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TRANSISTORIZED DC-TO-DC CONVERTERS EMPLOYING PIEZOELECTRIC TRANSFORMERS

Floyd Allen

18 March 1963

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18 March 1963
TR-1116

TRANSISTORIZED DC-TO-DC CONVERTERS EMPLOYING PIEZOELECTRIC TRANSFORMERS

Floyd Allen

FOR THE COMMANDER:
Approved by

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CONTENTS

ABSTRACT

A transistorized dc-to-dc converter has been designed using a ceramic transformer. This converter is particularly adaptable to equipment used in measuring magnetic fields. The ceramic transformer provides further advantages of reduced size and complexity over flyback type pulse and resonant rf transformers, which require the use of many turns of well insulated wire.

A prototype model, built to convert 28 v dc to 2200 v dc at 20 μa, operates satisfactorily from -35°C to 75°C and shows no substantial change in output after continuous operation for 3600 hr.

Included is a procedure for the design of a transverse transformer showing the voltage amplification to be a function of piezoelectric coefficients and transformer geometry.

1. INTRODUCTION

The purpose of this study was the investigation of high-voltage dc-to-dc converters incorporating nonferromagnetic materials, for use in satellites carrying magnetometers. For this application, conversion at radio frequencies by air core transformers was not attractive from the standpoint of efficiency and the requirement of many well insulated turns of copper wire for operation at high voltages. Although high output voltages could be obtained with charged capacitors (voltage multiplier circuits), the efficiency would be low and the internal impedance high, with attendant poor regulation. High-voltage ceramic transformers were therefore considered because of the absence of strong magnetic fields and high voltage windings.

2. GENERAL DESCRIPTION OF THE CONVERTER SYSTEM

The conventional method of dc-dc conversion is to modulate the source voltage with a semiconductor switch, step up the modulated voltage with a magnetic transformer, and rectify and filter the output of the transformer. The dc-dc converter described in this report is unique because it makes use of a nonmagnetic piezoelectric transformer, instead of the conventional magnetic type. For this reason the analysis and design of a piezoelectric transformer is covered in much greater detail than the design of the complete converter.

3. THE TRANSVERSE CERAMIC TRANSFORMER

3.1 General

The two basic all-piezoelectric transformers are the ring type and transverse type. The transverse type (fig. 1) is the more versatile and useful as a step-up high-voltage transformer. The open-circuit voltage amplification of the ring type is, unlike that of the transverse type,

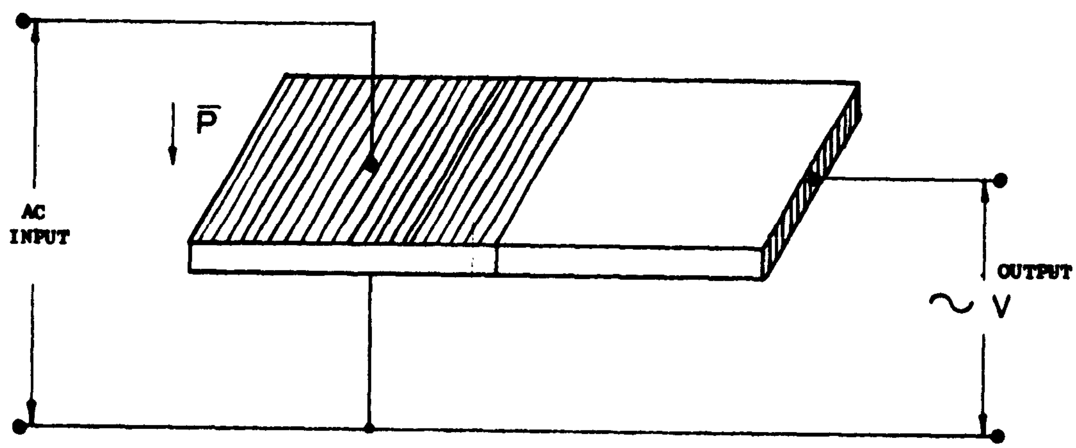

Figure 1. Complete ceramic transformer.

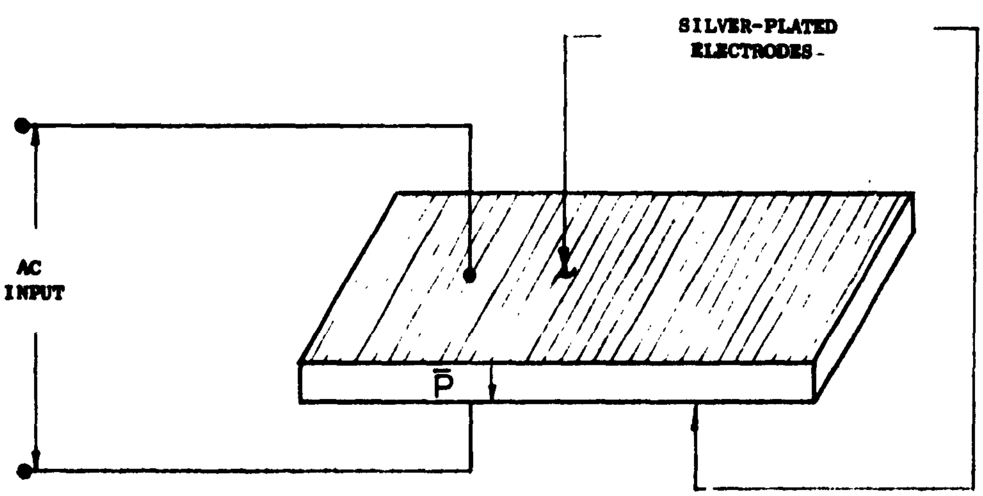

Figure 2. Polarized $BaTiO_3$ bar, driver section.

independent of the geometry, being a function of the mechanical quality factor Q_m and electromechanical coupling coefficient K_{33}^2, only. Typical values of open-circuit voltage amplification range from approximately 15 to 30 compared with 170 for the transverse type. Furthermore, the input impedance is substantially higher than that of the transverse transformer. Therefore, the transverse type can be more easily designed to specifications because the input and output characteristics are determined by the dimensions of the bar.

3.2 BASIC THEORY OF THE PIEZOELECTRIC TRANSVERSE TRANSFORMER

A ceramic transverse transformer is a three-terminal device that utilizes resonant vibrations of a piezoelectric ceramic to effect an impedance transformation between its input and output terminals.

The piezoelectric ceramic bar used in the transformers comprises two functional regions: the driver section and the generator section.

The driver section is used to convert an alternating input signal into mechanical vibration. Figure 2 shows the method of producing mechanical vibration of a polarized $BaTiO_3$ bar by the application of an a-c voltage to a pair of silver-plated parallel faces.

The generator section is used to convert the mechanical strain to an output voltage. Figure 3 shows the method of obtaining an output voltage from a mechanically stressed $BaTiO_3$ bar by means of silver electrodes at the ends of the bar.

For the transformation or conversion process the driver and generator functions are performed by a simple ceramic bar, as shown in figure 1. The frequency of the applied a-c voltage is set equal to the longitudinal mechanical resonant frequency of the bar. One of the face electrodes serves as a common terminal.

It will be shown that the complete transformer can produce a voltage step-up between input and output.

Figure 4 shows the displacement and strain distribution for a transverse transformer in its fundamental resonance mode. The resonating frequency of the transformer is given by

$$f = \frac{C}{2(L+L')}$$

where f = fundamental resonant frequency in cps
C = velocity of sound propagation in the ceramic material (~4200 m/sec)
L = length of driver section (m)
L′ = length of generator section (m)

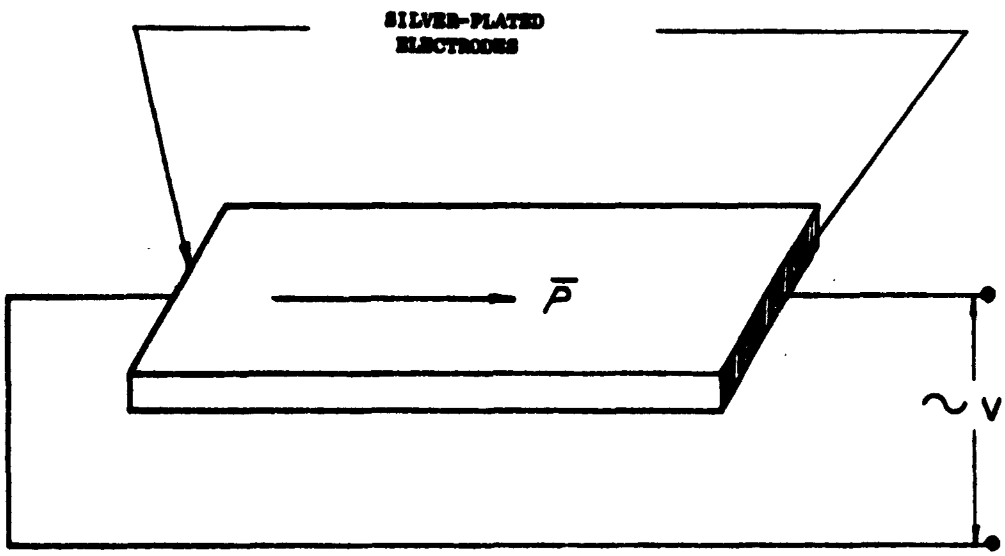

Figure 3. Polarized $BaTiO_3$ bar, generator section.

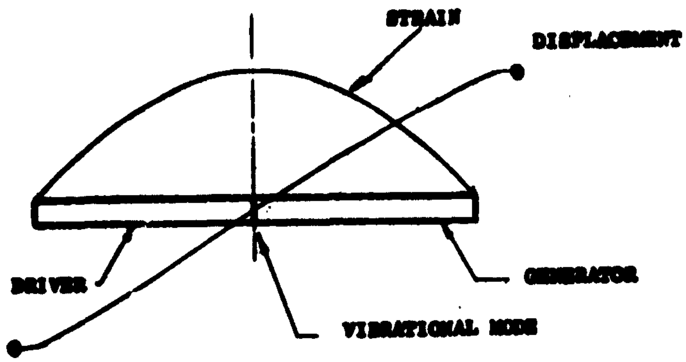

Figure 4. Fundamental resonance mode for a long thin bar.

The equivalent circuit for the transverse transformer is shown in figure 5. The pertinent equations relating the ceramic material constants and the geometry to the amplification factor, output impedance, etc are discussed below. For a complete analysis of the electromechanical system, Katz (ref 1) provides a comprehensive derivation of the necessary equivalent circuits for use in the transformation process.

The open-circuit voltage amplification of a transverse transformer is given by

$$A_{vo} = \frac{4Q_m}{\pi^2} \frac{Y_3^E g_{33} d_{31}}{(1 - K_{33}^2)} \frac{L}{T}$$

where Q_m = mechanical quality factor of the ceramic

Y_3^E = Young's modulus in the longitudinal direction and under constant electric field (new./m²)

g_{33} = ratio between longitudinal strain and charge density (m²/coul)

d_{31} = ratio between strain in the longitudinal direction and electric field in the vertical direction for constant stress in longitudinal direction (m/v)

K_{33}^2 = electromechanical coupling coefficient of the generator

L and T = length and thickness of the driver section (m)

In practice, ceramic transformers are designed to operate into some equivalent load resistance. The voltage amplification has been found to deteriorate rapidly as the generator terminals are resistively loaded. The load resistance required for maximum efficiency is approximately equal to the capacitive reactance of the generator section electrodes at the resonant frequency of the bar. The voltage amplification at maximum efficiency is then found to be

$$A_{V_{Eff_{max}}} = \sqrt{2} \frac{K_{31}}{K_{33}} \frac{L}{T} \left[1 + \frac{\frac{1}{\pi^2}}{2K_{33}^2 Q_m} \right]$$

and

$$Eff_{max} = \frac{\text{output power}}{\text{input power}} = 1 + \frac{\frac{1}{\pi^2}}{2K_{33}^2 Q_m}$$

where K_{31} is the electromechanical coupling coefficient of the driver section and is equal to

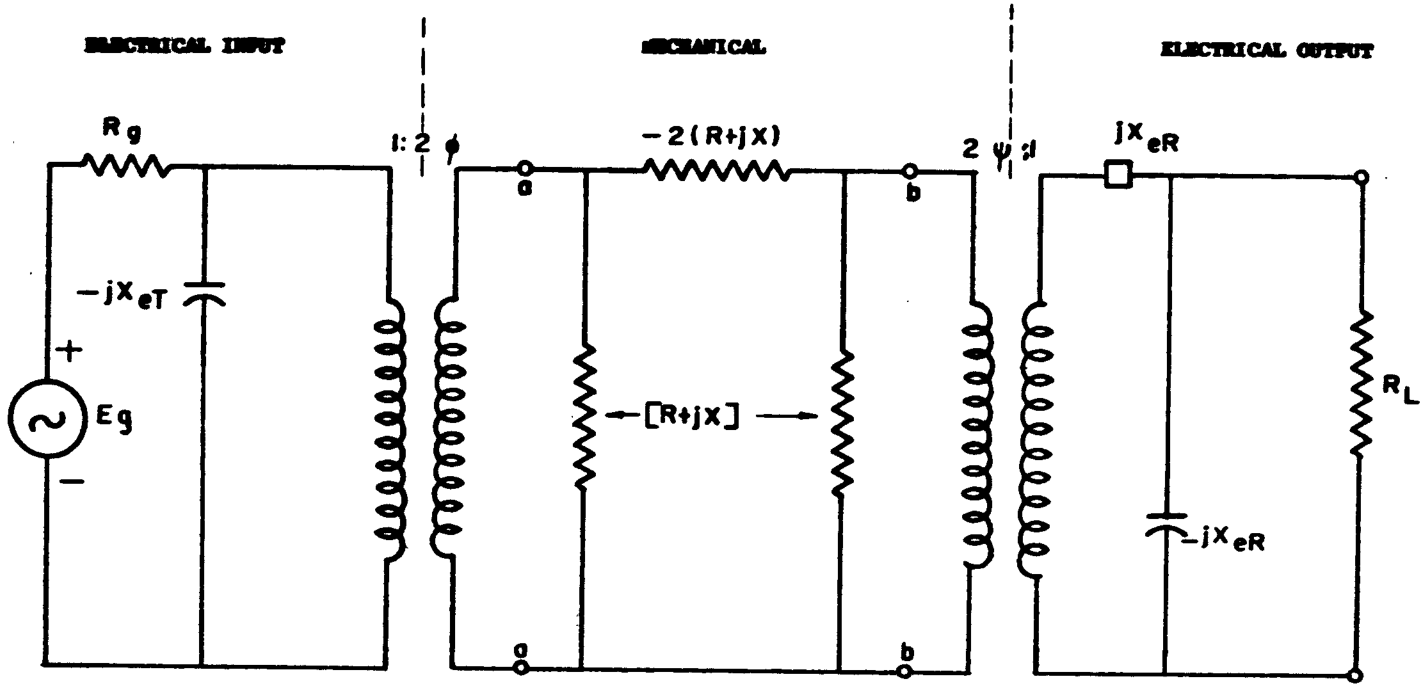

Figure 5. Simplified equivalent circuit for terminated transverse transformer.

$$K_{31} = \left(\frac{d_{31}\ Y_3^E}{\epsilon_{33}^T}\right)^{1/2}$$

and ϵ_{33}^T = dielectric constant of the material (f/m). The voltage amplification expression indicates that for $K_{33}^2\ Q_m \gg 10$, the amplification with maximum efficiency is nearly independent of this product but directly proportional to the length-to-thickness ratio of the driver section.

The L/T ratio is the most easily controlled for a given ceramic material, since the Q_m and coupling of the L/T ratio are limited by practical considerations, such as the fragility of a long, thin bar and the uncertain mechanical vibrational modes encountered with short, thick bars. Since, large values of A_{vo} are commonly desired, the fragility of the bar is usually the most restrictive consideration. Another factor in the use of a large L/T ratio is a result of the necessity for polarizing the generator section along its length. Modern ceramics require polarizing fields of 20,000 to 100,000 v/in. so that a prohibitively high voltage may be required to polarize generator sections several inches long.

The equation for voltage amplification of a transverse transformer under the conditions of maximum power transfer is derived (ref 1) and is approximately half the open-circuit amplification.

$$A_v \cong A_{vo}/2$$

Katz also shows that the generator reactance at resonance is equal to

$$X_{er} = \frac{2L^2}{\pi C \epsilon_{33}^T\ (1-K_{33}^2)\ T\ W}$$

where W is the width of the bar in meters and $\dfrac{X_{er}}{R_{load}} \cong \dfrac{\pi^2}{4Q_m\ K_{33}^2}$

Combining the above equations and solving for W yields

$$W = \frac{8Q_m\ K_{33}^2}{\pi^3\ C\ (1-K_{33}^2)^2\ \epsilon_{33}^T} \quad \frac{L^2}{R_{load}\ T}$$

This expression is very useful in designing a transformer for specific loads.

3.3 The Tapped Transverse Transformer

A tapped transformer to obtain multiple outputs may be formed by merely placing ring electrodes on the generator section of a conventional transverse transformer as shown in figure 6. The electrodes pick off a portion of the total output voltage, depending on their position, the electrical load, and the resonant mode of the ceramic bar. It will be shown later how the tapped output voltage is used to synchronize the oscillator frequency to the operating frequency of the transformer.

3.4 Transformer Design

The foregoing analysis gave expressions for the open-circuit voltage amplification at maximum efficiency and the maximum power transfer condition. It was shown that these characteristics depend upon the properties of the ceramic material and the bar geometry. Following is a step-by-step design procedure, given in Katz, for a step-up transformer driven from a constant voltage source under the conditions of maximum power transfer. Suppose the load resistance R_L, the voltage amplification A_v, and the rms output voltage E_2 are specified. The steps in the design are as follows:

The minimum length L is set by the operating field of 0.5 v/mil or about 20,000 v/m; thus

(1) $$L' = \frac{E_2}{20{,}000} \text{ meters}$$

(2) The thickness $$T = \frac{4Q_m Y_3^E g_{33} d_{31}}{2(1-K_{33}^2)} \frac{L'}{A_{vo}}$$

where $A_{vo} = 2A_v$ as specified.

(3) With L and T determined from the above step, the width W can be obtained by the expression

$$W = \frac{8Q_m K_{33}^2}{\pi^3 C (1-K_{33}^2)^2 \epsilon_{33}} \frac{L^2}{R_L T}$$

(4) The operating frequency (in cps) is determined from equation

$$f = \frac{C}{2(L+L')}$$

(5) The input impedance parameters are quite useful in estimating the requirements placed upon the network driving the transformer and are computed as follows

$$X_{et} = \frac{1}{\epsilon_{33}^T \omega (1-K_{31}^2)} \frac{T}{WL}$$

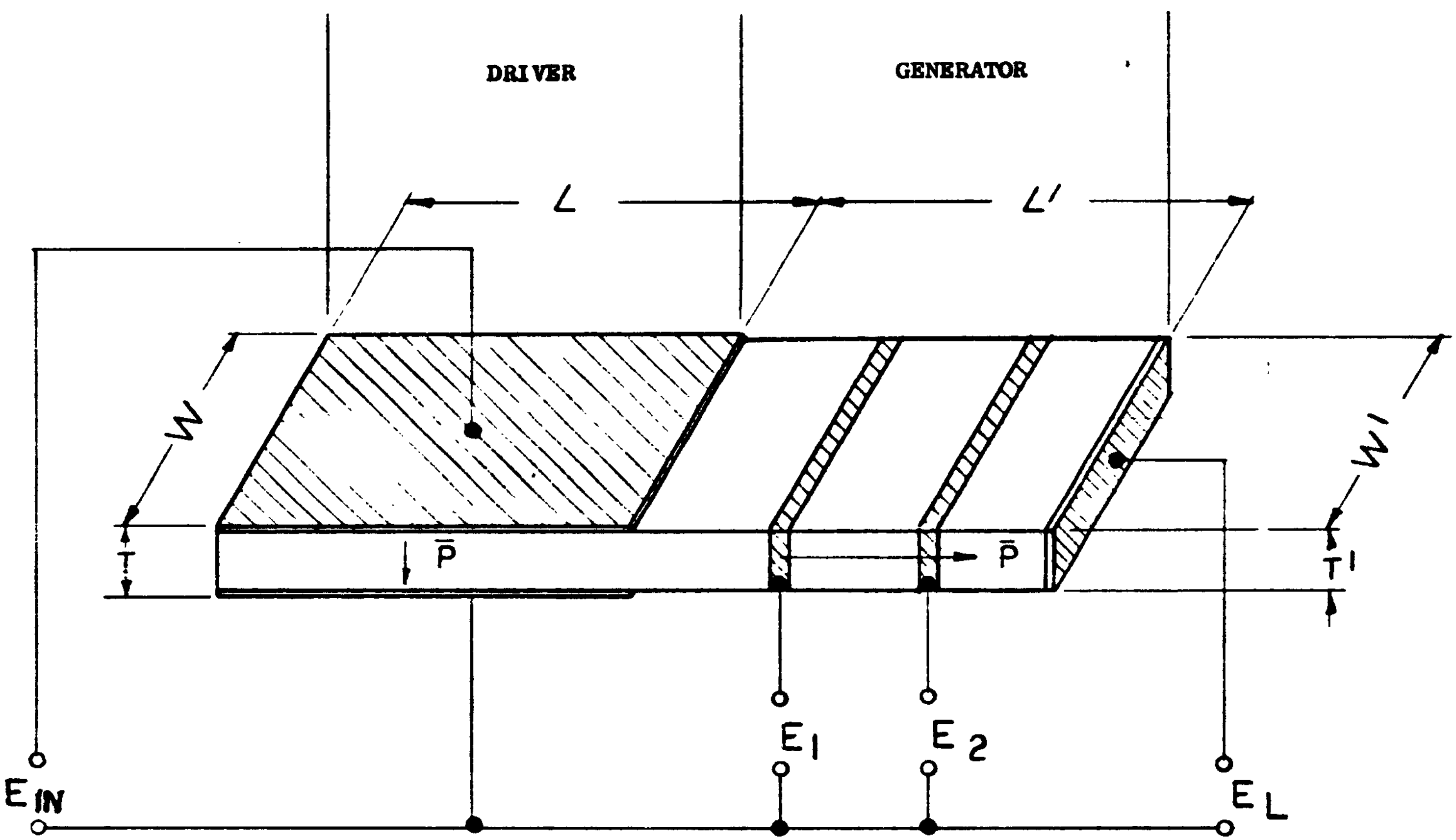

Figure 6. Tapped transverse transformer

where

$$\frac{1}{\omega} = \frac{2L}{\pi C}$$

and

$$R_e = \frac{\pi}{C\, Q_m\, Y_3^E\, d_{31}^2} \quad \frac{T}{W}$$

(6) In practice, the reactive part of the input impedance may be resonated out by use of an appropriate inductor in series with the transformer input; this usually results in an increased voltage amplification. The value of the resonating inductance L_e is computed from the equation

$$L_e = \frac{X_L}{\omega} = \frac{1}{\omega} \quad \frac{X_{et}}{1 + (X_{et}/R_e)^2}$$

For optimum performance, the bar should be supported at the junction of driver and generator with the ends mechanically free. However, this type of mount is not practical since the ceramic bar is brittle and will break under shock. It has been shown at HDL and verified by General Electric (ref 2) that a ceramic transformer can be placed on foam rubber supports without affecting performance. The bar is operated in the fundamental longitudinal mode as a half-wave resonator (total length equals one-half wavelength). The dimensions are such that the width W and thickness T are less than one eighth wavelength, so the transformer can be assumed to vibrate as a long thin bar.

4. EXPERIMENTAL RESULTS

4.1 Performance of Transverse-Type Ceramic High-Voltage Transformer

The performance of a typical ceramic high-voltage transformer was evaluated using the circuit of figure 7. The transformer, manufactured by the General Electric Company, is a modified barium titanate ceramic with the following properties:

Nominal operating frequency : 54 kc
Input capacitance: 2250 pf
Output capacitance: approximately 8 pf
Maximum voltage step-up: 76
Dimensions:
Overall length L + L′ : 12.70 cm
Width W : 1.30 cm
Thickness T : 0.25 cm

The voltage amplification shown in figure 8 as a function of input voltage at three conditions of R_L may be seen to be a maximum at an

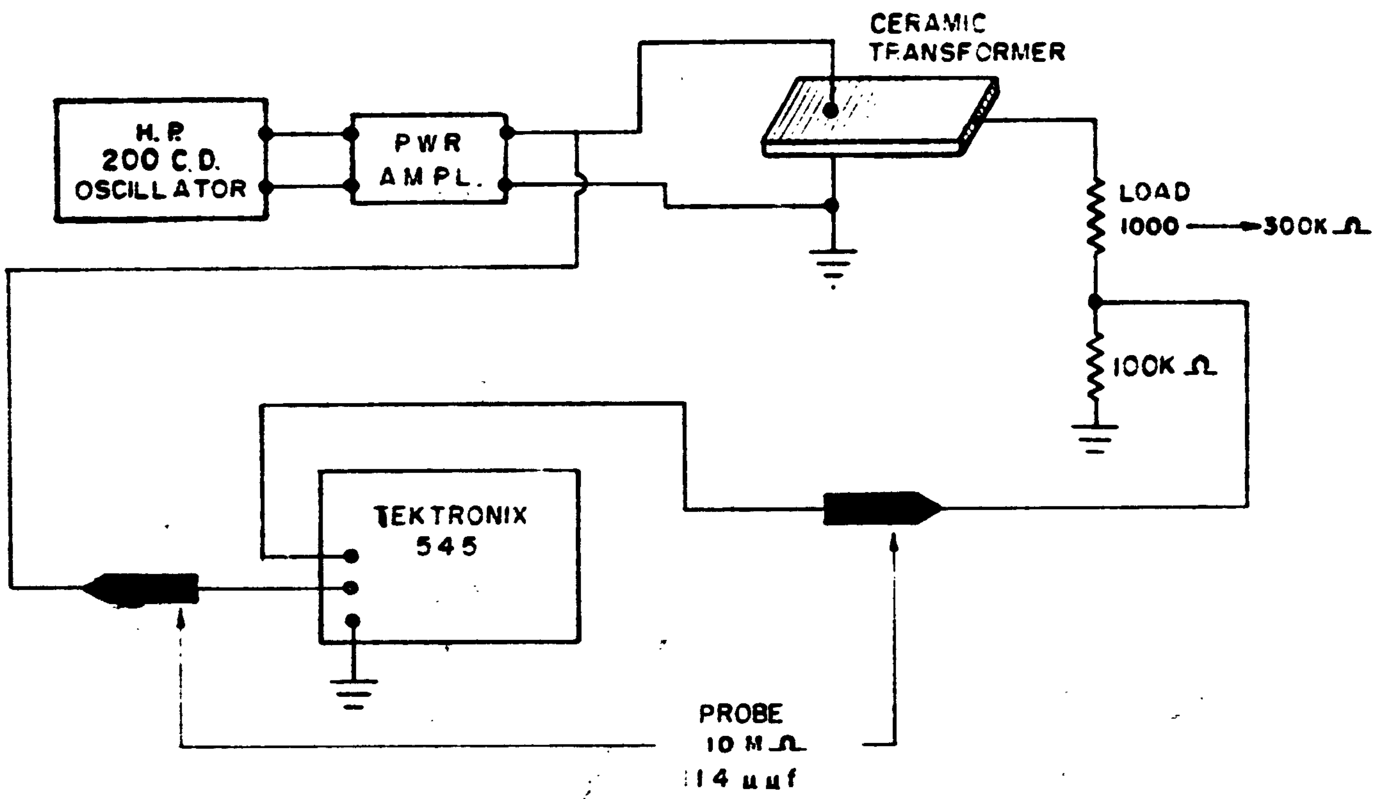

Figure 7. Ceramic transformer test setup.

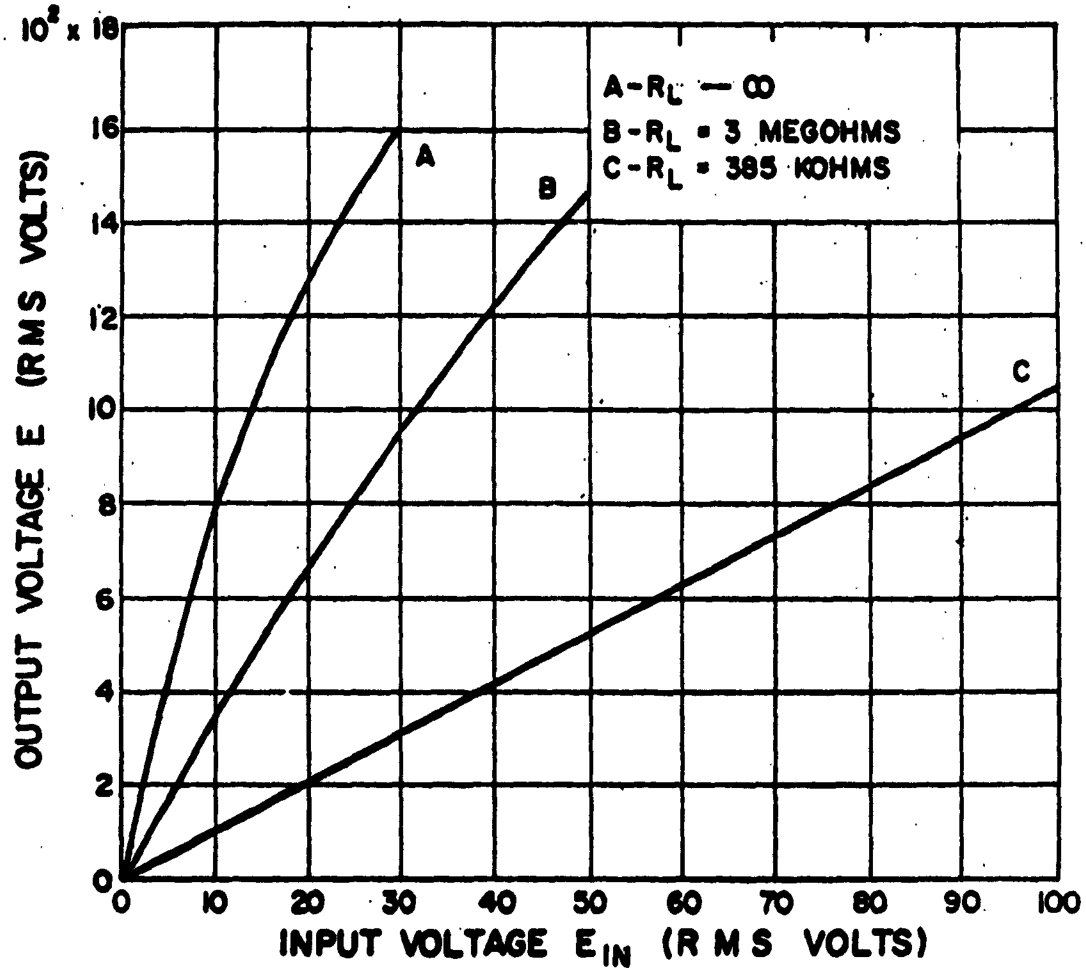

Figure 8. Output voltage versus input voltage for 54 kc ceramic transformer.

E_{in} between 0 and 9 v and $R_L = \infty$. The efficiency of the device as a function of load resistance R_L is plotted in figure 9. A maximum efficiency of 76 percent occurs at load resistances of 100 to 400 kohms. This load range agrees well with the reactance of the generator section capacitance, corresponding to an optimum load resistance of about 370 kohms (8 pf, X_c = 370 kohms at 54 kc). The voltage amplification at the optimum load was about 10.

4.2 Operation of Ceramic Transformers Subjected to External Vibrations

Since the ceramic transformer is a mechanically vibrating system, the effect of external vibrations on the voltage amplification is of particular interest. Therefore, a transverse transformer 9 cm long, 1.3 cm wide, and 0.25 cm thick, supported near its motional nodes by rubber cushions and packaged in a small plastic case, was incorporated in the converter circuit shown in figure 10. The plastic case, containing the transformer, was cemented to a vibrator table and was vibrated at the fundamental and subharmonic frequencies of the transformer at a constant level of 10 g. The amplitude and wave shape of the input and output voltages were monitored. The external vibrations at these frequencies had no measurable effect on the d-c output voltage. Although it may be argued that the shock-mounted transformer was relatively insensitive to external vibration, the test shows the feasibility of using a ceramic transformer in applications where vibrations are encountered.

4.3 Parallel Connection of Transverse Transformers

The feasibility of connecting transverse transformers in parallel to achieve higher output power was investigated. The parallel connection of smaller units is more desirable than increasing the cross-sectional area of a single unit, since the bar width W should be kept small compared with the length. If this is not done, spurious mechanical resonances may exist in the bar.

Two transverse transformers selected for evaluation in the parallel configuration were about 9.0 cm long, 1.30 cm wide, and 0.25 cm thick and exhibited half-wave mechanical resonance at 26.7 and 26.8 kc. The units are supported near their motional nodes by rubber cushions. Tests indicate that rubber mountings do not appreciably damp the mechanical motion of the bars.

The voltage amplification and output impedance of each unit were measured at a constant drive level of 60 v pp, using the circuit of figure 7. The voltage amplifications of the units were approximately 50 and 35, with corresponding output impedances of about 1 megohm. The transformers were then connected in parallel and the measurements repeated. The amplification factor of the combination was about 34 while the output impedance was reduced from 1 megohm to about 750 kohms. The relatively small reduction in output impedance is attributed to difference in

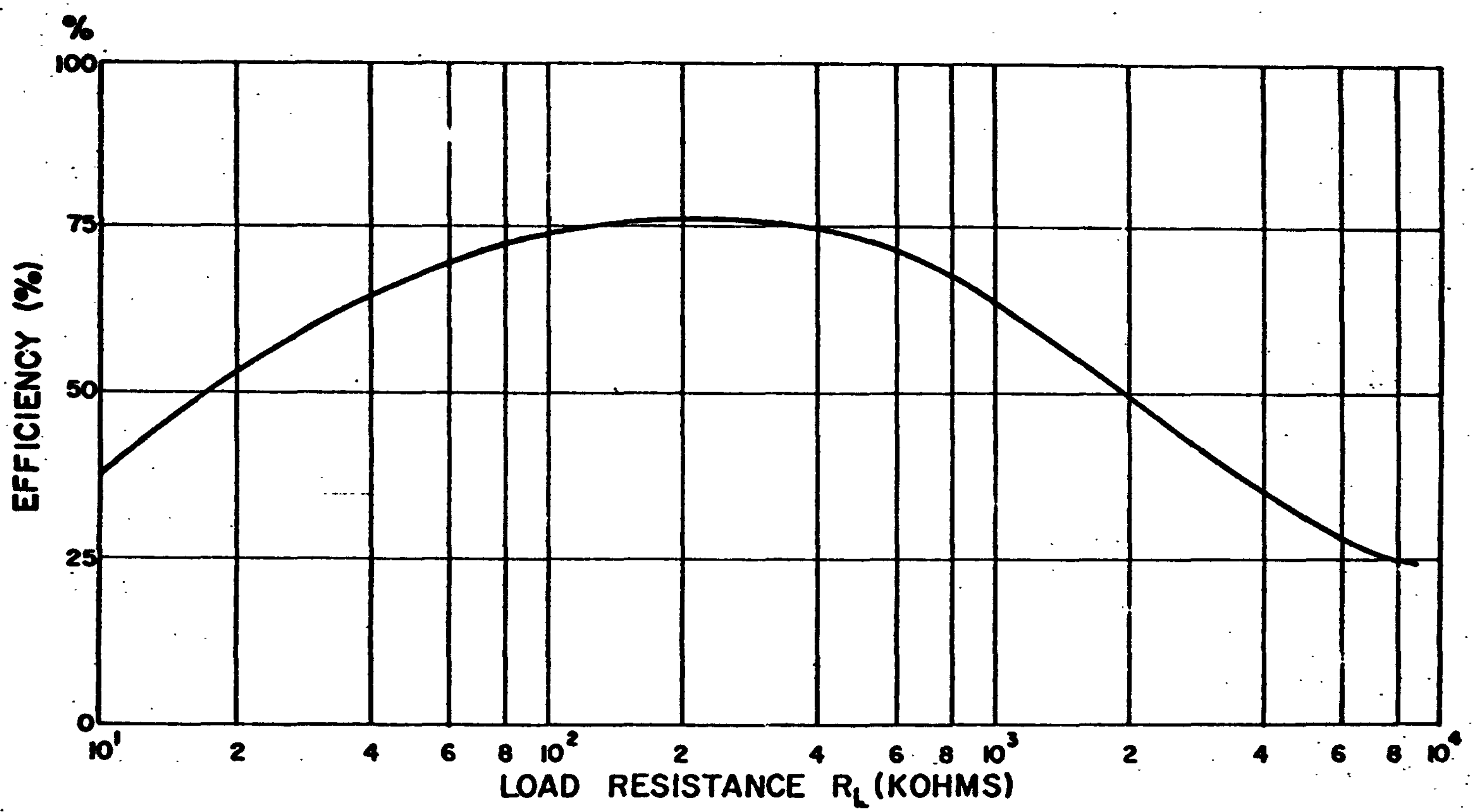

Figure 9. Efficiency versus load resistancd for 54 kc ceramic transformer.

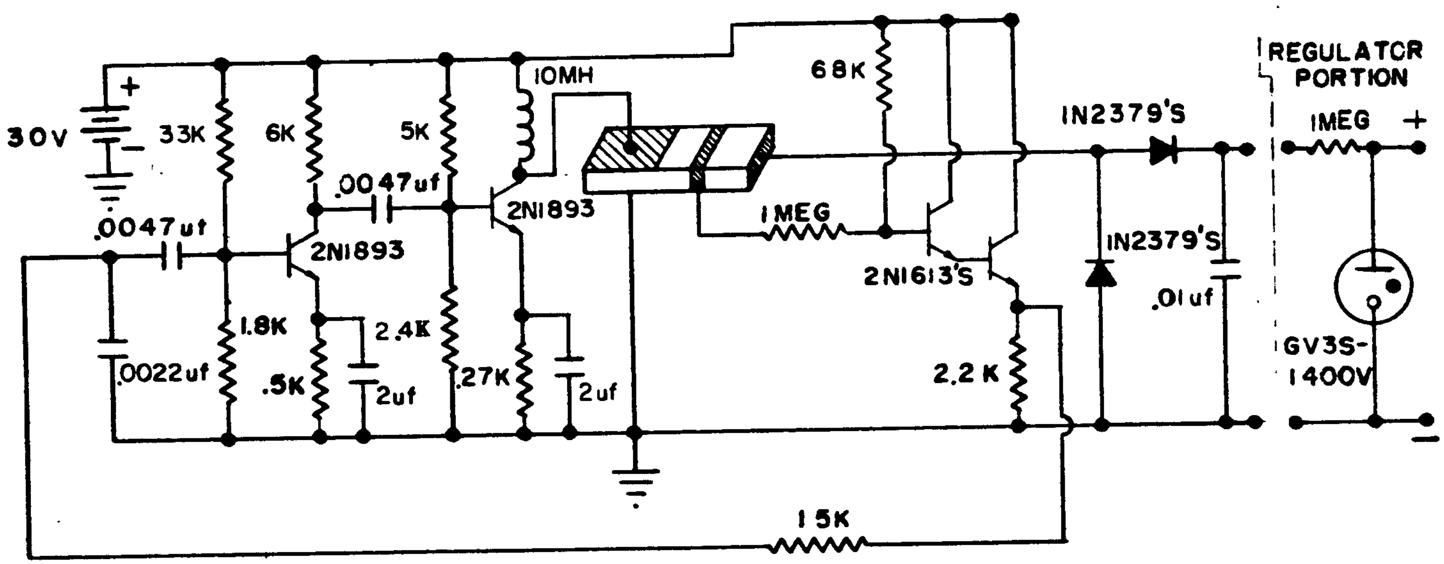

Figure 10. Nonmagnetic dc-to-dc converter.

properties of the two bars, apparently acting as two unequal batteries or generators in parallel. The resonant frequency of the parallel-connected pair was slightly lower than that of either unit when measured singly.

This shift in resonant frequency may be explained by considering the effects of loading on the operation of piezoelectric transformers. The resonance of a piezoelectric transformer is an inherent feature of the body itself in that it is a function of the dimensions and the properties of the material only. When an external load is placed on the unit, whether mechanical, electrical, or thermal, the properties of the body are altered and a change in resonance results; the increase or decrease in resonant frequency depends upon the type of load and the manner in which it is applied. In the case of the two bar transformers of slightly different properties, a parallel connection initiates mutual loading and results in a slight drop in each individual resonance, but both resonances continue to exist. The combined output impedance is lower, since they are operating in parallel, but the output of each individual transformer is slightly reduced.

4.4 High-Voltage Converter Employing a Ceramic Transformer

A practical circuit configuration for transforming 28-to-30 v dc to 2200 v dc using a transverse ceramic transformer is shown in figure 10. A barium titanate ceramic bar having the following dimensions was used:

Overall length $L + L'$	: 9.0 cm
Overall width	: 1.3 cm
Overall thickness T	: 0.25 cm
Input capacitance	: 2150 pf approx
Output capacitance	: 7 pf approx
Resonant frequency	: 26 kc

Since the input voltage must be furnished at the frequency of transformer resonance, an amplifier with feedback from the tapped output voltage was used to maintain optimum drive frequency. A two-stage emitter follower in the feedback loop is used for impedance matching. A 10-mh rf coil (air core) is used in the collector circuit of the driver stage to provide a large voltage swing to the input of the ceramic transformer.

Rectification is provided by two diodes, operating through the output capacitance of the transformer in a voltage doubler circuit. Balanced rectifier circuits (full-wave bridge, voltage doubler, etc) are recommended since no direct current can flow through the transformer output terminals.

The converter output voltage as a function of input voltage at two fixed loads is shown in figure 11. There is a decrease in amplification as the input is increased. Figure 12 shows the voltage amplification as a function of load resistance.

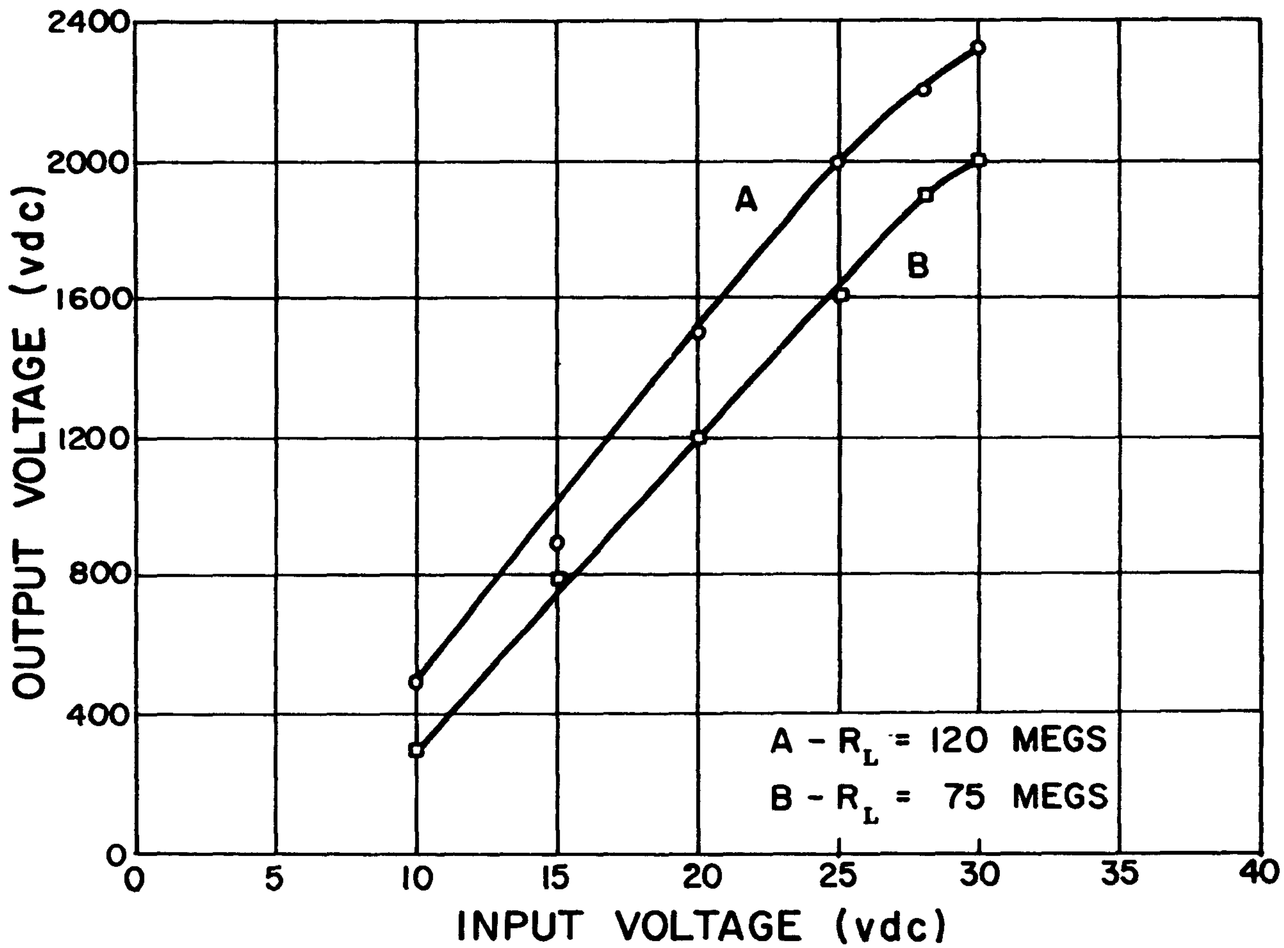

Figure 11. Converter output voltage vs. input voltage (F_R = 26 kc)

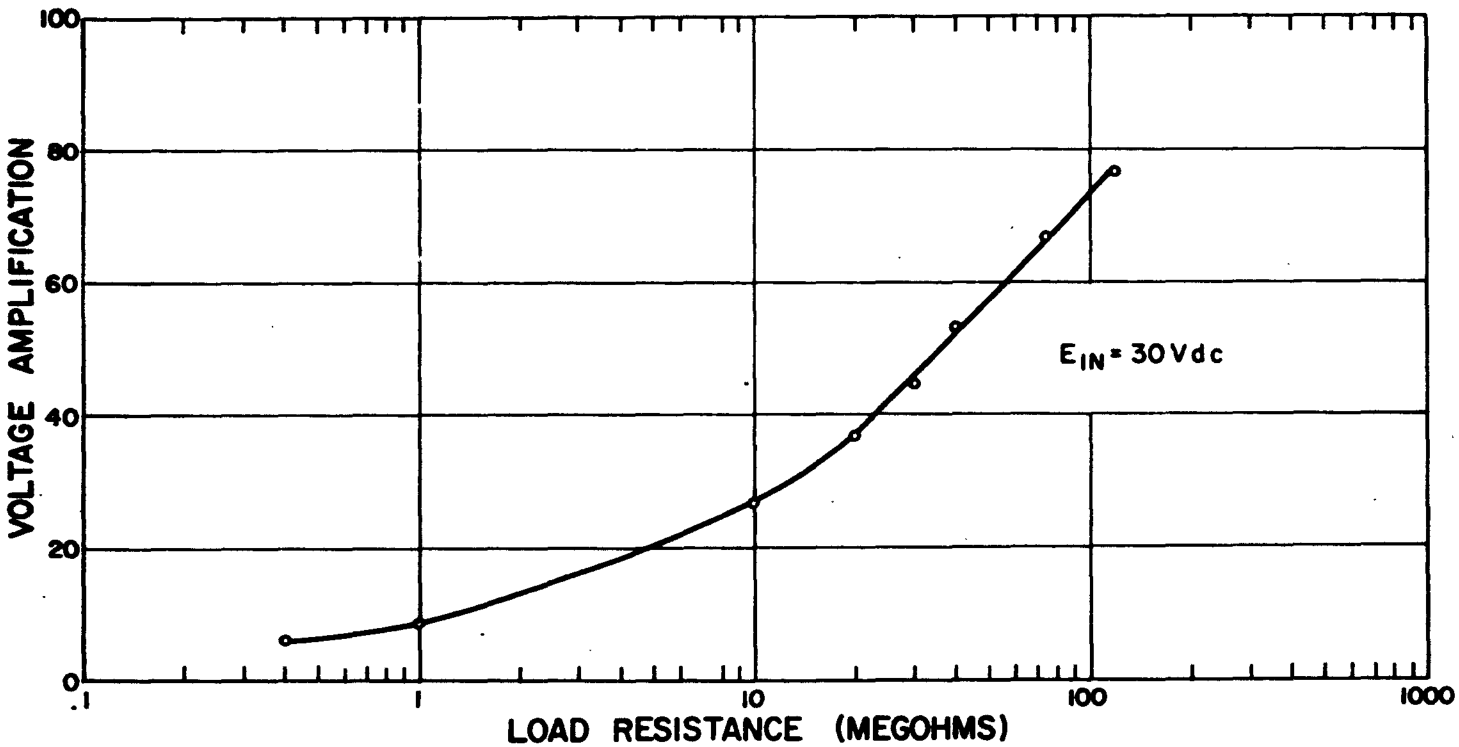

Figure 12. Voltage amplification versus load resistance F_R = 26 kc.

The performance of the converter at temperatures from -35 to +80°C is shown in figure 13. The results of tests made with the major converter components inside a temperature chamber and the transformer outside indicate that the observed output voltage variations are mostly attributable to the transformer. The temperature characteristics of ceramic transformers were found to agree well with data reported by General Electric.

A simple voltage regulator, using a Victoreen GV3S 1400-v tube, was used to compensate for these temperature-induced variations. This tube is of very rugged construction and requires only 3 μa to initiate regulation. The performance of the voltage-regulated converter as a function of temperature is shown in figure 14. However, these results were achieved at the expense of about 30 percent of the total output voltage.

The ceramic transformer was operated continuously for 3600 hr to determine its stability of output voltage with time. During this period, the unregulated output voltage remained within a 25-v range. Little or no change in the operating frequency was observed for this period and several weeks of intermittent operation. General Electric reports operation of a ceramic transformer for several weeks with no substantial change in output voltage and frequency.

5. DISCUSSION

The ceramic transformer provides an effective means of transforming voltage and current, with corresponding changes in impedance level, at frequencies as high as several hundred kilocycles per second. Its operation takes place through the interaction of mechanical vibrations and alternating electric fields. The ceramic transformer is best suited for operation at high-voltage, low-current levels, the requirement for devices such as cathode-ray and Geiger-Mueller tubes. Flyback type pulse transformers and resonant rf transformers require many well insulated turns of wire for their operation at high output voltages. Therefore, ceramic transformers are potentially attractive for these application when size, simplicity, and absence of high-voltage winding are prime considerations.

At present the most serious limitation with ceramic transformers is the rapidly increasing loss of power when they are operated at very high levels. It has been found empirically by Katz and General Electric that the losses become prohibitive when the generated field strength exceeds 500 v (rms)/in., averaged over the length of the generating portion of the transformer. The rise in temperature caused by operation beyond this limit causes depolarization of those areas subjected to the largest vibrational or electrical strains.

6. SUMMARY

The design of a high-voltage converter employing a ceramic transformer has been demonstrated. The device operates well over a wide temperature range and for periods of several weeks. Its use is particularly recommended in equipment for making magnetic field measurements, or in devices that are easily disturbed by strong magnetic fields.

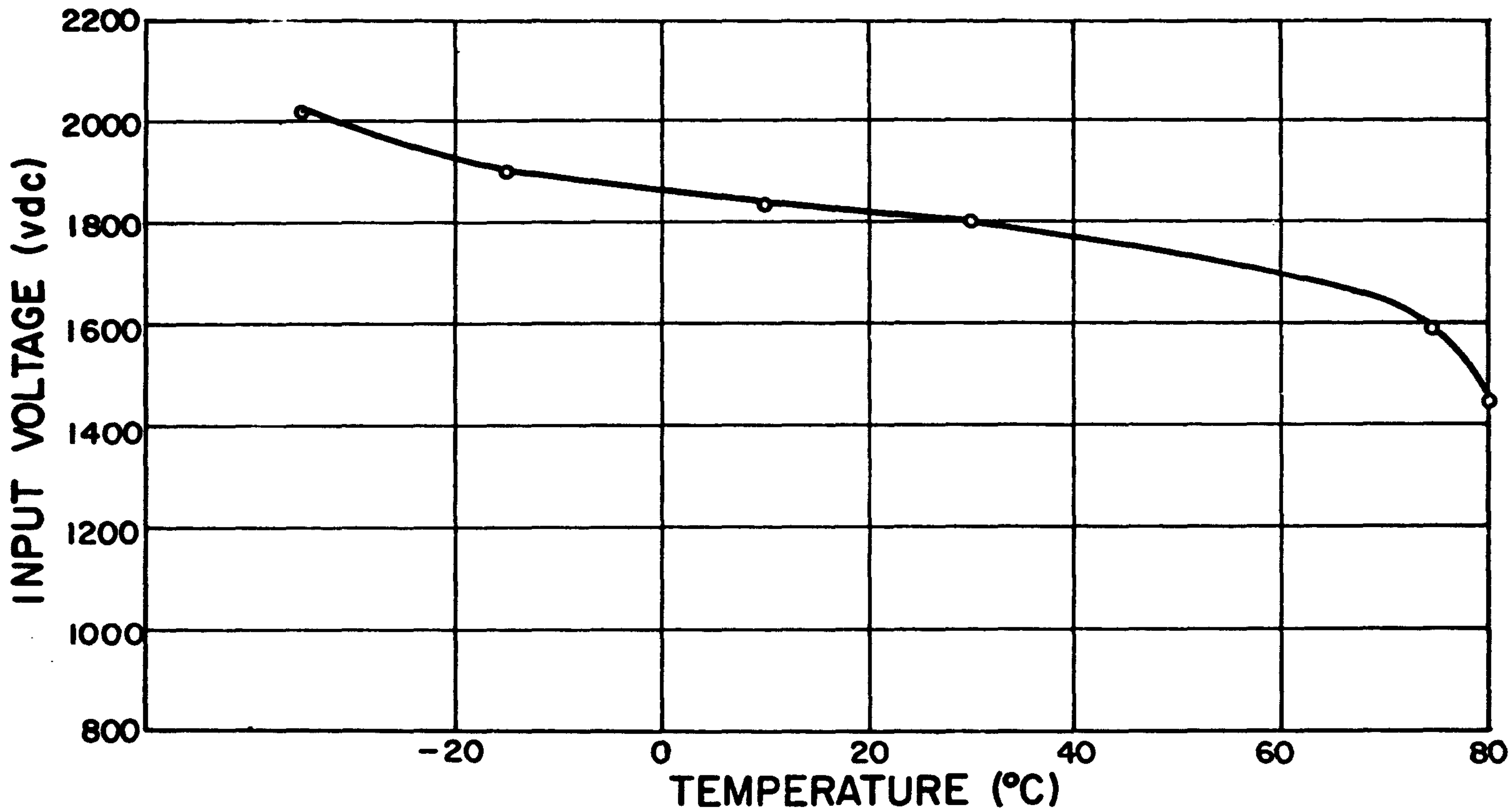

Figure 13. Output voltage vs. temperature for ceramic transformer converter.

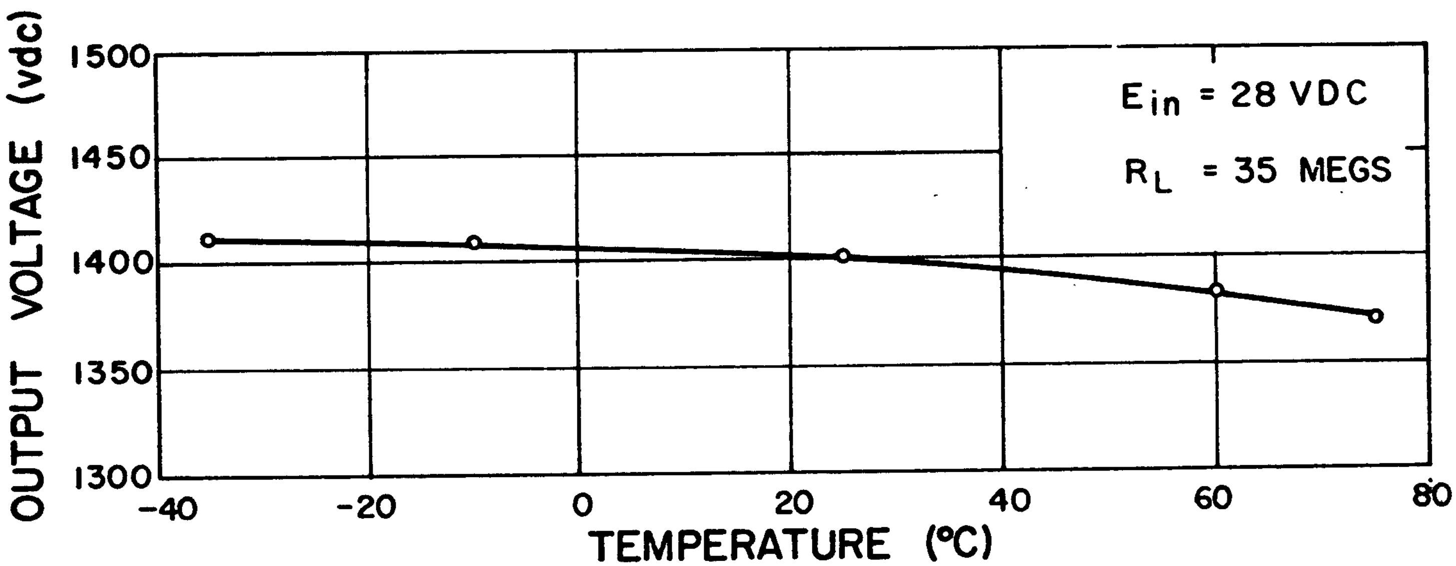

Figure 14. Converter regulated output vs. temperature.

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Ceramic transformers

Transistorized converters

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A transistorized dc-to-dc converter has been designed using a ceramic transformer. This converter is particularly adaptable to equipment used in measuring magnetic fields. The ceramic transformer provides further advantages of reduced size and complexity over fly-back type pulse and resonant rf transformers, which require the use of many turns of well insulated wire.
A prototype model, built to convert 28 v dc to 2200 v dc at 20 μa, operates satisfactorily from - 35°C to 75°C and shows no substantial change in output after continuous operation for 3600 hr.
Included is a procedure for the design of a transverse transformer showing the voltage amplification to be a function of piezoelectric coefficients and transformer geometry.

Ceramic transformers

Transistorized converters

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REMOVAL OF EACH CARD WILL BE NOTED ON INSIDE BACK COVER, AND REMOVED CARDS WILL BE TREATED AS REQUIRED BY THEIR SECURITY CLASSIFICATION.