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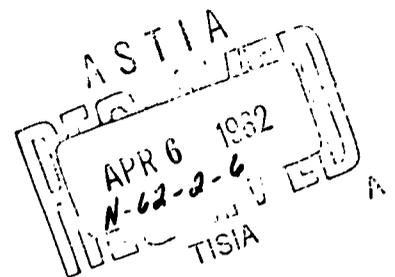
CERAMIC POWER TRANSFORMERS

FINAL DEVELOPMENT REPORT

1 June 1960 - 1 January 1962

BuShips Contract NObsr 81369
Index No. SRO080302, ST 144

Bureau of Ships
Department of the Navy
Washington, D.C.



U N C L A S S I F I E D

FINAL DEVELOPMENT REPORT
for
CERAMIC POWER TRANSFORMERS

This report covers the period from
1 June 1960 to 1 January 1962

GENERAL ELECTRIC COMPANY
ELECTRONICS LABORATORY
SYRACUSE, NEW YORK

NAVY DEPARTMENT - BUREAU OF SHIPS
ELECTRONICS DIVISION

Contract Number NObsr-81369
Index Number SR 0080302, ST 144

JANUARY 1962

U N C L A S S I F I E D

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ABSTRACT

This report summarizes the results of a ceramic transformer development program carried out under BuShips Contract N0bsr-81369. This program included an analytical study of device operation, measurement techniques, tapped transformers, oscillator circuits, and the effects of glass glazes on the ceramic material. Design, construction, and measurement procedures are described.

A detailed evaluation of four representative transformers fabricated during the Phase III of this program is included. These devices operate in the frequency range from 18 to 77 kilocycles at output powers from 2 to 22 watts. Efficiencies between 66 percent and 81 percent are realized.

PART I

1.0 PURPOSE

The purpose of this contract is to conduct an analytical study leading to the design, development and construction of a ceramic power transformer. The work shall be conducted in phases as follows:

- PHASE I:** 1. Conduct a brief analytical study of device operation for use as a guide in material selection and application. This study is to be based upon the use of ferro ceramic materials for the construction of power transformer. This study shall cover a voltage range on the input side from 10 to 150 volts and on the output side from 100 to 1000 volts at frequencies 10, 40 and 100 kilocycles. The output level of these transformers at maximum voltage shall be on the order from 2 to 20 watts. Based upon this study the Contractor shall construct representative transformers within the above range of characteristics and evaluations.

These transformers (maximum of 3 samples of each) shall be completely evaluated with and without tuning coils for:

- a. Efficiencies
- b. Maximum power density
- c. Range of temperature operation

In addition, these units shall be evaluated for efficiencies when the source of energy is a mechanical vibrator.

- PHASE II:** 2. Evaluate any newly developed materials by incorporating them into ceramic power transformer designs. Construct and evaluate tapped transformer (for multiple voltage outputs) and power oscillator circuits employing ceramic

transformers as frequency controlling elements. Measure stability of frequency and power output as a function of temperature on these transformers. In addition, investigate the feasibility of using tuning coils in determining maximum power density.

3. Submit reports, as specified herein.

PHASE III. 4. Construct, evaluate and furnish a representative group (3 or more models of a minimum of 3 designs) from the best materials.

2.0 GENERAL FACTUAL DATA

2.1 IDENTIFICATION OF TECHNICIANS

<u>Name</u>	<u>Title</u>	<u>Hours (1 June 1960 to 1 January 1962)</u>
S. W. Tehon	Project Engineer	120
R. C. Roberts	Engineer	2302
E. C. Henry	Consulting Engineer- Solid State Materials	23
E. M. Pruski	Technician	209
R. Minota	Technician	146
M. Simkulet	Technician	123
Other Technicians		<u>23</u> 2946

2.2 RELATED PATENTS

1. "An Electromechanical Transducer,"
C. A. Rosen, Pat. No. 816010 pending.
2. "Transverse Ceramic Transformer,"
C. A. Rosen, Pat. No. 2830274.

2.3 REFERENCES

1. I.R.E. Standards on Piezoelectric Crystals: Measurements of
Piezoelectric Ceramics, 1961. 61 IRE 14.51.
2. Katz, H.W., "Solid State Magnetic and Dielectric Devices,"
John Wiley and Sons, 1959.
3. Tehon, S. W., "Piezoelectric and Magnetostrictive Transducers,"
Ph.D. Dissertation, University of Illinois, 1958. Also General
Electric T.I.S. R58ELS-65, August 25, 1958.
4. Rosen, C. A., "Analysis and Design of Ceramic Transformers and
Filter Elements," Ph.D. Dissertation, Syracuse University, 1956.
Also General Electric T.I.S. R56ELS-123, September 12, 1956.

5. Mikus, L.E., "A Composite Electromechanical Filter," M.E.E. Thesis, Syracuse University, August 1961. Also Seventh Quarterly Report, "Solid State Filters, Delay Lines and Transformers," SC Contract No. DA-36-039-sc-85049, U.S. Army Corps, Fort Monmouth, New Jersey, April 1961.
6. Gerson, R., "Dependence of Mechanical Q and Young's Modulus of Ferroelectric Ceramics on Stress Amplitude," J. Acoust. Soc. Am., Vol. 32, No. 10, pp. 1297-1301, October 1960.

2.4 SUMMARY OF WORK PERFORMED

A ceramic transformer is a three or four terminal device that utilizes resonant vibrations of a piezoelectric ceramic bar to effect an impedance transformation, and hence a voltage transformation, between its input and output terminals. Part of the ceramic bar is normally used to convert an electrical input signal into mechanical vibrations and may be called the driver section. A second portion of the bar is then used to convert the mechanical strains to an output voltage, usually at a fairly high impedance level, and is called the generator section. Since mechanical coupling is used between the input (driver) and output (generator), there are no strong magnetic fields generated by this device. The transformer does, however, exhibit a band-pass response near any resonant frequency due to the use of resonant mechanical vibrations for coupling.

The purpose of this contract is to conduct an analytical study leading to the design, development and construction of a ceramic power transformer. The work performed during this program has been conducted in three phases. Detailed descriptions of the results obtained in each phase have been presented in the Type I Interim Development Reports prepared during the program. The following sections are intended to provide a summary of the work performed under each phase. The five Interim Development Reports should be referred to for more detailed work descriptions.

2.4.1 Work Performed Under Phase I.

Effort was devoted to determining the general characteristics of ceramic transformers during this phase. An analytical study of device operation was performed in order to serve as a guide for transformer construction and material selection. The analysis was based upon the electrical equivalent circuits for both the transverse transformer shown in Figure 1 and the skew transverse transformer shown in Figure 2. Both of these transformers use a polarized ferroelectric ceramic material and depend upon mechanical vibrations for coupling between their input (driver) and output (generator) sections.

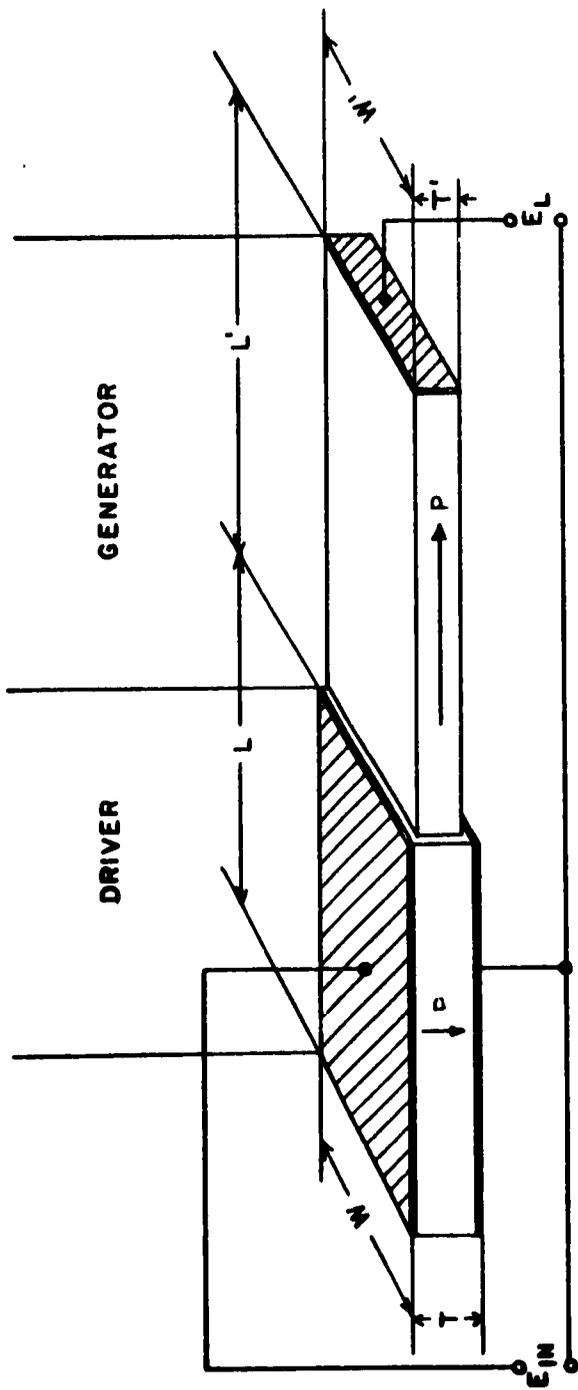
The most important results of the analysis consist of expressions for the open circuit voltage amplification, the voltage amplification with maximum efficiency, the maximum efficiency of operation, and the input impedance. It was found that these characteristics depend upon both the properties of the ceramic material and the transformer geometry.

2.4.1.1 Transverse Transformer

The open circuit voltage amplification of the transverse transformer is given by

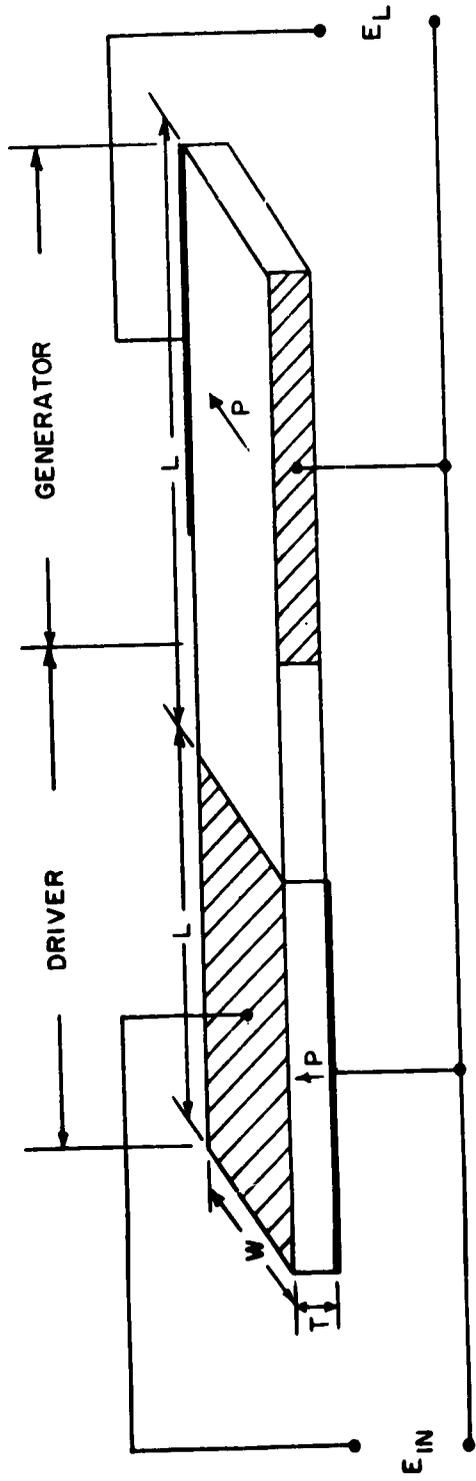
$$A_{V_0} = \frac{4 Q_m}{\pi^2} \cdot \frac{K_{31} K_{33}}{1 - K_{31}^2} \cdot \frac{L}{T}, \quad (1)$$

where Q_m is the mechanical quality factor of the ceramic, K_{31} and K_{33} are the electromechanical coupling coefficients of the driver and generator sections, and L and T are the length and thickness of the driver section. The L/T ratio is the variable most easily controlled for a given ceramic material since the Q_m and the coupling coefficients are then fairly well determined. The extreme values of the L/T ratio are predicated by practical considerations such as the extreme fragility of a very long thin ceramic bar and the uncertain mechanical vibrational modes encountered with short thick bars. Since large values of A_{V_0} are commonly desired,



TRANVERSE CERAMIC POWER-TRANSFORMER

FIGURE 1



SKEW TRANSVERSE TRANSFORMER
FIGURE 2

the fragility of the bar is usually the more restrictive consideration. Another factor in the use of a large L/T ratio is a result of the necessity of polarizing the generator section along its length. Modern ceramics require polarizing fields of from 20,000 to 100,000 volts per inch so that a prohibitively high voltage may be required to polarize generator sections several inches long. In certain instances, this requirement may be alleviated by the use of a glass glaze on the ceramic as will be discussed later in this report.

Although large values of A_{V_0} may be obtained by using a long thin bar, it was found that the voltage amplification deteriorates rapidly as the generator terminals are resistively loaded. As the load resistance approaches the reactance of the generator section, it was also found that the transformer efficiency η approaches a maximum given by

$$\eta_{\max} = \frac{\text{Output Power}}{\text{Input Power}} = \frac{1}{1 + \frac{\pi^2}{2 K_{33}^2 Q_m}} \quad (2)$$

Ceramic power transformers were assumed to operate into this load resistance so that the maximum efficiency could be realized. The voltage amplification was then found to be

$$A_V \Big|_{\eta_{\max}} = \sqrt{2} \cdot \frac{K_{31}}{K_{33}} \cdot \frac{L}{T} \left\{ \frac{1}{1 + \frac{\pi^2}{2 K_{33}^2 Q_m}} \right\} \quad (3)$$

Expression (3) indicates that for $K_{33}^2 Q_m \gg 10$ the voltage amplification with maximum efficiency is nearly independent of this product but is directly proportional to the length to thickness ratio of the driver section. It therefore follows again, that the length to thickness ratio is the primary factor in determining the voltage amplification with maximum efficiency. In fact, since the bracketed term in expression (3)

is simply the maximum efficiency and is only slightly less than unity for $K_{33}^2 Q_m \gg 10$ and since $K_{33} \approx 2K_{31}$ for most ceramics, the voltage amplification with maximum efficiency is approximately $L/\sqrt{2}T$.

The load resistance required for maximum efficiency was, as mentioned above, found to be equal to the capacitive reactance of the generator section electrodes at the mechanical resonant frequency of the bar. Since this capacitance is a function of the length to thickness ratio, it is apparent that the optimum load resistance R_L and the voltage amplification are related for a given ceramic material. This relationship is best expressed by the following inequalities for the transverse transformer:

$$\frac{R_L}{A_V \eta_{\max}} > 14,800 \quad (\text{For Barium Titanate Type Ceramics}),$$

$$\frac{R_L}{A_V \eta_{\max}} > 16,400 \quad (\text{For Lead Zirconate Titanate and Lead Metaniobate Ceramics}).$$

These figures clearly indicate that the optimum efficiency occurs at a relatively high impedance level if a substantial voltage amplification is desired.

The final important characteristic of interest was the nature of the impedance seen looking into the driver section terminals. This impedance is extremely dependent upon both frequency and output loading and may exhibit a highly resonant behavior. At the frequency of maximum voltage amplification, however, the input impedance can always be represented by a parallel combination of a resistor and a capacitor. The value of the capacitor is approximately the dc capacitance of the driver section electrodes whereas the parallel resistance depends upon the output load placed on the generator section terminals. When the generator

terminals are open-circuited, the ratio of the parallel input capacitive reactance to the parallel input resistance is given by

$$\frac{X_{IN}}{R_{IN}} = \frac{4 K_{31}^2 Q_m}{\pi^2}, \quad (4)$$

and when the transformer is operating at maximum efficiency, the ratio is

$$\frac{X_{IN}}{R_{IN}} \approx 2 \frac{K_{31}^2}{K_{33}^2} \quad (5)$$

for $K_{33}^2 Q_m \gg 10$. These expressions are useful in estimating the requirements placed upon the network driving the transformer and indicate that the input is predominantly resistive for the open-circuited case and considerably more capacitive for the case of maximum efficiency.

2.4.1.2 Skew Transverse Transformer

The results obtained for this device were similar in form to those for the transverse transformer. The open circuit voltage amplification of the skew transverse transformer is given by

$$A_{V_o} = \frac{4Q_m}{\pi^2} \cdot \frac{K_T K_R}{1 - K_R^2} \cdot \frac{W}{T}, \quad (6)$$

where Q_m is again the mechanical quality factor of the ceramic, K_T and K_R are the driver and generator coupling coefficients, and W and T are the width and thickness of the device. The same practical considerations apply here that were discussed for the transverse transformer; however, the efficiency of the skew transformer was found to be

$$\eta_{max} = \frac{1}{1 + \frac{\pi^2(1 - K_R^2)}{2K_R^2 Q_m}} \quad (7)$$

which is less than that for a transverse transformer constructed from the same ceramic. The corresponding voltage amplification was determined to be

$$A_V|_{\eta_{\max}} = \sqrt{2} \frac{K_T}{K_R} \cdot \frac{W}{T} \cdot \frac{l}{1 + \frac{\pi^2 (1 - K_R^2)}{2 K_R^2 Q_m^2}}, \quad (8)$$

which is again less than that for a transverse transformer since good mechanical resonance requires that the width of the bar be considerably smaller than the length.

The ratio of the load resistance to the voltage amplification is somewhat lower for the skew transformer:

$$\frac{R_L}{A_V|_{\eta_{\max}}} > 3700 \quad (\text{For Barium Titanate Type Ceramics})$$

$$\frac{R_L}{A_V|_{\eta_{\max}}} > 4100 \quad (\text{For Lead Zirconate Titanate and Lead Metaniobate Ceramics}).$$

2.4.1.3 Summary of Experimental Work

Several ceramic materials were evaluated during this phase. Samples of Barium Titanates, Lead Metaniobates, and Lead Zirconate Titanates were tested for coupling coefficients and mechanical quality factors. Although it was found that Lead Zirconate Titanates and Lead Metaniobates generally exhibited higher coupling coefficients and $K^2 Q_m^2$ factors than the Barium Titanates, it was decided that future transformers would, for the most part, be fabricated from a modified Barium Titanate, General Electric Type 235. There were two reasons for this choice: First, this material was commercially available and hence its properties

were more reproducible than the more recently developed materials whose parameters might vary considerably from sample to sample. Second, the relatively low polarizing field of Barium Titanate would enable a considerably longer generator section to be polarized than with the other materials.

Several representative transformers were constructed and evaluated during this phase. A 36 kilocycle transverse transformer with a voltage amplification of about 3 was constructed from Type 235 ceramic with a length of 6 inches, a width of 1.85 inch and a thickness of 0.33 inch. The efficiency of this device was between 70 and 80 percent at output powers up to 10 watts and the transformer was operated at temperatures from -20 degrees centigrade to +80 degrees centigrade. It was estimated that efficiencies in the order of 90 percent would be obtained if the source of energy were a mechanical driver.

A 93 kilocycle skew transverse transformer was also constructed from this material. Its length was 2.0 inches and its width and thickness were 0.325 inch and 0.090 inch. The voltage amplification was 2.90, the efficiency was 69 percent and the maximum output power was about 0.4 watt.

Finally, an 8 kilocycle skew transverse transformer was constructed from a Lead Zirconate Titanate type ceramic. Considerable difficulty was encountered in the fabrication of this device due to fractures caused by the large strains developed in the ceramic during polarization. Several bars were fractured before one was successfully polarized, moreover, even this transformer contained a flaw which made complete evaluation impossible.

2.4.2 Work Performed Under Phase II.

It became apparent during work on Phase I that the low level characteristics of the ceramic transformers changed considerably when operation took place at higher power levels. The fairly high mechanical stresses produced in the ceramic at high levels apparently caused a

decrease in $K_{33}^2 Q_m$ with a resulting loss in efficiency and subsequent heating of the transformer. Some effort to determine the cause of this behavior took place during Phase II. Measurement techniques were developed to measure the ceramic properties of interest at higher stress levels. In addition, effects of glass glazes on the ceramic bar were considered.

Other areas considered during Phase II were the use of multiple output taps on a transverse transformer and an evaluation of some oscillator circuits employing ceramic transformers as frequency controlling elements.

2.4.2.1 Measurement and Techniques

Several measurement techniques were described during Phase II. Of particular interest were techniques for determining peak mechanical stress in a ceramic bar by use of external tuning coils and for measuring the $K_{31}^2 Q_m$ and $K_{33}^2 Q_m$ factors of ceramic resonators at higher stress levels. When these techniques were applied to samples of 235 ceramic, it was found that both the $K_{31}^2 Q_m$ and $K_{33}^2 Q_m$ factors decreased at elevated stress with the change in Q_m dominating this behavior. It was also found that the Q_m of a transversely polarized ceramic is more affected by stress than that of a longitudinally polarized ceramic. This was attributed to larger losses involved in the 180 degree domain wall motion induced by mechanical stress perpendicular to the polarization in the transverse case as contrasted to the 90 degree motion induced by stress parallel to the polarization in the longitudinal case.

2.4.2.2 Glass Glazes on Ceramics

It was hoped that the decrease in Q_m at high stress could be improved by a mechanical "pre-stressing" of the ceramic bar through the use of a glass glaze fired on the ceramic before polarization. Glazes were available with the thermal coefficient of expansions needed to place the ceramic in a state of tension or compression near room temperature. The effects of two such glazes on both transverse and

longitudinal ceramic resonators were investigated during this phase.

The low stress level characteristics of the resonators were found to be significantly affected by the application of these glazes. In particular, it was found that the coupling coefficient of a transverse resonator was decreased by the use of a glaze with a lower temperature coefficient than that of the ceramic and was increased by a glaze with a higher coefficient than the ceramic. Moreover, the overall mechanical Q of the glazed ceramic could be lowered or increased depending upon the relative quality factors of the glaze and the ceramic. It was also found that the coupling coefficient of a longitudinal resonator was decreased by a glaze with a higher temperature coefficient than the ceramic and was increased by a glaze with a lower temperature coefficient than the ceramic. The overall mechanical Q of the glazed longitudinal resonator was again found to depend upon the relative quality factors of the glaze and the ceramic.

When these resonators were measured at higher stress levels, it was found that glazing operation resulted in a displacement of the $K^2 Q_m$ vs. stress curves but did not alter their general shape. An appropriate glaze could, however, produce some increase in $K^2 Q_m$ at a given stress level.

One characteristic of a glaze may prove useful in the construction of long thin transverse transformers. This is due to the fact that a glaze can tend to "bootstrap" the polarization of a generator section when a lower than normal poling field is used as a result of the stresses developed by the glaze during cooling of the transformer from its poling temperature. In other words, a longer generator section can be polarized with a given polarizing supply voltage if the proper glaze is applied on the generator section of the transformer. A transformer employing this procedure was fabricated during Phase III and is described later in this report.

2.4.2.3 Tapped Transverse Transformers

A tapped transformer may be formed by merely placing ring electrodes on the generator section of a conventional transverse transformer as shown in Figure 3. These electrodes pick off some portion of the total output voltage depending on their position, electrical load, and the resonant mode of the ceramic bar. They may be applied either before or after polarization is completed.

Construction and evaluation of a tapped transformer was completed during Phase II. This device had two output taps and operated at a frequency of 26 kilocycles. The three outputs provided voltage amplifications of 2.25, 4.85, and 8.3 at power levels of 1.34 watt, 0.84 watt, and 0.40 watt.

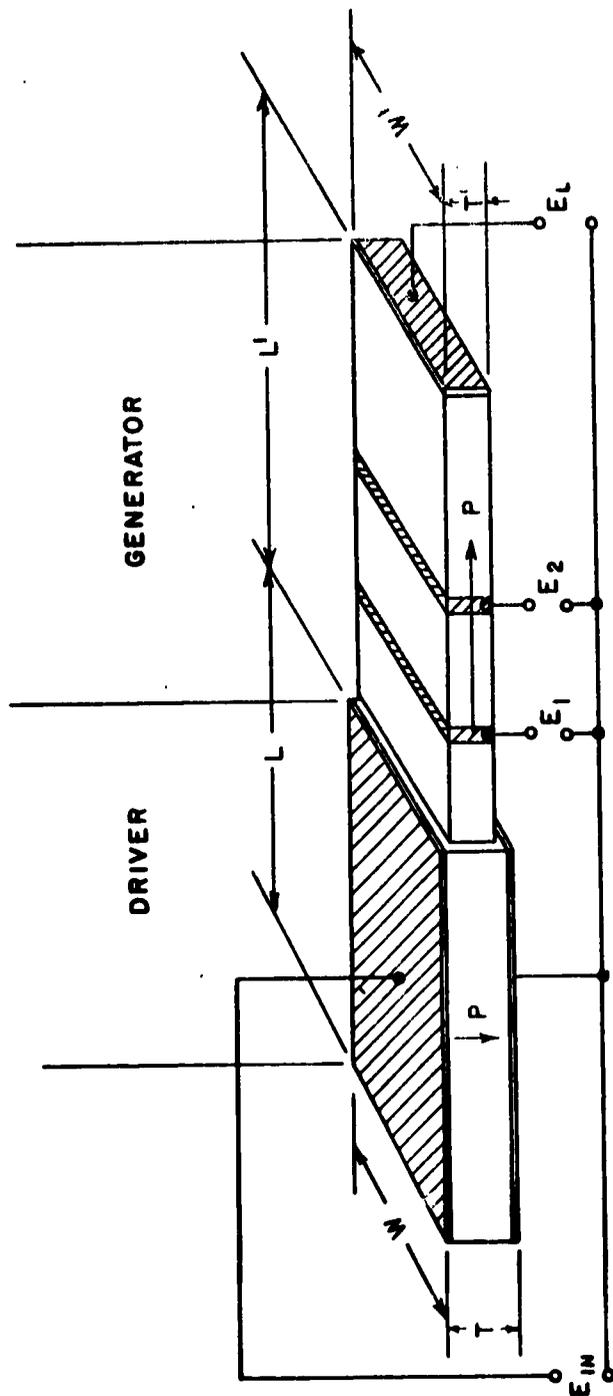
2.4.2.4 Oscillator Circuits Employing Ceramic Transformers

Several oscillator circuits employing ceramic transformers as frequency controlling elements were investigated during Phase II. In general, these circuits used a tapped transverse transformer with the tap output voltage used to synchronize both sinusoidal and non-sinusoidal oscillators to the operating frequency of the transformer.

A simple oscillator was constructed and evaluated over the temperature range of -20 degrees to +70 degrees centigrade. The stability of output voltage using this circuit was found to be considerably better than could be obtained using a fixed frequency driver. Although this circuit was not intended to be the optimum design for use with ceramic transformers, it did indicate the feasibility of using the transformer to provide a relatively constant output voltage over a wide range of temperatures with a frequency stability determined by the ceramic material.

2.4.3 Work Performed Under Phase III.

The purpose of Phase III was to construct, evaluate and furnish a representative group of ceramic transformers. This group is composed of four packaged assemblies operating in the range of frequencies from



TAPPED TRANSVERSE TRANSFORMER

FIGURE 3

18 kilocycles to 77 kilocycles. All these transformers except the 18 kilocycle sample are composed of two or more parallel elements. Each sample will be described and evaluated in the following sections.

2.4.3.1 Sample A: 77 Kilocycle Skew Transverse Transformer.

This transformer consists of four identical skew transverse elements operating in parallel. The elements are 2.4 inches long, 0.42 inch wide, 0.10 inch thick and are fabricated from General Electric Type 235 ceramic. Each element operates at full-wave mechanical resonance and is supported at its motional nodes by rubber cushions. The four element array is packaged in a plastic case 3.0 inches long, 1.3 inch wide and 0.4 inch thick.

The driver and generator capacitances are 0.00455 mfd and 265 pf, respectively, so that the optimum load impedance is about 9 kilohms. This transformer was evaluated using the procedure described in Section 3.3 and the resulting data is presented in Figures 4 through 6. Figure 4 indicates that the efficiency is maximized at 66 percent with a load resistance of about 9 kilohms and is greater than 50 percent for load resistances between 4 kilohms and 18 kilohms. Figure 5 shows that a load resistance of 9 kilohms corresponds to a voltage amplification of 3.7. The output voltage is linear with respect to the input voltage up to a level of 80 volts as shown in Figure 6. This level corresponds to a field of 0.2 volt/mil in the generator section and represents a nominal output power of 0.70 watts. Table I summarizes these and other characteristics of this device.

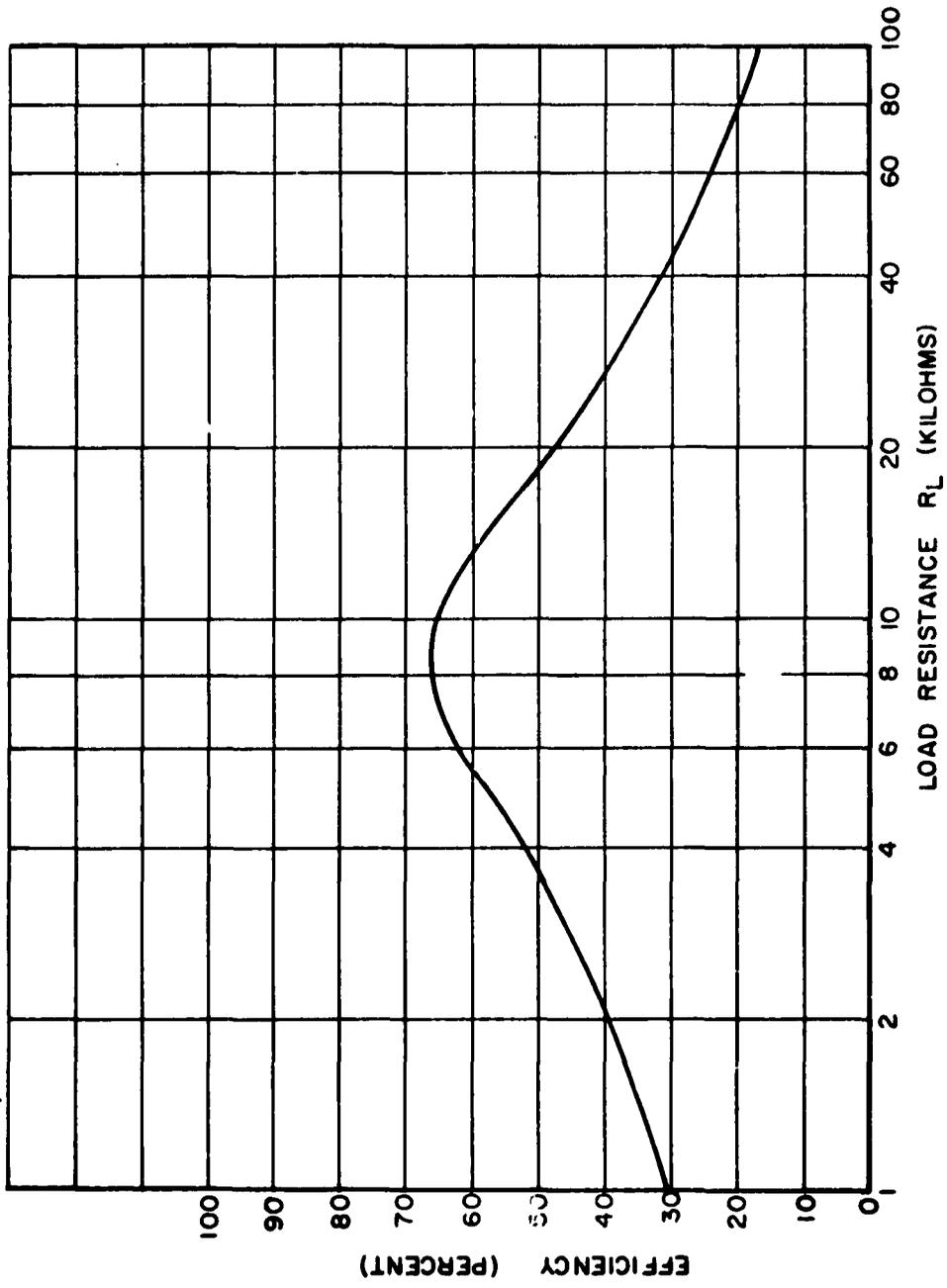
2.4.3.2 Sample B: 54 Kilocycle Tapped Transverse Transformer

This transformer is composed of two tapped transverse elements operating in parallel at full wave mechanical resonance. The elements are 3.5 inches long, 0.52 inch wide, 0.10 inch thick and made from Type 235 ceramic. Output taps are placed 0.9 inch and 1.4 inch from the generator output electrode and the elements are packaged in a plastic case 3.85 inches long, 1.3 inch wide and 0.4 inch thick.

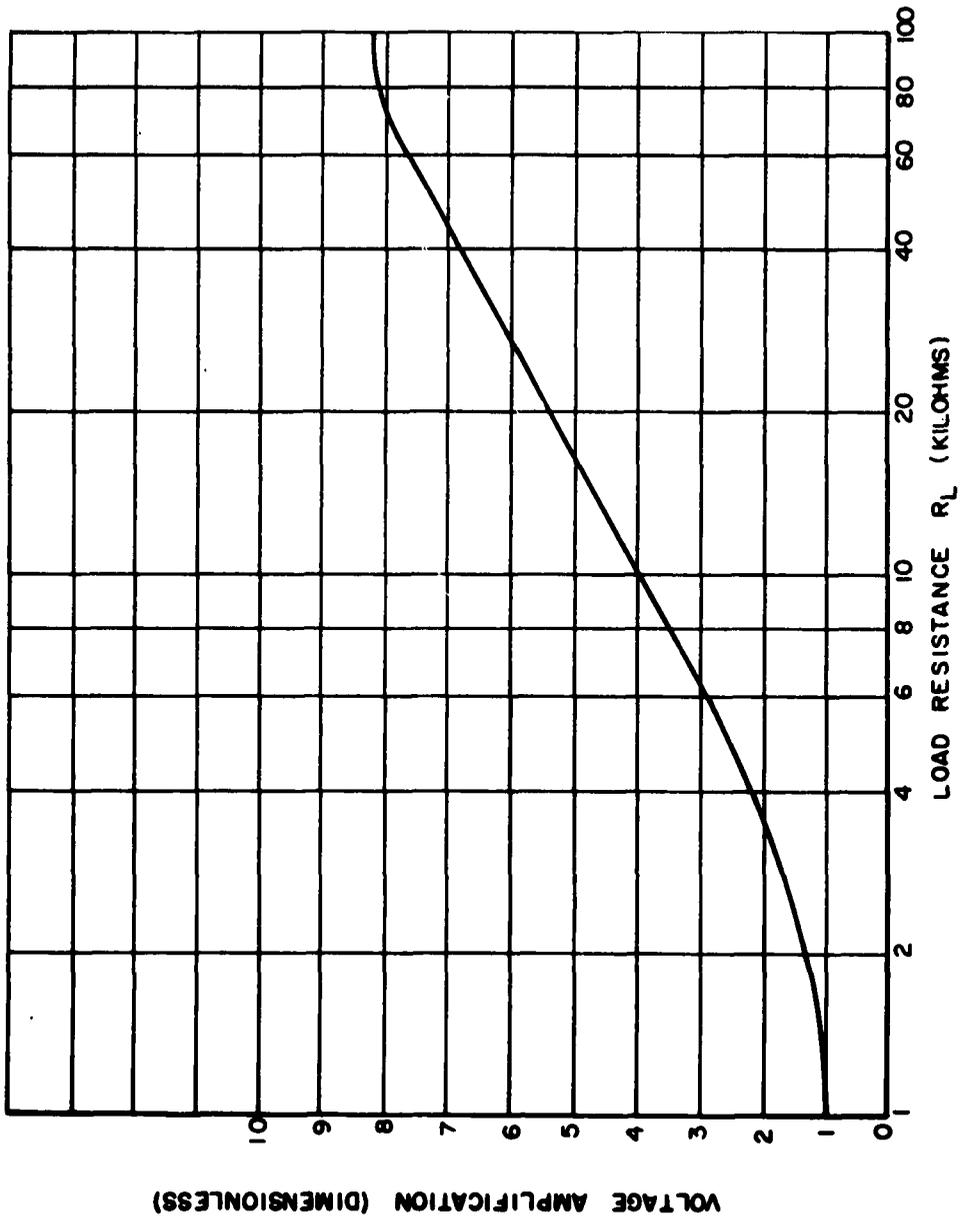
TABLE I
 REPRESENTATIVE CHARACTERISTICS OF SAMPLE TRANSFORMERS

	Sample: A B C D			
Operating Frequency (Kilocycles)	77	54	54	18
Number of Elements	4	2	4	1
Total Weight Including Case (grams)	48	45	80	52.5
Total Volume Including Case (inches ³)	1.5	1.9	2.1	19.6
Ceramic Volume (inches ³)	0.403	0.380	0.760	4.00
Maximum Voltage Amplification ($R_L = \infty$)	15	125	104	170
Optimum Load Impedance (Kilohms)	9	240*	170	400
Maximum Efficiency (Percent)	66	75	77	81
Voltage Amplification with Maximum Efficiency	3.7	12*	12.5	13.5
Maximum Output Power at Optimum Load (watts)	2.5	4.9*	13.5	22.5
Nominal Output Power at Optimum Load (watts)	0.70	3.1*	4.5	15.7
Maximum Power Density in Ceramic ($\frac{\text{watts}}{\text{inch}^3}$)	6.2	12.9*	17.8	5.6
Nominal Power Density in Ceramic ($\frac{\text{watts}}{\text{inch}^3}$)	1.74	8.1*	5.9	3.9
Maximum Operating Temperature (degrees C.)	80	80	80	80

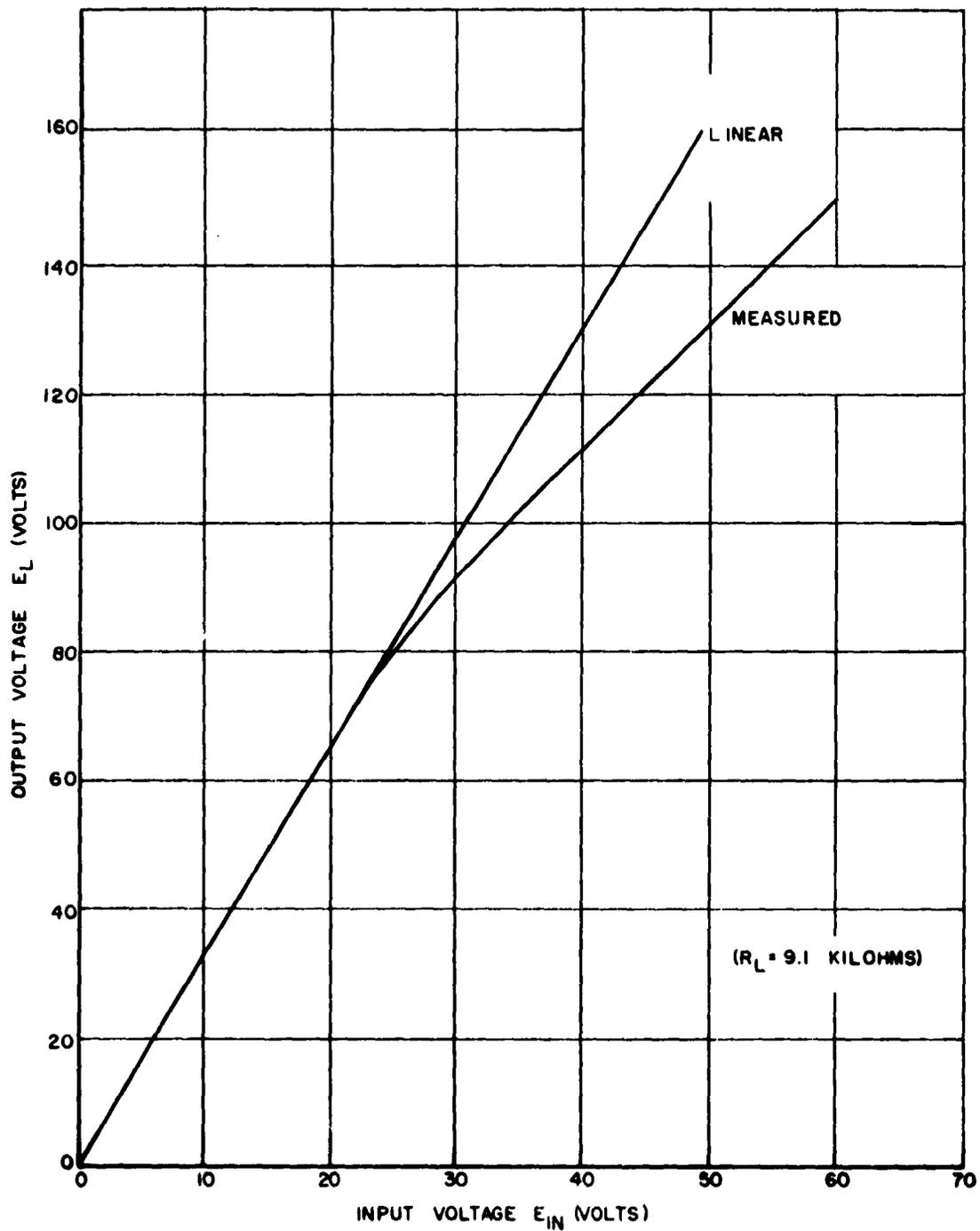
* High Voltage Tap Only



EFFICIENCY VS. LOAD RESISTANCE FOR SAMPLE A
 FIGURE 4



VOLTAGE AMPLIFICATION VS LOAD RESISTANCE FOR SAMPLE A
 FIGURE 5



OUTPUT VOLTAGE VS. INPUT VOLTAGE FOR SAMPLE A
 FIGURE 6

The clamped capacitance of the driver section is 0.00465 mfd, the tap capacitances are 56.5 pf and 27.3 pf, and the generator output electrode capacitance is 14.5 pf.

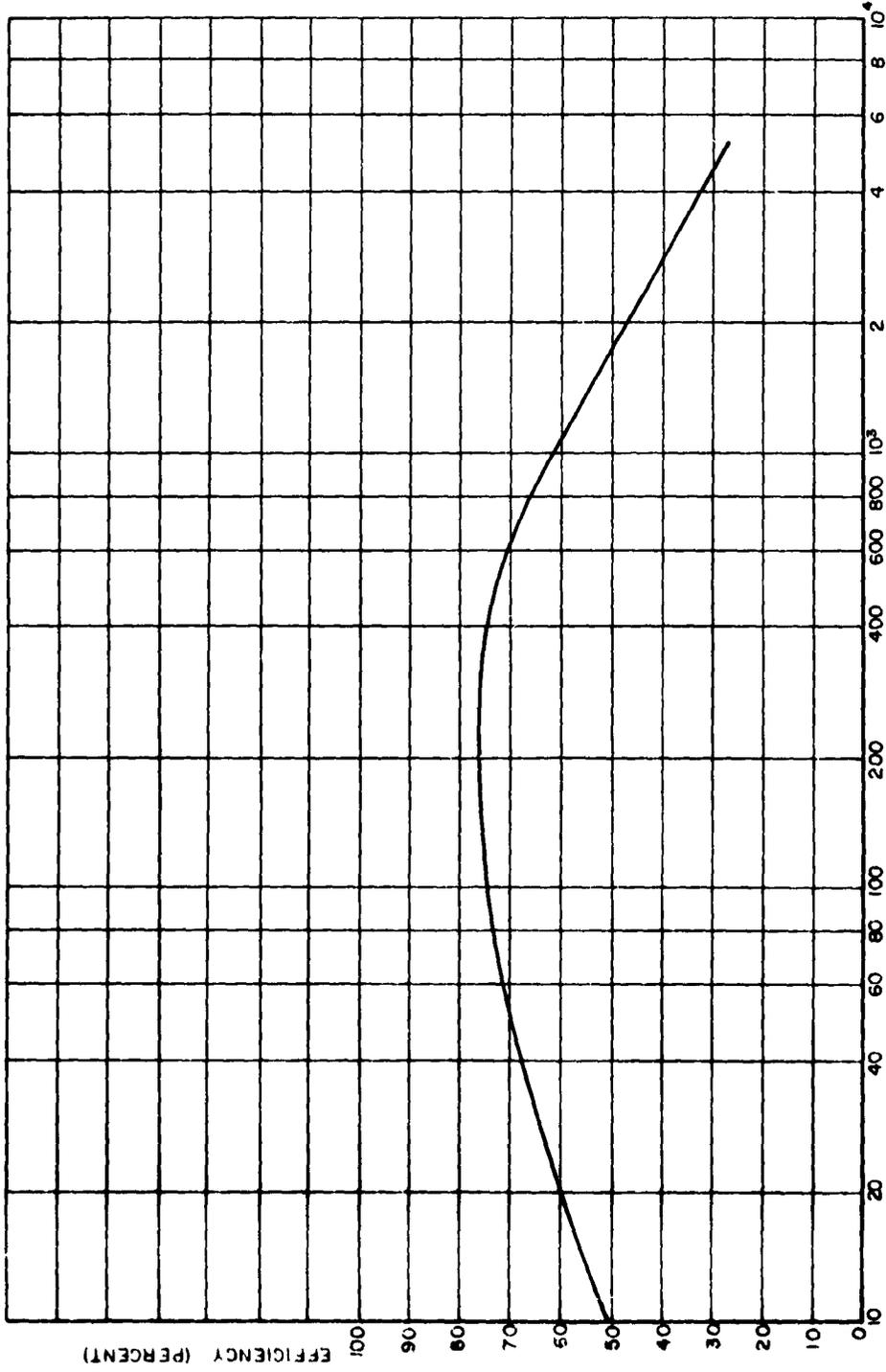
The efficiency of this device as a function of load resistance was measured and is plotted in Figure 7. A maximum efficiency of 76 percent occurs at a load of about 240 kilohms and the efficiency is greater than 50 percent for loads between 10 kilohms and over 1 megohm. Figure 8 shows the voltage amplification as a function of load resistance. The voltage amplification is seen to be about 12 with a load of 240 kilohms. The three output voltages of this transformer are plotted in Figure 9 as a function of input voltage. For this test, tap 1 was loaded with 56 kilohms, tap 2 with 130 kilohms and the output terminal with 240 kilohms. It may be seen that all the curves are linear up to the limit of the test. At this point the output of the generator electrode is 4.9 watts and taps 1 and 2 are supplying 0.21 watt and 1.0 watt respectively. A summary of the characteristics of this transformer may also be found in Table I.

The effects of three tap loading conditions on the generator output E_L are shown in Figure 10. It may be seen that the short circuiting of the output taps does not deteriorate the operation of the transformer.

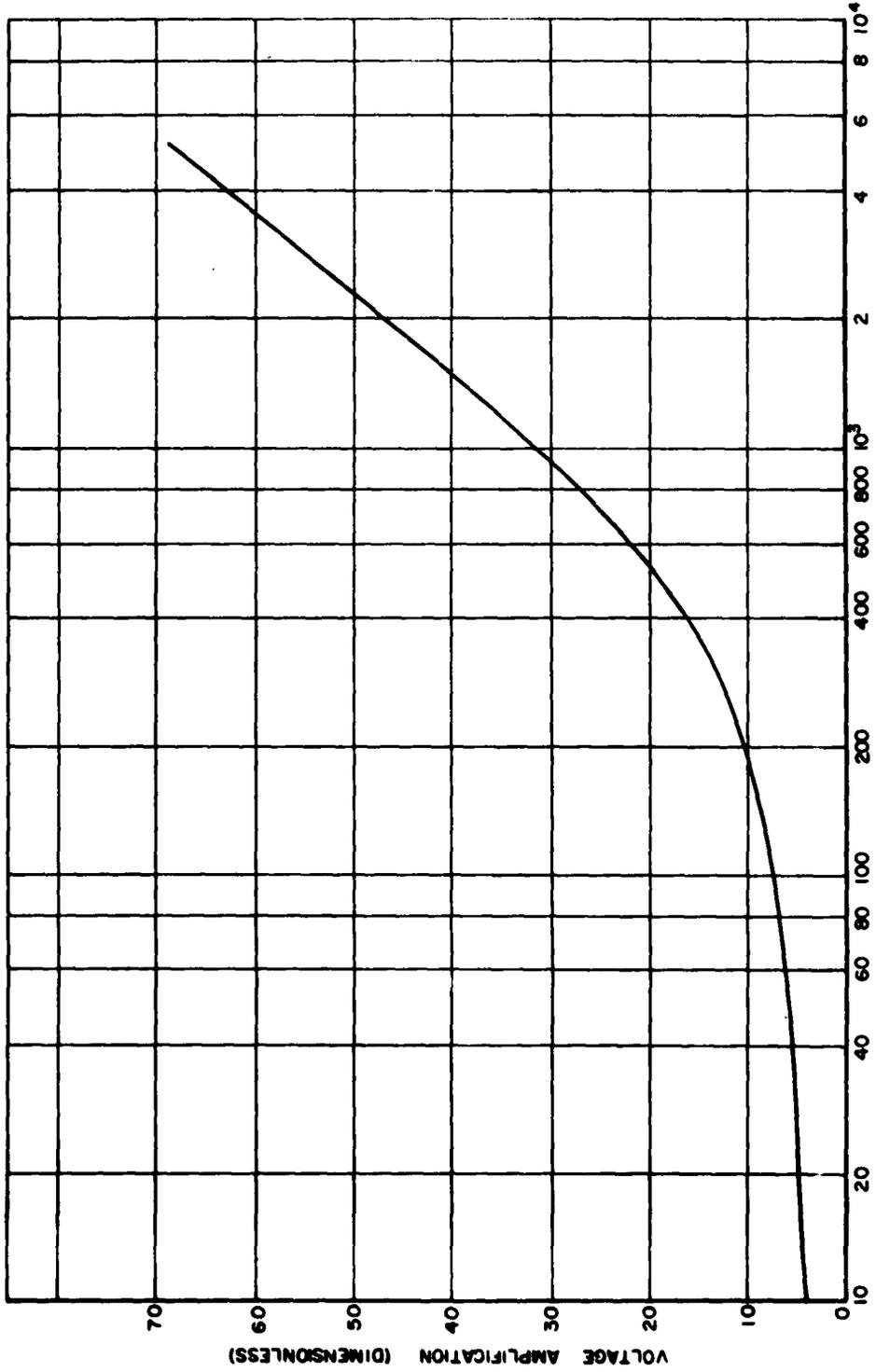
2.4.3.3 Sample C: 54 Kilocycle Transverse Transformer

The third representative transformer is a four element full-wave transverse transformer constructed from Type 235 ceramic. The elements are 3.5 inches long, 0.50 inch wide, 0.10 inch thick and are packaged in a plastic box 4.2 inches long, 1.3 inch wide and 0.4 inch thick.

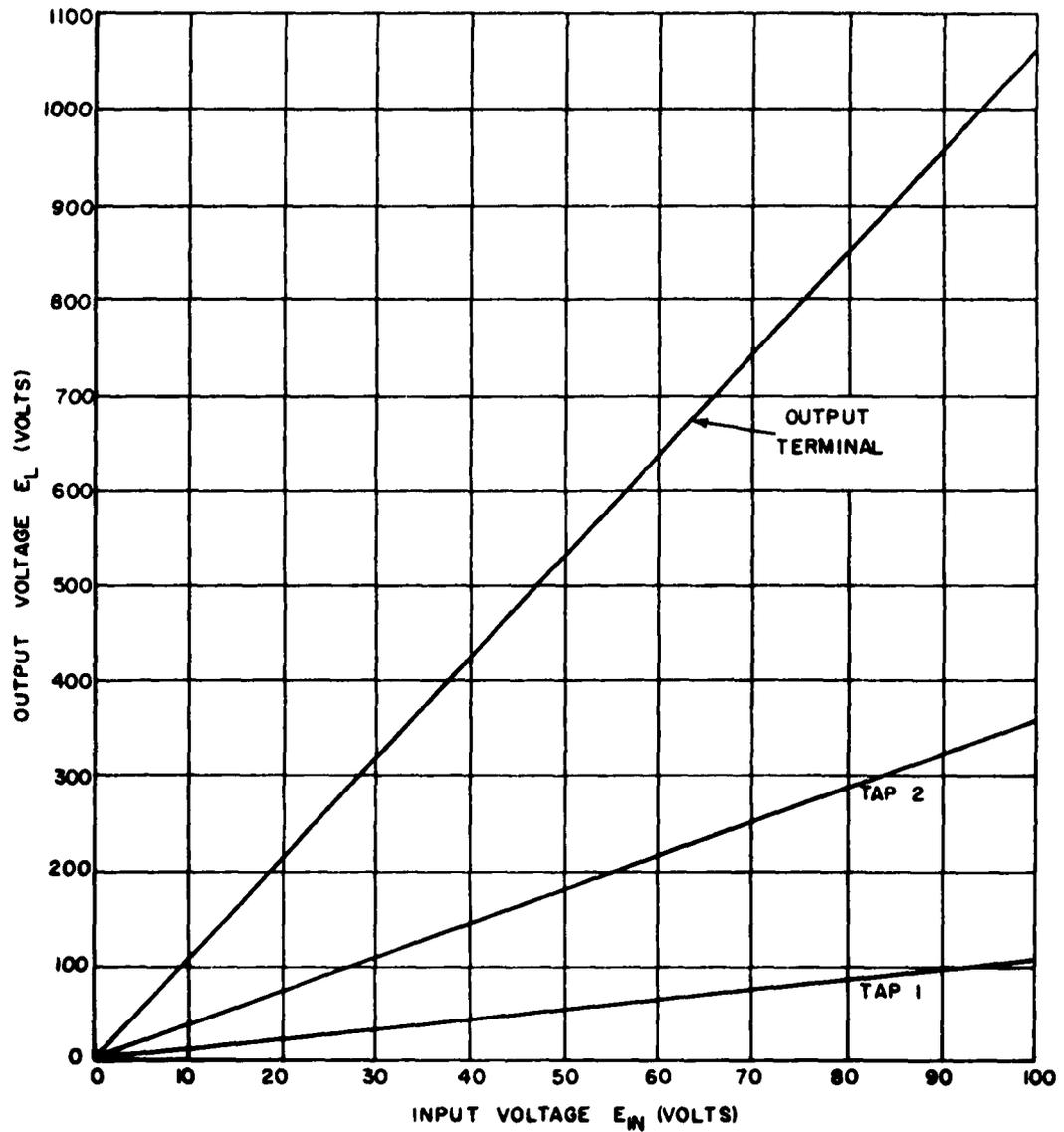
The driver section capacitance is 0.00885 mfd and the generator section capacitance is 30 pf corresponding to an optimum load resistance of about 100 kilohms. The measured efficiency as a function of load resistance is shown in Figure 11. A maximum efficiency of 77 percent occurs with a load resistance of about 170 kilohms. The voltage amplification with this load is seen from Figure 12 to be about 12.5. The output voltage as a function of input voltage is plotted in Figure 13. The output



LOAD RESISTANCE R_L (KILOHMS)
 EFFICIENCY VS. LOAD RESISTANCE FOR SAMPLE B
 (TABS OPEN CIRCUIT)
 FIGURE 7

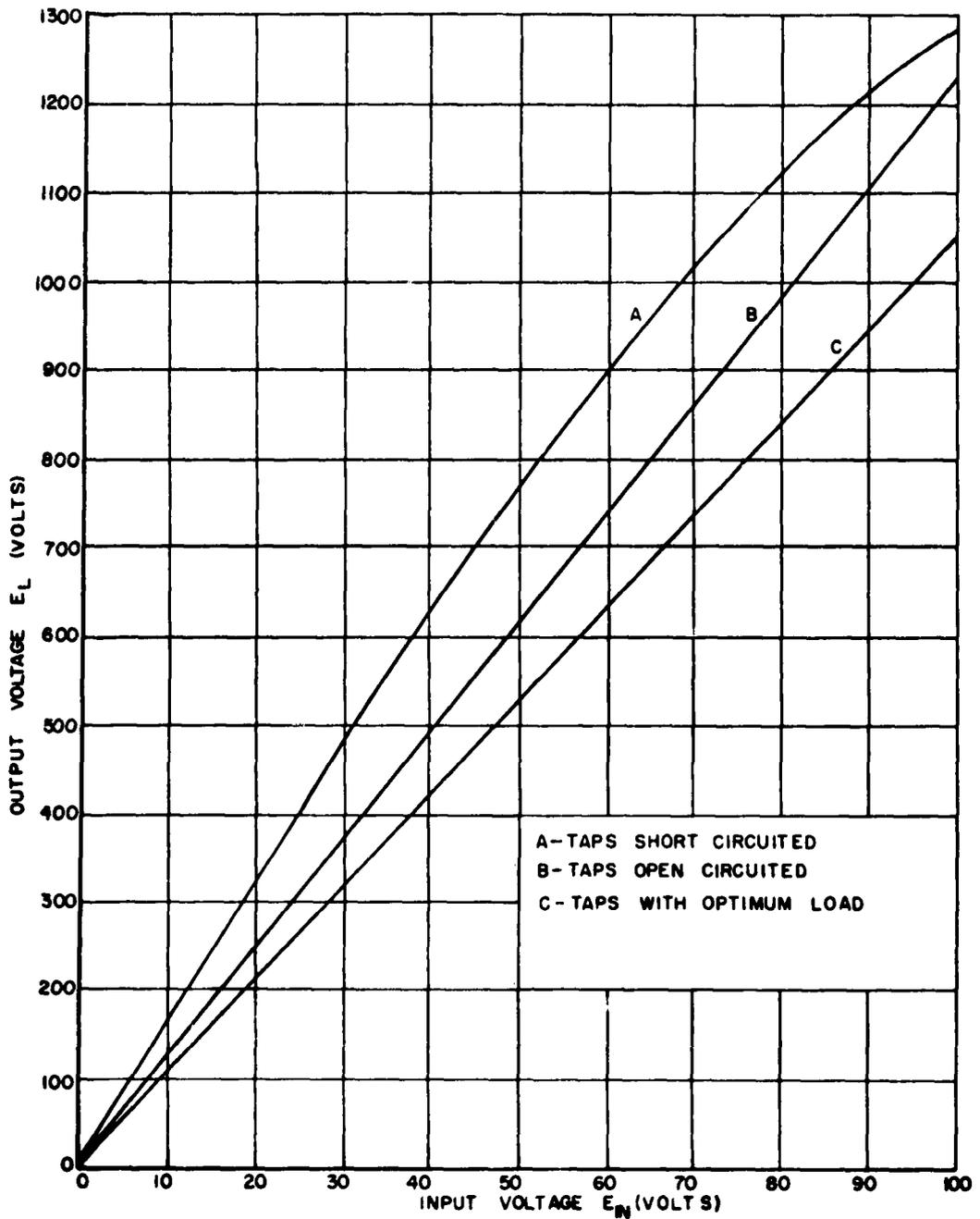


VOLTAGE AMPLIFICATION VS. LOAD RESISTANCE FOR SAMPLE B
(TAPS OPEN CIRCUIT)
FIGURE 8



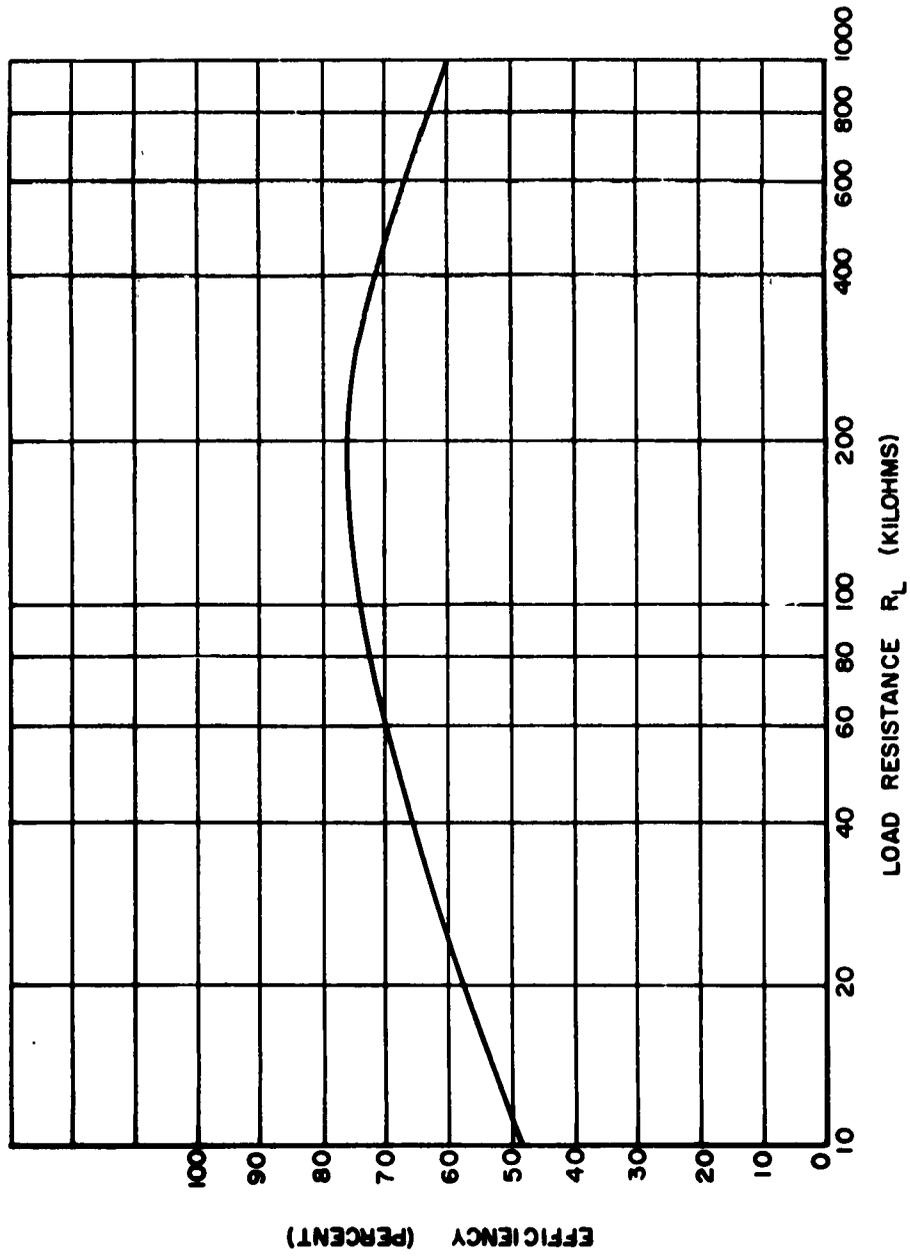
OUTPUT VOLTAGE VS. INPUT VOLTAGE FOR SAMPLE B
(ALL OUTPUTS WITH OPTIMUM LOAD)

FIGURE 9

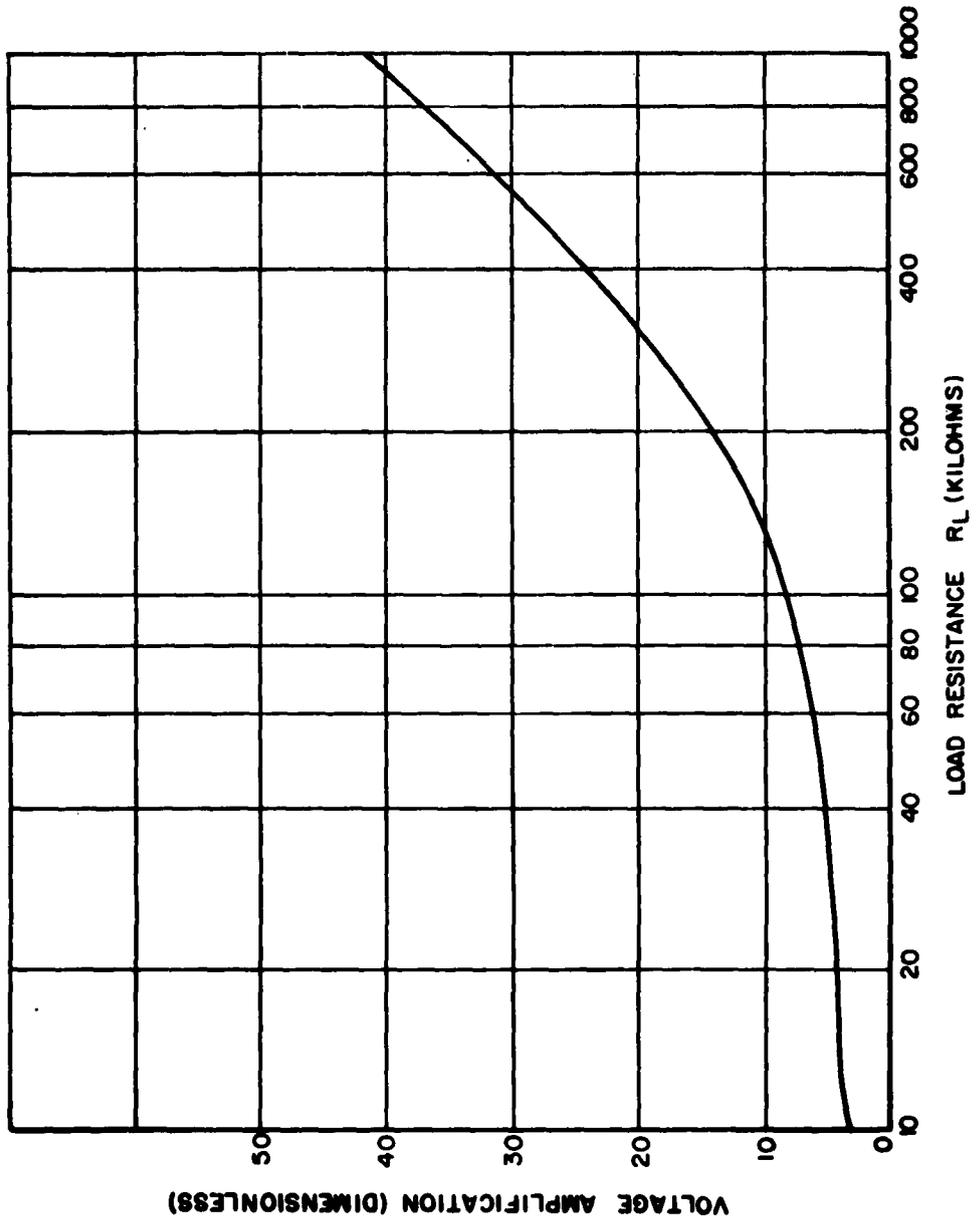


OUTPUT VOLTAGE VS INPUT VOLTAGE FOR SAMPLE B

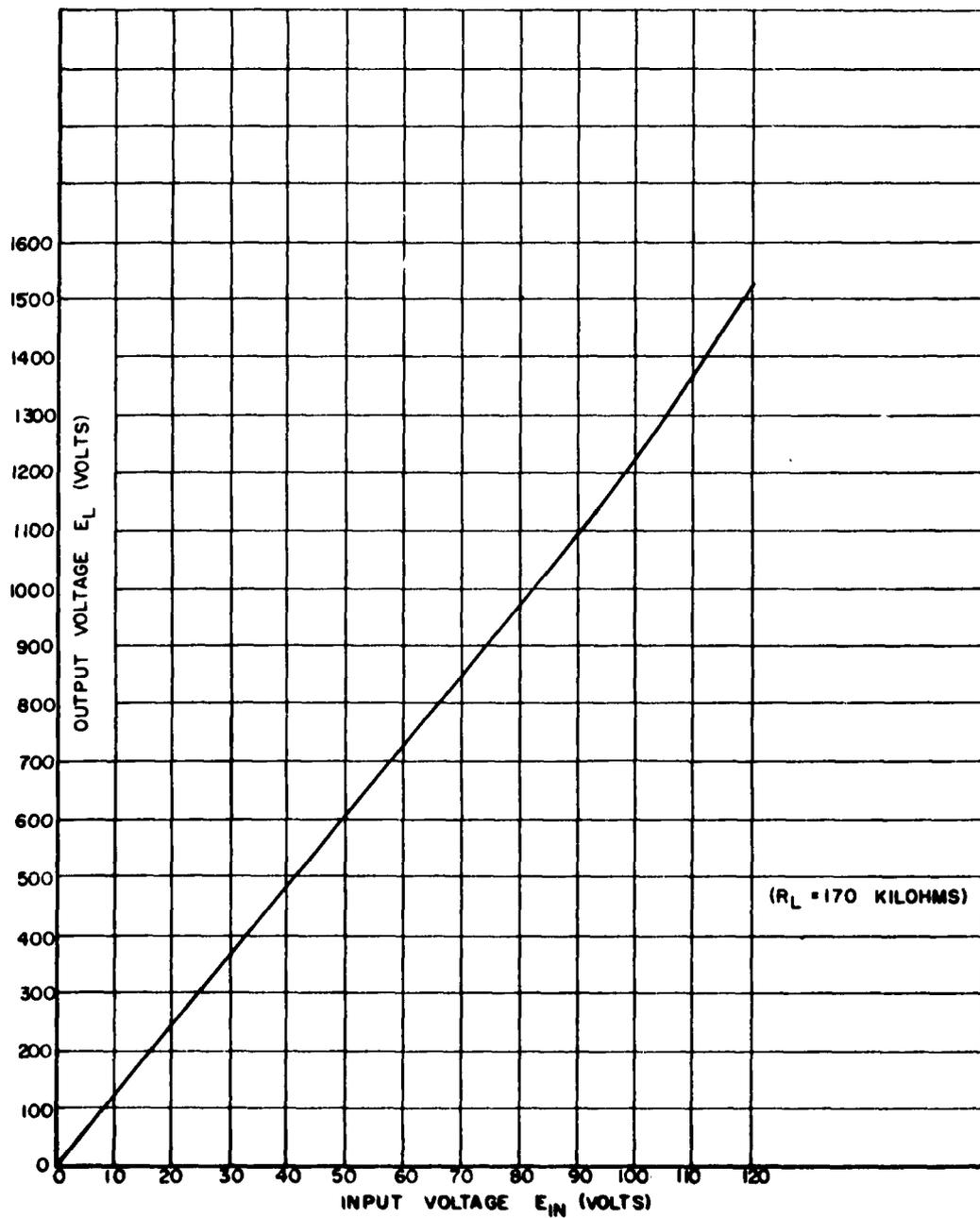
FIGURE 10



EFFICIENCY VS. LOAD RESISTANCE FOR SAMPLE C
FIGURE 11



VOLTAGE AMPLIFICATION VS LOAD RESISTANCE FOR SAMPLE C
 FIGURE 12



OUTPUT VOLTAGE VS. INPUT VOLTAGE FOR SAMPLE C

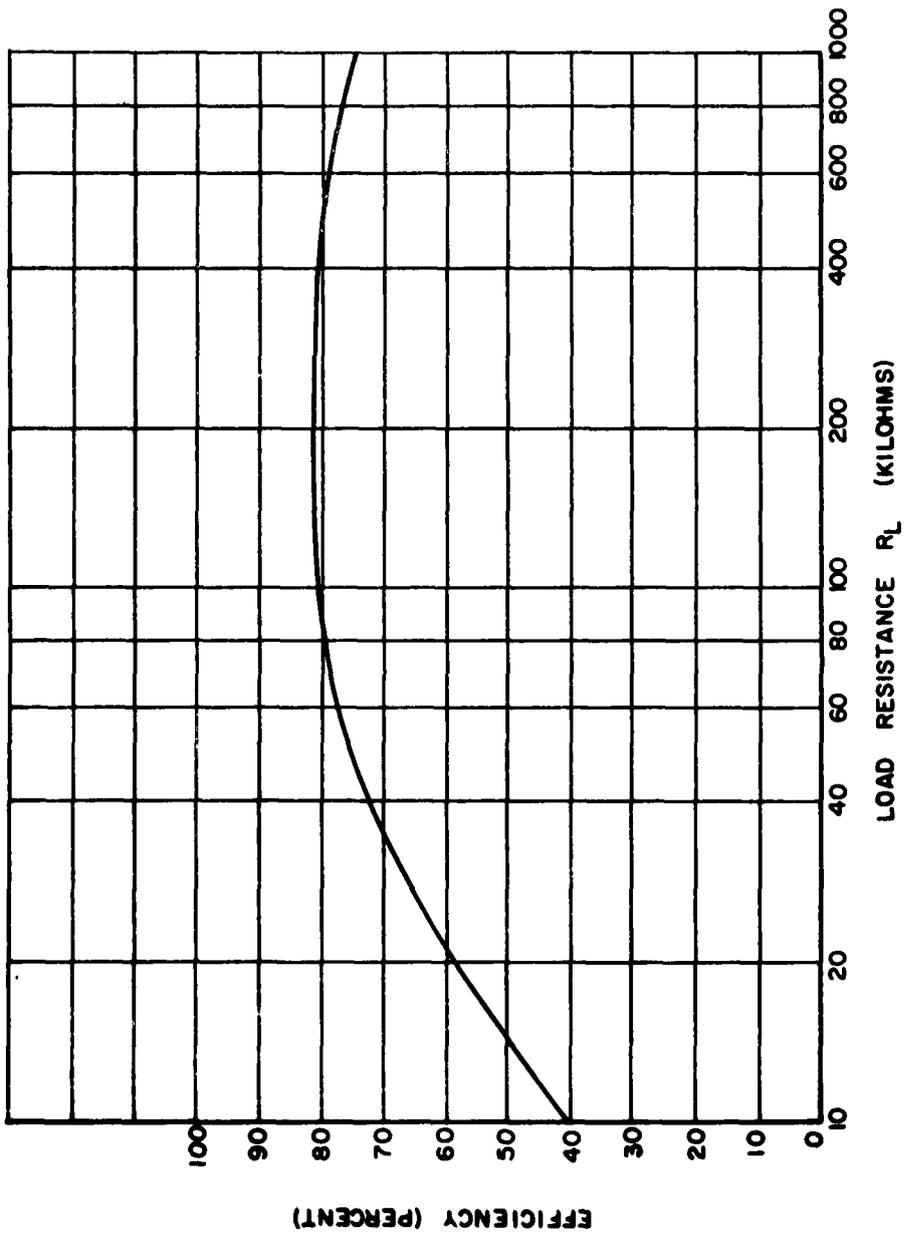
FIGURE 13

power at the limit of the test is 13.5 watts and the nominal output power corresponding to a field of 500 volts per inch in the generator is 4.5 watts. Table I also includes a summary of the characteristics of this device.

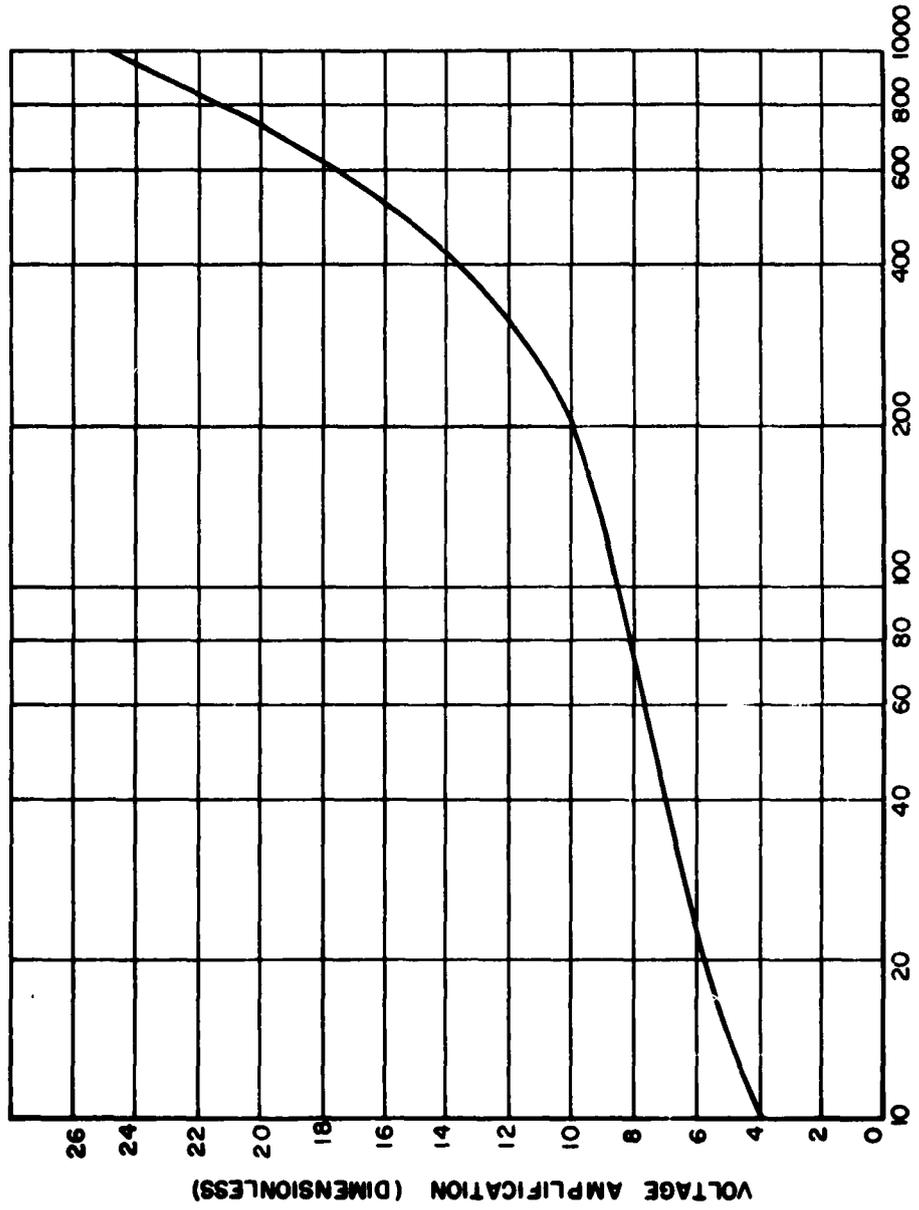
2.4.3.4 Sample D: 18 Kilocycle Transverse Transformer

The final representative sample is a single element full-wave transverse transformer which operates at 18 kilocycles. The ceramic element is 10 inches long, 1.95 inch wide, 0.20 inch thick and is inclosed in a tectolite case 10.8 inches long, 2.5 inches wide and 0.75 inch thick. Due to the length of the generator section and the maximum available polarizing voltage, the polarizing field was restricted to less than 10 volts per mil which was undesirably low for the Type 235 ceramic employed. For this reason, glaze 407 was applied to the generator section to increase the $K_{33}^2 Q_m$ factor.

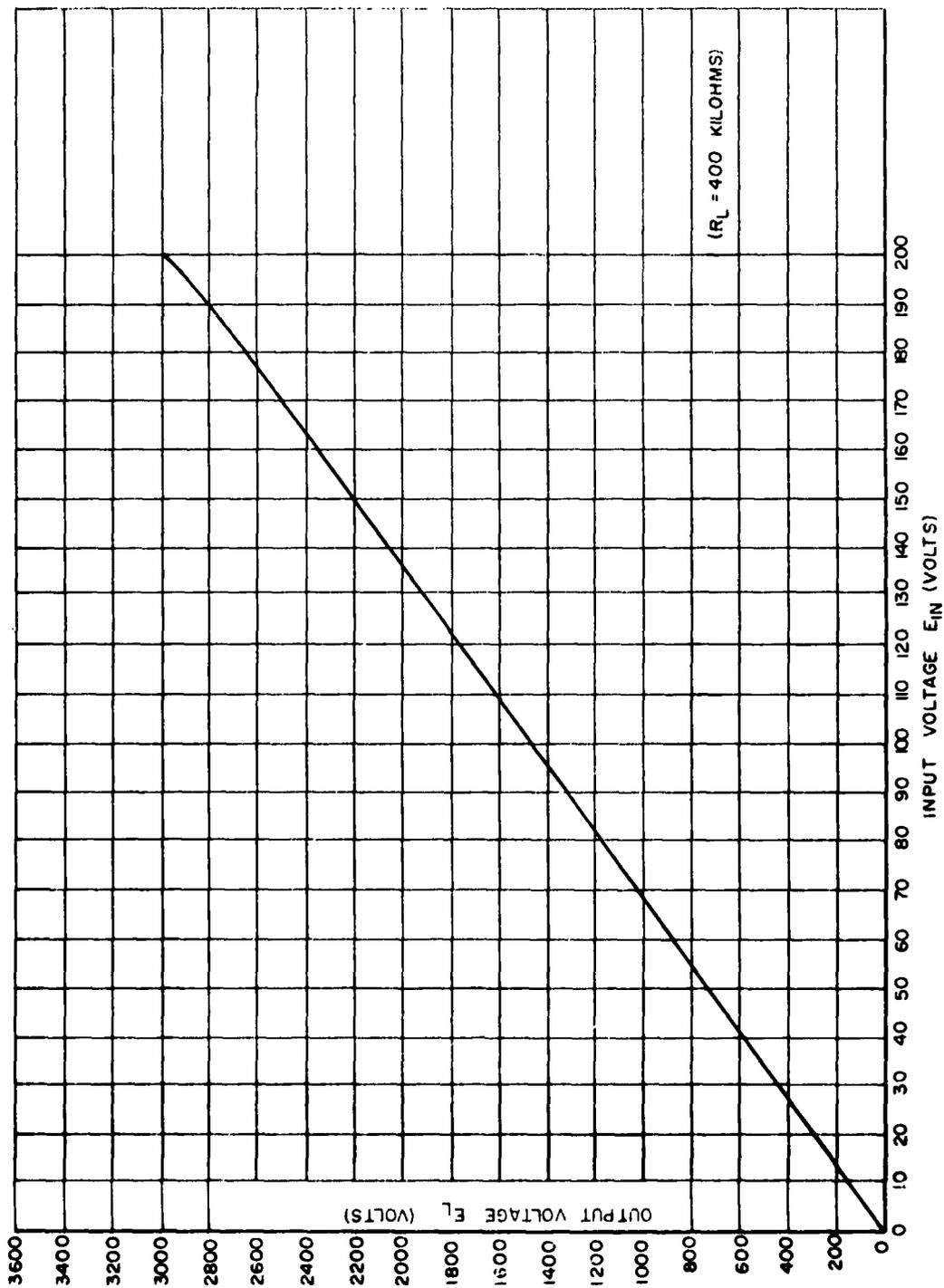
The driver section capacitance of this transformer is 0.014 mfd and the generator capacitance is 19 pf corresponding to an optimum load resistance of about 400 kilohms. Figure 14 shows the measured efficiency as a function of load resistance. Loads between 150 kilohms and 400 kilohms are seen to result in an efficiency of about 81 percent. The fact that this value is higher than for the other samples is attributed to the increased $K_{33}^2 Q_r$ factor due to the glass glaze. The voltage amplification is plotted as a function of load resistance in Figure 15. It is seen that a load of 400 kilohms corresponds to a voltage amplification of about 13.5. The output voltage as a function of input voltage is plotted in Figure 16. With an input of 200 volts, the output power is 22.5 watts and with a generator field of 500 volts per inch the output power is 15.7 watts. A summary of the characteristics of this device is included with the other samples in Table I.



EFFICIENCY VS. LOAD RESISTANCE FOR SAMPLE D
 FIGURE 14



VOLTAGE AMPLIFICATION VS. LOAD RESISTANCE FOR SAMPLE D
 LOAD RESISTANCE R_L (KILOHMS)
 FIGURE 15



OUTPUT VOLTAGE VS. INPUT VOLTAGE FOR SAMPLE D
FIGURE 16

3.0 DETAIL FACTUAL DATA

3.1 DESIGN PROCEDURE

The analysis performed during Phase I resulted in the expressions necessary to predict the performance of a ceramic transformer. Several of these formulae may be re-expressed in a form more suitable for a design procedure; however, this procedure must not be considered exact but rather a guide to a satisfactory design. There are several reasons for this.

The first reason is that several of the parameters in the design formulae may vary considerably from their low level values if the transformer is operated at high drives. For example, the Q_m of the ceramic is strongly dependent upon mechanical stress and the dielectric constant ϵ_{33}^T is dependent upon temperature, particularly near the Curie point of the ceramic.

A second reason for considering the design equations as a first-order approximation is that the coupling coefficient and mechanical Q_m are not known exactly beforehand since the polarization process occurs after the design is completed. Although typical values of these parameters are usually known for a given ceramic, their exact values are not available until after polarization of the bar.

Despite these considerations, a design procedure is useful in estimating transformer characteristics. The procedure is implemented by assuming typical values for coupling coefficient and mechanical Q_m and by constraining one dimension of the transformer in such a way that mechanical stress in the bar will not be excessively high. The constraint used in the following designs will limit the electric field in the generator section to an arbitrary value dependent upon the type of transformer.

3.1.1 Transverse Transformer

The constraint on the electric field for this transformer has been placed at a value of 20,000 volts/meter. It has been found that this value insures a conservative operation of the transformer and prevents excessive heating of the device. Although this value was determined for Barium Titanate, it should also be valid for Lead Zirconate Titanate since the degradation in mechanical Q_m of the latter material has been reported to be at least as great as that of Barium Titanate at high stress levels (Reference 6).

It is assumed that the output load impedance R_L , the output voltage E_L and the transformer amplification ratio $A_V|_{\eta_{max}}$ are specified. In addition, the coupling coefficients K_{31} and K_{33} , the mechanical quality factor Q_m , the sonic velocity C^E , and the dielectric constant ϵ_{33}^T are assumed to be known. Then, due to the electric field constraint, the generator section length L' is given by

$$L' \text{ (meters)} = \frac{E_L \text{ (volts)}}{20,000 \text{ (volts/meter)}} \quad (9)$$

The driver section length L is

$$L \text{ (meters)} = L' \sqrt{1 - K_{33}^2}, \quad (10)$$

and the driver thickness is

$$T \text{ (meters)} = \sqrt{2} \frac{K_{31}}{K_{33}} \cdot \frac{L}{A_V|_{\eta_{max}}} \cdot \left\{ \frac{1}{1 + \frac{\pi^2}{2K_{33}^2 Q_m}} \right\} \quad (11)$$

The driver section width W is given by

$$W \text{ (meters)} = \frac{1}{\pi C^E \epsilon_{33}^T (1 - K_{33}^2)^2} \cdot \frac{L^2}{R_L T} \quad (12)$$

Finally the efficiency is given by

$$\eta = \frac{1}{1 + \frac{\pi^2}{2 K_{33}^2 Q_m}} \quad (13)$$

It should be noted that the width W should be small compared to L or L' . If this is not the case, spurious mechanical resonances may exist in the bar. In this case, the transformer should be fabricated as a parallel array of elements with a smaller width.

It is also apparent that the cross-sectional areas of the driver and generator sections are not adjusted to match their mechanical impedances as was done in the analysis of Phase I. This is because the slight mismatch introduced by this simplification is more than offset by the ease of fabrication of a uniformly dimensioned ceramic bar.

3.1.2 Skew Transverse Transformer

The field constraint on the skew transformer has been placed at 8,000 volts/meter, a value lower than that of the transverse transformer due to the higher losses involved with transverse coupling in the generator section. It is again assumed that the load impedance R_L , the output voltage E_L , the amplification ratio $A_V|_{\eta_{\max}}$, and the operating frequency ω_0 are specified. In addition, the coupling coefficients K_T and K_R of the driver and generator sections, the mechanical quality factor Q_m , and the dielectric constant ϵ_{33}^T are assumed to be known. Then the width W of the transformer is given by

$$W(\text{meters}) = \frac{E_L (\text{volts})}{8,000 (\text{volts/meter})} \quad (14)$$

and the thickness T by

$$T(\text{meters}) = \sqrt{2} \frac{K_T}{K_R} \cdot \frac{W}{A_V|_{\eta_{\max}}} \cdot \left\{ \frac{1}{1 + \frac{\pi^2 (1 - K_R^2)}{2 K_R^2 Q_m}} \right\} \quad (15)$$

The length of the driver and generator sections is

$$L(\text{meters}) = \frac{1}{\omega_0 \epsilon_{33}^T (1 - K_R^2)} \cdot \frac{W}{R_L T} \quad (16)$$

Finally, the efficiency is given by

$$\eta = \frac{1}{\pi^2 (1 - K_R^2) + \frac{Z K_R^2 Q_m}{1}} \quad (17)$$

It is not necessary to adjust the cross-sectional areas in this case since the driver and generator sections use the same transverse coupling.

3.2 CONSTRUCTION PROCEDURE

The ferroelectric ceramics used for ceramic transformers are usually hard, dense and brittle so that ordinary metal fabrication techniques cannot be used for shaping them. However, shaping by abrasive cutting, grinding, lapping, and ultrasonic cutting are feasible if reasonable care is exercised. Abrasive cutting is commonly used if only a relatively few bars of any one size are fabricated at a time. For larger scale production it would probably be desirable to have the individual bars fired to the approximate size and then use abrasive grinding and lapping to obtain the correct dimensions.

A diamond saw provides a convenient means for abrasive cutting of the ceramic. For this process, the ceramic is usually bonded to a glass mounting plate with a sealing wax. The cuts should be made slowly to avoid chipping of the ceramic and a coolant should be provided in order to avoid excessive heating and damage to the diamond wheel. Since the cross-sectional area of the transverse transformer is not normally adjusted to match acoustical impedances, the cutting process results in a uniformly dimensioned bar which is ready for application of electrodes and polarization.

The electrode arrangements for the transverse, skew transverse and tapped transverse transformers are shown in Figures 1 through 3. Care must be taken to avoid placing the driver and generator electrodes too close together on the skew transformer in order to prevent electrical breakdown during polarization. The distance between either broad electrode and the narrow electrodes should be at least as great as the width of the bar. This introduces an area of poor polarization at the center of the bar, however, if the bar is operated at full-wave resonance, the stresses here are small and the performance is not seriously impaired.

A convenient electroding material is a silver and glass suspension, DuPont 6020, which is brushed on the ceramic bar. Two coats are normally applied with the first coat being dried under a heat lamp before application of the second coat. Thin ring electrodes may also be applied on the generator section at this time if output taps are desired (see Figure 3). The electrodes are fired on by placing the transformer in a furnace and firing at 750 degrees centigrade for 10 minutes. Care should be exercised to avoid subjecting the ceramic to thermal shocks which might fracture the ceramic.

After cooling, thin wires are soldered to the center of the electrodes and the transformer is ready for polarization. The polarization procedure depends greatly upon the type of ceramic used in the transformer and in general has to be determined experimentally for a given material. In general, however, the transformer is attached to a polarizing jig to which electrical connections with the high voltage supply can be made. The jig is immersed in a silicone oil and heated to the poling temperature (about 150° to 170° centigrade). The high voltage supplies are then adjusted to produce fields of from 20,000 to 100,000 volts/inch between the driver electrodes and the generator electrodes. The silicone oil may be maintained at this temperature or slowly cooled to room temperature depending on the particular ceramic.

After polarization, the transformer is ready for mounting and testing. The transformers are presently mounted by supporting the bar in a suitable case by means of thin foamed silicon rubber pads located at the motional nodes of the bar.

3.3 MEASUREMENT PROCEDURE

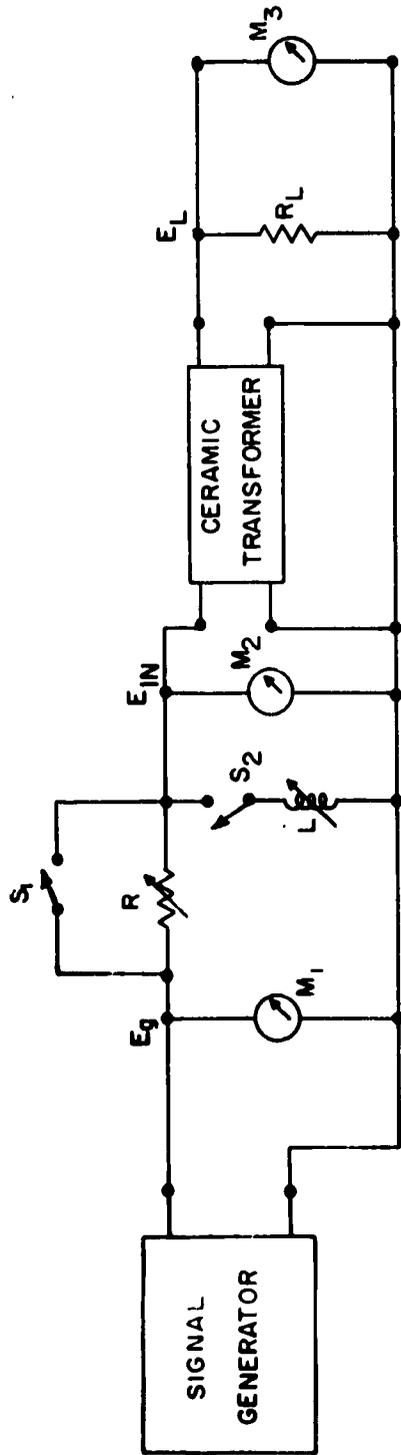
Various measurement procedures have been described in the Interim Development Reports prepared during this contract. Many of these procedures involved the determination of the ceramic properties under both low and high stress levels and are not of great value in describing the transformer as a circuit element. The following paragraphs describe a procedure used to determine the input and output capacitances of the device as well as its voltage amplification, output power and efficiency.

The first step in this procedure is to measure the clamped capacitance of the driver and generator sections. This is usually done at a frequency of 1 kilocycle using a standard capacitance bridge. The reactance of the generator section at the transformer operating frequency then equals the value of load resistance R_L at which maximum efficiency occurs.

The other measurements are made in the test set-up shown in Figure 17. The signal generator should have a low impedance output and be capable of supplying the required input voltages. The generator used during this contract was capable of supplying 300 watts into a 200 ohm load at frequencies from 3 to 300 kilocycles. Meters M_1 , M_2 and M_3 are vacuum tube voltmeters. A high impedance high voltage probe on the input of M_3 . The nominal value of the low loss inductor L is chosen to resonate with the driver section capacitance at the transformer operating frequency.

The voltage amplification is readily determined for a given value of R_L by closing S_1 and opening S_2 . The signal generator frequency is adjusted for maximum output voltage E_L and the readings of M_3 and M_2 are recorded. Next S_1 is opened and S_2 is closed; the inductance L is tuned for a maximum reading on M_2 . The generator output voltage E_g and the resistor R are now adjusted so that E_{IN} is the same as previously recorded and E_g is exactly twice E_{IN} as measured on meters M_1 and M_2 . The value of the resistance R is recorded and is equal to the shunt resistive component of the transformer input impedance. The following quantities are now readily obtained:

$$\text{Voltage Amplification} = \frac{E_L}{E_{IN}}$$



CERAMIC TRANSFORMER TEST SET-UP
 FIGURE 17

$$\text{Output Power} = \frac{E_L^2}{R_L}$$

$$\text{Input Power} = \frac{E_{IN}^2}{R}$$

$$\text{Efficiency (\%)} = \frac{\text{Output Power}}{\text{Input Power}} \times 100 = 100 \times \left(\frac{E_L}{E_{IN}} \right)^2 \cdot \frac{R}{R_L} .$$

The data presented in Section 2.4.3 of this report were obtained using this measurement procedure.

4.0 CONCLUSIONS

In summary, the ceramic transformer provides a means for transforming voltage and current, with corresponding changes in impedance level, at frequencies from as low as perhaps 5 kilocycles to as high as several hundred kilocycles. The power rating may be related to the volume of the ceramic material, and a power density of 17.8 watts per cubic inch has been demonstrated. Maximum output voltage, developed along the length of the generator half of the ceramic bar, for conservative operation without cooling means should be held to about 500 volts rms per inch of generator length, or about 250 volts per inch of total transformer length. The frequency of operation is given approximately by a constant of 180 kilocycle inches, which is equal to the product of frequency times transformer length. In terms of maximum rms voltage, therefore, the product of output voltage rating times frequency is 45,000 kilocycle-volts.

Rectification most suitable for use with the ceramic transformer is provided by two diodes, operating through the output capacitance of the transformer in a voltage doubler circuit. The dc output voltage provided is 2.828 times the rms output voltage. Since input voltage must be furnished at the frequency of transformer resonance, an oscillator with feedback from the transformer output can be used to maintain optimum drive frequency. Waveform is not critical, although output waveform is sinusoidal, and so relaxation oscillator drivers are advantageous.

The numbers given here apply directly to the G-E 235 ceramic material. This is a modified barium titanate ceramic, available commercially, and developed for high level operation. This is generally superior to other materials tested for ceramic transformer use, and is more easily processed than other materials which were tested for the application.

In use, the ceramic transformer is not as small as an air-core transformer designed for radio frequency use, but has a number of unique features. It may be tapped readily, and provides its own capacitance

internally for rectification in the voltage doubler circuit. It operates well over a wide range of temperatures, and cannot be damaged by short circuit loading. It is capable of short time outputs well in excess of the ratings assigned above, and can be operated steadily at ratings above these when externally cooled.

Finally, perhaps the most unusual property is the absence of magnetic fields and ferromagnetic material. Since all operation takes place through mechanical vibrations and electric field interactions, no magnetic field is required for operation, and the transformer will not distort existing magnetic fields in its vicinity. Its use is suggested in equipment used for magnetic field measurement, or in devices such as electron gun structures which show sensitivity to field distortion.

PART II

1.0 RECOMMENDATIONS

The device development program described here has carried out an analysis of ceramic transformer operation, verified the results of the analysis, and provided design methods which are adaptable to the material constants of any ferroelectric ceramic. These have been evaluated numerically for G-E 235 ceramic, which has proved superior to other presently available materials.

The device development, therefore, is substantially complete. Further device work could be carried out with novel configurations designed to provide high power or extremely high voltage transformers. However, the most basic limitation now being imposed is the nonlinear behavior of all ferroelectric ceramics at large values of vibrating stress. Very wide ranges of maximum stress were found among available materials, and the particular G-E 235 ceramic selected from these shows definitely superior characteristics.

Therefore, future work might most profitably be concerned with development of materials with higher threshold values of non-linear operation. This would have value extending beyond the ceramic transformer range, since such an improved material would offer distinct advantages for the reduction of size and cost, or increases in power ratings, of sonar transducers. The G-E 235 material was originally developed from a series of elementary ceramic transformer evaluations of new materials, and it appears that the ceramic transformer provides one of the simplest and most economical means for evaluating and guiding materials development along these lines.