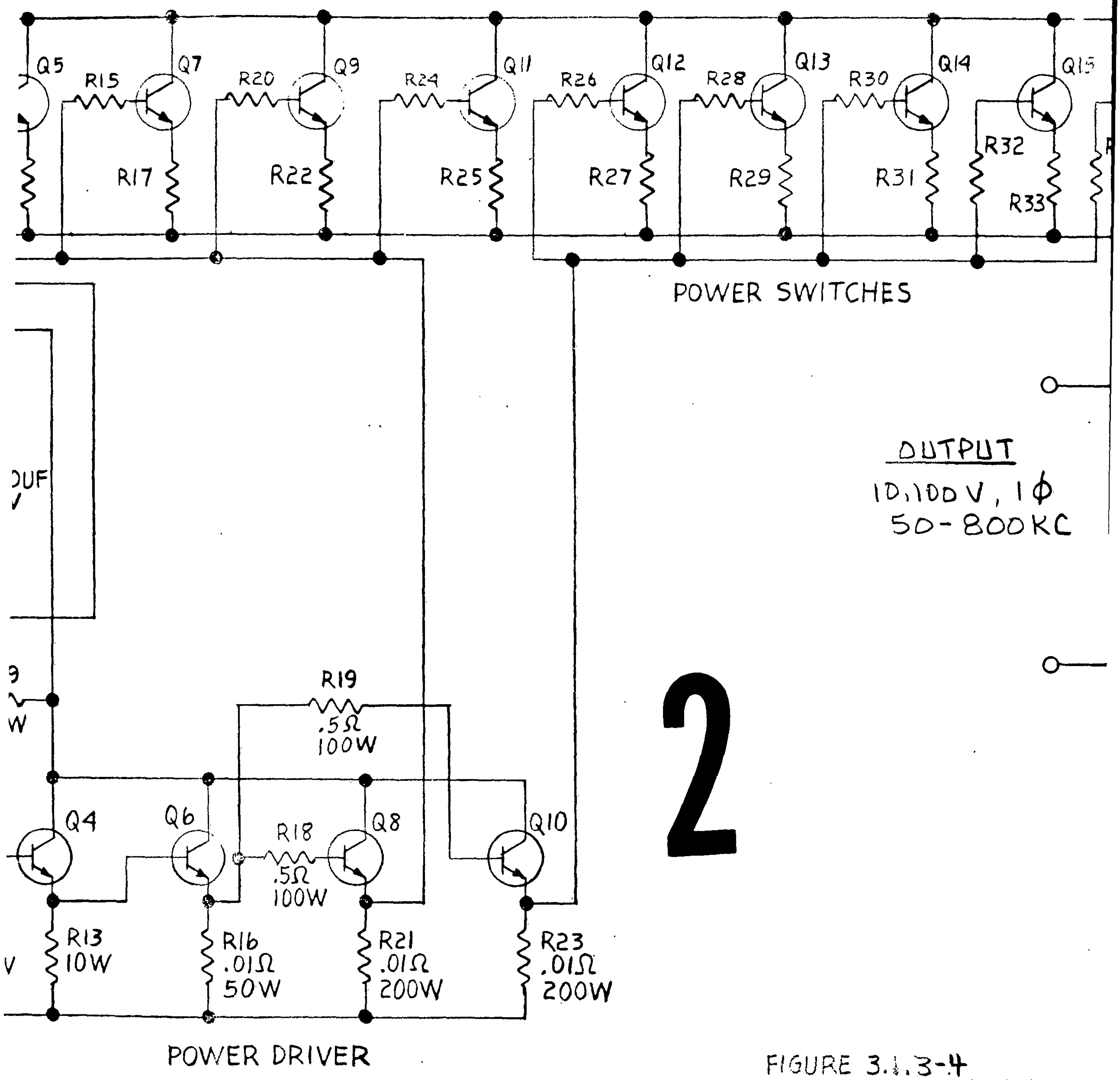
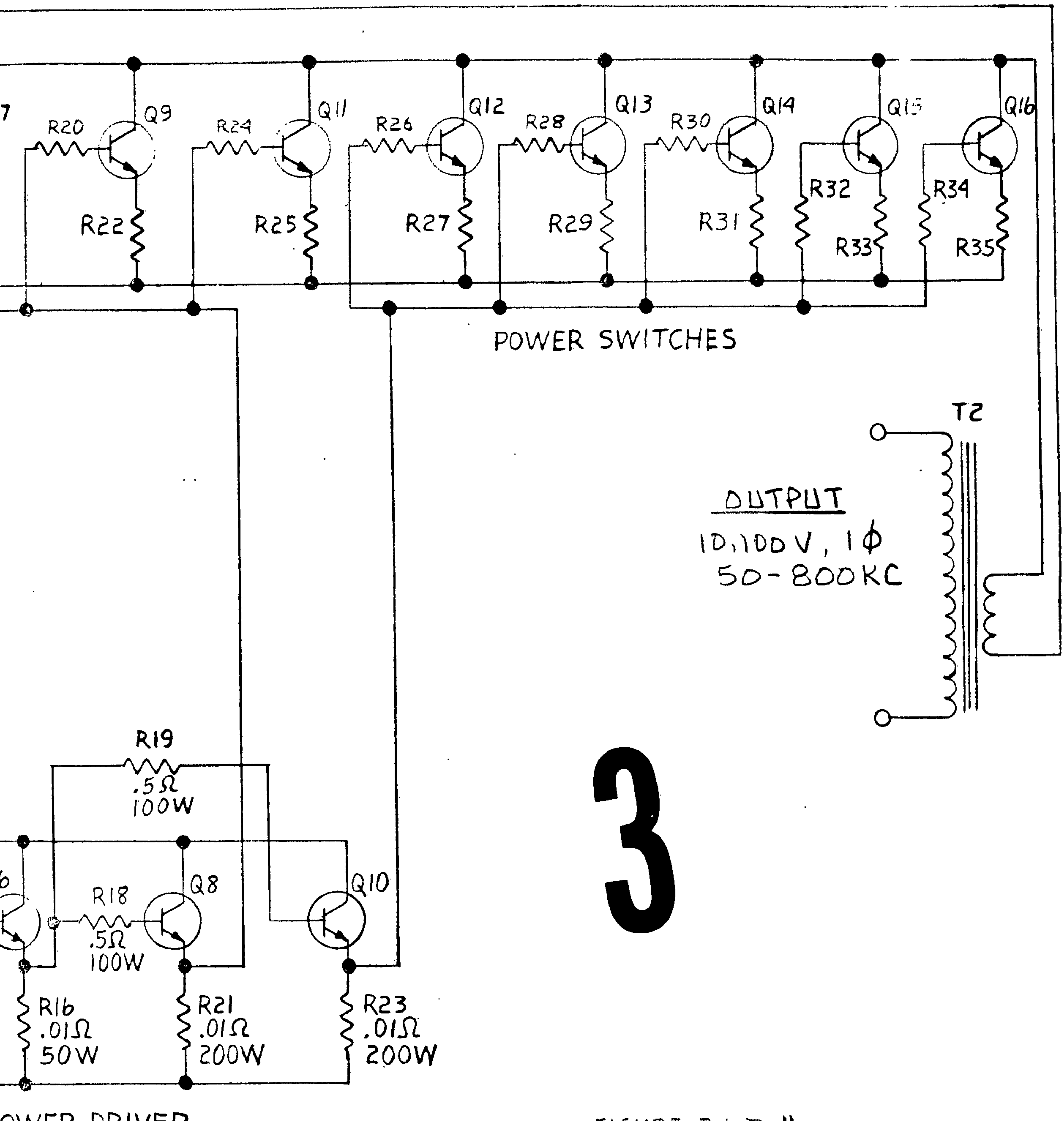


FIGURE 3.1.3-4
PRELIMINARY SCHEMATIC (
1Ø, STATIC (TRANSISTOR) C



3

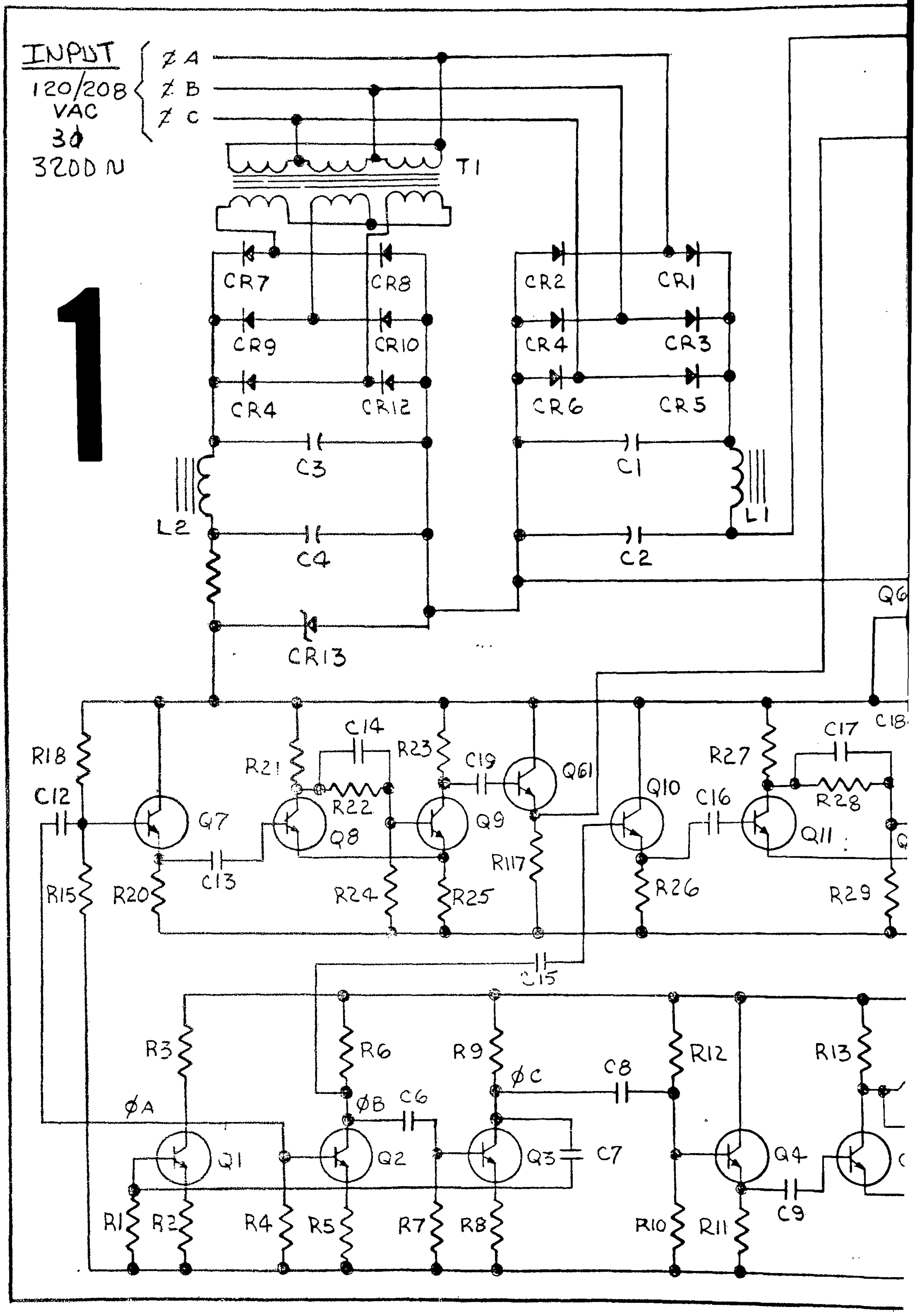
FIGURE 3.1.3-4
PRELIMINARY SCHEMATIC OF 300 KW, 1Ø, STATIC (TRANSISTOR) CONVERTER

NA-63-755-2

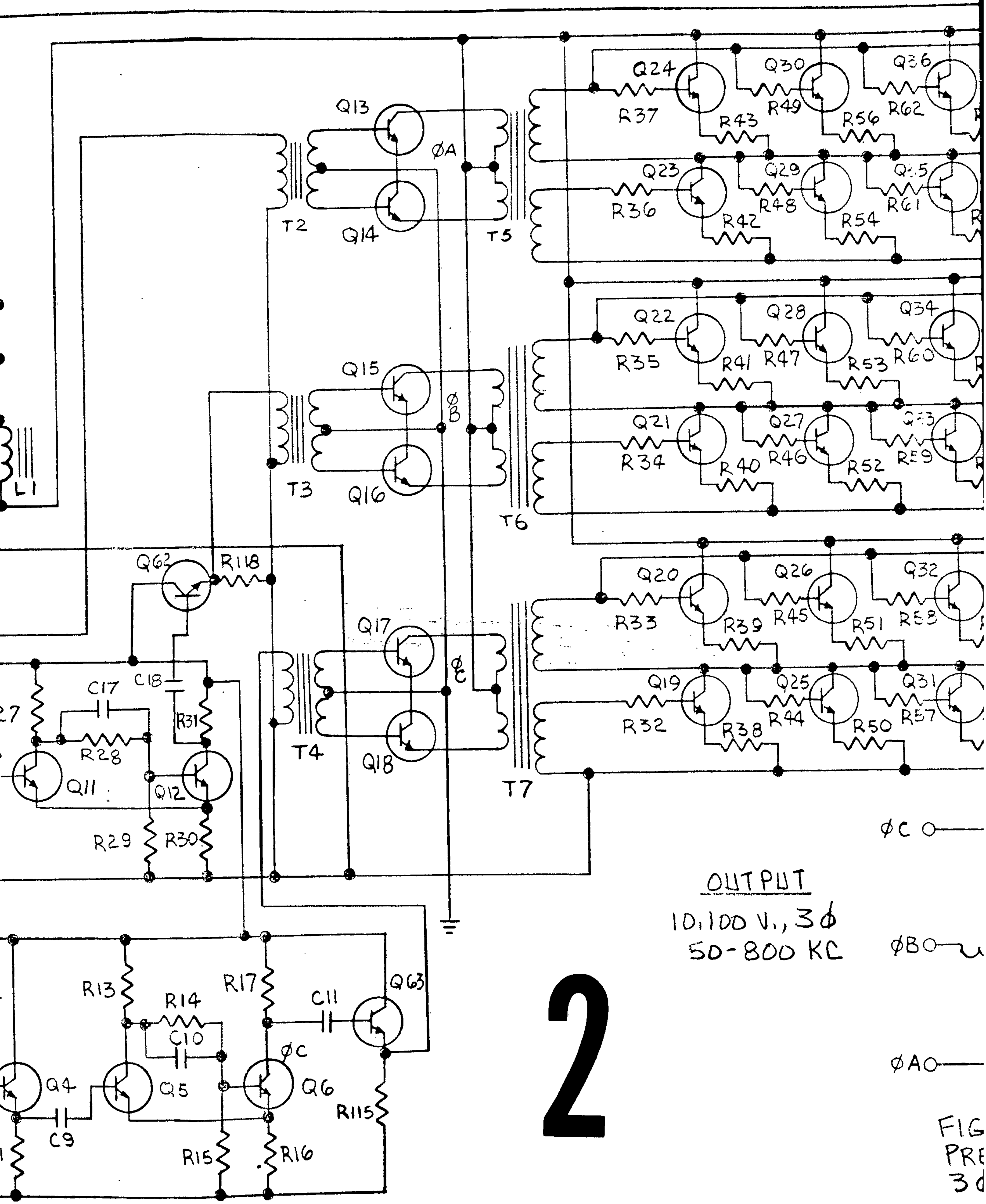
TABLE 3.1.3-6

PRELIMINARY COMPONENT LIST FOR A 300 KW STATIC (TRANSISTOR) CONVERTER (3Ø)

		50 KC		200 KC		800 KC	
NO.	COMPONENTS	WT	LOSSES (Watts)	WT	LOSSES (Watts)	WT	LOSSES (Watts)
	POWER SUPPLY (LOW VOLTAGE)						
2	Capacitor, filter	2.0	2.0	2.0	2.0	2.0	2.0
1	Filter Choke	10.0	1000	10.0	1000	10.0	1000
1	Diode, zener reference	.1	1.0	.1	1.0	.1	1.0
1	Resistor	.2	10.0	.2	10.0	.2	10.0
6	Rectifier, semiconductor	1.5	344	1.5	344	1.5	344
1	Transformer	18.0	429.5	18.0	429.5	18.0	429.5
	POWER SUPPLY (HIGH VOLTAGE)						
6	Rectifier, semiconductor	3.0	2004	3.0	2004	3.0	2004
2	Capacitor, filter	.5	--	.5	--	.5	--
1	Filter Choke	31.0	200	31.0	200	31.0	200
	OSCILLATOR SECTION						
3	Transistor	1.5	30.0	1.5	30.0	1.5	30.0
3	Capacitor	.75	--	.75	--	.75	--
3	Resistor, base drive	.6	6.0	.6	6.0	.6	6.0
6	Resistor	.6	6.0	.6	6.0	.6	6.0
	WAVE SHAPER AND DRIVER						
4	Transistor, low power	.3	1.5	.3	1.5	.3	1.5
15	Capacitor	4.0	--	4.0	--	4.0	--
6	Resistor	.75	60.0	.75	60.0	.75	60.0
4	Transistor, med power	.75	20.0	.75	20.0	.75	20.0
4	Transistor, high power	1.0	30.0	1.0	30.0	1.0	30.0
26	Resistor	.5	26.0	.5	26.0	.5	26.0
	OUTPUT SECTION						
12	Transistor, power	14.0	10,752	14.0	10,752	14.0	10,752
42	Resistor, emitter	10.5	4200	10.5	4200	10.5	4200
1	Transformer, output	65.7	3362.3	18.8	3423	10.0	2783
3	Transformer, push-pull driver	18.9	1065	6.0	1329	3.0	1818
3	Transformer, driver	.3	10.0	.3	10.0	.3	10.0
3	Transistor	1.0	199.8	1.0	199.8	1.0	199.8
42	Resistor, base	4.0	2100	4.0	2100	4.0	2100
	MISCELLANEOUS						
--	Mounting plate and enclosure	40.8	--	40.8	--	40.8	--
--	Cooling ducts	3.0	--	3.0	--	3.0	--
--	Controls	10.0	--	10.0	--	10.0	--
--	Wire and Hardware	20.0	--	20.0	--	20.0	--
	TOTALS	265.3#	25859.0	205.5#	26,183	193.7#	26,032

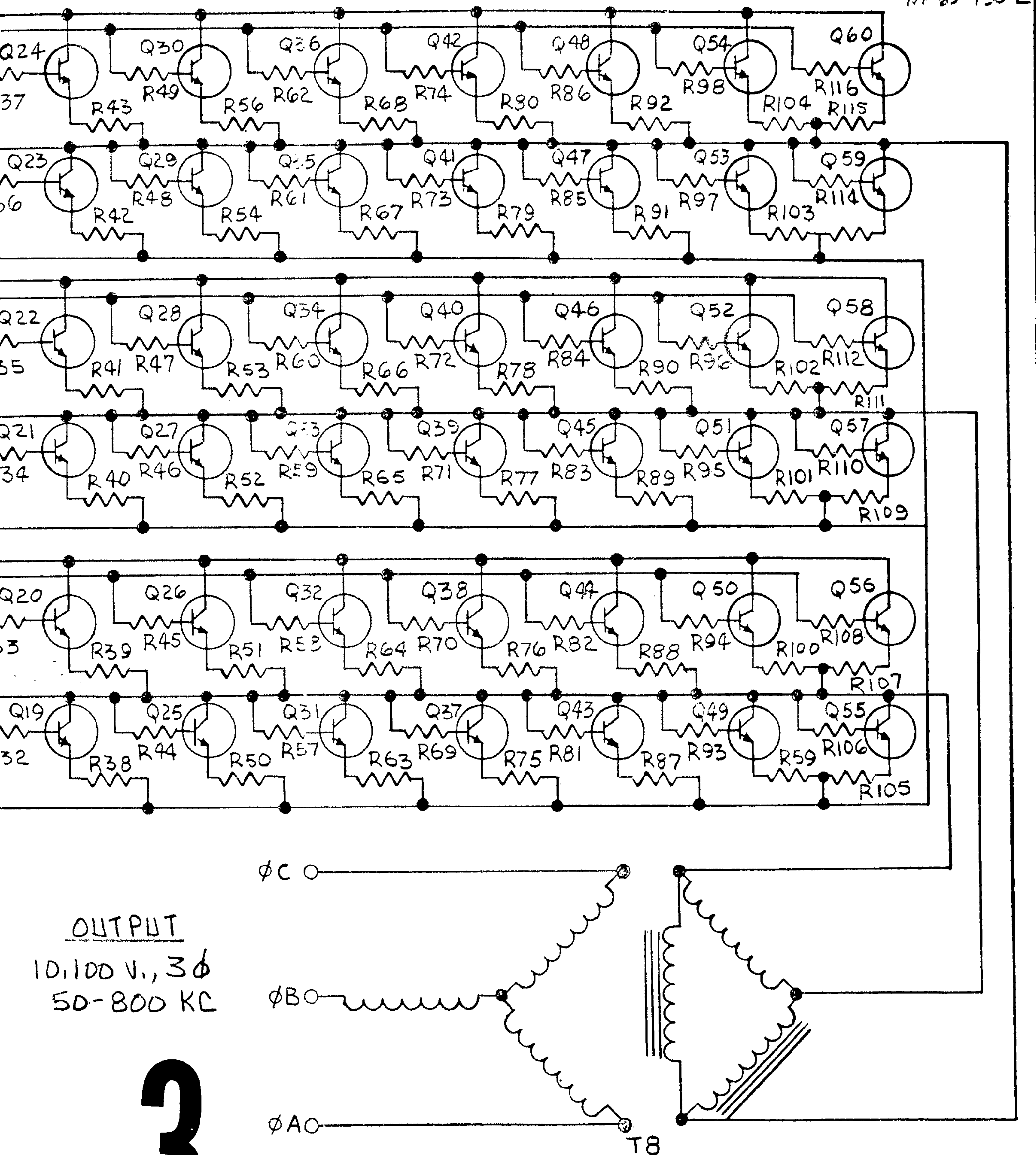


INPUT
120/208 VAC
3Ø
320D N
ØA
ØB
ØC
T1
1
CR1
CR2
CR3
CR4
CR5
CR6
CR7
CR8
CR9
CR10
CR4
CR12
CR13
C1
C2
C3
C4
L1
L2
Q6
C18
R18
C12
Q7
R21
C14
R22
Q8
R23
C19
Q61
Q9
R117
Q10
C16
R27
C17
R28
Q11
R15
R20
C13
R24
R25
R26
R29
C15
R3
R6
R9
C8
R12
R13
ØA
ØB
C6
ØC
Q1
Q2
Q3
C7
Q4
C9
R1
R2
R4
R5
R7
R8
R10
R11


Q13
Q14
T2
ØA
T5
Q15
Q16
T3
ØB
T6
Q17
Q18
T4
ØC
T7
Q62
R118
C17
C18
R28
R31
Q11
Q12
R29
R30
Q24 Q30 Q36
R37 R43 R49 R56 R62
Q23 Q29 Q35
R36 R42 R48 R54 R61
Q22 Q28 Q34
R35 R41 R47 R53 R60
Q21 Q27 Q33
R34 R40 R46 R52 R59
Q20 Q26 Q32
R33 R39 R45 R51 R58
Q19 Q25 Q31
R32 R38 R44 R50 R57
L1
R13
R14
C10
R17
C11
Q63
Q4
Q5
Q6
ØC
C9
R15
R16
R115
ØC
ØB
ØA
OUTPUT
10,100 V., 3Φ
50-800 KC

2

FIG
PRE
3



3

FIGURE 3.1.3-5
PRELIMINARY SCHEMATIC OF 300 KW
3Ø, STATIC (TRANSISTOR) CONVERTER

C. THERMAL DESIGN

For purposes of a cooling analysis, it is assumed that all transistors will be mounted on a heat sink material which is part of the heat exchanger or cold plate. In the thermal analysis, thermal drop through electrical insulation, allowable junction temperatures of the transistors and internal heat flow from each device to the heat exchanger were considered.

Since present transistors are limited in temperature to below 300°F, this is the governing factor in determing the system operating point. Figure 3.1.3-6 shows the total lbs/KWout for both single-phase and three-phase converter outputs at 50 KC, 200 KC and 800 KC for the 60 KW unit. The curves show the trend of system weight with temperature. From these curves, the optimum operating point from a weight basis is higher than the maximum transistor operating temperature (300°F). Lighter weight systems are possible only as transistor temperature capabilities are increased.

Figure 3.1.3-7 is an analysis of total system weight versus system operating temperatures for the 300 KW (input) system.

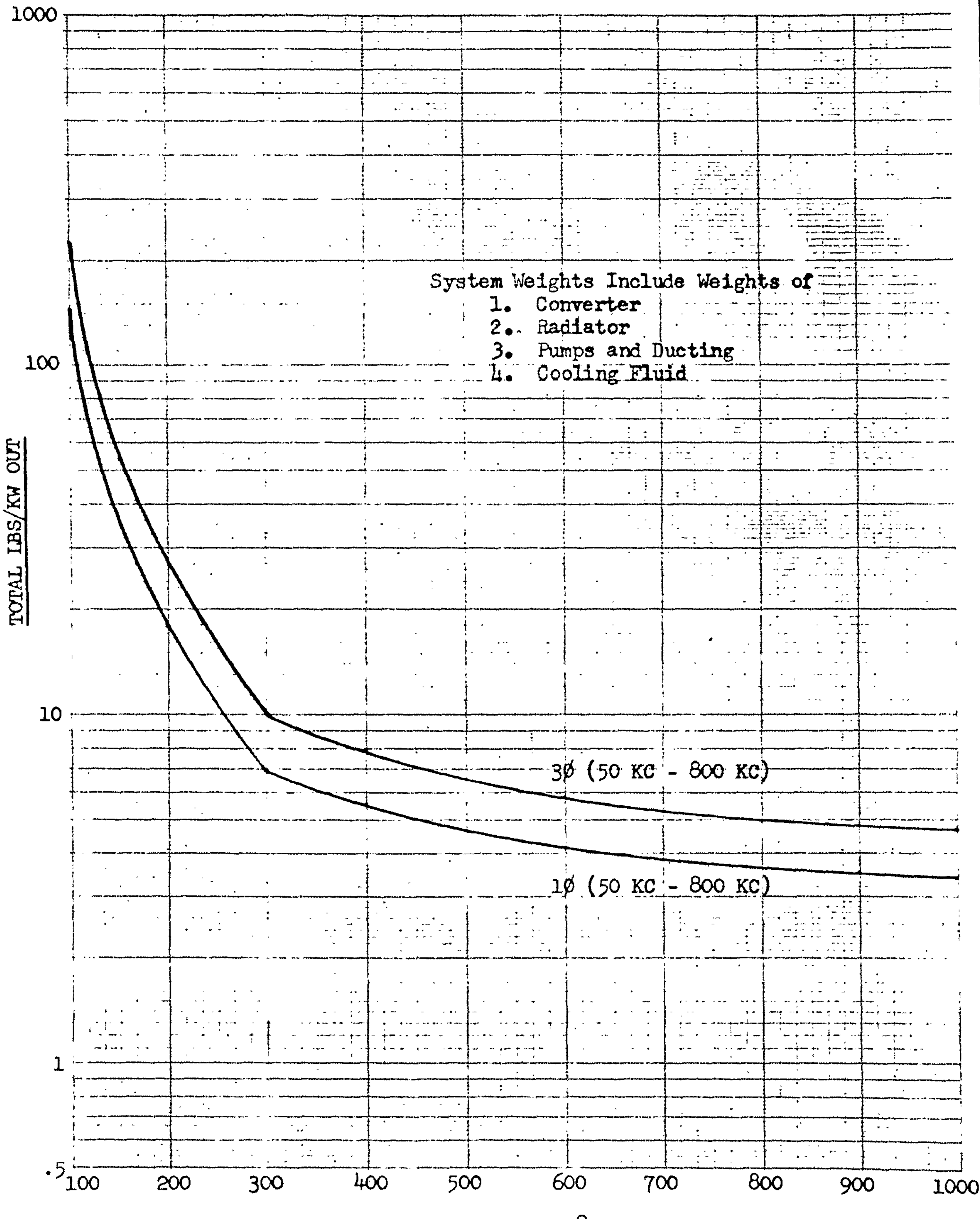


Figure 3.1.3-6 Analysis of System Weight vs Temperature for 60 KW Static (Transistor) Converter

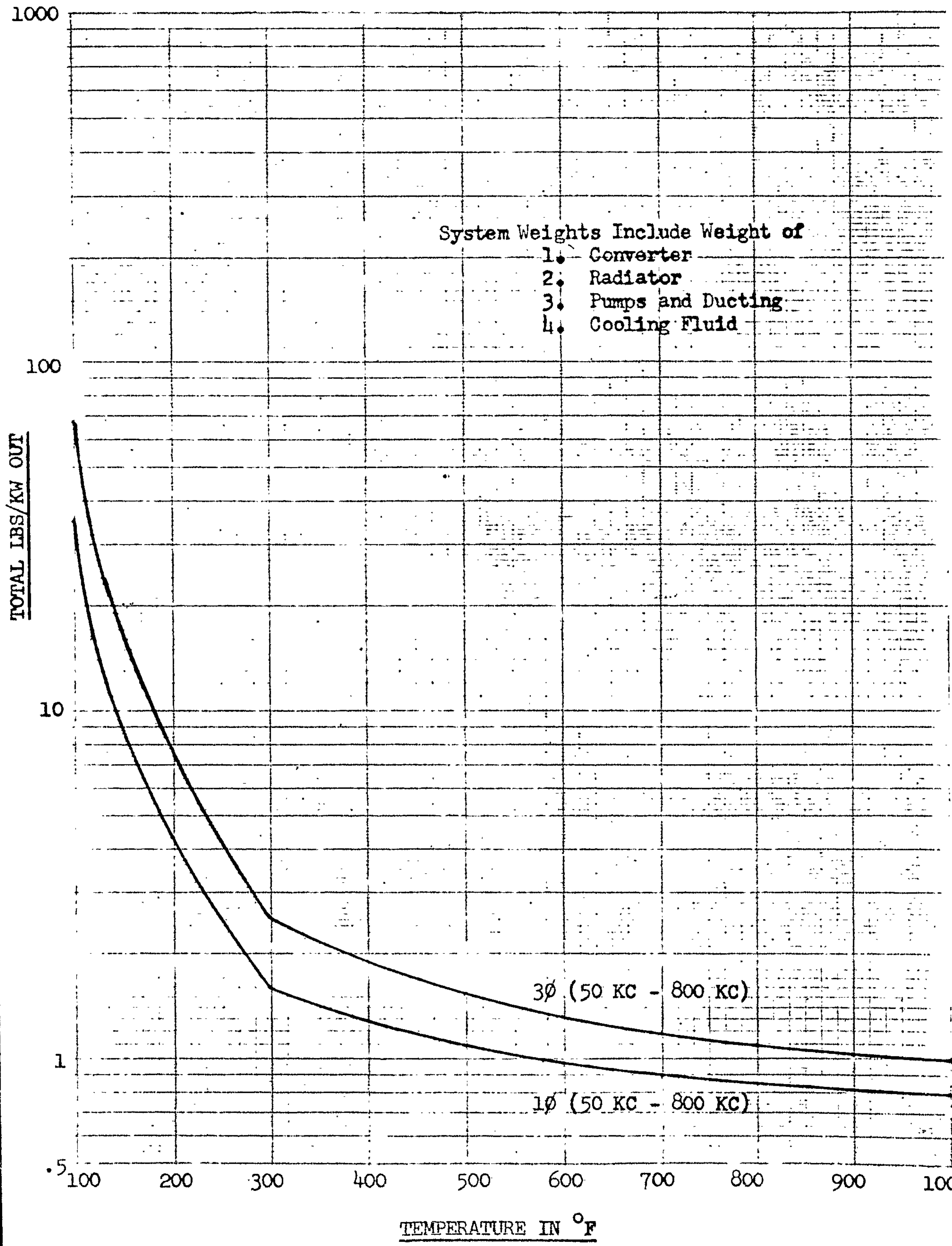


Figure 3.1.3-7 Analysis of System Weight vs Temperature for 300 KW Static (Transistor) Converter

D. MECHANICAL DESIGN

This converter concept can be packaged within an aluminum structure for protection against radiation and space erosion. This structure will provide minimum weight to maximum strength plus good thermal conductance characteristics. A preliminary package design for a 60 KW, 1Ø, 200 KC concept is typical of the other designs and is shown in Figures 3.1.3-8A - C. Unit dimensions and volumes for each of the concepts are summarized in Tables 3.1.3-1 and 3.1.3-4.

The internal portion may be considered to be in a tray configuration, in which each tray holds a portion of the circuit. The trays are formed from aluminum sheets so that coolant tubes may be imbedded in them to form a cold-plate structure.

In order to isolate the transistors and diodes from the high power components, such as resistors and transformers, thin insulation barriers may be set up around the transistors. These barriers will consist of thin aluminum foil against thin glass or asbestos cloth. This will provide a means of controlling the temperature of the transistors and diodes which are the most heat sensitive of the electrical components.

Since the parts are in general rather small in a transistor type of unit, there is greater flexibility in package design and this concept can be packaged to match the generator configuration and the electric propulsion engine configuration.

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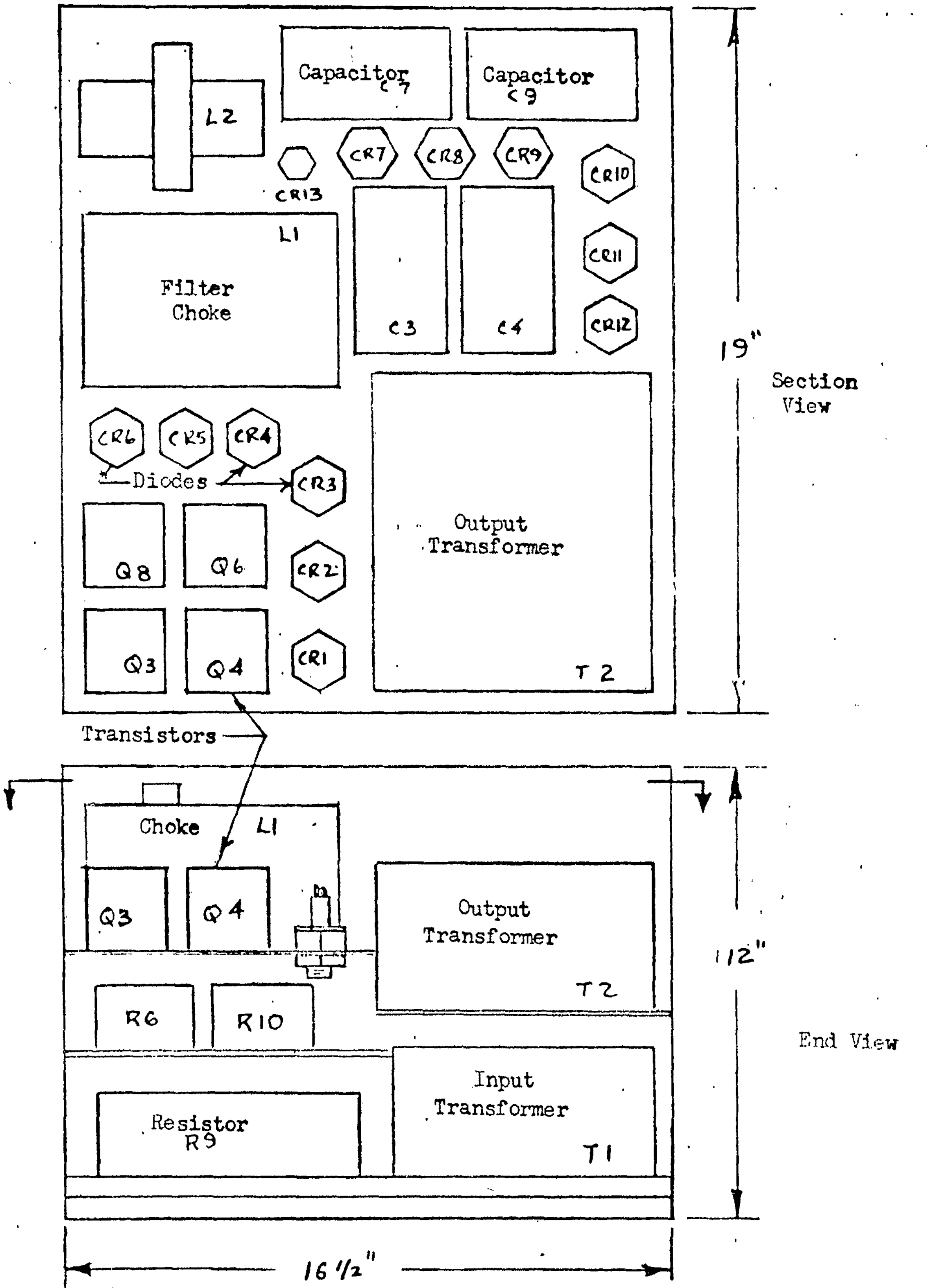


60KW, 1Ø, 200KC STATIC CONVERTER
SCALE: 1/4

Figure 3.1.3-8A

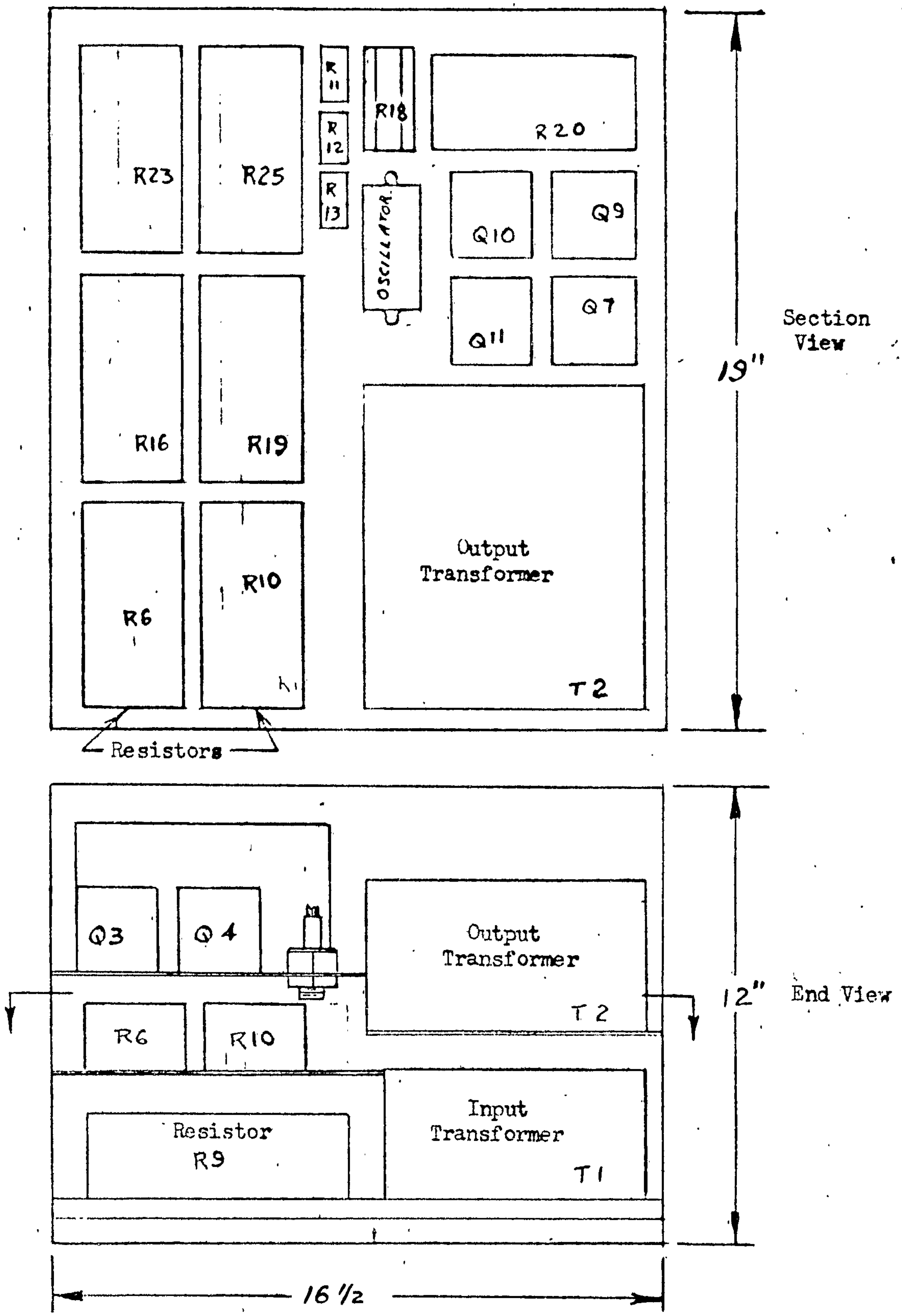


Figure 3.1.3-8B Section View of 60KW, 1Ø 200 KC Converter

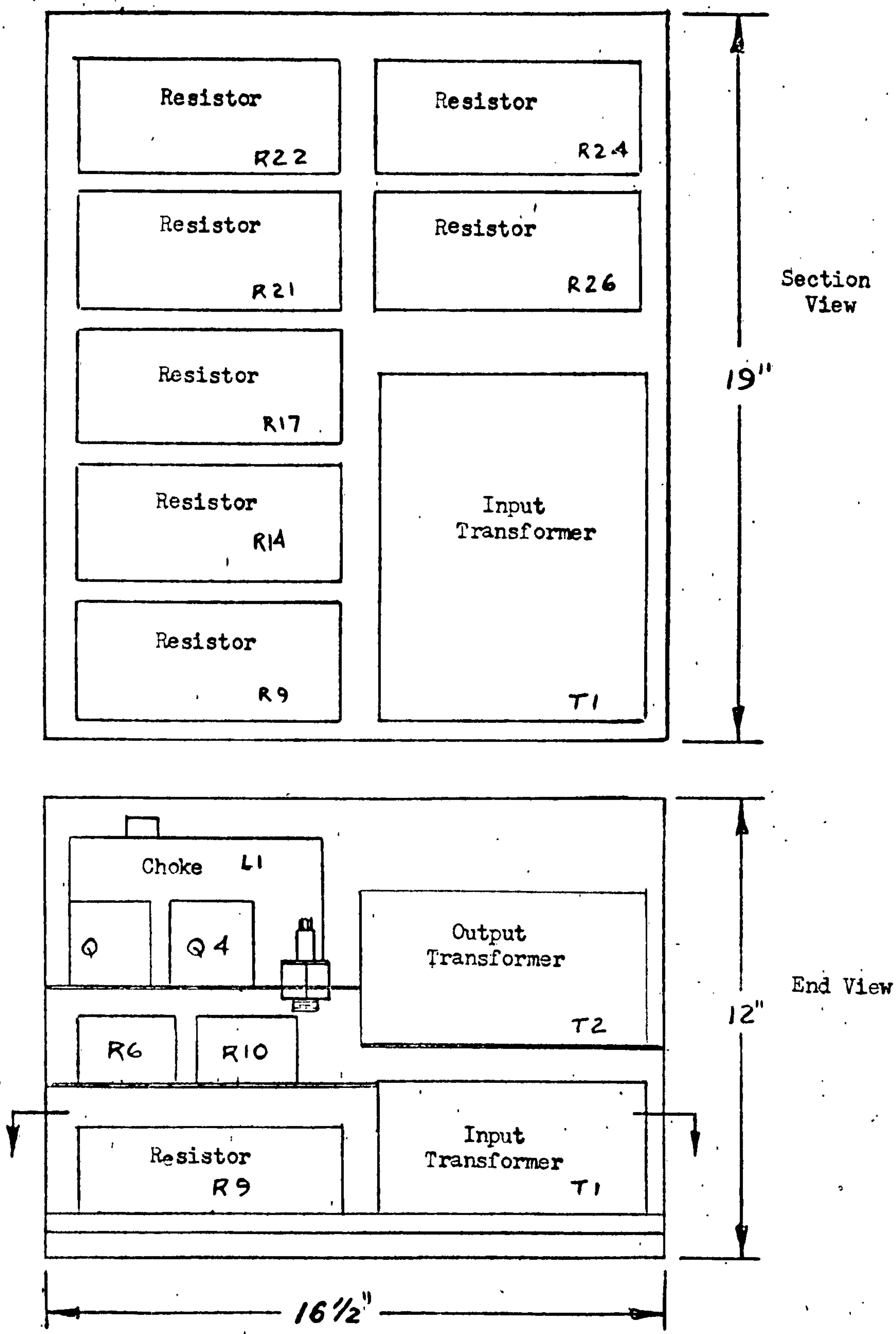


Figure 3.1.3-8C Section View of 60 KW, 1Ø 200 KC Converter

3.2 HIGH-FREQUENCY GENERAT
DESIGN

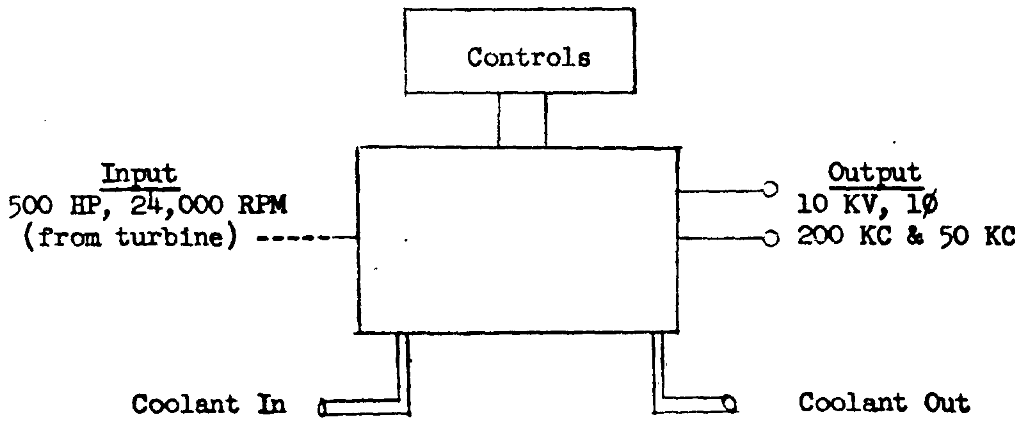
3.2 HIGH - FREQUENCY GENERATOR CONCEPT

3.2.1 300 KW, 50 KC AND 200 KC, 24,000 RPM (ELECTROMAGNETIC) GENERATOR

A. BASIC DESIGN

This generator design is similar to the generator design considered for use in the 300 KW motor-generator concept and is to be driven directly from a turbine. In comparing the weight of the two concepts, the generator system weight should be less than the weight of the motor-generator concept by the amount of motor weight required by the converter system. To be considered also is the fact that this generator design is based on a 500 HP input from the turbine which is really 373 KW input. Performance and loss data is shown in Table 3.2.1-1 and 3.2.1-2 which follows for a 50 KC and 200 KC high-frequency generator design, and is based on inputs and outputs shown in the block diagram below.

Figure 3.2.1-1 illustrates the basic generator concept and the 200 KC design is further described in mechanical detail in Figure 3.2.1-2. Details of a 50 KC, 1Ø generator concept are shown in Figure 3.2.1-3. Design details for a 100 KC and additional details for a 200 KC, 1Ø configuration are being determined at the writing of this report and will be available at the next report.



BLOCK DIAGRAM OF A HIGH FREQUENCY GENERATOR CONCEPT

TABLE 3.2.1-1

SUMMARY OF HIGH-FREQUENCY GENERATOR PARAMETRIC DATA

1Ø	50 KC	200 KC
WEIGHT (lbs)	425	1525
KW RAD (LOSSES)	16.4	25.4
KW OUT	356.6	347.6
EFFICIENCY (%)	95.6	93.2
LENGTH (inches)	10.7	28
DIAMETER (inches)	15.8	17.9
VOLUME (cu. ft.)	1.2	4.1
LBS/KW RAD	25.0	60.0
LBS/KW OUT	1.2	4.4

NOTE: Values do not include cooling system weights

TABLE 3.2.1-2

HIGH FREQUENCY GENERATOR DESIGN DATA

	50 KC, 1Ø		200 KC, 1Ø	
WEIGHT (LBS.)				
Generator	400		1500	
Controls	11		11	
Cooling (Structure)	7		7	
Bearings	7		7	
Total (Lbs)	425		1525	
LAMINATION MATERIALS	HYMU 80	48 Alloy	HYMU 80	48 Alloy
Thickness	.0005"	.0005"	.0005"	.0005"
LOSSES (WATTS)				
Stator Iron	5900	11300	5600	8450
Stator I^2R	3240	3600	6430	6700
Field I^2R	527	586	3640	3800
Windage	1019	1019	4650	4650
Stray Load	3000	3000	3000	3000
Total (Watts)	13686	19505	23320	26600
GENERATOR EFFICIENCY (%)	95.6	94.0	93.2	91.8
OTHER DATA				
Avg. Stator Tooth Flux Density in Kilolines/Square Inch	22.8		15.8	
In Gausses	3,540		2,400	
Stator Conductor Current Density in Amperes/Square Inch	6,400		6,400	
Field Conductor Current Density in Amperes/Square Inch	3,500		3,500	
Conductor	28 Ni-Clad Cu.			
Curie Temperature, °F	860°	932°	860°	932°

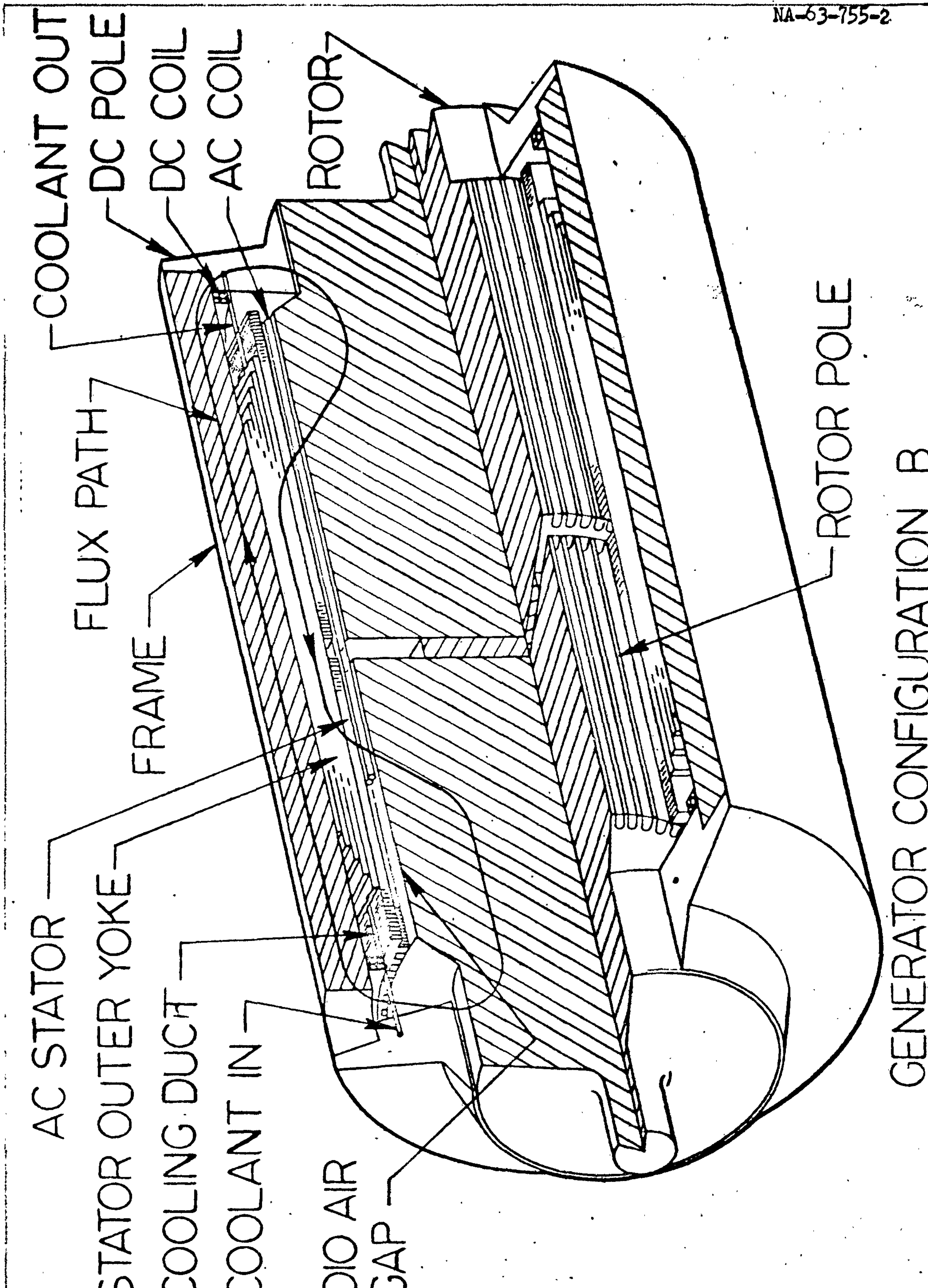
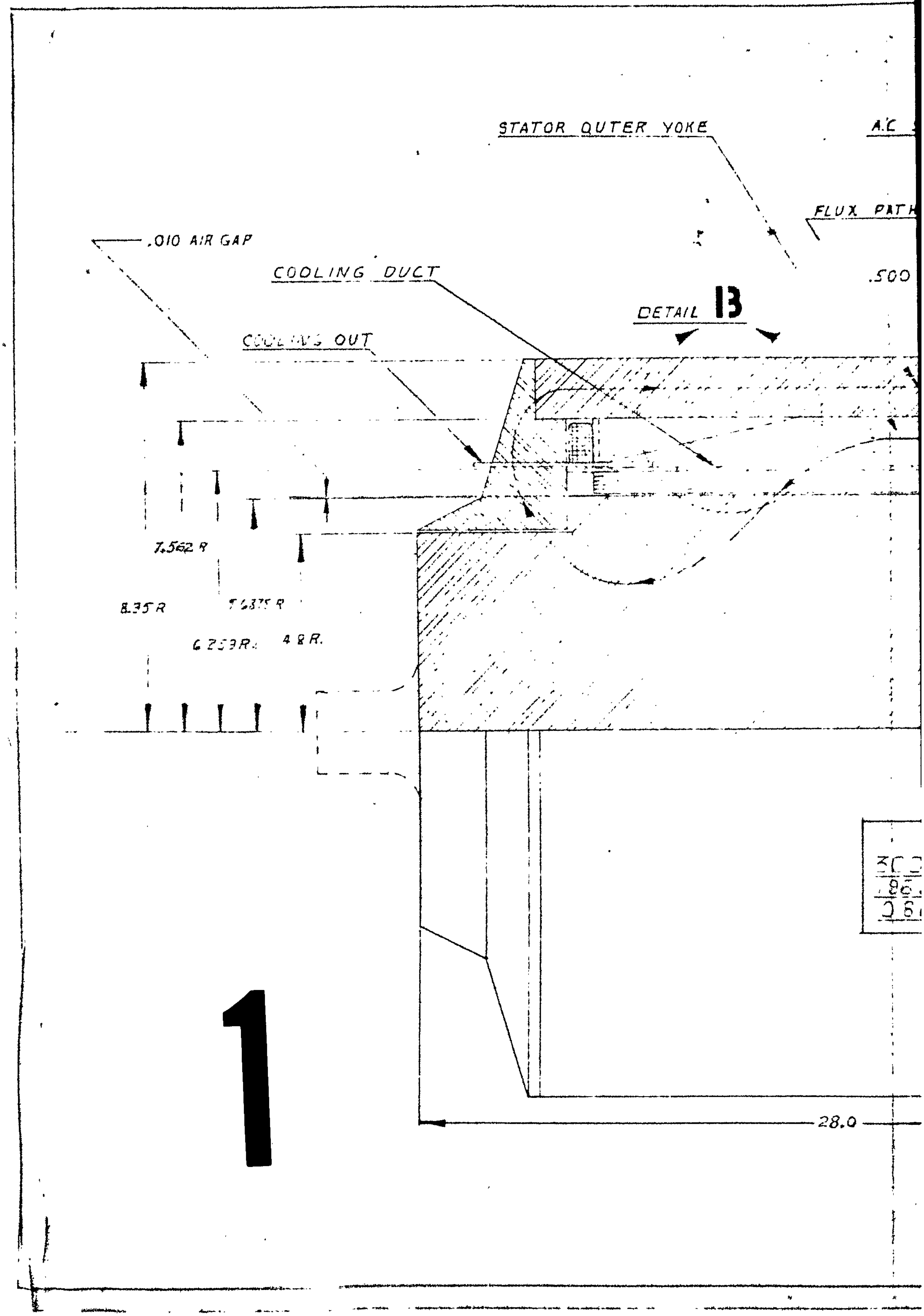
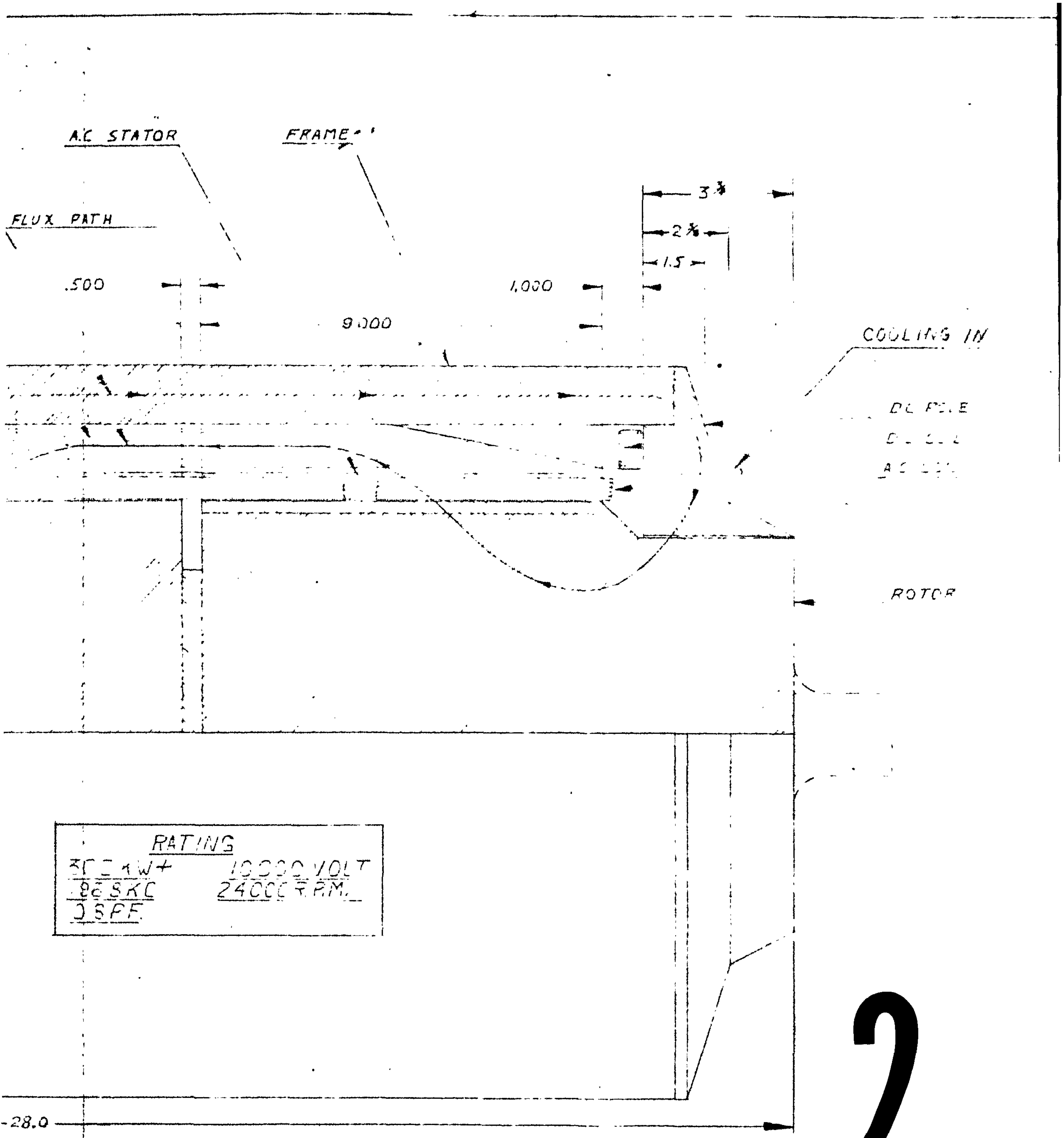


Figure 3.2.1-1 Basic Generator Configuration

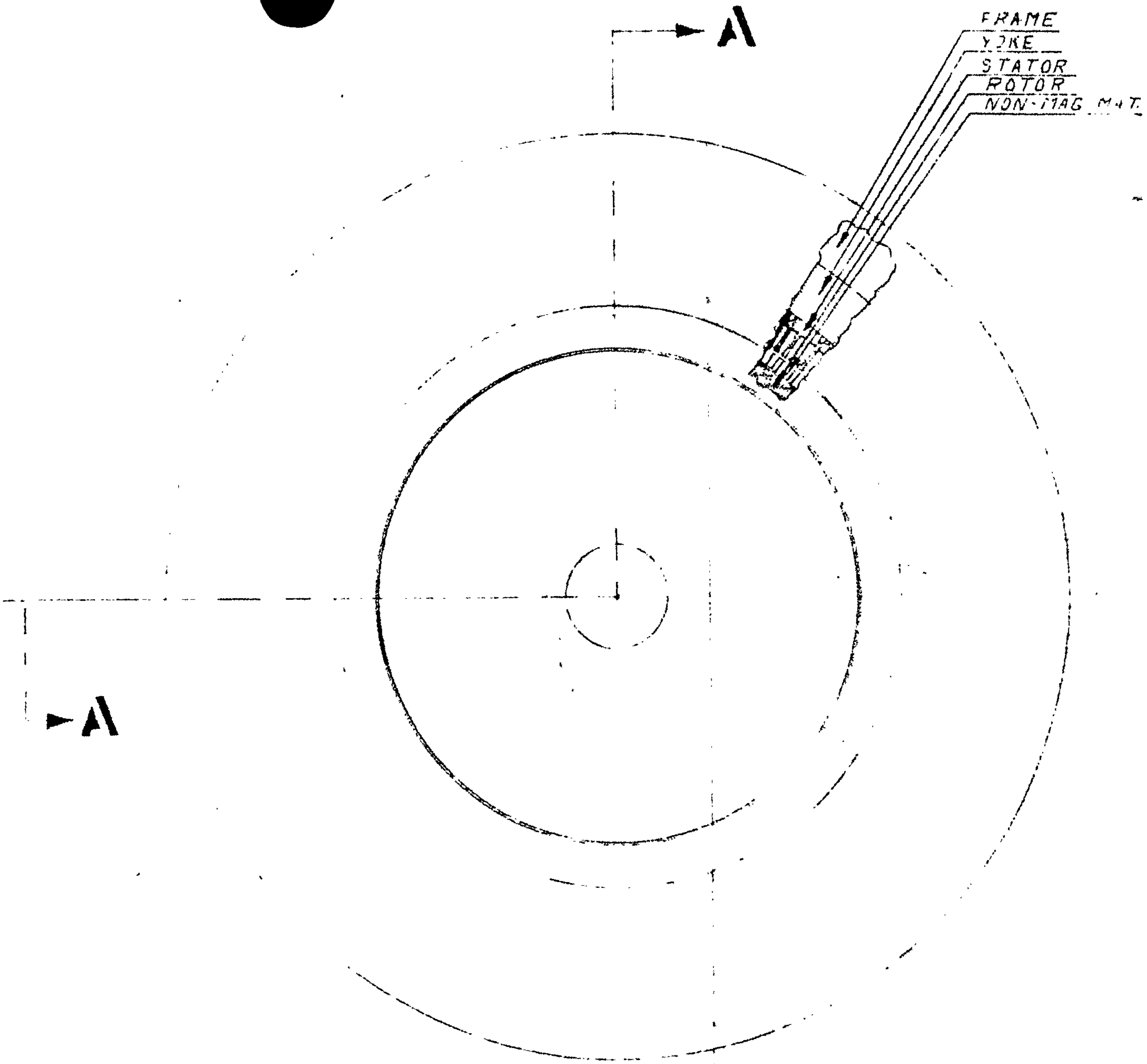

STATOR OUTER YOKE
FLUX PATH
.010 AIR GAP
COOLING DUCT
DETAIL B
COOLING OUT
.500
7.562 R
8.35 R
4.8 R.
28.0
1


A.C STATOR
FRAME
FLUX PATH
3 ¾
2 ⅜
1.5
.500
1,000
9.000
COOLING IN
ROTOR
RATING
10000 VOLT
24000 R.P.M.
-28.0

SECTION A-A

2

3



PRELIMINARY DESIGN OF 200KC.
HIGH FREQUENCY GENERATOR
CONFIGURATION "B"
FIGURE 3.2.1-2

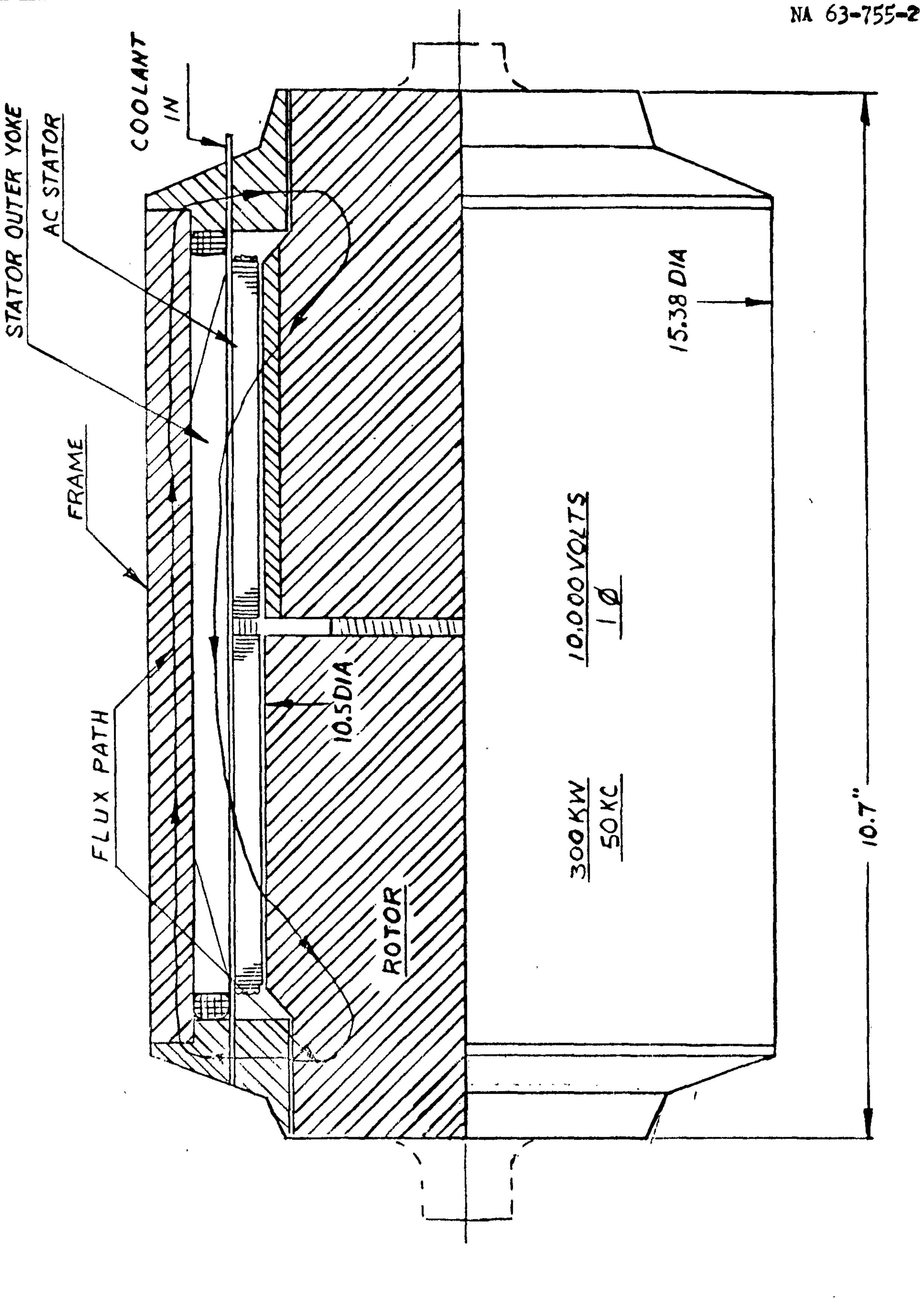
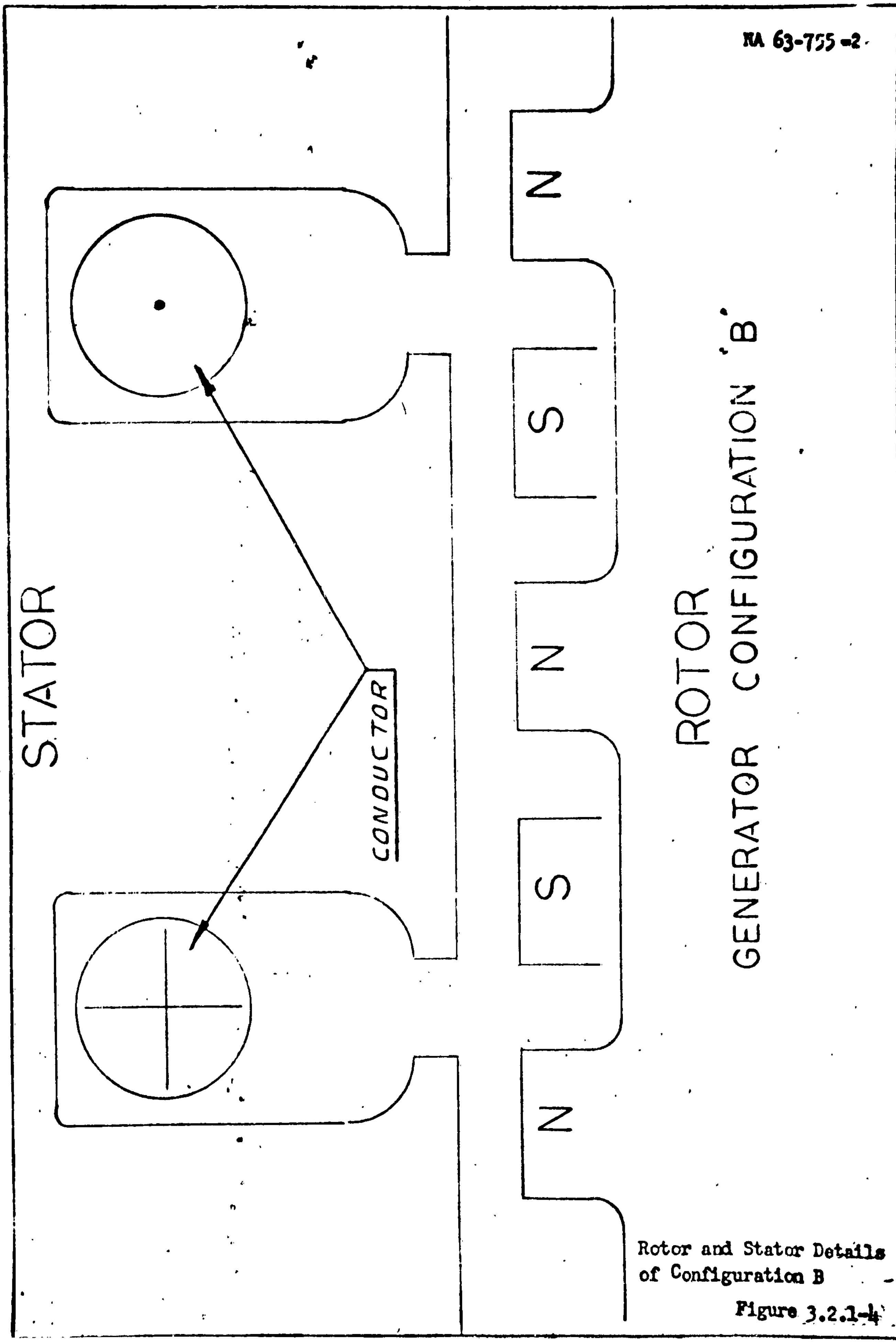


Figure 3.2.1-3 Preliminary Mechanical Design of 50 KC High Frequency Generator

Figure 3.2.1-4 shows the relationship between rotor poles and stator slots for the proposed generator. The South poles of the rotor are displaced axially from the rotor North poles. The stator slots are so chosen that adjacent stator slots are located one for every three poles of the rotor (counting both North and South poles). A stator slot may have a maximum width of a pole pitch, the distance from the center of a North pole to the center of a South pole. This places the slots so that the induced voltages are in opposite directions in adjacent slots. Figures 3.2.1-1 and 3.2.1-5 show cross sections through the generator.

Rotor - The rotor is made of a high-strength, solid magnetic material and the outer circumference is slotted to form poles similar to gear teeth. The teeth in one section are displaced 180 electrical degrees from the teeth in the other axially displaced section as shown in figure 3.2.1-4. The depth of slot depends on the air gap between stator and rotor teeth and must be sufficient to reduce the flux from the space between poles to the stator to a low percentage of the flux from the teeth to the stator. The two sections of the rotor are spaced by a nonmagnetic material to minimize flux leakage between the north and south section.

The flux in the rotor is a dc flux and produces no loss during steady state operation. A ripple flux in the pole tips will produce some losses; this loss may be reduced by reducing the stator slot opening to less than the width of a rotor tooth to prevent the flux from changing in the teeth.

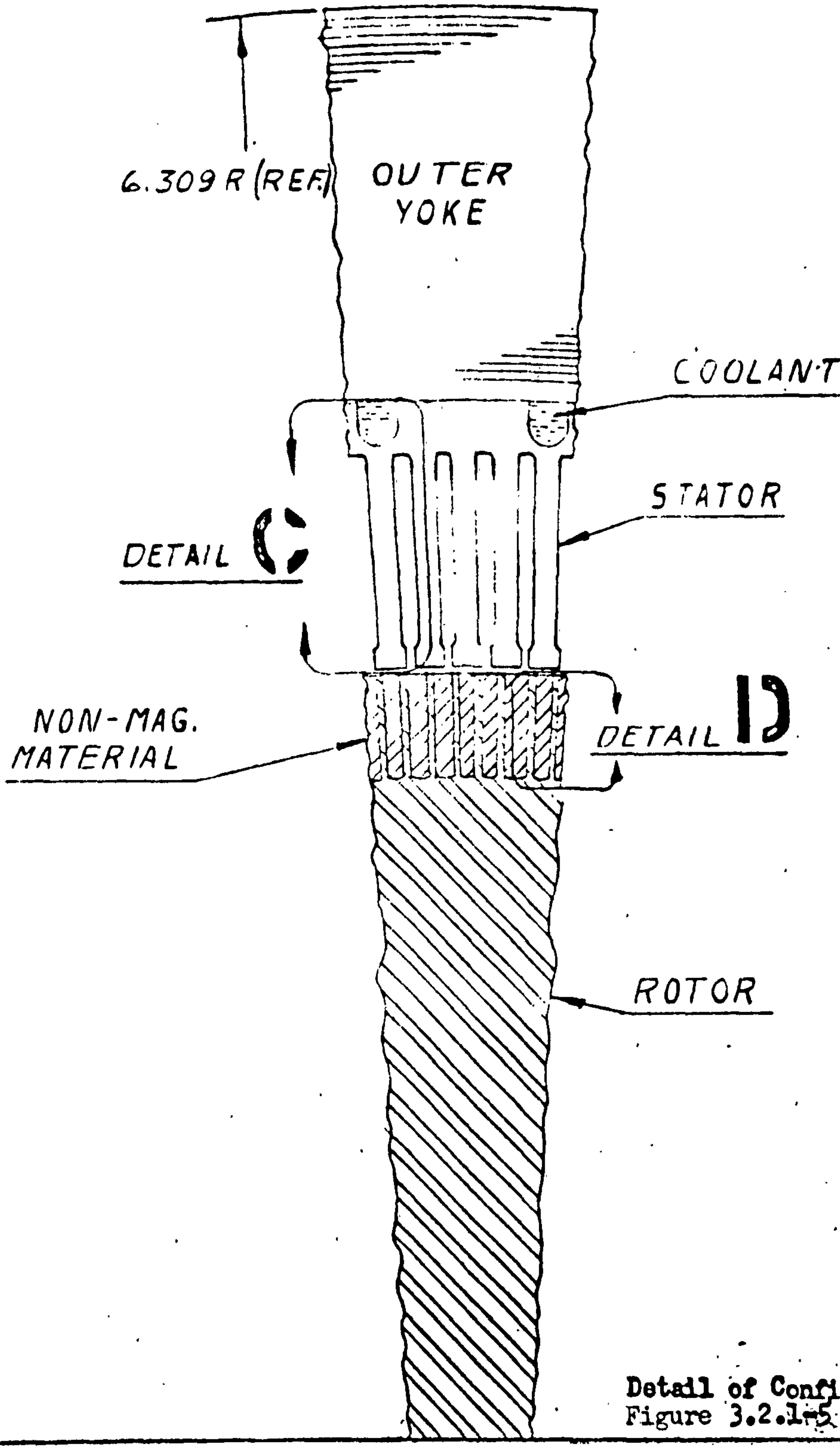


Rotor and Stator Details of Configuration B

Figure 3.2.1-4

DETAIL B

GENERATOR CONFIGURATION "B"



Detail of Configuration B
Figure 3.2.1-5

Outer Yoke - The outer yoke carries the flux from the North stator section to the South stator section. The flux rotates in the outer yoke at the same speed (RPM) as the rotor is turning. It is an unchanging or dc flux for any load condition. The outer yoke is shown as a tape wound core and very little loss is generated by a constant spinning flux. The outer yoke lamination may be from a thicker and higher loss material than the stator iron, and be operated at high flux densities.

Stator Iron - The stator iron is subjected to a pulsating flux of the generating frequency of a single polarity in each stator section. The flux rotates in the yoke section of this lamination at a rate the same as the rotor speed (RPM) and is pulsating at the generating frequency. This material must be of a low loss magnetic material and of very thin laminations to minimize iron losses at high frequencies. Laminations of .001 inches and .0005 inch thickness have been considered in this design. The flux density must also be at reduced values to minimize losses at high frequencies. Ferrites are usable for this core, but limit the operating temperature to lower values than possible with nickel-iron alloys.

B. THERMAL ANALYSIS

The cooling system of the high-frequency generator unit is made up of thin parallel tubing located in the stator yoke. The parallel tubes then converge into a collection ring at each end. Heat is removed from the stator to the coolant fluid by means of conduction. High-frequency generator units are capable of operating at temperatures above 1000°F, but designs considered here are based on coolant temperatures in the 500°F to 800°F range. Figure 3.2.1-6 shows the effect of system operating temperature on generator system weight. Calculated electrical losses for a 50 KC and 200 KC unit and other thermal design data including efficiencies for 48 Alloy and HYMU 80 materials are shown in Tables 3.2.1-1 and 3.2.1-2.

Efficiency - Efficiency of the generator is reduced as the temperature of the generator iron increases. Figure 3.2.1-7 shows how the efficiency changes as of function of temperature for a 300 KW, 200 KC design. HYMU 80 material in .0005 inch laminations can be used to nearly 800°F stator iron surface temperatures with a calculated efficiency of 93.2% (Table 3.2.1-1). Alloy 48 is shown on the efficiency versus temperature curve at a lower efficiency and has been considered for use because of its lower weight. If higher operating temperatures are required, the silicon irons will have to be used with resulting lower efficiencies. Effort will be expended to give an indication of efficiency versus weight trade-off potentials.

Stator Iron Losses - The iron losses at high frequencies become very important in the design of generators as they affect the temperature of the parts and the efficiency of the generator. The effect of frequency on iron losses, magnetic materials, and various lamination

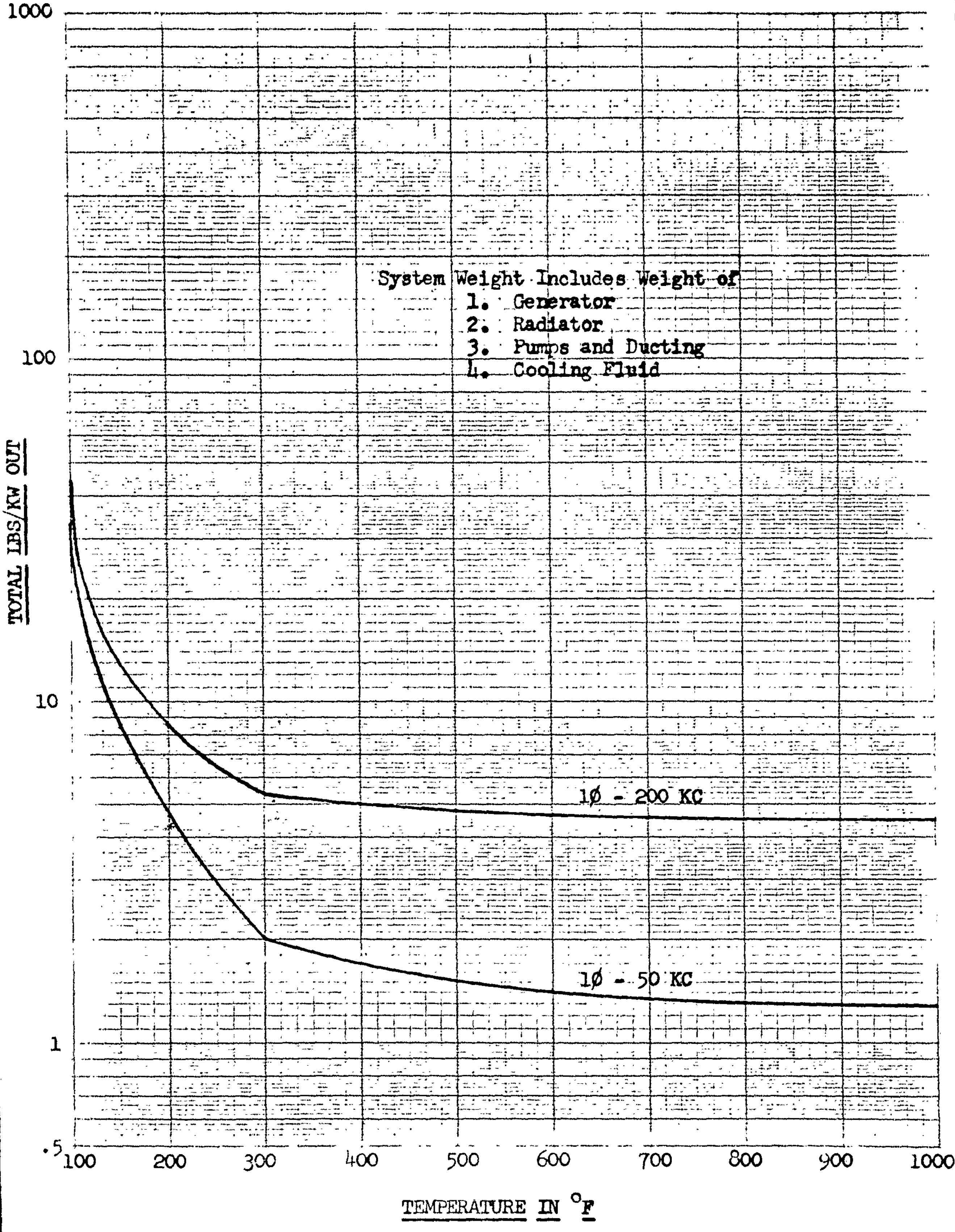


Figure 3.2.1-6 Analysis of System Weight vs Temperature for High Frequency Generator

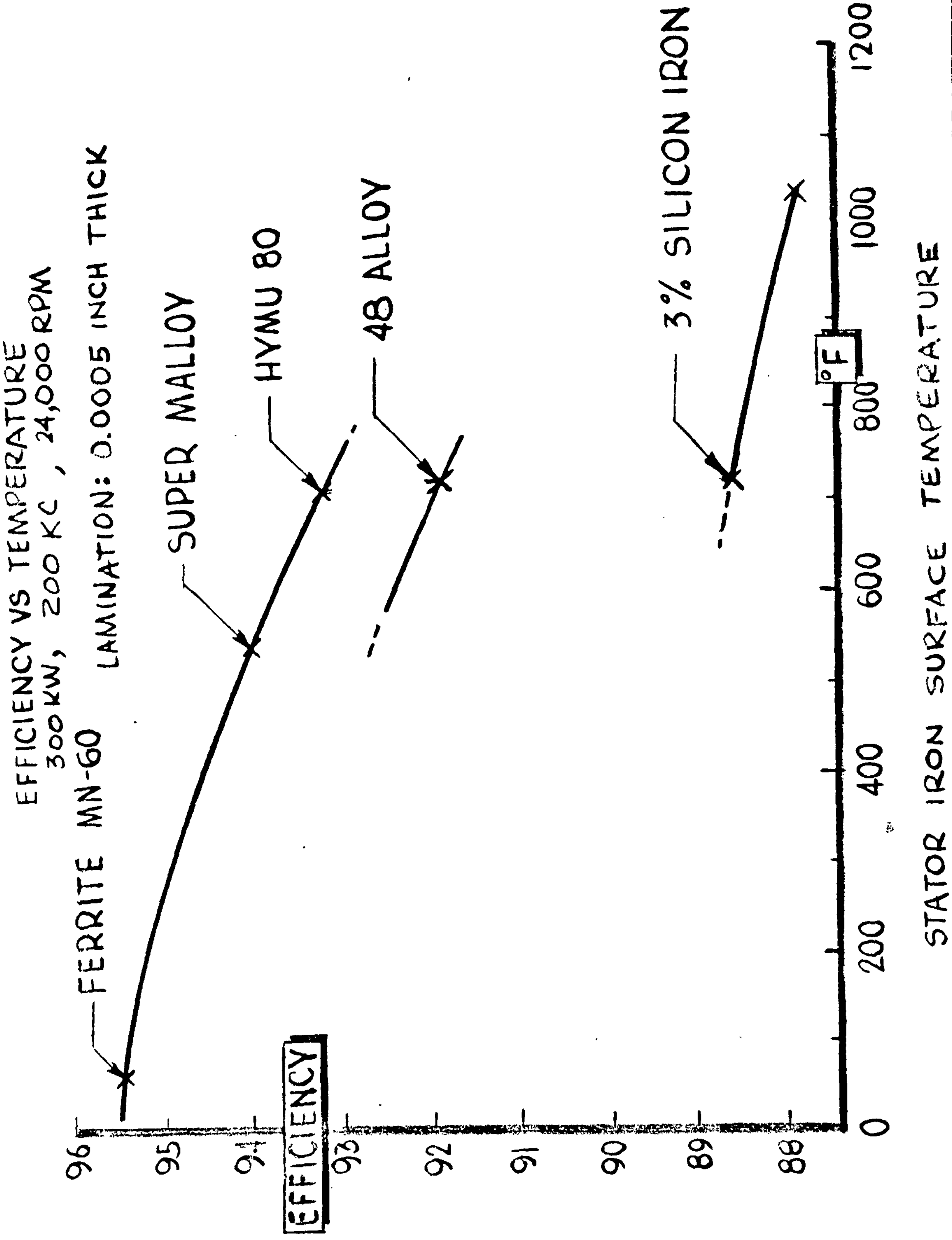


Figure 3.2.1-7 Efficiency vs. Temperature for 300 KW Generator

thicknesses are reviewed in a later section on Materials. Only a limited amount of information exists on losses at the 50 to 200 KC level at elevated temperatures. Tests need to be conducted to determine the magnitude of these losses before finalized generator designs can be made.

Copper Losses - The conductor I^2R losses vary as a function of temperature, resistivity, and the square of current density. All the copper losses have been calculated for the same material resistivity and current density (see Table 3.2.1-1) in the stator winding and a lower current density in the field coils. These losses may be reduced by additional conductor material and weight. The increase in this loss due to increase in conductor resistance as a function of frequency (skin effect) can be minimized by using small diameter conductors in parallel.

3.3 RELATED STUDIES

3.3 RELATED STUDIES

3.3.1 ANALYSIS OF COMPONENTS

3.3.1.1 TRANSISTOR POWER CAPABILITIES

The design of the transistorized power converter was based on the availability of a transistor capable of switching 100 amps of current with a voltage rating of 500 volts and a frecuency capability of 1 megacycle. Although this type of device is not presently on the market it should be available in 5 to 7 years through normal development. Consultation with several of the leading transistor research engineers has led to the conclusion that these devices can be made available sooner with an accelerated development program. The problems associated with development of these devices are discussed in the section which follows.

The mesa transistor developed in 1956 initiated high-frequency power transistor development, and, although it has largely been replaced by the planar configuration, the mesa type of transistor still has the important advantage of high-voltage and high-current capability. First, high collector breakdown voltage, difficult to realize in shallow planar devices, is readily obtainable in the larger mesa junctions. Secondly, by comparison with planar junctions, substantially larger mesa junctions areas are economically feasible due to their relative freedeom from contamination-induced defects such as phosphorus "pipe". Figure 3.3.1-1 shows the power-frequency-material interrelationship (1963) for semiconductors. Power capability in the 50 - 800 KC range is limited to a 1 KW maximum (which is the product of voltage and current).

If we review some of the basic design theories of power transistors, we find that the theories consist of the original junction transistor theory of Shockley plus a collection of analyses attempting to improve upon this theory. Most of these theories are multi-dimensional and non-linear, and although these theories serve as a qualitative guide, they fall short of a precise quantitative theory.

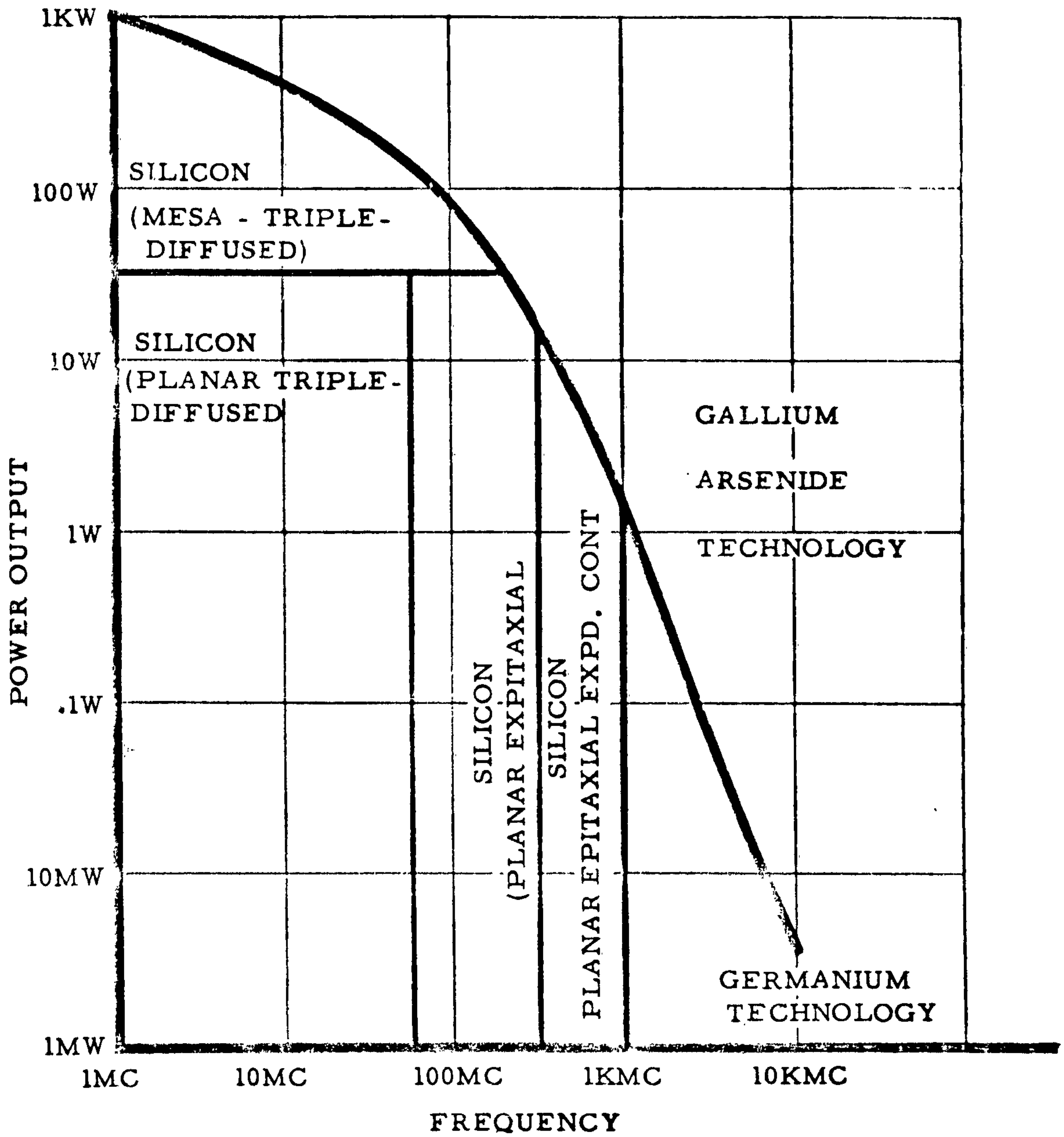
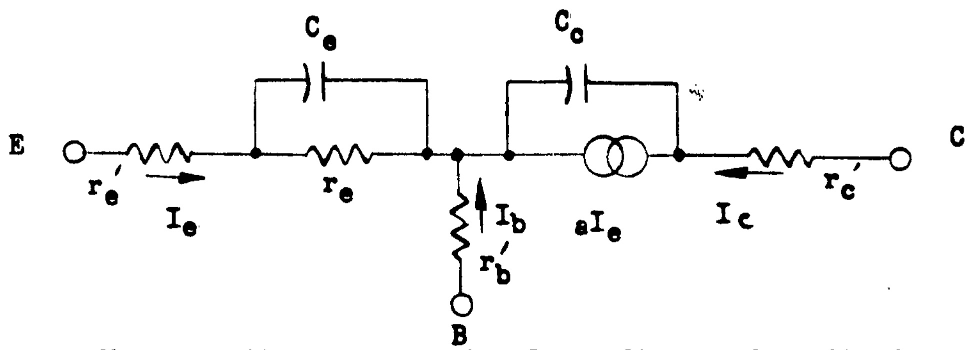


Figure 3.3.1-1 Power - Frequency - Material Interrelationship (1963)

Let us look at the T-equivalent circuit representations of a power transistor as shown below:



We can write an expression for a figure of merit of a transistor, and if we use the power-gain bandwidth squared product, we will have an expression relating the high frequency performance of a transistor to the product of certain device parameters.

$$G_p\,(BW)^2 \approx \frac{f_b}{4} \cdot \frac{1}{\frac{1}{Af_o} + \frac{1}{f_c} + \frac{1}{f_e}} \qquad \text{where } A_{f_o} = \left(\frac{A_o}{1 + J\,f/f_{a_o}}\right)$$

A_o = low frequency gain

and

$$f_b = \frac{1}{2\pi r_b'\,C_c}, \qquad f_c = \frac{1}{2\pi\,(r_e + r_e' + r_c')\,C_c}$$

$$f_e = \frac{1}{2\pi r_e\,C_e},$$

r_e = Emitter parasite resistance

r_b = Base Parasite resistance

C_c = Collector junction capacitance

$r_e' = \frac{26}{I_e(M_a)}$

If we rewrite the equation and substitute values for A_{f_o} + fb + fe the equations takes the form

$$G_p\,(BW)^2 = \frac{1}{8\pi r_b'\,C_c} \cdot \frac{A_{f_o}}{1 + 2\pi\,(r_e + r_e' + r_c')\,C_c A f_o + 2\pi\,C_e\,A_{f_o} r_e}$$

This expression shows that the frequency response is dependent on certain RC time constants in the T-equivalent circuit.

Now, if we relate the geometry of a device to its effect on the transistor parameters we note the following effects:

1. For high-current density, the active volume will be much smaller than the total available volume due to the "edge effect". The current flow will be concentrated at the emitter edge. Therefore, the major power dissipation will take place at the collector junctions opposite the emitter edge. The active cross-sectional area of the transistor for high-current densities is proportional to the emitter edge length 2L and not to the emitter area.
2. Junction capacitances are, to a first order approximation, proportional to the geometry areas involved, and are therefore proportional to L.
3. Parasitic resistances are inversely proportional to the cross-sectional area of the material through which the current flows. Applying the geometry-parameter relationships to low-power, high-frequency devices and scaling-up the dimensions of the semiconductor junctions has led to the development of high-power, high-frequency, devices with linear geometry, or interdigitated constructions. The scaling-up process is limited so far by the size of a semiconductor junction that can be produced that is free from contaminant-induced defects.

Now consider several design parameters that arise from the foregoing considerations.

1. For high current gain, the base must be thin.
2. To reduce effects of high-current density, utilize thin bases with low resistivity material. Maintain emitter efficiency close to unity by means of heavy emitter doping.
3. For low base resistance, the base layer should be thick.
4. For high collector to base breakdown voltage, utilize high resistivity in the base regions.

From these considerations we notice several conflicting parameters which result in the necessity of trading off high-voltage for high current or vice-versa. Present day requirements have been for the high current capability. The problem of obtaining increased power handling capabilities (higher current and higher voltage in the same unit)can be solved by material processing refinements and the use of different diffused structures such as the NPiN structure.

3.3.2 ANALYSIS OF MATERIAL

3.3.2.1 MAGNETIC MATERIAL CHARACTERISTICS

The frequencies considered for this study were 50 to 200 KC for the high-frequency generator and 50 to 800 KC for the frequency converter units. Average coolant temperatures used in the design studies were in the 200 to 1100°F range. Major determinants in the selection of magnetic materials for these conditions are the Curie point, core loss at the design frequency and operating temperature, and usable flux density at the design temperatures. Aspects of these determinants will be discussed in the section which follows with specific materials to be discussed later in this section.

Flux Density

A survey was made of the maximum flux density of various low-loss magnetic materials over the 100 to 800°C range. The results of this survey are shown in Figure 3.3.2-1. As can be seen in this figure, there is a decreasing maximum flux density in going to high temperature operation. Oriented-silicon steels are best for flux capability with low-loss ferrites being extremely temperature limited.

Curie Point

Care will have to be exhibited to insure that operating temperatures of both transformers and generators will not exceed the Curie point of the magnetic materials. The flux density value at which magnetic materials become saturated decreases until at the Curie temperature, approximately 750°C for silicon steel, it is totally non-magnetic.

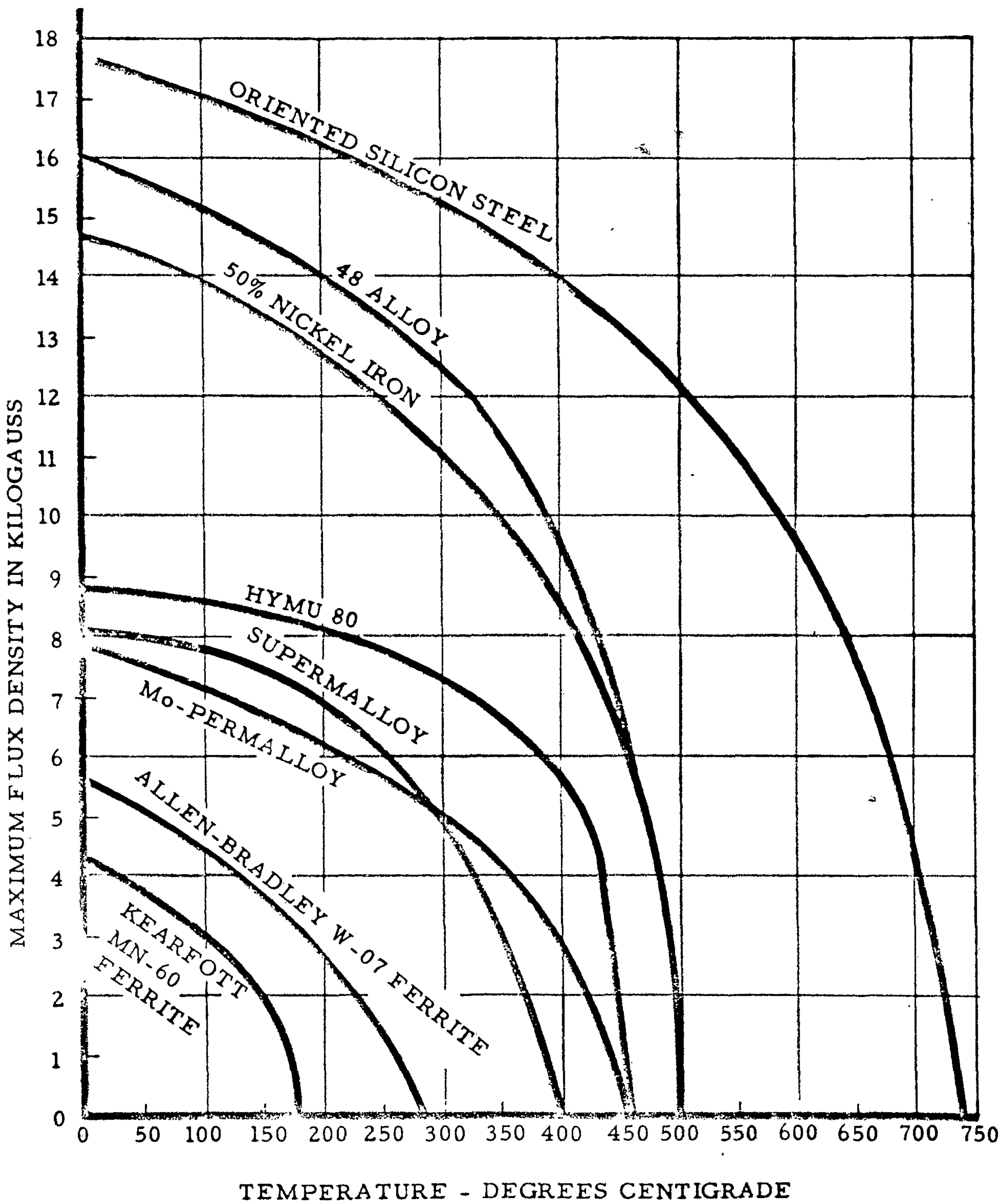


Figure 3.3.2-1 Flux Density vs. Temperature for Various Materials

Core Loss vs. Temperature

Core loss data for high temperatures and low frequencies is available but not much information is available on core losses to be expected in high-temperature, high-frequency devices. From the report of a previous study,* it is indicated that core losses at 550°C are reduced to about 60% of room temperature values for various laminated core shapes. This variation did not appear to be a function of flux density.

Typical core loss vs. flux density and core loss vs. temperature curves at the low frequencies and high temperatures are shown in Figure 3.3.2-2 and 3.3.2-3. The effect of temperature on total core loss (including both eddy current and hysteresis loss) at 1KC frequency is shown in Figure 3.3.2-4. In general, the core loss for both HYMU 80 and Supermalloy drops off steadily with increasing temperature. The significant reduction in core loss in going from HYMU 80 to Supermalloy is obvious from this data but Supermalloy is both temperature and flux density limited as shown in Figures 3.3.2.-4.

Core Loss vs. Lamination Thickness

An examination was made of available data on various magnetic materials in order to determine the effect of using reduced thicknesses of laminations. Figure 3.3.2-5 indicates that significant reductions are achieved by going from two mil to one mil materials, and that even greater reductions could be achieved by using 1/2 Mil or less. Unfortunately, no data is presently available on the relative core losses of ultra-thin laminations. A test program to evaluate such magnetic materials appears extremely desirable.

* WADC TR57-492 Vol I

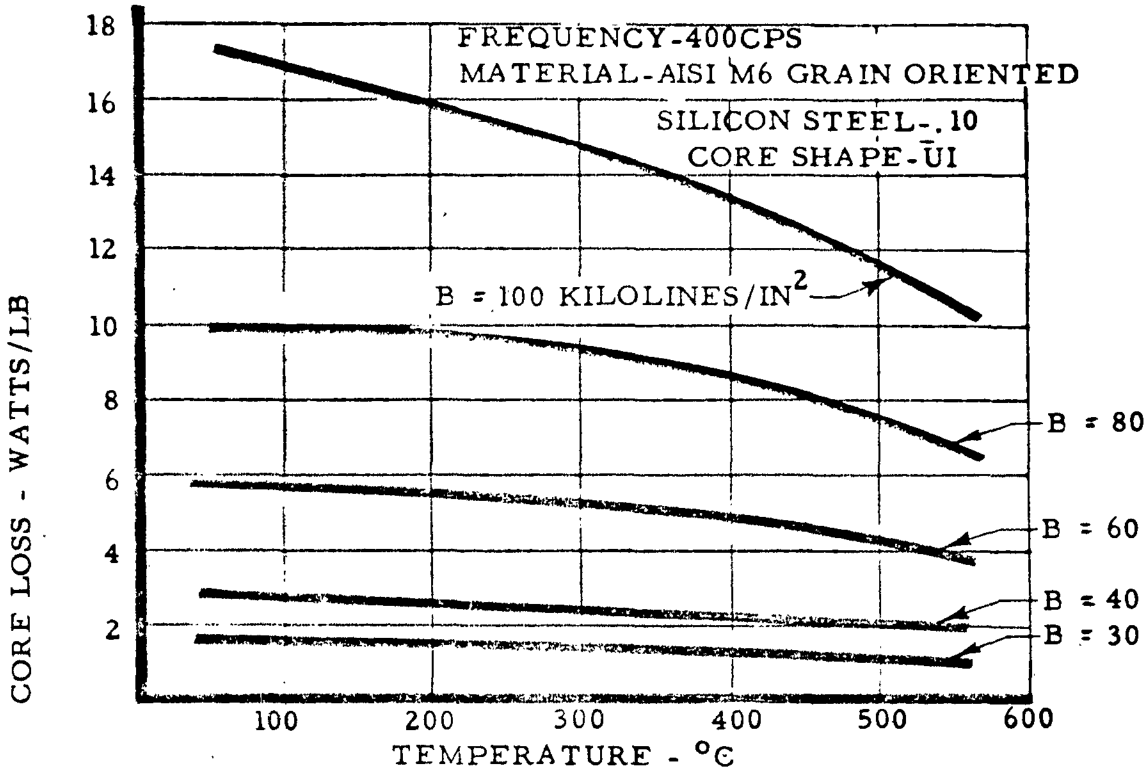


Figure 3.3.2-2 Core Loss vs. Temperature for 3-1/4% Silicon Steel

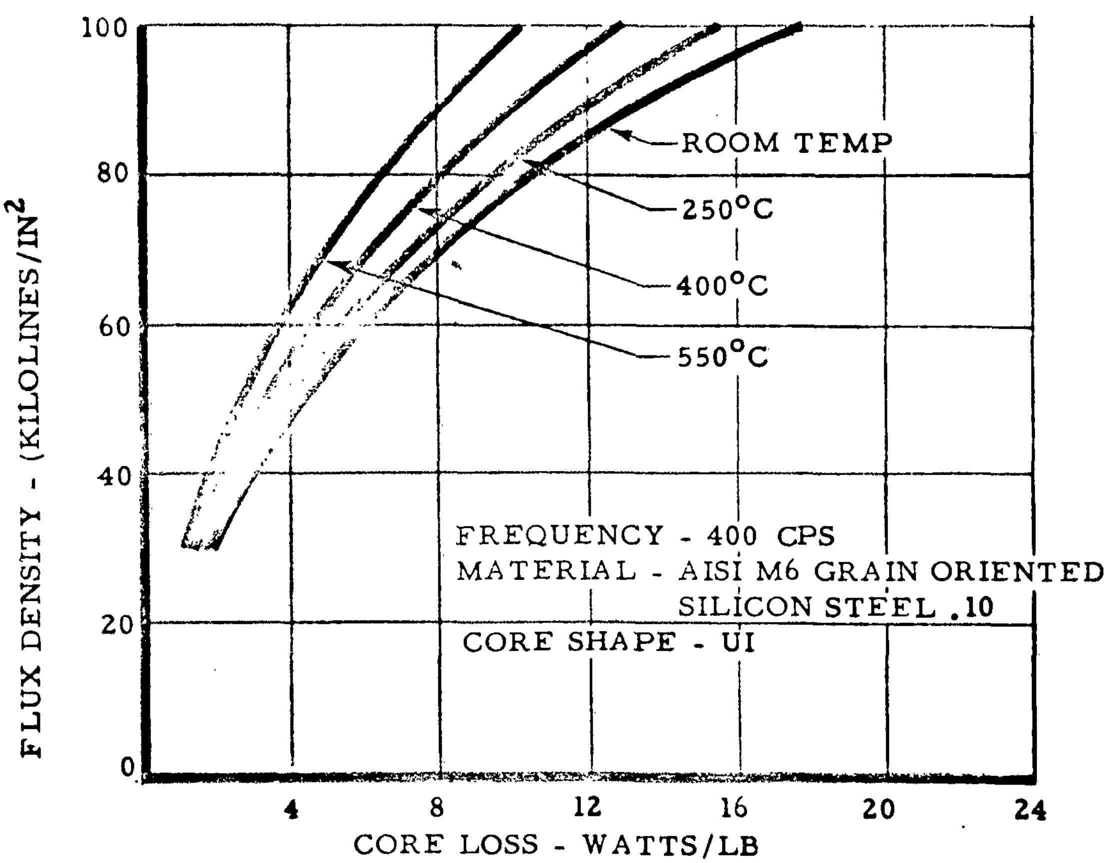


Figure 3.3.2-3 Core Loss vs. Flux Density for 3-1/4% Silicon Steel

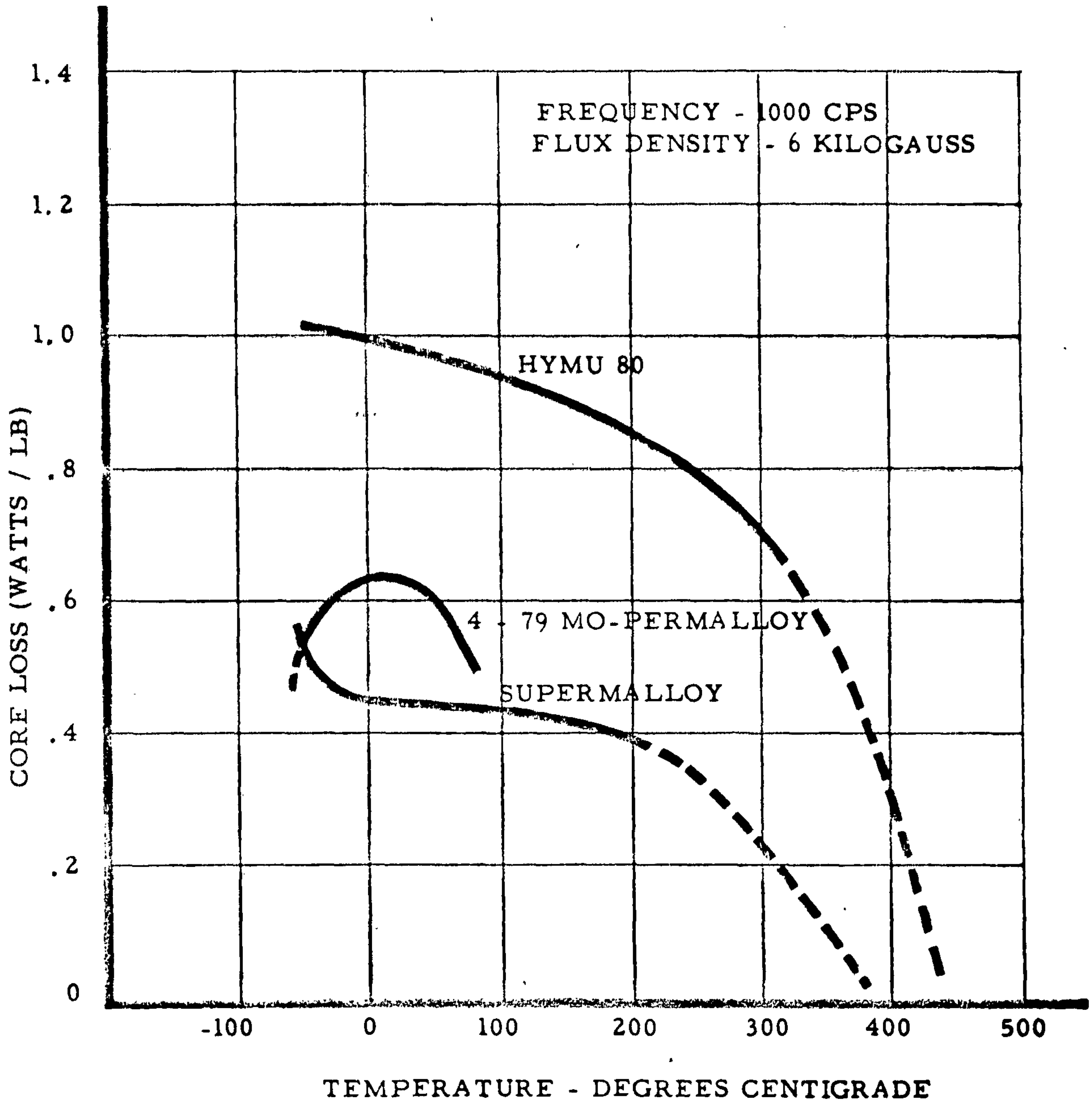


Figure 3.3.2-4 Core Loss vs. Temperature

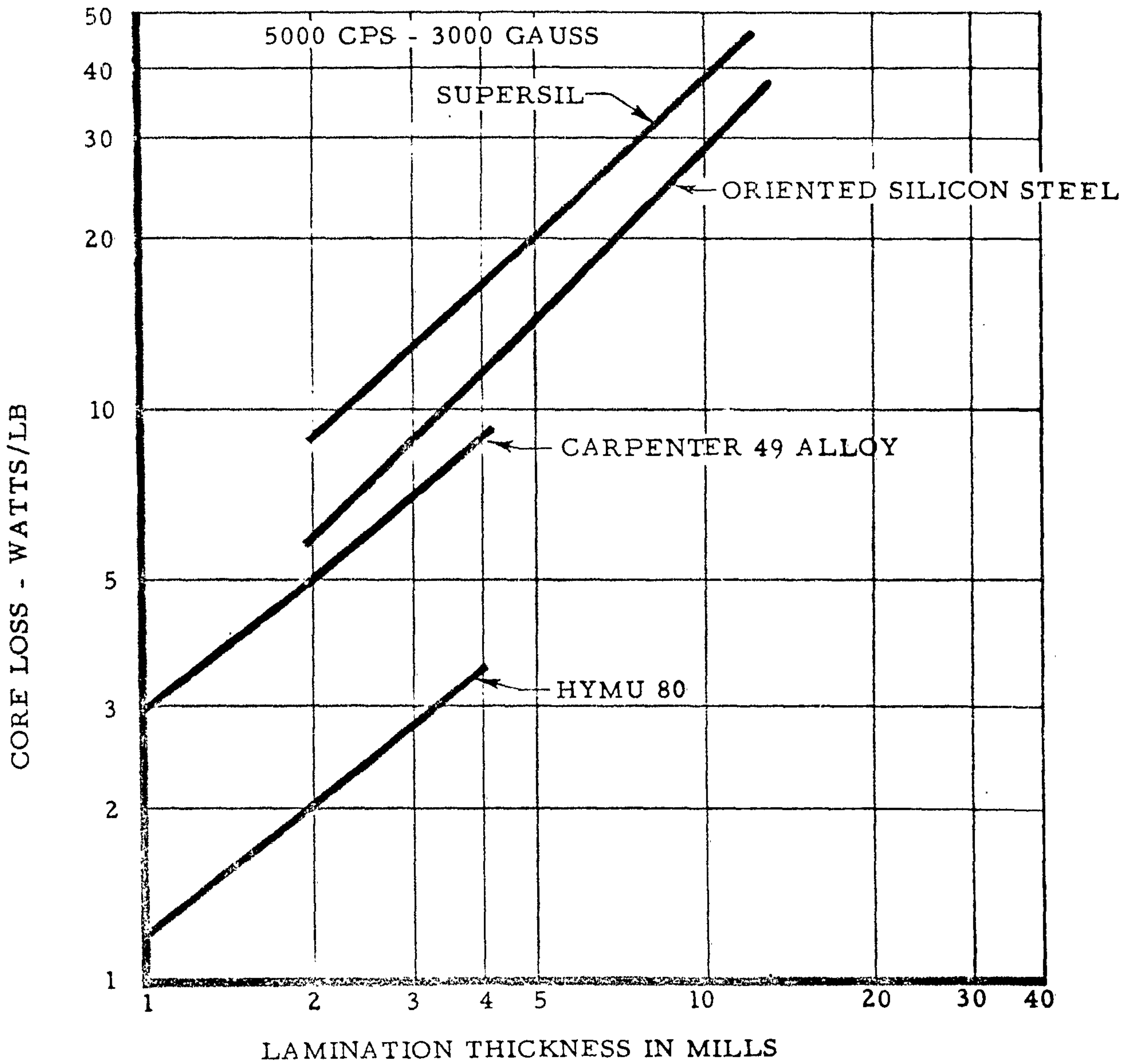


Figure 3.3.2-5 Lamination Thickness vs. Core Loss

Core Loss vs. Frequency

The effect of operating frequency on core loss is shown in Figure 3.3.2-6A and 6B. This figure is a compilation of core loss data from "Reference Data for Radio Engineers" (Fourth Edition) for 60 cycle to 100 kilocycle operation with the addition of data from various core material specification sheets at the 100 and 200 kilocycle frequencies. Information on core loss magnitudes at the 800 KC level has been unavailable in addition to core loss magnitudes to be encountered at elevated temperatures.

It can be seen from this limited data that the use of conventional oriented silicon steel material would result in comparatively high losses at 200 KC unless extremely thin laminations are used. The superiority of HYMU 80 over other materials is evident in these figures with respect to other low loss materials. If thin laminations are used, the core losses can be reduced to levels approaching that of the ferrites.

Loss calculations in this study have been based on data from these curves. Before firm converter and generator designs for the high-frequency ranges specified in this study can be completed it will be necessary to perform experiments to determine the magnitude of actual core losses to be encountered. Such experiments are being recommended as part of this study program in a separate letter and also in the Summary and Recommendation section.

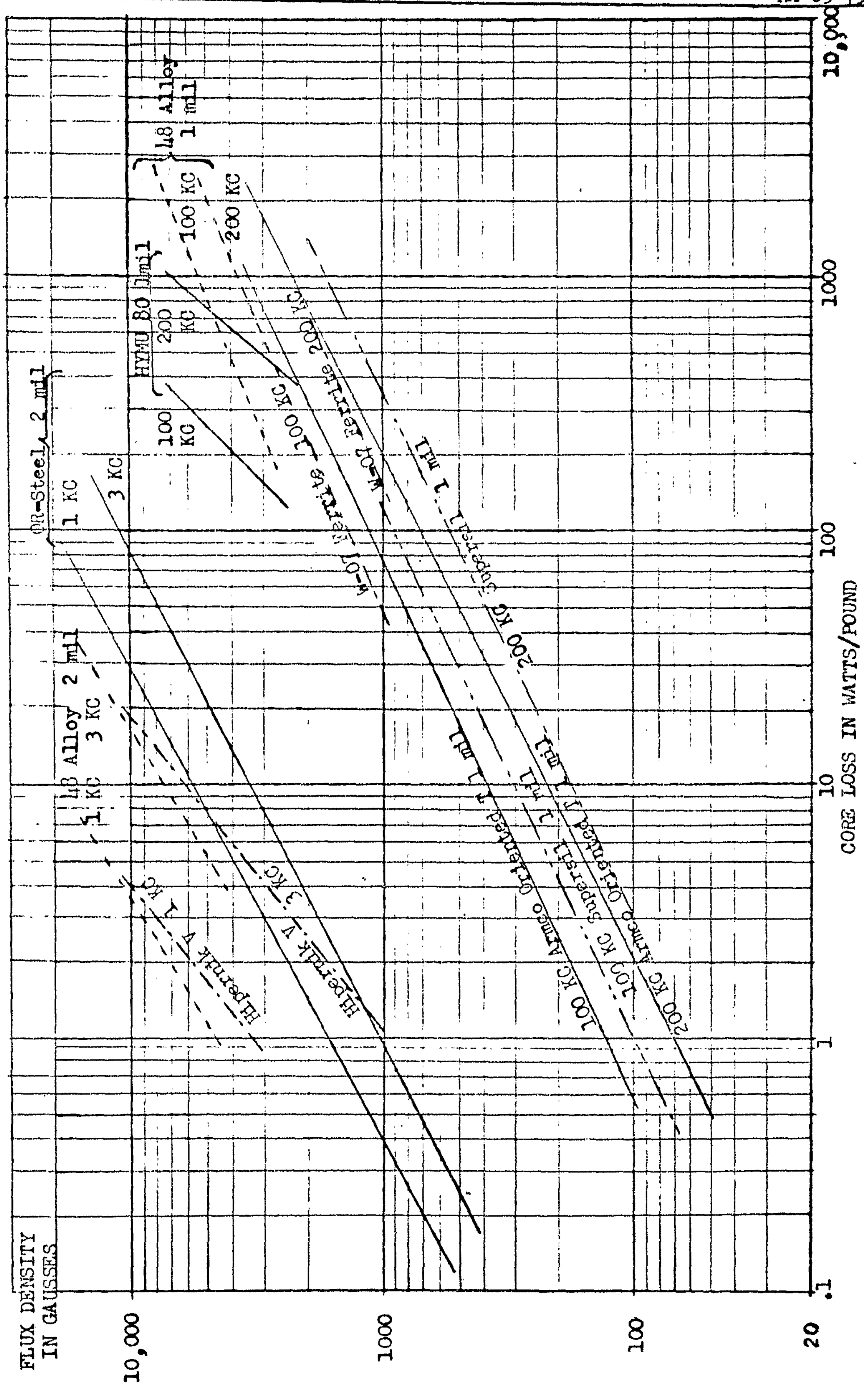


Figure 3.3.2-6A Typical Core Losses for Power Transformers

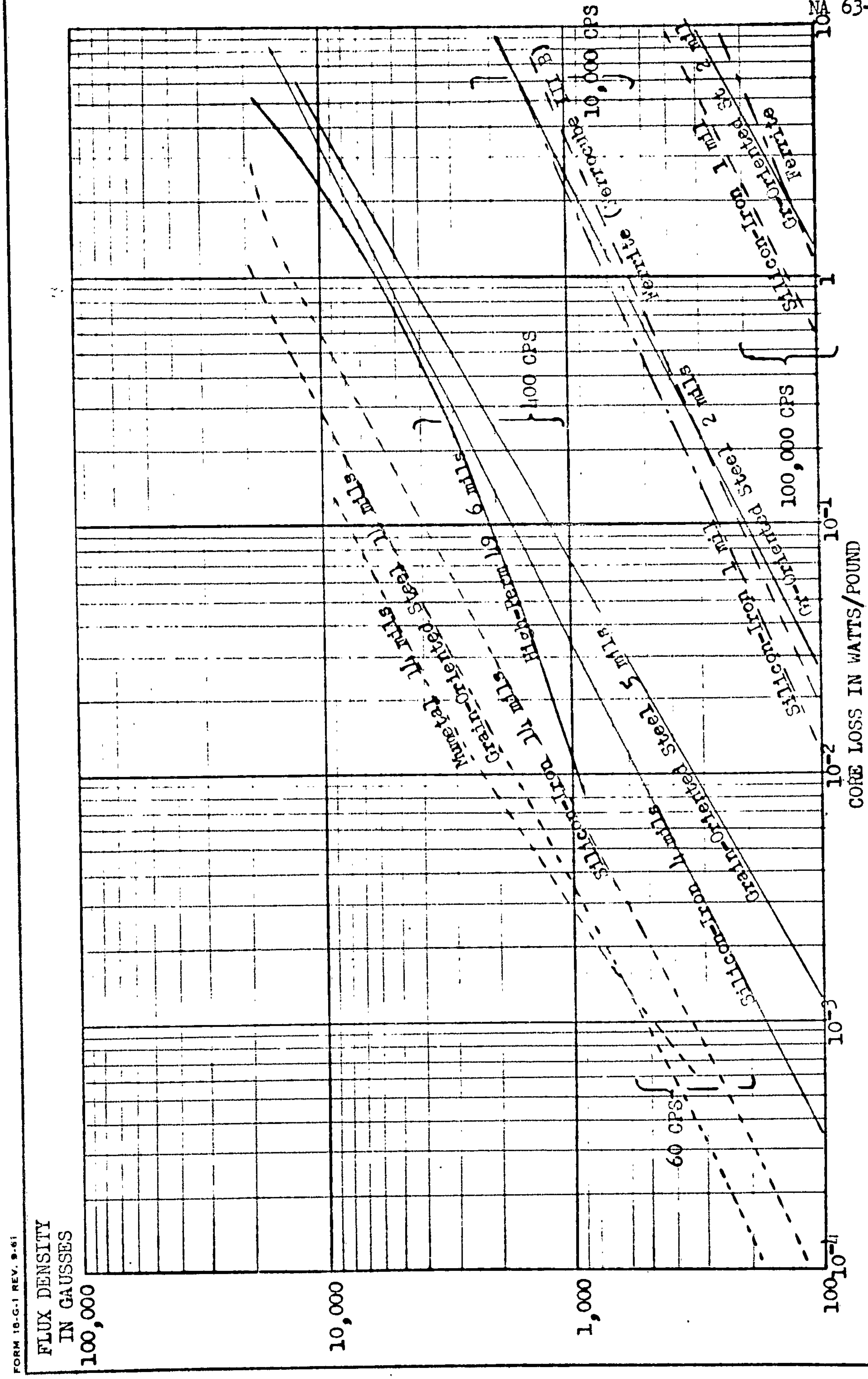


Figure 3.3.2-6B TYPICAL CORE LOSSES FOR POWER TRANSFORMERS

3.3.2.2 SELECTION OF MATERIALS

A. MAGNETIC MATERIALS

Selection of magnetic core material for the final transformer and generator designs will be based on standard design criterion with the additional requirement of stability of the magnetic properties in the specified environment. Based on Curie temperatures, cobalt alloys must be used if the magnetic components are to operate at the maximum temperature of 1500°F. For a 1000F range, the choice is between Hiperco 27 or Hiperco 35 with Hiperco 27 being favored. If the maximum temperature of transformer operation is limited to 1000°F, oriented-silicon-iron is recommended as the best material. Silicon-iron has been used in the preliminary transformation design calculations with HYMU 80 being considered for the high frequency output transformers.

GENERATOR MATERIALS

Housing - Low carbon steel

Stator - HYMU 80

Rotor - Nickel-maraging Steel

Windings - Nickel clad copper, or ceramic coated copper for high temperatures.

Insulation - Ceramic slot liners or mica sheets backed with glass cloth.

TRANSFORMER MATERIALS

Cores - Silicon-Iron (Low Frequency)
HYMU 80 (High Frequency)

Windings - Nickel plated copper

Insulation - Synthamica asbestos compound

B. MATERIALS CONSIDERED

Information on the characteristics of ferromagnetic materials at other than room temperatures is not readily available. The magnetic properties of all promising alloys must be evaluated as much as possible over the selected temperature range in order to provide parametric data for design trade-off studies.

The magnetic materials considered for this study are commercially available alloys and alloys under development which might be available in the near future. These materials include the following:

(1) Unoriented silicon-iron: A widely used transformer core material with a Curie temperature of 1274°F.

(2) Oriented silicon-iron: Material having superior magnetic properties in the rolled direction and having a Curie temperature of 1364°F.

(3) Hiperco 27 and Hiperco 50: A cobalt-iron alloy (27% for Hiperco 27 and 49% plus 2% vanadium for Hiperco 50) with a high saturating flux density. The Curie temperature is 1780°F.

(4) Supermendur: A cobalt-iron alloy with the same composition as Hiperco 50 but differs in that it becomes annealed in a magnetic field. It is characterized by high saturating flux density and low losses. The Curie temperature is 1796°F, but the alloy is known to undergo an order-disorder transformation at lower temperatures thus limiting its usuable temperature range.

(5) Supermalloy: One of the latest developments in the field of high permeability nickel-iron alloys. It is closely related to HYMU 80 in chemical composition and has the highest initial and maximum permeability and the lowest core loss of any commercially available material, but is temperature limited.

(6) Alloy 48 and 49: A material having high permeability at low and moderate induction levels. Its initial permeability is about twice that of the oriented silicon steels and one-fifth that of HYMU 80.

(7) HYMU 80: An unoriented 79% nickel-iron-molybdenium alloy which offers very high initial permeability and maximum permeability at low magnetizing forces with minimum hysteresis loss.

(8) Hypersil: A highly oriented cold rolled sillicon-iron alloy. The orderly prearrangement of the iron crystals assures much layer losses and higher permeability than that provided by unoriented silicon-iron alloys of similar chemical composition.

(9) MN-60 (KEARFOTT); A ferrite material used in transformer cores. Losses are low but the material is temperature limited for this application.

(10) W-03 (Allen-Bradley): A low loss ferrite used for transformer cores. This material is also temperature limited.

C. WINDING MATERIALS

Conductors and conductor insulations for the transformer and generator windings at three performance levels, 500°F, 1000°F and 1500°F, are being considered. Several insulations are available at the 500°F and 1000°F ranges, but the selection is limited at the 1500°F level.

a. 500°F Insulated Conductor System - Copper and aluminum conductors are available for use in transformers and generators. For equal current-carrying capacity, the volume of copper is less than that of aluminum. Aluminum electrical joints are fabricated more easily now than previously, and aluminum can now be handled quite easily.

b. 1000°F Insulated Conductor System - At the higher temperatures, copper conductors must be protected by a coating of oxidation resistant metal such as nickel. Cladding has the disadvantage of reducing the conductivity of copper, especially at the higher frequencies. Inorganic insulations must be considered at this temperature with special attention given to assembly of conductors and insulation.

c. 1500°F Insulated Conductor System - Stainless steel cladding or plating over copper appears to be the most suitable conducter design for 1500°F. Refractory oxides appear to be the only insulations available for use. Fabrics and papers will probably be used as inter-layer material and as wrappings.

D. INSULATION MATERIALS

Transformer and generator insulation is required to insulate electrical circuits from each other, from mechanical structure, and from the magnetic circuits. Two types of insulation are considered, a major insulation to provide electrical insulation and a minor insulation whose function is mainly to add mechanical strength to the component.

Most materials have a rated operating temperature based on a given life. When the component is operated above its normal operating temperature, the average insulation life is shortened. Organic compounds, for the most part, will not withstand high temperatures. Common organic materials can be used to about 400°F and conventional polyesters to a limiting temperature of 650°F.

Newly developed inorganic insulations are available for use over the 500°F to 1500°F temperature range. They are not as good electrically, mechanically or fabrication wise as the organic insulations, but they are much more stable at the high temperatures. The critical parameter for high temperature insulation is the flexibility.

The table 3.3.1-1 lists transformer insulations available for use in the 500°F, 1000°F, and 1500°F temperature ranges.

TABLE 3.3.1-1

MAXIMUM TEMPERATURE OF TRANSFORMER INSULATIONS

MAJOR		MINOR		POTTING AND IMPREGNATING	
MATERIAL	TEMP	MATERIAL	TEMP	MATERIAL	TEMP
		Beryllium Oxides	4000 F		
		Alumina 99%	3540 F		
		Boron Silicides	2500 F	Tipersul	2200 F
Tipersul	2200 F	Tipersul	2200 F	Silicone Silicate Asbestos Compound	2000 F
Synthamica	1832 F	Supramica	1550 F	Silico Ceramic-Silicic Acid	2000 F
		Isomica	1550 F	Synthetic Mica Cement	2000 F
Quinorgo R4	1000 F	Isomica	1000 F	Lead-Oxide/Boric-Oxide Eutectic	1000 F
Samica	1000 F	Steatite at High Volt	1000 F		
Alkophos	1000 F				
Mica-Flakes-Silicone Bonded	500 F	Silicone Micarta	500 F	Silicone	500 F
Teflon	500 F	Micalex	500 F		