THIRD QUARTERLY REPORT

FOR

HIGH POWER, HIGH VOLTAGE, AUDIO FREQUENCY TRANSFORMER DESIGN MANUAL

THIS REPORT COVERS THE PERIOD JANUARY 1, 1963 TO MARCH 31, 1963

NAVY DEPARTMENT BUREAU OF SHIPS ELECTRONICS DIVISIONS

CONTRACT NUMBER NObsr 87721, PROJECT SERIAL NO. SR-008-08-02, TASK 9599

GENERAL ELECTRIC

HIGH VOLTAGE SPECIALTY TRANSFORMER SECTION

HOLYOKE, MASS.

COPY No. 18

INTERIM DEVELOPMENT REPORT
FOR
HIGH POWER, HIGH VOLTAGE, AUDIO FREQUENCY TRANSFORMER
DESIGN MANUAL

THIS REPORT COVERS THE PERIOD 1/1/63 TO 3/31/63

GENERAL ELECTRIC

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HOLYOKE, MASSACHUSETTS

NAVY DEPARTMENT BUREAU OF SHIPS ELECTRONICS DIVISION

CONTRACT NUMBER NObsr 87721, PROJECT SERIAL NO. SR-008-08-02, TASK 9599

APRIL 1, 1963

PURPOSE

The purpose of this project is the investigation, presentation, and verification of data and design methods used to design high power, high voltage, audio frequency transformers. Ratings of these transformers fall within the following characteristics:

(a) Peak power levels from 15 to 350 kilowatts.

(b) Operating frequencies from 20 cps to 20,000 cps.

(c) Peak voltage ratings from 4,000 volts to 28,000 volts.

(d) Impedance levels of 300 to 3,000 ohms primary and 10 to 1,200 ohms secondary.

The scope of this work includes a thorough discussion of the mechanical and packaging aspects of the design, the insulation materials and processing of those materials, and the electrical and magnetic characteristics of audio frequency transformers.

ABSTRACT

During the Third Interim Period, two internal reports were released, and are included in this report. They are:

EXHIBIT I - Design parameters for insulation for 105 C and 130 C hot spot transformer designs.

EXHIBIT 2 - Calculation methods for determining frequency response of various equivalent circuits.

Progress on Milestones 6, 9 and 10 is described. Included are heat transfer studies of the fluorogases, dielectric tests of the transformerettes with various gaseous media and conditions, and accelerated aging tests of class H materials.

IDENTIFICATION OF PERSONNEL

1. Personnel working on this contract during the period covered by this report are as follows:

John G. Howe Design Engineer Material Components and Mechanical Design	204 hours
R. D. Smith Design Engineer High Frequency Transformers	151 hours
J. J. Kingsley Specialist	370 hours
R. E. Gearhart Transformer Engineer	515 hours

2. During the period covered by this report, the following people were contacted:

Mr. Harold Lord Electronic Engineer	Research Laboratory General Electric Co.
Mrs. Nancy D. Fitzroy Heat Transfer Engineer	Advanced Technology Laboratories General Electric Co.

DISCUSSION - INSULATION AND MECHANICAL WORK DONE DURING THE THIRD INTERIM PERIOD

1. Milestone #4 - This milestone was completed and is included as exhibit #1 of this report.

2. Milestone #6 - This milestone, which was originally scheduled for completion by May 1, 1963, will be approximately four weeks late due to a manpower shortage. It will still be completed, however, within the fourth quarterly report period as was originally planned. This milestone is a compilation of established technical information. Only a small amount of additional data will be added in the form of heat run results on oil filled transformerettes. This is mainly for comparison purposes with other major insulation systems such as gas and silicone oil.

3. Milestone #9 - This milestone concerning components and mechanical design has only slightly progressed during the third quarterly period. Sample high temperature, feedthrough bushings for the hermetic sealing of gas insulated transformers have been made by interested vendors. One vendor's samples (Alberox, Inc. of New Bedford, Mass.) have been tested with promising results. These bushings have been made to High Voltage Specialty Transformer design and were returned to the vendor for slight modification which should make them corona free at values close to the bushing withstand voltage.

   A typical high temperature blower with motor power suitable for high gas density was purchased. This fan is being used in heat runs for comparison of forced convection with natural convection. This work will be included in milestone #10.

4. Milestone #10 - Three phases of work pertaining to this milestone have progressed during the third interim period:

   a. heat transfer of gases
   b. evaluation of transformerettes
   c. life testing of various solid insulations to be used in conjunction with silicone fluids and fluorogases (C_2F_6)

   Using two transformerettes, twenty different conditions of ambient temperature, major insulation, and convection were run to stabilization. The data obtained clearly shows:

   a. the higher heat transfer at higher ambient temperatures of all insulation systems.

b. the improvement of natural convection fluorogas heat transfer over air by a factor of approximately 2:1.

c. the slight advantage of heavier fluorogases over lighter fluorogases since increased density outweighs slightly inferior specific heat.

d. the higher heat transfer of forced convection over natural convection by a factor of approximately 2:1.

e. the heat transfer with forced convection fluorogas is the same order as that with natural convection transformer oil.

f. the hot spot rise obtained with natural convection gas is of the order of magnitude that would indicate a class H (180°C) operating temperature of similar power density resulted in a natural oil convection class A (105°C) unit. This is important because it bears out the theory that normal transformer packaging including copper and iron densities resulting in reasonable regulation and exciting current can be accommodated by class A oil or class H gas both with natural convection. This subject is covered in detail in milestones #6 and #10.

g. the improvement gained by higher filling gas pressure (higher density).

Dielectric tests were run on several complete transformerettes with different filling gases and densities. The data obtained clearly shows the improvement obtained by using a heavier gas or a higher density. The results were in all cases recorded as corona start voltage of the complete transformerette. The data is not too conclusive, however, because it seems to be the corona start voltage of the smallest diameter connecting lead in the transformerette as would be expected from basic dielectric theory. This prohibits the determination of the corona start voltage of the windings themselves. Even at this early stage of investigation, however, the corona start levels are up above 20 KV or near the limit of the working voltages covered by the contract.

Life studies have been started on proposed class H materials for use with the silicone fluids or fluorogases. Samples of asbestos-silicone, glass-silicone, glass polyester, and terephthalate polyester (Kodar*) have been aged in C_2F_6 and silicone fluid (GE SF97) for periods of up to four weeks at 230°C and 260°C. The results obtained so far have been dissapointing as they show that manufacturer's expectations for some of these materials have been optimistic. At this point, it can be

*Eastman Kodak trademark

clearly seen that Kodar itself is not a suitable class H material, nor is the glass polyester material (fabrithem*). In addition, (and more surprising), the glass silicone fabric which is being tested (General Electric #76511) also has shown very poor performance at 230 and 260°C.

By far, the best material tested so far has been the silicone-asbestos composite which, although the additional dielectric strength is low, maintains a constant dielectric strength irregardless of time of exposure to C_2F_6. In silicone fluid, the dielectric strength increases to ten times its original and continues steadily at this value due to the impregnation by the fluid.

Much additional work is needed on this subject which is extremely important since it is possible to build units with any of these inferior solid materials which could pass initial short time acceptance tests, but would deteriorate and fail after extended service.

5. Dielectric Strength vs. Frequency

Much searching of past literature was done to obtain information on the effect of frequency on dielectric strength. Very little information was obtained except for the repeated findings by independent investigators that if corona (internal or external discharges) is present, the life of the material will be shortened inversely proportional to the frequency. In other words, life will be dependent upon the number of cycles the insulation is exposed to. For this reason, high frequency has been proposed for accelerated life testing of solid insulations. However, since good design precludes any corona internal or external to the insulation structure, there is very little published information showing the effect of frequency on critical corona start gradients. For this reason, a high frequency transformer previously designed by the High Voltage Specialty Transformer Section is being built. It will be used in conjunction with the high frequency generator to determine the effect of high frequency on corona start voltages and gradients.

*General Electric Trademark

GENERAL ELECTRIC CO.

PROJECT PERFORMANCE AND SCHEDULE

PROJECT SERIAL NO. SR 008-03-02 TASK 9599

Contract No. NObsr-87721 Date: March 31, 1963

Period Covered: 1/1/63 to 3/31/63

Legend

■ - Work performed

▭ - Schedule of Projected Operation

Estimated completion in percent of total effort expected to be expended (not chronological)

	% As Of Jan. 1	% As Of March 31
1. Inductance and capacitance calc.	100	100
2. Selection of insulation system	100	100
3. Winding arrangements	75	100
4. 105 C cooling and insulation	50	100
5. Frequency response	0	80
6. 130 C cooling and insulation	25	40
7. Core and copper losses	0	0
8. Complete sample designs	0	0
9. Mechanical design	10	20
10. 200 C cooling and insulation	30	50
11. Build sample units	0	0
12. Test sample units	0	0
13. Final report	0	0

GENERAL ELECTRIC COMPANY

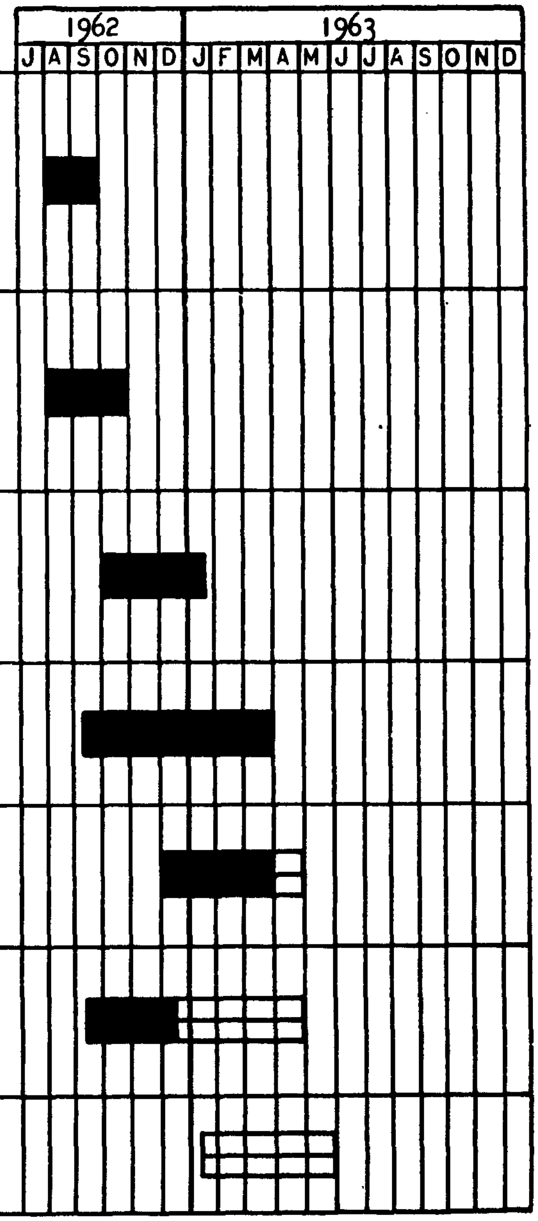
PROJECT PERFORMANCE AND SCHEDULE

PROJECT SERIAL NO. SR 008-03-02 TASK 9599

CONTRACT NO. NOBSR-87721 DATE: MARCH 31, 1963

PERIOD COVERED 1/1/63 TO 3/31/63

Milestone
MILESTONE 1 PROCEDURE COVERING DESIGN PRACTICE FOR CALCULATING: (A) DISTRIBUTED CAPACITANCE (B) LEAKAGE INDUCTANCE (C) OPEN CIRCUIT INDUCTANCE
MILESTONE 2 PROCEDURE STATING CHOICE OF MATERIALS FOR INSULATION SYSTEMS FOR 105, 130 AND 200 C HOT SPOT TRANSFORMER DESIGNS AFTER HAVING COMPLETED LITERATURE SURVEY AND STATE OF ARE REVIEW.
MILESTONE 3 PROCEDURE COVERING WINDING ARRANGEMENTS AND DESIGN FORMULAE FOR CALCULATION OF DISTRIBUTED CAPACITANCE AND LEAKAGE INDUCTANCE FOR THESE WINDING ARRANGEMENTS.
MILESTONE 4 PROCEDURE COVERING DESIGN PARAMETERS FOR INSULATION FOR 105 C AND 130 C HOT SPOT TRANSFORMER DESIGNS.
MILESTONE 5 PROCEDURE COVERING CALCULATION METHODS FOR FREQUENCY RESPONSE OF VARIOUS EQUIVALENT CIRCUITS.
MILESTONE 6 PROCEDURE COVERING DESIGN PARAMETERS FOR COOLING FOR 105 C AND 130 C HOT SPOT TRANSFORMER DESIGNS.
MILESTONE 7 PROCEDURE COVERING PROCEDURE FOR CALCULATING CORE AND COPPER LOSSES.



GENERAL ELECTRIC COMPANY

PROJECT PERFORMANCE AND SCHEDULE

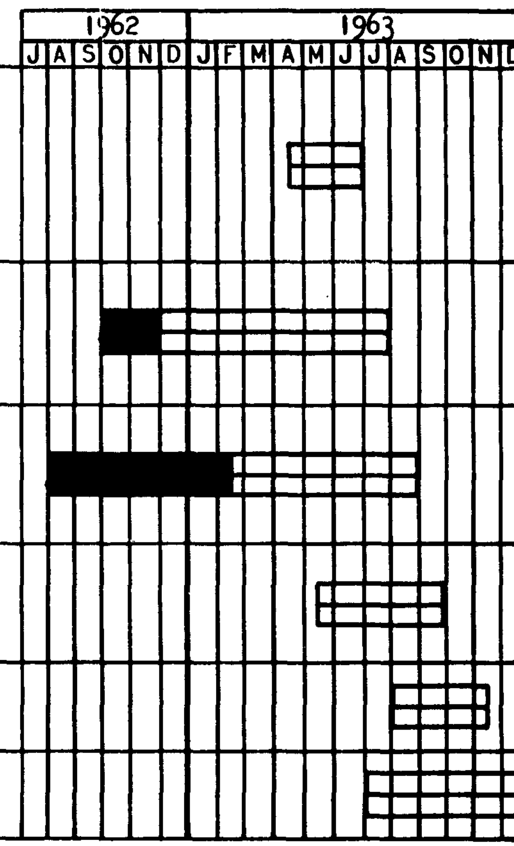
PROJECT SERIAL NO. SR 008-03-02, TASK 9599

CONTRACT NO. NOBSR-87721

DATE: MARCH 31, 1963

PERIOD COVERED: 1/1/63 TO 3/31/63

Milestone
MILESTONE 8 COMPLETE DESIGN (ENGINEERING AND DRAFTING) AND RELEASE TO MANUFACTURING SECTION OF HOLYOKE G.E. FOR MANUFACTURE OF THREE VERIFICATION UNITS.
MILESTONE 9 PROCEDURE COVERING MECHANICAL DESIGN PARAMETERS AND COMPONENT SELECTION FOR 105, 130 AND 200 C HOT SPOT TRANSFORMER DESIGN.
MILESTONE 10 PROCEDURE COVERING DESIGN PARAMETERS FOR INSULATION AND COOLING FOR 200 C AND CALCULATION FORMULAE FOR WINDING RISE.
MILESTONE 11 BUILD VERIFICATION UNITS AND START TO TEST AREA FOR TEST.
MILESTONE 12 ISSUE TEST REPORT ON VERIFICATION UNITS.
MILESTONE 13 COMPLETE PROJECT - MANUAL TO PRINTER.



GENERAL ELECTRIC CO.

PROJECT PERFORMANCE AND SCHEDULE (REVISED)

PROJECT SERIAL NO. SR 008-03-02 TASK 9599

Contract No. NObsr-87721 Date: March 31, 1963

Period Covered: 1/1/63 to 3/31/63

Legend

- Work performed
- Schedule of Projected Operation

Estimated completion in percent of total effort expected to be expended (not chronological)

	% As Of Jan. 1	% As Of March 31
1. Inductance and capacitance calc.	100	100
2. Selection of insulation system	100	100
3. Winding arrangements	75	100
4. 105 C cooling and insulation	50	100
5. Frequency response	0	70
6. 130 C cooling and insulation	25	30
7. Core and copper losses	0	0
8. Complete sample designs	0	0
9. Mechanical design	10	15
10. 200 C cooling and insulation	30	40
11. Build sample units	0	0
12. Test sample units	0	0
13. Final report	0	0

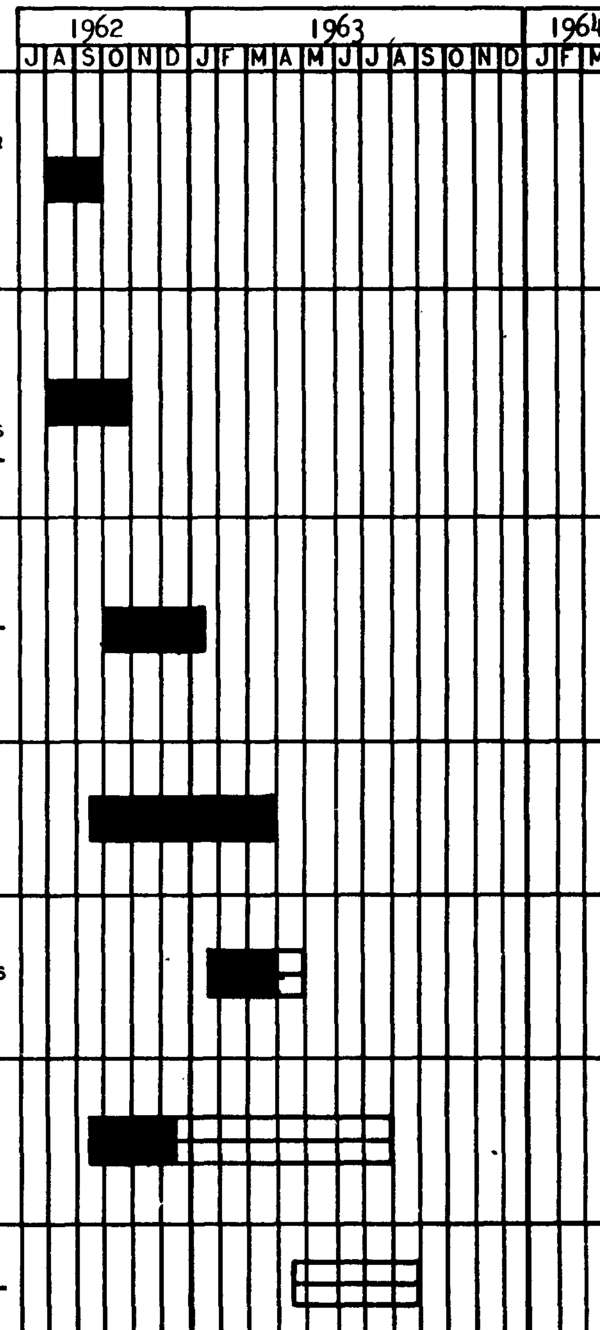
GENERAL ELECTRIC COMPANY

PROJECT PERFORMANCE AND SCHEDULE (REVISED)

PROJECT SERIAL NO. SR 008-03-02 TASK 9599

CONTRACT NO. NOBSR-87721 DATE: MARCH 31, 1963

PERIOD COVERED: 1/1/63 TO 3/31/63



MILESTONE 1

PROCEDURE COVERING DESIGN PRACTICE FOR CALCULATING:
(A) DISTRIBUTED CAPACITANCE
(B) LEAKAGE INDUCTANCE
(C) OPEN CIRCUIT INDUCTANCE

MILESTONE 2

PROCEDURE STATING CHOICE OF MATERIALS FOR INSULATION SYSTEMS FOR 105, 130 AND 200 C HOT SPOT TRANSFORMER DESIGNS AFTER HAVING COMPLETED LITERATURE SURVEY AND STATE OF ART REVIEW.

MILESTONE 3

PROCEDURE COVERING WINDING ARRANGEMENTS AND DESIGN FORMULAE FOR CALCULATION OF DISTRIBUTED CAPACITANCE AND LEAKAGE INDUCTANCE FOR THESE WINDING ARRANGEMENTS.

MILESTONE 4

PROCEDURE COVERING DESIGN PARAMETERS FOR INSULATION FOR 105 C AND 130 C HOT SPOT TRANSFORMER DESIGNS.

MILESTONE 5

PROCEDURE COVERING CALCULATION METHODS FOR FREQUENCY RESPONSE OF VARIOUS EQUIVALENT CIRCUITS.

MILESTONE 6

PROCEDURE COVERING DESIGN PARAMETERS FOR COOLING FOR 105 C AND 130 C HOT SPOT TRANSFORMER DESIGNS.

MILESTONE 7

PROCEDURE COVERING PROCEDURE FOR CALCULATING CORE AND COPPER LOSSES.

GENERAL ELECTRIC COMPANY

PROJECT PERFORMANCE AND SCHEDULE (REVISED)

PROJFCT SERIAL NO. SR 008-03-02 TASK 9599

CONTRACT NO. NOBSR-87721 DATE: MARCH 31, 1963

PERIOD COVERED: 1/1/63 TO 3/31/63

Milestone	Description
MILESTONE 8	COMPLETE DESIGN (ENGINEERING AND DRAFTING) AND RELEASE TO MANUFACTURING SECTION OF HOLYOKE G.E. FOR MANUFACTURE OF THREE VERIFICATION UNITS.
MILESTONE 9	PROCEDURE COVERING MECHANICAL DESIGN PARAMETERS AND COMPONENT SELECTION FOR 105, 130 AND 200 C HOT SPOT TRANSFORMER DESIGN.
MILESTONE 10	PROCEDURE COVERING DESIGN PARAMETERS FOR INSULATION AND COOLING FOR 200 C AND CALCULATION FORMULAE FOR WINDING RISE.
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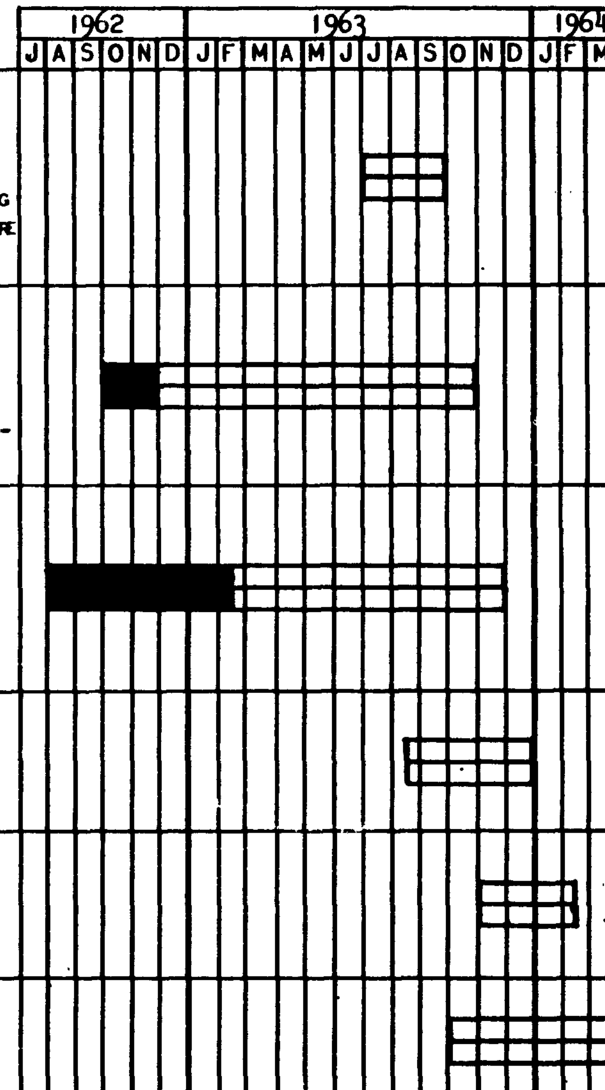


WORK PLANNED FOR THE FOURTH INTERIM PERIOD

Insulation and Mechanical

1. Complete milestone #6 on the cooling for oil-filled 105 and 130°C hot spot designs.

2. Continue milestones #9 and #10.

3. Continue evaluation of and search for suitable class H solid insulations for use with fluorogases and silicone fluids.

4. Determine effect of frequency on insulation dielectric strength and corona start voltages using the newly acquired high frequency generator and high voltage transformer.

Electrical

The high power audio frequency generator needed to start work on milestone report #7 was received on April 16 and is presently being installed in the engineering laboratory.

During the fourth interim period, the following is planned:

5. Complete milestone report #5 in time to be included as Exhibit 2 of this report.

6. Start work on milestone #7. Model cores and coils will be built and tests started to determine the core and copper losses.

7. Continue to work on distortion calculations and measurements. Although distortion has not been included in any milestone schedule, it is felt that it should be covered in the overall report. For this purpose, sample coils have been built and are being tested in an audio amplifier circuit.

8. It is intended to compare shielded and unshielded windings in order to more clearly define their effect on frequency response and distortion. As time permits, work will be started on designing model coils for this purpose.

EXHIBIT I

MILESTONE REPORT #4

FOR

HIGH POWER, HIGH VOLTAGE, AUDIO FREQUENCY TRANSFORMER

DESIGN MANUAL

DESIGN PARAMETERS FOR INSULATION MATERIALS TO BE USED FOR HIGH POWER AUDIO TRANSFORMERS

NAVY DEPARTMENT BUREAU OF SHIPS ELECTRONICS DIVISION

CONTRACT NUMBER NObsr 87721, PROJECT SERIAL NO. SR-008-08-02, TASK 9599

GENERAL ELECTRIC

HIGH VOLTAGE SPECIALTY TRANSFORMER SECTION

HOLYOKE, MASS.

INSULATION GENERAL

Insulation, as applicable to this report, denotes a classification of materials, gases, solids, liquids that are relatively poor conductors of electric current.

The function of insulating materials within the scope of this report is to maintain electrical isolation between two or more electrical conducting members. However, as mechanical, chemical, thermal, and cost factors are considerations of any transformer design, it is not possible to consider only the electrical parameters of insulation structures.

Insulation materials are subject to degradation electrically and mechanically under certain conditions. A comprehension of the causes of the functional deterioration of insulations is paramount, because the useful life of a transformer is dependent upon how the insulation material is used during the transformer life.

Before proceeding with a discussion of the sundry properties and design parameters of the various dielectrics, a general review of the electrical factors relating to the application of the insulations is in order.

1. Dielectric Strength

   The dielectric strength of an insulation is the average maximum potential gradient that the material can withstand without rupture. This value can be expressed as the potential across the specimen in volts or as the potential gradient (rupture voltage divided by material thickness.)

   Numerical values of dielectric strength provide a useful tool for use in the comparison of materials, for specifying materials, and as a design criteria. Material comparison is probably the most important use that can be made of the values of dielectric strength. To be useful for comparative purposes, however, the dielectric testing of various materials should be accomplished using standard conditions and procedures (See ASTM).

   Although all insulations inherently possess dielectric strength, the determination of what strength value is required for design application is extremely difficult to assay because of the multitude of variables that affect the insulation life in service.

   Rate of voltage application, uniformity of electric field, moisture content, insulation aging characteristics and other factors have a pronounced influence on the property of dielectric strength.

2. Electric Field

By definition, an electric field is any region in which a stationary electric test charge Qt would experience a force if placed there.

Insulations in application are rarely placed in uniform electric fields, but rather by necessity are frequently located in fields distorted by electrode edge effects or ground points. Non uniform fields subjects the dielectrics to localized electric field strengths in excess of the average electric field strength.

This concentration of potential gradient usually occurs at the conductor surface at locales of sharp edges, irregularities of conductor surfaces. Ionization occurs at these points of concentrated potential gradient, manifesting itself in what is commonly known as corona.

The calculation of the maximum voltage gradient for many electrode configurations is either analytically impossible or too burdensome for practical use. However, many common electrode configurations lend themselves too readily to an analytical solution of the maximum voltage gradient.

A derivation of the maximum voltage gradient for a coaxial cable (concentric cylinders) is shown as follows: **Table 1 lists values for various electrode configurations.**

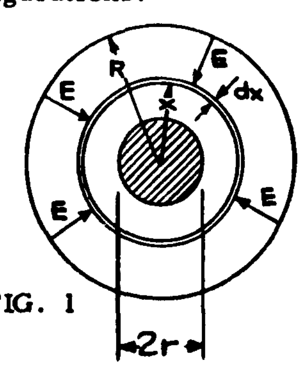


FIG. 1

E = Electric intensity = $\left.\frac{dv}{dx}\right]$ max.
V = Potential drop
A = Area
ψ = Electric flux
D = Density of electric flux = ψ/A
ϵ_o = Permittivity of free space.
ϵ_r = Relative permittivity of the medium
$\epsilon = \epsilon_o \epsilon_r$

Considering cylinder of radius x :

$$\psi = \int (D \cos \theta)\, da$$

as the flux lines are directed radially from the cylinder surfaces; $\theta = 90°$

$$\psi = \int (D \cos 90°)\, da = D \int 2\pi\, dx = D\, 2\pi x$$

(1) $\psi = D\, 2\pi x$

$D = \epsilon_0 \epsilon_r E = \epsilon E$

(2) $E = \dfrac{\psi}{\epsilon 2\pi x}$ FROM EQUATION (1)

$$E = \left.\frac{dv}{dx}\right]_{max}$$

$$V = \int_{x=r}^{x=R} E \cos(\phi)\, dx$$

WHERE ϕ IS THE ANGLE BETWEEN E DIRECTION AND DIRECTION OF THE x PATH

$$V\Big]_{x=r}^{x=R} = \int_r^R (E_x \cos 180°)\, dx = \int_r^R \frac{\psi}{\epsilon 2\pi x}(-1)\, dx$$

$$= -\frac{\psi}{\epsilon 2\pi} \int_r^R \frac{dx}{x} = -\frac{\psi}{\epsilon 2\pi} \ln \frac{R}{r}$$

NOW $V\Big]_{x=R}^{x=r} = -V\Big]_{x=r}^{x=R} \therefore V\Big]_{x=R}^{x=r} = -\left(-\dfrac{\psi}{\epsilon 2\pi} \ln \dfrac{R}{r}\right)$

$$V\Big]_{x=R}^{x=r} = \frac{\psi}{\epsilon 2\pi} \ln \frac{R}{r}$$

(3) $V = \dfrac{\psi}{\epsilon 2\pi} \ln \dfrac{R}{r}$

FROM EQUATION (2) $\psi = E \epsilon 2\pi x$

FROM EQUATION (3) $\psi = \dfrac{V \epsilon 2\pi}{\ln \frac{R}{r}}$

$$\therefore E \epsilon 2\pi x = \frac{V \epsilon 2\pi}{\ln \frac{R}{r}}$$

(4) $E = \dfrac{V}{x \ln \frac{R}{r}}$

NOW E = MAX. WHEN x = r THEREFORE THE MAXIMUM VOLTAGE GRADIENT OCCURS AT x = r SO EQUATION (4) BECOMES

(5) $E_{max.} = \dfrac{V}{r \ln \frac{R}{r}}$

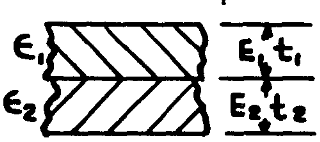
3. Dielectric Constant (Permittivity)

The dielectric constant is that property of a dielectric which determines the electrostatic energy stored per unit of volume per unit potential gradient.

The permittivity of a vacuum is unity in the electrostatic system unit. If a capacitor, with a vacuum capacitance of C_0 and the dielectric constant of ϵ_0 is filled with some substance with a real dielectric constant of ϵ' then the capacitor will increase its capacitance to: $C \doteq C_0 \frac{\epsilon'}{\epsilon_0}$ where ϵ' and ϵ_0 are the real permittivities (dielectric constants) of the dielectric material and vacuum respectively. The ratio of ϵ'/ϵ_0 is the relative dielectric constant, ϵr of the material.

Although, by definition, the relative dielectric constant is based on the dielectric constant of a vacuum, it is common to use dry air as the relative base as dry air has a permittivety of only 1.00058 at one atmosphere pressure, $0^{\circ}C$. It is more convenient to determine unknown dielectric constants using dry air as a base.

Insulating materials are used in a transformer to insulate electrical networks from each other and to ground. Frequently, different dielectric materials are used in series with each other, for example, oil and solids, gas and solids. In composite dielectric structures, the dielectric constants of the various materials becomes important. The A.C. voltage stress in the various dielectrics is inversely proportional to the respective dielectric constants.



E = Electric stress
t = Thickness
ϵ = Dielectric constant

(2) Dielectrics in series

(6) $$\frac{E_2}{E_1} = \frac{\epsilon_1/t_1}{\epsilon_2/t_2}$$

This relationship is such that the highest voltage stress appears across the material with the lowest permittivety. Unfortunately, the materials with the lower dielectric constants generally have lower dielectric breakdown strengths. Thus, for example, in a series insulation structure of transformer oil with $\epsilon r = 2.2$ and kraft pressboard with $\epsilon r = 4.5$, the stress on the oil in volts per unit thickness is about twice the stress on the solid; although the pressboard has a higher dielectric strength, therefore, as the stress is increased, failure will occur in the oil. **The numerical values of the permittivities of typical insulation materials are listed in Table 2 (Ref. 7).**

4. Dielectric Loss

All commercially used insulating materials consume power when subjected to a potential difference. The electrical behavior of a dielectric material corresponds to an equivalent parallel RC circuit. Figure (2) when the applied potential is A.C.

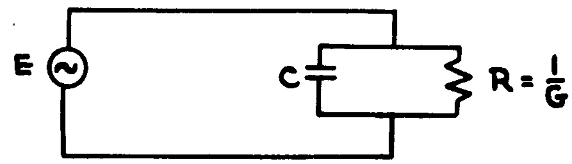


FIG. 2
EQUIVALENT PARALLEL CIRCUIT

Terms used to express dielectric loss are dissipation factor, power factor and dielectric loss factor.

A. Dissipation Factor

The dissipation factor (D) of an insulating medium is the ratio of the loss current, I_e, to the charging current I in the equivalent RC circuit, figure 2. This relationship is shown in figure 3.

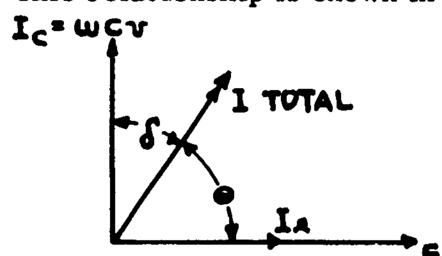


FIG. 3
CURRENT VECTOR DIAGRAM

(7) $D = \tan\delta = \frac{I_\ell}{I_c} = \frac{G}{wC} = \frac{1}{wRC}$

B. Power Factor

Power factor of a dielectric is a measure of the power loss within the material. In the capacitor analogy, it is the ratio of the watts dissipated in the capacitor, in which the insulating material is the capacitor dielectric, to the product of the applied sinusoidal voltage and effective amperes.

$$\text{Power Factor} = \frac{\text{losses in dielectric (watts)}}{\text{apparent power (volt-amperes)}}$$

The loss current I_e is in phase with the applied voltage, E, and in good dielectrics, its magnitude is small. The power factor is the cosine of angle θ the angle by which the total current leads the applied voltage E. In low loss dielectrics, the dissipation factor and the power factor are equivalent and with some slight error equals the tangent of δ, figure (3). The exact relationship of power factor and dissipation factor referring to figure 3 is as shown:

$$\cos\theta = \sin\delta$$

$$\cos\theta = \sin\delta \, \frac{\cos\delta}{\cos\delta}$$

$$\cos\theta = \frac{\tan\delta}{\sec\delta} = \frac{\tan\delta}{\sqrt{\sec^2\delta}}$$

$$\cos\theta = \frac{\tan\delta}{\sqrt{1 + \tan\delta}}$$

From equation (7) $\tan\delta = D$

$$\cos\theta = \frac{D}{\sqrt{1 + D^2}}$$

(8) $$\text{Power Factor} = \frac{D}{\sqrt{1 + D^2}}$$

In terms of the dissipation factor

(9) $$D = \frac{PF}{\sqrt{1 - (PF)^2}}$$

C. Dielectric Loss Factor

The loss factor of a dielectric ϵD, is the product of the dielectric constant, ϵ, and the dissipation factor D. It is proportional to the energy loss per cycle per required potential gradient per unit volume (ASTM)

5. Resistivity

With a D.C. potential impressed across an insulating material, current will flow because of the conductance of the dielectric. Resistivity is the reciprocal of the conductance, and it is expressed in two ways, volume resistivity or surface resistivity.

Volume Resistivity

Volume resistivity expresses the ratio of the direct current potential gradient, usually in ohms per centimeter, paralleling the current flow within the dielectric to the current density in amperes per square centimeter, after a prescribed time of voltage application, and under prescribed temperature and other conditions (ASTM)

Surface Resistivity

The surface resistivity of a dielectric is the resistance of the material per unit length and unit width, usually expressed as ohms per square.

6. Corona

Corona has been defined as a luminous discharge due to ionization of the air surrounding a conductor around which exists a voltage gradient exceeding a certain critical value (AIEE-35.60.125).

In insulation systems, however, the corona may not be limited to an environment of air, a luminous discharge or to a conductor surface. Today, then, any electrical field intensified ionization that is electrically detectable, is termed corona when it takes place in an insulation-electrode system.

Corona has many adverse effects on organic and inorganic materials that may result in a large reduction of transformer insulation service life. Most insulants will eventually break down when exposed to the ion bombardment produced by corona. In an air environment, corona produces ozone (O_3) and oxides of nitrogen. Ozone chemically affects most organic substances while the oxides of nitrogen in conjunction with moisture forms nitric and nitrous acids that may cause mechanical embrittlement of inorganic materials and other deleterious defects. Localized heating takes place within the insulation material because of the high current density of ionization. Gasification of the dielectric whether liquid or solid, takes place because of the excessive thermal gradients existing, which intensifies the ionization to a level generally referred to as corona. This ultimately manifests itself by the surface charring of solid dielectrics resulting in carbonized electrically conducting paths and ultimate equipment failure.

This intensified ionization occurs in gas filled voids and in bubbles located in areas of high electrical stress, such stress being lower than the permissable operational stress of the surrounding solid or liquid dielectric. The unequal distribution of potential stresses in a series composite insulation structure results from the differences in the permittivities of the materials; the stresses being inversely proportional to the permittivities. The permittivity of gases is much lower than that of dielectric solids or insulant liquids, therefore, the potential gradient will be higher in the gases than in the surrounding media.

Gases (air) are inherent in air insulated transformers, as the solids may be considered to be air impregnated, which limits the application of these transformers to the lower voltage levels because of the problems of corona around the 10KV level. Encapsulated transformers (epoxy, silicone rubber, varnishes, etc.) are likewise usually limited to approximately the same voltage levels as air insulated transformers. It is extremely difficult to successfully impregnate this type of transformer void free, therefore, the possibility is prevalent for gas voids to be in areas of high electrical stress resulting in a structure that is conducive to the inception of corona.

Completely void free insulation structures are obtainable with a liquid impregnated solid system. However, insulant oil impregnated solid structures are subject to corona degradation. Deterioration of the liquid and solid materials may occur as a result of a variety of processes that are discussed in some detail under insulation properties in this milestone. Gases can evolve in oil insulants and voids can be spontaneously formed by excessive electrical stresses, promoting the conditions for the formation of corona.

LIQUID DIELECTRICS

Liquid dielectrics are used in transformers usually in combination with solids as the major insulation structure. As such, they serve several purposes, namely, they function as a heat transfer medium, to dissipate internal heat generated within the transformer and they enhance the dielectric strength properties of the transformer assembly.

The most commonly used insulant liquids fall within the following classes:

Table 3

- Mineral petroleum oils
- Askarels
- Organic esters
- Vegetable oils
- Polyhydrocarbon liquids
- Fluorinated hydrocarbons
- Silicone oils

The milestone will cover a discussion on mineral oils and the askarels only. Organic esters and the vegetable oils are most commonly used as plasticizers in resin formulations and, therefore, are not within the intent of this milestone. The fluorinated liquids and silicone oils are employed in temperature applications above the 130°C hot spot temperature, and they, therefore, will be discussed under milestone #10.

Mineral oils are produced as the heavy distillate of crude petroleum, whereas, the askarels are synthetic non-flammable insulating liquids. The selection of using a mineral oil or an askarel as a transformer insulating liquid depends upon the factors of the liquid properties, the liquid environment, the physical size requirements of the transformer, and costs.

A detailed discussion of the properties of mineral oils and askarels ensues, followed by a discussion of the properties of the various solid dielectrics within the scope of this milestone.

Mineral Oils

Mineral oil is the most common insulant liquid in use for transformer application, usually as a liquid impregnant of a solid insulation system. The mineral oils are organic by nature, and they possess many characteristics which should be considered depending upon the particular use of the product. Table 4 lists the various properties of a light mineral oil in common use - General Electric Company type 10C*

Table 4

Average characteristics of type 10C* mineral oil:

Property	
Color	Clear
Viscosity (Saybolt seconds)@ 37.8°C	58
Specific gravity (15.5/15.5°C)	0.885
Burn point (open cup)	148°C
Flash point (open cup)	135°C
Pour point	-45°C
Dielectric strength K.V.	26-30
Dielectric constant 60 cycles 25°C	2.18
100°C	2.14
Power factor, 60 cycles, 100°C max.	0.3%
Resistivity (ohm-centimeter)	$30x10^{-12}$
Coefficient of expansion	.0008
Thermal conductivity-watts/in-°C	.0034

Three important electrical properties are conductivity, dielectric strength and the dielectric constant. Dielectric strength and conductivity property values are dependent on the amount of impurities present within the insulating oil, whereas, the dielectric constant depends upon the liquid's chemical composition, temperature, and the frequency of the applied potential.

1. Dielectric Strength

The dielectric strength test is a measure used for the detection of moisture and other deleterious contaminants in the transformer oil. The presence of contaminants is reflected by a decrease in the numerical value of the dielectric strength. However, a high value of dielectric strength does not positively indicate a freedom of contaminants.

A. Variables That Affect Dielectric Strength

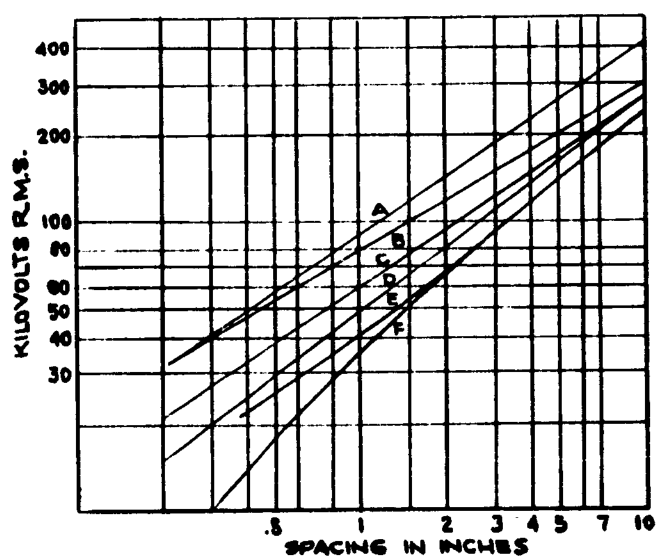
1. Electrode Shape - The uniformity of the applied electric field has a significant effect on the dielectric strength of an insulant oil. Standard electrodes used for the testing of transformer oils in this country are polished metal discs 1.00 inches diameter with square edges, mounted with the disc axes horizontal and with a gap spacing of 0.1 inches (ASTM-D-877-99).

Most commercially available transformer oils will have dielectric strength values ranging from 25 KV to 35 KV when tested to the prescribed arrangement above. The normal minimum acceptance

*Registered G.E. Trademark

test value is 22KV. Values below 17KV indicate that the oil is unsafe for transformer application.

2. Electrode Spacing - An increase in electrode spacing is generally reflected in a decrease in the dielectric strength. Empirically, the dielectric strength varies closely with the electrode spacing raised to the 2/3 power. This relationship does not hold true for all electrode shapes, and it definitely does not apply to near zero electrode spacing. Figure (4) shows the 60 cycle (1) minute dielctric strength of transformer oil at 25°C with various electrode shapes related to the electrode gap. Figure 5 depicts the dielectric strength of oil at small electrode spacings.



A - 2-3/8" DIAMETER RODS
B - 1/2" DIAMETER RODS
C - SQUARE EDGE FLANGE AND PLANE
D - 2 NEEDLE POINTS
E - NEEDLE AND 4" DISC
F - NEEDLE AND PLANE

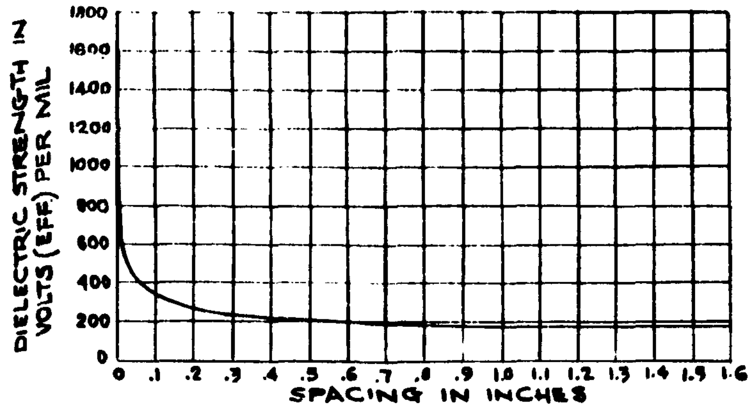
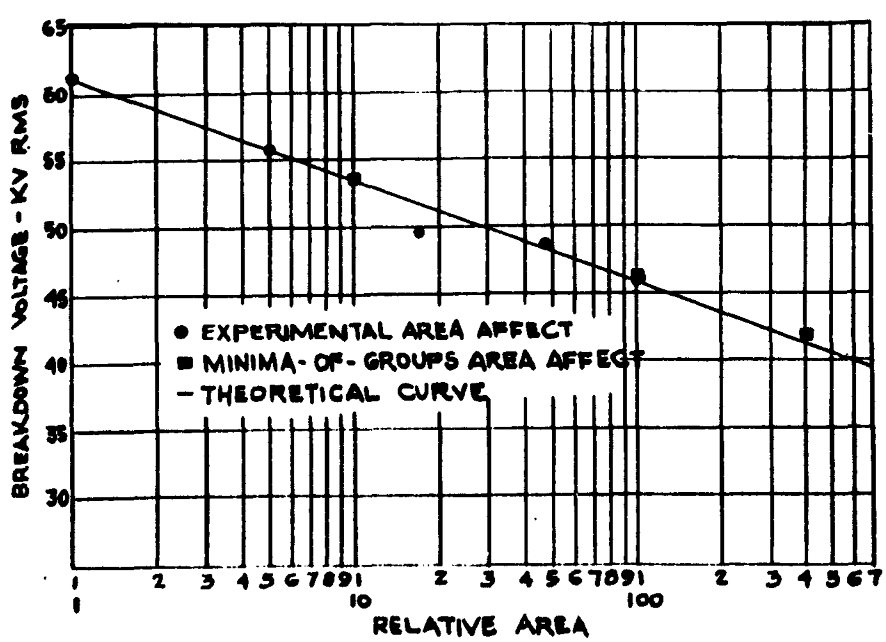


FIG. 5
(Ref. 8)

3. <u>Electrode Area</u> - The dielectric strength of oil decreases with increased electrode surface area. This relationship is attributed to the increased amounts of gas available at the electrode surfaces (see figure 6).



The effect of Electrode Area on the Breakdown Voltage (or strength) of Transformer Oil. Uniform Field - Rogowski Gaps.

FIG. 6
(Ref. 9)

4. Temperature - Transformer oil dielectric strength increases with increases in temperature up to some maximum temperature value. Peek (3) attributes this relationship partly due to the decrease in insulation resistance, permitting the increase in loss current to redistribute the electric stress, and mostly due to the removal of moisture by the increased temperature. Figure (7) shows the electric strength characteristics versus temperature and the change in insulation resistance versus temperature.

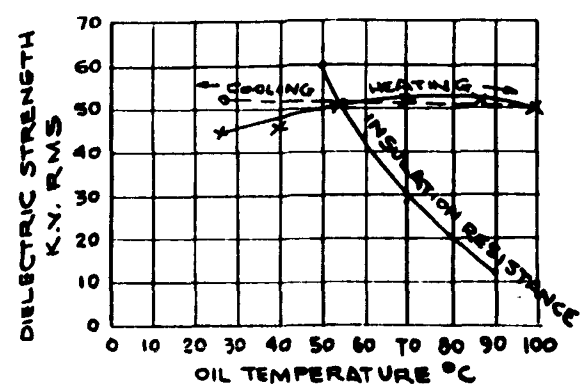


FIG. 7

Effect of temperature on dielectric tests and insulation resistance - Electrode discs at 0.5 centimeter spacing: (Fig. 179b - ref. 3)

5. Moisture - Moisture may be introduced into insulating oils directly or as a by-product of oil oxidation. It is generally accepted that the dielectric strength of mineral oil is degraded by the presence of water. Moisture does not affect the electric strength of oil until it separates from the oil and it is deposited on electrode surfaces, or it is absorbed by minute fibrous contaminants, (dust, lint, etc.) suspended in the oil. In actual practice, however, all commercial oils contain moisture and contaminants to some degree, therefore, it is generally recognized that moisture degrades the property of dielectric strength. (See figure 8).

The solubility of water in mineral oil increases with temperature. (Figure (9) depicts the saturation content of a typical transformer oil versus temperature.

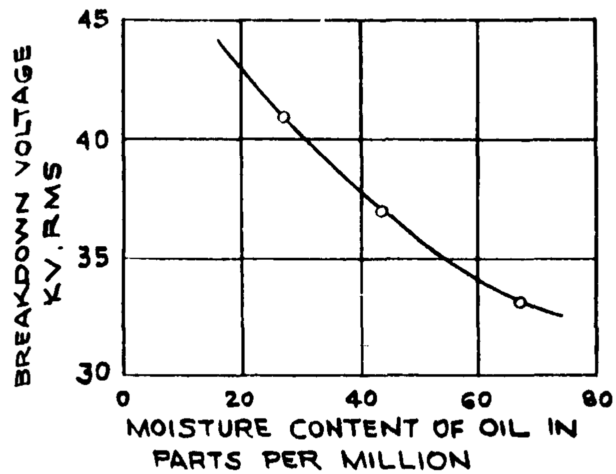


FIG. 8
Breakdown Voltage Versus Moisture Content of Oil.
(Ref. 4)

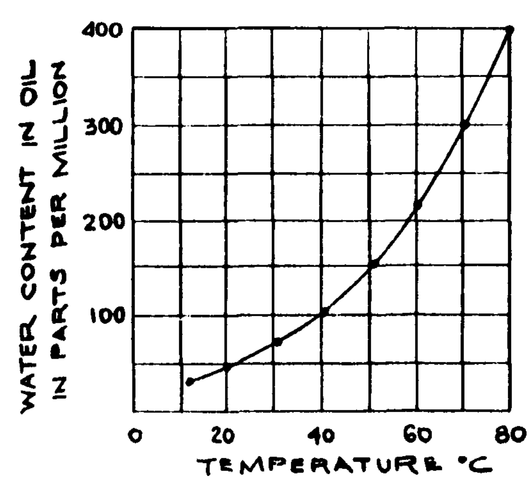


FIG. 9
Water Content of Oil Versus Temperature
(Ref. 5)

6. <u>Dissolved Gases</u> - The dielectric strength of insulant oil is dependent upon the amount of gases (air) dissolved in the oil in that an increase in the amount of dissolved gases results in a lowering of the dielectric strength. As the solubility of gas (air) in mineral oil is dependent upon the applied pressure and temperature, the electric strength, therefore, is a function of pressure and temperature. Figures (10) and (11) show the effects of temperature and pressure on the air content of oil.

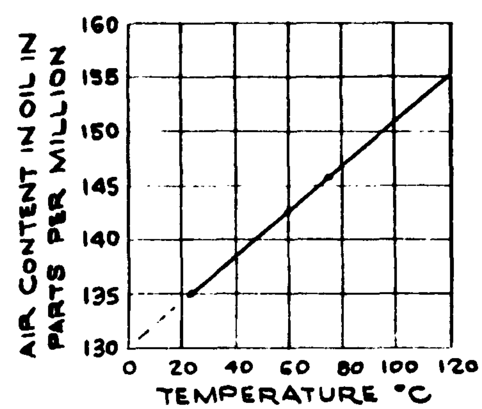


FIG. 10
Air Content In Oil Versus Temperature
(Ref. 5)

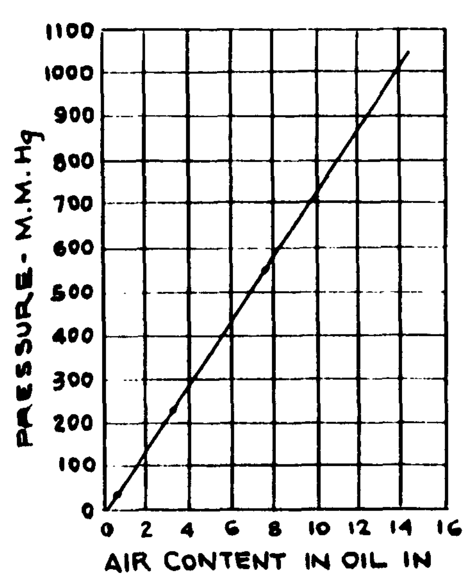


FIG. 11
Air Content in Oil Versus Pressure
(Ref. 5)

The increased solubility of air with increased temperature is due to the pressure of nitrogen. Nitrogen solubility in oil increases with temperature while the oxygen solubility decreases slightly.

Gases will remain in solution below the saturation level, however, under conditions where the gas is slightly over saturation, it will diffuse from the oil slowly. The diffusion rate increases with increased levels of super saturation. It has been determined (ref. 10) that when a positive differential pressure of 2 PSI between the partial pressure of the gas and the applied pressure on the oil exists, gas bubbles will start to evolve from the oil upon slight agitation. Sufficient agitation can result from the normal vibration inherent in a transformer due to its electrical excitation, to cause the formation of gas bubbles under the required pressure conditions.

Figure 12 shows the relationship of the dielectric strength versus applied pressure on the oil.

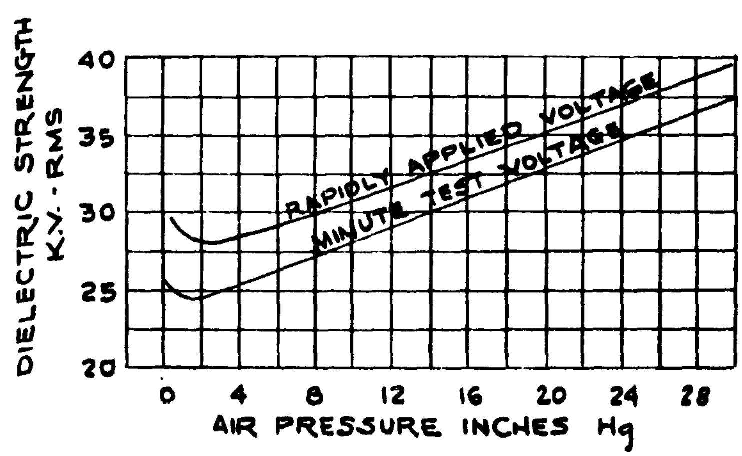


FIG. 12

Dielectric Strength of Transformer Oil Versus Applied Air Pressure. Electrodes-Standard 1.0 in brass discs, axes horizontal - 0.1 in. spacing. - Temp. 25°C.

(Ref. 8)

7. Time of Voltage Application - The dielectric strength of transformer oil varies with the time of voltage application in that the oil will break down at a higher voltage with a faster rate of applied voltage. This effect is due to the time required for impurities in the liquid to align themselves in the electric field and bridge the electrode spacing. Figure (13) shows an average curve for the dielectric strength versus time relationship for no. 10 transil oil.

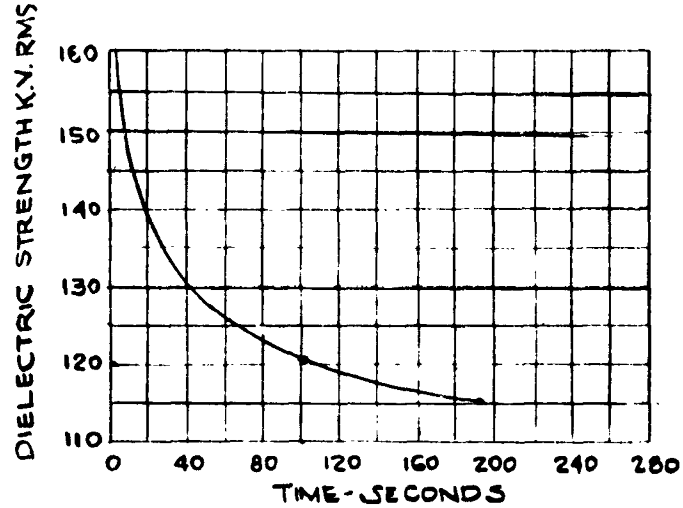


FIG. 13
(60 Cycle Strength - Time Tests @ 25°C-10 cm. round edged electrodes - 0.375 in. spacing)
(Ref. 8)

2. Resistivity

Volume resistivity measurement of an insulating oil is a means of determining the conductivity properties of the liquid. High resistivity indicates a relatively pure oil, low in conducting impurities and free ions. Oil samples should be tested in accordance with standard procedures as detailed in ASTM-D1169-54T by subjecting the sample to a low direct current voltage stress ranging from 1 to 15 volts per mil. This is normally accomplished by subjecting the test sample to a (1) minute period of electrification at 500 volts direct current, using a 100 mil test gap, with the oil at a temperature of 100°C.

Volume resistivity is a very sensitive test that is capable of detecting the pressure of oil impurities that are not readily detectably by other means. Because of this sensitivity, extreme care must be taken in performing measurements of resistivity. Any testing errors, or uncleanliness of test equipment will seriously affect the test results.

For this reason, power factor is frequently used as a quality measurement of mineral oils.

The resistivity of insulating oils varies greatly with temperature. Fig. 14 shows a typical commercial quality control gauge showing the relationship of resistivity to temperature, that is utilized in determining the continued use of a transformer oil in service.

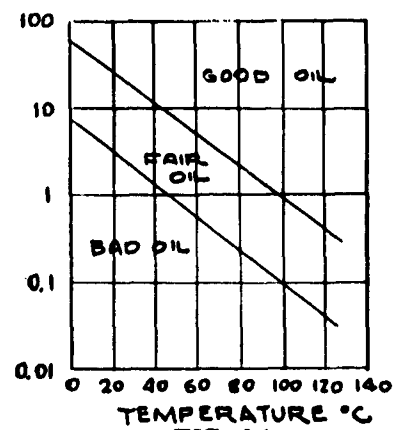


FIG. 14

One Commercial Resistivity Gage for Evaluating Transformer Oil Quality.

(Ref. 4)

3. Power Factor

Power factor is a significant measure for evaluating the electrical quality of transformer oils. The contaminant level of an insulating oil is reflected in its power factor, therefore, the measurement of power factor can be a most useful tool in evaluating both new insulant oils and oils that are in service. New transformer oils may contain excessive moisture and other oil soluble contaminants as a result of improper handling after refining or because of initial substandard oil quality. Transformer oils in industrial service may be subject to electrical degradation because of an increasing contaminant level. An increase in the power factor of in-service oils is evidence of a change in the characteristics of the dielectric. A continuing trend toward higher power factor indicates that an unsatisfactory condition is developing.

Insulating oils in service may become contaminated from the products of oil oxidation or from the presence of oil soluble materials resulting from the degradation of solid dielectrics in the insulation system. The continued use of transformers in service with an increasing oil power factor deserves consideration; however, the removal of such equipment from service, or its retention in use should be based on an evaluation of costs, failure hazards, and sundry operating considerations. Oil samples taken from service transformers should be tested electrically and chemically if the power factor of the sample exceeds a test value of 0.8% when tested in accordance with ASTM-D924-49.

4. Dielectric Constant

The dielectric constant of American transformer oil ranges from 2.1 to 2.3 when tested at 60 CPS and room temperature. Frequency and temperature have very little effect on the dielectric constant of American insulant oils. Table (5) shows the change in the dielectric constant of #10-C* transformer oil with applied frequency at a temperature of 26°C

(Table 5)

Frequency At 26°C	Dielectric Constant (ϵ_r)
$1x10^2$	2.22
$1x10^3$	2.22
$1x10^4$	2.22
$1x10^5$	2.22
$1x10^6$	2.22
$1x10^7$	2.22
$1x10^8$	2.20
$3x10^8$	2.19
$3x10^9$	2.18
$1x10^{10}$	2.10

The permittivity value of American oil decreases with temperature, increases in a linear relationship, decreasing by approximately .045 per cent per degree centigrade increase from 20°C to 150°C.

Important consideration must be given to the use of a low dielectric constant insulant liquid in a composite insulation structure when it is in series with a higher dielectric constant material. As pointed out under the preceding section on insulation terminology, the voltage distribution across a series insulation structure is unbalanced with the maximum voltage stress appearing across the material with the lower permittivity. As most solid insulations used in transformer insulation systems have a higher dielectric constant than transformer oils, design consideration must be given to the use of series composite insulation structures. This will be discussed under a later section of this report.

*Registered General Electric Trademark

5. Dielectric Loss

The dielectric loss of transformer oil varies with the frequency of the applied voltage, however, the change in the dielectric loss for the frequency range applicable to this contract is negligible. Table (6) shows the typical dissipation factor, frequency relationship of type 10C* transformer oil.

Table 6

Frequency	Tan δ
$1x10^2$	.0004
$1x10^3$	<.0001
$1x10^4$	<.0001
$1x10^5$	<.0006
$1x10^6$	<.0005
$1x10^7$	.0008
$1x10^8$	.0048
$3x10^8$	.0055
$3x10^9$	.0028
$3x10^{10}$	.0020

Other important properties of transformer oils are:

1. Oxidation resistance
2. Low viscosity
3. Low pour point
4. Thermal conductivity
5. Non solvent action

6. Oil Oxidation

Oxidation is the reaction that takes place between transformer mineral oil and oxygen. In designing transformers, especially long service life types, serious consideration should be given to the causes and controls of the oxidation problem. The reaction of insulant oils with oxygen produces peroxides, water, acids, metal soaps, evolved gas, and ultimately, a high molecular weight oil insoluble sludge. Water, acids and the peroxides may cause the mechanical and electrical weakening of solid insulations used in conjunction with the insulant oil. Gaseous by-products of oxidation can cause ionization and ultimately the voltage breakdown of the transformer oil if the gas collects in areas of high electrical stress. Sludge formation has a degrading affect on the heat transfer characteristics of a transformer due to the coating of the

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solid insulations, cooling ducts within the transformer coils, and the metallic structures.

The rate of oxidation is dependent upon temperature, the presence of catalysts and the presence of antioxidants or inhibitors in the oil. Figure (15) shows the increase in oxidation with temperature increases, as measured by the oil acidity which is a criteria of oil oxidation.

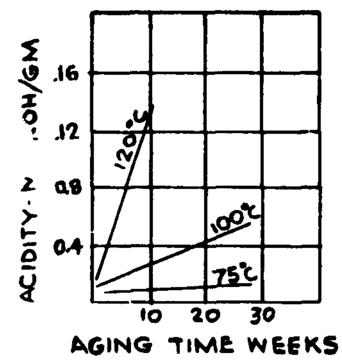
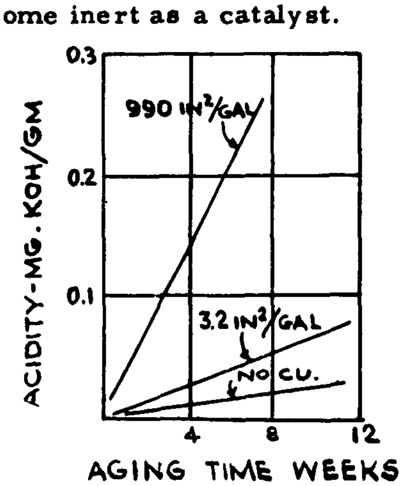


FIG.15

TRANSFORMER OXIDATION VERSUS TEMPERATURE (REF.5)

For each 8 to 10°C increase in temperature, the oxidation rate will be approximately double. Although this is not an exact relationship because of the many variables, it is a realistic average value. The presence of bare copper in the mineral oil is one variable that will affect the oil oxidation rate. Bare copper acts as a catalyst and its presence in oil, in conjunction with an unlimited supply of oxygen, can increase the rate of oxidation from two to tenfold of the rate without the catalyst. The actual increase is dependent upon the ratio of copper to oil. Figure (16) shows the effect of copper on oil oxidation.

In sealed systems where the availability of oxygen is limited, the copper tends to become inert as a catalyst.



AFFECT OF EXPOSED COPPER AREA ON OIL OXIDATION (REF.5)

FIG.16

Methods available to the transformer designer to minimize oil oxidation include:

1. Sealed systems, wherein, the transformer is hermetically sealed. Sealed transformers may be designed with an air head to allow expansion volume for the oil. Although an air head design allows oxygen contact with the oil, it limits the available oxygen by exclusion of the environmental atmosphere. Air heads may be eliminated by the use of a bellows device (smaller transformers), oil conservator device, or the recently developed Atmoseal* device. Transformers utilizing either a bellows or atmoseal device are impregnated with degassed oil after the evacuation of air from the transformer, thereby, removing the oxygen supply necessary for the oil oxidation process.

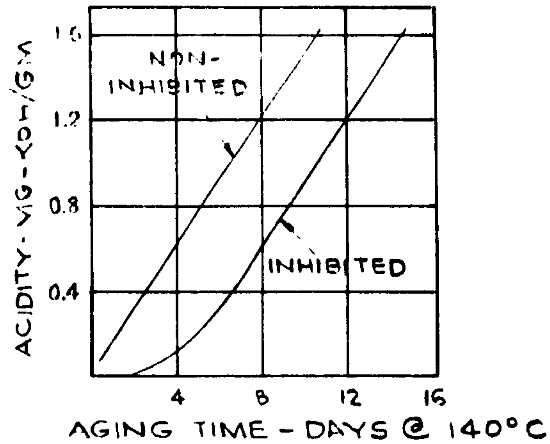
   The Atmoseal* system basically consists of an external tank connected to the transformer casing by plumbing. This external tank provides a reservoir for the thermal expansion of the transformer oil. The oil within the external tank does not come in contact with the environmental gas, the normal air head being displaced by a bladder-sealed to the oil system and open to the environmental atmosphere through a suitable breathing device.

2. Oxidation inhibitors can be added to a transformer oil to minimize the oxidation problem. One of the most additives for this purpose is Ditertiary Butyl Para Cresol (DBPC) which is usually added to the oil as 0.3% by weight of the inhibitor. This additive extends the oxidation life of oil, and it finds its most important use in transformers designed to breathe the environment. (DBPC) does not alter the physical or chemical characteristics of the mineral oil, and it is stable under exposure to light and heat.

   This inhibitor does have a finite life that is dependent upon the operating characteristics of the transformer such as the temperature and the availability of oxygen.

   Although a (DBPC) additive can reduce the oxidation rate to one third the value of a non-inhibited oil, the actual rate reduction is difficult to ascertain because of the many variables relating to the oxidation process in practical use. Figure (17) depicts the retardation of transformer oil oxidation with the use of an inhibitor.

*General Electric Co. trademark for a constant oil preservation system.



RETARDATION OF TRANSFORMER OIL OXIDATION BY THE USE OF AN INHIBITOR (REF. 5)
FIG. 17

7. Viscosity

Transformer oil viscosity is of major importance. One of the primary functions of an insulant oil other than as a dielectric, is to provide a media for transferring heat from a transformer core and coil assembly. This is accomplished by the oil circulating through the core and coil structure. Fluidity of the oil, at low environmental temperatures is a requirement if the liquid is to serve its function as a cooling medium. as the temperature of an oil is reduced, a point is reached where the oil will barely flow under certain prescribed conditions (ASTM). This point is referred to as the pour point. As the heat transfer characteristics of an oil depends upon its fluidity, the operation of a transformer under conditions where the oil remains immobile, can result in overheating of the transformer and the ultimate destruction of the apparatus.

Oil viscosity is also an important consideration of the liquid impregnability of porous solid dielectrics used in conjunction with the liquid as part of the overall transformer insulation structure. In order to produce void free solid insulations, it is required that the transformer oil be fluid enough to thoroughly penetrate the solid. Figure (22) shows the viscosity of 10C* transformer oil with temperature.

8. Specific Gravity

The specific gravity of an oil is the ratio of the weight of equal volume of oil and water, both weights being determined at 60°F (15.56°C). This value is expressed as specific gravity 60/60F (ASTM D117-54T). There exists no relationship between the electrical quality of an insulant oil and its specific gravity.

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9. Coefficient of Expansion

The coefficient of expansion of a transformer oil is a measure of the volumetric change per change in temperature. Although the volume change of insulating oil per unit change in temperature is not an absolute linear relationship, for all practical purposes, the oil volume will change .08 per cent per degree centigrade. Therefore, the coefficient of expansion can be considered as .0008.

The equation for expressing the volumetric oil expansion versus temperature can be stated as:

$$V_t = V_o (1 + \alpha T)$$

(10) V_t = Volume at temperature T
V_o = Volume at 0 degrees centigrade
α = Transformer oil coefficient of expansion = .0008
T = Temperature in degrees centigrade.

10. Thermal Conductivity

Thermal conductivity of a material is a measure of the temperature differential that must exist across two opposite surfaces of a material in order to conduct a quantity of heat per unit of time per unit of material volume, through the material. In most thermal applications, the thermal conductivity (k) is expressed in the units, British thermal units per foot length of heat travel per square foot of material area per degree fahrenheit.

(11) $$k = \frac{BTU\text{-}F_t}{F_t^2 \ hr. \ ^oF}$$

It is advantageous in transformer design applications to express the thermal conductivity in units: Watts per inch of heat travel per square inch of material area per degree centigrade.

$$k = \frac{\text{watts-inch}}{\text{inch}^2 \ ^oC}$$

(12) $$k = \frac{\text{watts}}{\text{in} \ ^oC}$$

*Registered General Electric Trademark

The thermal conductivity of transformer oils varies with temperature, decreasing slightly with increasing temperatures, however, for all practical purposes, it is considered as .0034 watts/in-°C. Further considerations of the thermal parameters will be discussed in Milestone Report #6.

TRANSFORMER ASKAREL

1. General

Askarel is the class name applied to non-flammable insulating liquids. The askarels are identified by the American and European tradenames, Pyranol*, Inerteen, Arochlor, Clophen, Dykanol, Nepolin and Pyralene. Unlike transformer oils, askarels are a synthetic product generally consisting of an eutectic mixture of chlorinated diphenyl and chlorinated benzene.

Transformer oils have two undesirable characteristics: (a) Oils are subject to oxidation, (2) They present a fire and explosion hazard under certain conditions. The askarels, on the other hand, are not subject to oxidation, and they are non-flammable.

The use of the askarel liquids for audio transformer applications is not generally recommended because of their high dielectric constant value which ranges between 3.5 to 4.5. This presents a serious disadvantage to their use because the permittivity of a series askarel solid structure being greater than an equivalent series oil solid structure, increases an audio transformer's inter-winding, inter-layer, and winding to tank capacitance. High capacitance values degrade the frequency response characteristics of audio transformers. It is possible to minimize the affects of this increased capacitance by changing the electrical and mechanical geometry of the transformer core and coil assemblies, however, this departure from the optimum design methods results in a structure of disproportionate costs, weight, and physical size. If the non-flammable characteristics of the askarels are a requirement, then the selection of a silicone dielectric liquid could be justifiable. The silicone oils will be discussed under Milestone #10.

2. Advantages In Transformer Applications:

A. Askarels are non-flammable

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B. Not subject to oxidation - no reactions producing insoluble sludges or corrosive acids.
C. Chemically stable.
D. When decomposed by an electric arc, no flammable gases are evolved.

3. Disadvantages In Transformer Applications

A. Cost - Transformer askarels cost six to seven times more than transformer oils on a volume basis.

B. Weight - Askarels weigh 175 per cent more than mineral oils on a per unit volume basis.

C. High dielectric constant - In audio transformers, this is a serious disadvantage, however, this is considered an advantage in some transformer applications because of the more equal voltage distribution across a series solid liquid structure.

D. Solvent Action - Although askarels are chemically stable, they are strong solvents of many of the materials commonly used in conjunction with transformer oils.

E. Toxicity - Although not overly toxic, when handled properly, however, prolonged contact with liquid askarel can produce skin irritation. Hydrogen chloride gas is evolved under electric arc decomposition which is highly toxic in large concentrations.

4. Physical Properties

Table (7) lists the properties of a typical transformer askarel - Pyranol* #1470

Table 7

Properties	
Dielectric strength @ 25°C	35 KV
Dielectric constant @ 1000 CPS, 100°C	3.8 - 4.2
Resistivity - ohm cm @ 100°C	$100X10^9$
Fire point °C max.	None
Pour point °C max.	-44
Viscosity Saybolt Universal Seconds @ 37.8°C	41-45

(continued)

*G.E. Registered Trademark

Table 7 (continued)

Properties	
Specific Gravity @ 15.5/15.5°C	1.56-1.57
Water content (PPM max.)	30
Coefficient of Expansion	.0007
Thermal conductivity, watts/inch °C	.0032

5. Solvent Action

Askarels, while chemically stable, are strong solvents of many of the materials commonly used in conjunction with transformer oils. In general, most vegetable oil type varnishes, gums, binders, adhesives, rubbers and paints are soluble in askarel. Materials suitable for use in askarels include the synthetic resins, phenolic, polyurethane and epoxy. Cellulose acetate and the cellulosic insulation materials are generally compatible with askarel.

Transformer oils are soluble in askarel, therefore, extreme care should be taken in the handling of askarel. Currently, no method is known to separate this contaminate from askarel.

6. Materials Compatible With Askarel

The following material lists represents a partial listing of materials determined to be compatible with askarel.

A. Coil insulations.
  1. Laminated phenolic treated cellulosic paper cylinders and tubes.
  2. Kraft and rag insulating papers and pressboards.
  3. Cotton and linen tapes and yarns.
  4. Polyester films (Mylar).
  5. Vulcanized fibre (regenerated cellulose rag paper).

B. Structural material
  1. Wood-Kiln dried magnolia, maple and birch.
  2. Porcelain - glazed and unglazed.
  3. Metals - Mostly all finished metals except zinc. Zinc liberates hydrogen from the hydrochloric acid evolved from electric arc decomposition of askarel.

C. Gasket materials
  1. Cork - granulated and bonded with phenolic resins.
  2. Synthetic rubber - special Buna N - (Maximum exposure area to askarel or askarel vapors should not exceed 1/2 square inch per gallon of askarel.
  3. Silicone rubber

D. Adhesives
   1. Cellulose acetate solutions
   2. Polyvinyl butyral with phenolic resin (Must be heat cured prior to askarel immersion) .
   3. Epoxy

E. Soldering flux.
   1. Lactic acid, 40% with water.

F. Wire insulation
   1. Film enamels

      a. Polyamide resins
      b. Epoxy resins
      c. Modified oleo resins

   The selection of a wire insulating enamel deserves careful consideration. Although the above listed enamels have been determined to be suitable, some formulations of these materials may prove incompatible with askarel. It is recommended to obtain assurance from the wire manufacturer of the suitability of a selected wire film enamel for askarel use p.ior to its acceptance.

   2. Fibrous coverings
      a. Cellulosic papers
      b. Cellulosic cloths
      c. Textiles
      d. Synthetic fibers

7. Decomposition Products

Askarels will decompose when subjected to an electric arc. The molecular breakdown of the liquid causes the evolution of non-flammable hydrogen chloride gas and small quantities of carbon dioxide, carbon monoxide, and inert gases. Hydrogen chloride, the main gas evolved, will slowly attack cellulose and other solid insulations causing their deterioration and ultimate failure.

The detrimental effects of hydrogen chloride can be eliminated by the addition of tetraphenyltin, or epoxide scavengers,(.11 to .14% by weight) either of which will react with the gas, eliminating its' reaction with the cellulosic solids.

8. Effect of Moisture

Water contamination of askarel is of major importance. Sufficient levels of dissolved moisture in askarel can result in increases in dielectric losses and dielectric strength impairment, resulting in localized dielectric heating, corona inception and ultimate dielectric failure. New askarel generally contains less than 30 parts per million of water, and increases in the dissolved moisture content should not be allowed to exceed 70 PPM in operating transformers. At 25°C, only about 125 PPM of water can dissolve in askarel, therefore, it is possible to have water condensate existing within the transformer. Excess water will distribute itself on the askarel surface because of the higher density of the askarel, presenting a dielectric breakdown problem, especially between coil lead terminations. Table (8) shows the comparison of askarel insulation values after various stages of use.

SOLID DIELECTRICS - GENERAL

Dielectric liquids are rarely used as the sole insulation structure in transformers. Liquid insulants behave erratically when used alone, which is attributable to the alignment of impurities, (present in all commercially available liquid dielectrics), across the various electrode spacings that are inherent in all transformers. Composite series liquid and solid insulation assemblies provide an electrically and mechanically stronger system than could be obtained through the use of only an insulant liquid.

The solid insulation materials most commonly used are listed in Milestone Report #2 by thermal classification and are repeated here for convenience.

Class A (105°C)

Papers
Pressboard
Wood
Chipped wood products
Cotton products
Silk products
Glass or inorganic products using class (A) varnishes.
Vulcanized fibre products
Paper and cotton - phenolic or epoxy laminates.

Class B (130°C)

Uprated cellulosic paper
Uprated cellulosic pressboard
Asbestos products
Mica products with class B varnishes
Glass products
Dacron
Mylar and other polyester films

1. Effect of Insulation Voids

Gas voids in solid insulations are objectionable in that the concentration of voltage stress in the void gas (air) is much greater than the stress in the solid proper. The voltage stresses in two series insulation materials with different permittivities can be determined from:

$$g_1 = \frac{E}{x_2 \left(\frac{\epsilon_1}{\epsilon_2}\right) + x_1} \quad (13)$$

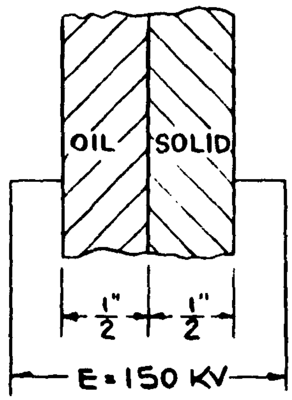
E = Total applied potential in kilovolts.

g_1 = Voltage stress in material (1) in volts per mil of thickness.

$x_1; x_2$ = Thickness of materials (1) and (2) in inches.

$\epsilon_1; \epsilon_2$ = Permittivities of materials (1) and (2)

Example: Given a composite series insulation structure shown in figure (18):



ϵ oil = 2

ϵ solid = 4

FIG. 18

$$g_{oil} = \frac{150}{1/2\ (2/4) + 1/2} = 200 \text{ volts per mil}$$

$$g_{solid} = \frac{150}{1/2\ (4/2) + 1/2} = 100 \text{ volts per mil}$$

The expression for the voltage gradient at any point (x) in a combination of (n) insulations in series is:

$$(14) \qquad g_x = \frac{E}{\epsilon_x\left(\frac{x_1}{\epsilon_1} + \frac{x_2}{\epsilon_2} + \ldots + \frac{x_x}{\epsilon_x} + \cdots + \frac{x_n}{\epsilon_n}\right)}$$

The effect of the pressure of a gas void in a solid dielectric on the voltage stresses is shown by the following example:

Example: Given the same insulation structure depicted in figure (22), except a gas void is included in the solid dielectric as shown in figure (19)

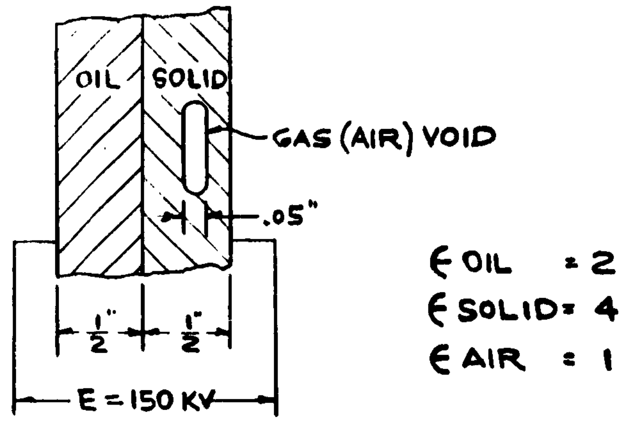


FIG. 19

The voltage stresses across each of the three materials, oil, solid, air can be determined using equation (13):

$$g_{oil} = \frac{150}{2\left(\frac{.5-.05}{4} + \frac{.05}{1} + \frac{.5}{2}\right)} = 182 \text{ volts per mil.}$$

$$g_{solid} = \frac{150}{4\left(\frac{.5-.05}{4} + \frac{.05}{1} + \frac{.5}{2}\right)} = 91 \text{ volts per mil.}$$

$$g_{air} = \frac{150}{1\left(\frac{.5-.05}{4} + \frac{.05}{1} + \frac{.5}{2}\right)} = 364 \text{ volts per mil}$$

The potential appearing across the three materials equals the voltage stress times the material thickness:

$$E_{oil} = 182 \frac{\text{volts}}{\text{mil}} \times 500 \text{ mils} = 91 \text{ KV}$$

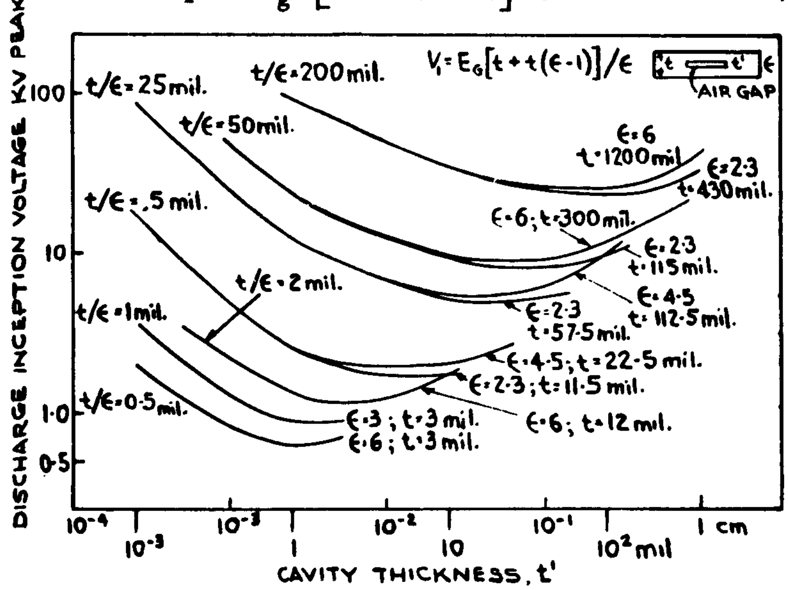
$$E_{solid} = 91 \frac{\text{volts}}{\text{mil}} \times 450 \text{ mils} \cong 41 \text{ KV}$$

$$E_{air} = 364 \frac{\text{volts}}{\text{mil}} \times 50 \text{ mils} \cong 18 \text{ KV}$$

As the dielectric strengths of the three materials, solid, oil, air are approximately 300, 200 and 50 volts per mil respectively, the air will break down before the other materials fail, causing local heating within the solid, and ultimately failure of the solid.

J. H. Mason (1) has shown that the inception voltage in gaseous inclusions in solid dielectrics is equal to:

(15) $V_i = E_g \left[t + t' (\epsilon - 1) \right] / \epsilon$ Ref. (2)



VARIATION OF DISCHARGE INCEPTION VOLTAGE AT 20°C IN CAVITIES OF VARYING THICKNESS t', CONTAINING AIR AT ATMOSPHERIC PRESSURE, ENCLOSED IN DISCS OF THICKNESS t, AND PERMITTIVITY ε. REF. (2)

FIG. 20

V_i = Discharge inception voltage
E_g = Dielectric strength of occluded gas
t = Thickness of solid insulation
t' = Thickness of occluded gas cavity
ϵ = Permittivity of the solid dielectric

Equation (6) is a useful guide if the occluded gas cavity is a thin wide disc, normal to the electric field, when the stress on the cavity (E_c) is equal to (ϵE) where (ϵ) is the permittivity of the gas and (E) is the stress in the solid. However, most voids tend to be spherical configuration, therefore, $E_c = 3 \epsilon E / (1 + 2\epsilon)$ when (t') is small compared to the solid thickness (t).

For values of $\epsilon \gg 1$, the stress on the spherical gas cavity approaches 3 E/2. Then, the inception voltage becomes:

$$(16) \quad V_i \cong \frac{2 E_g t}{3} \qquad \text{Ref. (2)}$$

2. Variables Affecting Dielectric Strength

A. Electrode shapes and areas

As with liquid dielectrics, the configuration and surface areas of the conductors and ground planes within a transformer assembly have their affect on the dielectric strength of solid dielectrics because of the non-uniformity of the electric fields. The effect of electrode shapes has already been discussed in this report.

Electrode surface areas affect the electric strength of adjacent solid insulations especially if the insulation is relatively thin. As the electrode area is increased, the probability of volume imperfections in the solid, appearing adjacent to the electrode surface, increases. Consequently, it is desirable to use laminated thin solid insulation structures rather than an equivalent thickness of a single dielectric solid, as the probability of an imperfection extending through the insulation thickness is minimized.

B. Effect of insulation thickness

It is well documented that the dielectric strength of most insulations does not increase linearly with its thickness. The breakdown voltage per unit of insulation thickness is greater for thin sheets.

An empirical equation for expressing the relationship of strength to insulation thickness is:

$$(17) \quad KV = AT^n$$

- K V = Dielectric strength in kilovolts.
- A = Dielectric strength per unit of thickness which is a constant for solid insulations dependent on the material.
- T = Thickness of insulation between electrodes.
- n = Numerical value ranging from 0.5 to 1.0 dependent on the material history (previous heating and drying), and on the electrode shape.

With a uniform field (n) approaches 1.0, however, for most practical applications, the value of (n) approximates 2/3. In general practice then, as the voltage on a system is doubled, the insulation thickness must be increased threefold. However, the dielectric strength does not increase ad infinitum with increases in thickness.

Increased conduction resulting from increases in electrical stress causes greater dielectric heating with a subsequent temperature rise until thermal equilibrium is established between the heat generated in the solid insulation and the heat dissipated. At some potential stress, the generated heat rate exceeds the rate of dissipation resulting in a continuous temperature rise until breakdown occurs through thermo electric failure of the material.

In practice, the thermal limiting voltage is not usually a determining factor except for applications with extremely thick insulations, applied voltage frequency in the megacycles, or high temperature operation.

C. Breakdown by surface tracking

Surface tracking (formation of carbon conducting paths) is caused by the thermal deterioration of the solid surface between electrodes that are at a different potential. Thermal degradation takes place as a result of (1) a power arc striking between the electrodes on or near the insulation surface or (2) high leakage current flowing through contamination on the solid surface.

Dielectric breakdown ensues when the electrically conductive carbon tracks extend a sufficient distance between the electrodes to increase the voltage stress across the untracked surface to a critical breakdown value.

D. Breakdown by surface discharges

Discharges emanate from high voltage electrode surfaces because of high voltage gradients. These discharges impinge on the solid insulation at the interface of the liquid impregnate and solid dielectric surface, causing areas of high stress and localized heating. Thermal deterioration of the solid surface manifests itself as carbon conducting paths, radiating from the electrode periphery, on the solid surface, or just below the surface.

The number of discharges is related to the frequency of the applied voltage and the time of voltage application. Early investigators (ref. 13) show this relationship to be:

(18) $V = K f^{-n} (1 + \alpha T^{-1/4})$

V = Dielectric breakdown voltages

f = Frequency

T = Time

K, n, α are constants

Equation (17) has been substantiated by many tests, however, its practical use is limited because of the disagreement on the value of the constants.

The stress concentration is related to the insulation thickness being more concentrated at the point of discharge impingement with increased insulation thickness. Equation (17) will give the short time electric strength of the insulation versus thickness with the value (n) approaching a value of (0.5).

PROPERTIES OF SOLID DIELECTRICS (105°C)

I. Cellulosic Insulations:

Liquid impregnated cellulosic paper and pressboard insulations are extensively used in high voltage transformer applications for class (A-105°C) operation. Kraft paper and pressboards, which are derived from alkaline chemical pulping of coniferous woods, is the most generally used material because it is relatively inexpensive, and it has excellent mechanical and electrical properties.

The term "kraft papers" generally designates thin insulation sheets usually from .00025 inches to .031 inches in thickness, whereas, the pressboards generally range in thickness from .031 inches to .125 inches, although thicknesses up to .625 inches are available. Most of the data that applies to kraft paper applies also to the pressboards, taking into consideration differences in thickness and rigidity of the two classes of material.

A. Applications

1. Kraft papers

a. Layer insulation

Used as an interlayer dielectric. Paper .005 inches to .015 inches thick are more generally used for this purpose, either singularly or most often in multi layers.

b. Winding supports

To fabricate winding support cylinders and tubes. Kraft paper is mandrel wound with thermosetting phenolic resins to form cylinders of high mechanical and dielectric strength.

c. Wire insulation

Kraft paper tapes of .001 to .002 inches thickness are used to cover rectangular and larger diameter round wires.

2. Kraft pressboards

a. Barrier insulation

Single or multi layer of pressboard usually of (.0625-.125) inches thick material used to prevent voltage breakdown from coils to ground points and between sections of coils at different voltage levels.

b. Spacers

Laminated in strips to provide electrical and mechanical spacing for liquid ducts between coil windings and at axial ends of coils. Also utilized as margin strips to retain the coil winding axial end wire turns in place.

B. Properties:

Tables (9) and (10) shows the properties of typical kraft papers and kraft pressboards.

1. Density

a. Effect on dielectric constant

The liquid impregnability of kraft papers and pressboards is related to the material desnity, the less dense materials being more readily impregnated. The dielectric constant of the impregnated material depends upon the degree of liquid impregnation. Papers with a density in the viscosity of 1.5 grams per cubic centimeter are considered non-impregnable, therefore, the dielectric constant of the material will remain at its dry value in the vicinity of 4.5 to 5.0. With decreasing density values, the effective density of the impregnated insulation will decrease with impregnants of lower permittivity value than that of the non-impregnated solid. Conversely, the effective dielectric constant of an impregnated paper of lower density will increase with values of impregnant permittivity higher than that of the non impregnated paper. Fig. (21) shows the dielectric constant relationship of oil impregnated proper to the paper density.

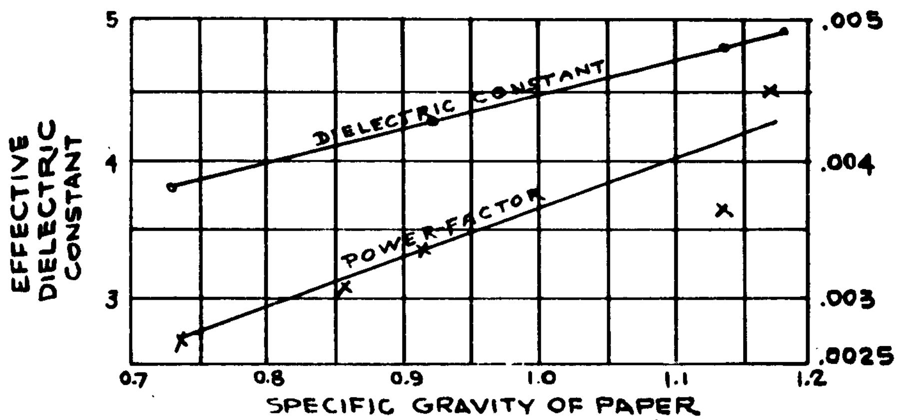


FIG. 21 (REF. 19)

EFFECT OF SPECIFIC GRAVITY ON DIELECTRIC CONSTANT AND POWER FACTOR

b. Effect on power factor

The power factor of impregnated papers increases with increasing paper densities. Fig. (21) shows this relationship for a typical oil impregnated paper.

2. Tensile strength

The tensile strength of cellulose insulating papers is of importance for two primary reasons:

a. Coil winding interlayer insulation of higher tensile strength permits increased coil winding tension, resulting in a mechanically more rigid coil structure.

b. The change in the tensile strength of cellulose insulations brought about by the effects of moisture, heat and other degrading influences, provides a means of evaluating the extent of these influences on the material.

3. Surface finish

Surface finishes of kraft papers range from rough finishes to high glazed finishes, each having advantages and disadvantages.

a. Rough finish

Advantages:

1. Minimizes slippage of coil winding wires and insulation parts.

2. Liquid impregnates readily.

3. Lower effective dielectric constant when impregnated with transformer oil.

Disadvantages:

1. Usually lower dielectric strength than equivalent thickness hard finished paper.

2. Lower tensile strength

3. Lower tear strength.

This finish results from a minimum of machine calendering during manufacture.

b. Hard finish

Advantages:

1. Good space factor on a dielectric strength basis.

2. Increased mechanical strength properties.

Disadvantages:

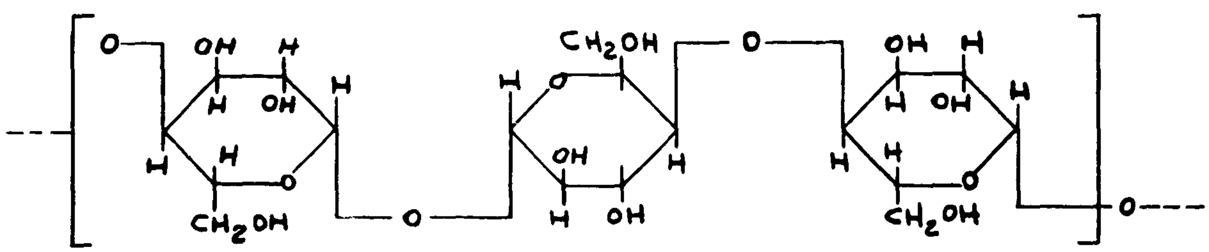
1. Offers minimum of resistance to mechanical slippage of coil wires. This is of primary importance on larger transformer coils.

2. Effect of Moisture

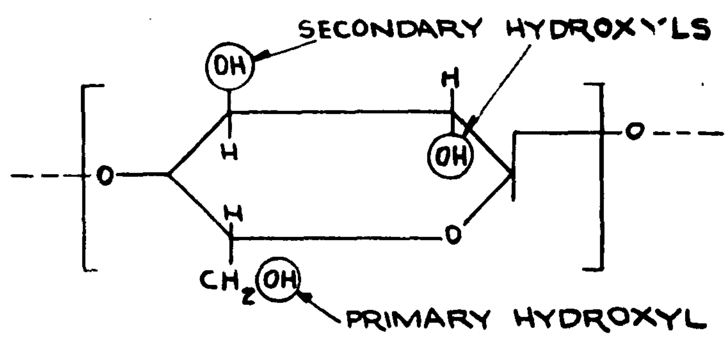
The cellulosic insulations will readily absorb moisture from their environment, the rate of absorption being dependent upon the characteristics of the insulation and the environment.

Moisture equilibrium will take place between the cellulosic solid, the liquid dielectric and the gas environment of the liquid after a given time, depending upon the viscosity of the liquid, the exposed area of the cellulose, density of the cellulose, and the physical movement of the liquid dielectric.

Moisture is absorbed on the cellulose solid surface and within the interstitial structure of the solid. It is also chemically taken up in the form of hydrated water by the chemical action with the hydroxyl groups in the glucose units of the cellulosic molecular chain. Figure (22) shows the accepted cellulosic chain and glucose unit.



CHEMICAL STRUCTURE OF CELLULOSE CHAIN
FIG. 22A



SINGLE GLUCOSE UNIT
FIG. 22B

Moisture weakens the resistance of cellulose to thermal degradation. Oil immersed cellulose, when subjected to heat, decomposes in that the glucose units of the molecular chain deteriorate with the formation of water and carbon dioxide gas, resulting from the bonding of hydrogen with the glucose hydroxyl groups. The retention of the decomposition products by the cellulose, increases the deterioration process, with the consequent lowering of the electrical and mechanical properties.

Hydrolysis degrades the dielectric strength of enameled insulated wires at elevated temperatures. The effect of moisture on enameled wire provides a means of evaluating the decomposition of cellulosic insulations at higher temperatures.

The decrease in the dielectric strength of relatively moisture resistant polyvinyl formal enameled wire, due to its moisture absorption is used as a means of measuring the generation of moisture resulting from the decomposition of cellulosic insulations in a sealed oil, wire paper system at elevated temperatures. Figure (23) shows a plot of the Arrhenius rate reaction equation:

$$\ell n \; t = A + \frac{B}{T}$$

t = life in hours

T = Temperature degrees Kelvin

A, B = Constants

showing the effect of dried kraft paper and cyanoethylated* kraft paper (discussed under 130°C hot spot temperature insulation) on the half life of the dielectric strength of polyvinyl formal insulated wire in transformer oil.

3. Effect of Thickness on Dielectric Strength

The relationship of the dielectric strength of the cellulosic insulation thickness follows the form discussed previously; ($KV = AT^n$). The value (n) for the cellulosics is dependent upon the empirical conditions of the drying and impregnation processes as well as the test electrode configurations, and the rate of voltage application. Values of (n) for pressboards may vary from 0.66 to 0.8 for a minute step up

*H.F. Miller, R.G, Flowers: U.S. Patent #2,535,690 Dec. 26, 1950 voltage application or a rapidly applied voltage, respectively. Table (11) shows the empirically determined design values for the constant A, and n.

TABLE 11

Material	AT^n
Oil treated Kraft paper	$230\ T^{.67}$
Oil treated Kraft pressboard	$230\ T^{.67}$
Laminated Kraft paper phenolic resin binder	$260\ T^{.64}$

4. Effect of Time of Voltage Application on Dielectric Breakdown.

It was previously discussed that dielectric heating of the insulation is an important factor in the voltage breakdown versus insulation thickness relationship. Thermal instability of the insulation takes time to develop, therefore, a short time dielectric strength value must be decreased when the voltage application is extended over a long period of time because of the dielectric heating ensuing from the a-c voltage application. Peek (Ref. 3) shows the dielectric strength time curve takes the form:

$$g = g_{\Delta}\left(1 + \frac{a}{\sqrt[4]{T}}\right)$$

where: g = Voltage gradient
g_{Δ} = Voltage gradient in K.V./m.m. for indefinite time.
a = Constant for a given insulation thickness and temperature.

5. Effect of Impulse on Dielectric Breakdown

The dielectric strength of oil impregnated cellulose insulation for very short time applications exceeds the long time dielectric strength. As audio transformers may be subject to voltage surges due to lightning discharges and switching, the dielectric strength for short time applications becomes important.

Steep wave front impulse voltages exceeding the long time dielectric strength of the insulation may be applied without breakdown of the insulation providing the time of voltage application is short. (microseconds). Figure (24) shows an impulse full wave known as 1.5 x 40 wave that is used as a test standard in this country.

This wave is intended to simulate a traveling wave of lightning discharge origin. The wave rises from time zero to crest in 0.5 to 2.5 microseconds and decays to 50 percent of its crest value in 40 microseconds from time zero.

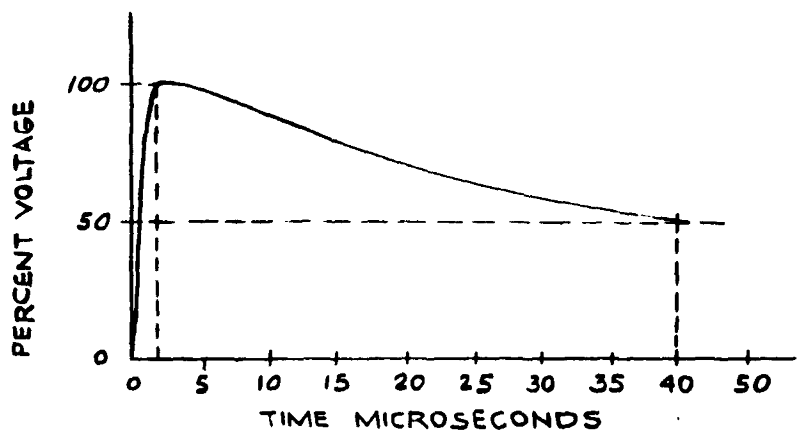


FIG. 24

FULL WAVE IMPULSE VOLT TIME CURVE

The ratio of the full wave impulse dielectric strength to the one minute 60 cycle dielectric strength is referred to as the impulse ratio. This ratio varies depending upon the condition of the cellulose insulation because the long time dielectric strength is affected by the moisture content and temperature of the material to a greater degree than the impulse strength characteristics are. Empirically, it has been determined that the 1.5 x 40 full wave impulse factor varies from 2.2 to 3.0 depending upon the thickness ratios of oil ducts to cellulose thickness, and the thicknesses of the materials. Experience shows that 2.3 is a good average impulse ratio value.

It should be pointed out that the effects of corona under impulse conditions should be considered. Under conditions of one impulse, destructive corona may be present, at some voltage level, dependent upon the electrode geometry.

Some irrepairable damage to the insulation system will occur, so that under repetitive impulses, failure will ensue.

5. Effects of Frequency on Dielectric Strength

The dielectric loss of cellulose increases with frequency, and as previously shown, the dielectric strength decreases with increased temperature. The dielectric strength value should then decrease with increased frequency. Monsinger (Ref. 8) gives the following relationship between dielectric strength and frequency within the limits of 25-420 cps.

$$R_f = \frac{K}{F^n} \qquad (19)$$

where: R_f = Ratio of the dielectric strength at frequency F to the 60 cycle dielectric strength.

F = Frequency in cycles per second.

n = Empirical value 0.137.

The relationship of the dielectric strength to applied frequency must be evaluated for frequencies up to 20 kilocycles. Such an evaluation will be presented in Milestone Report #10.

II. Wood

Wood is primarily used in larger size transformers for mechanical purposes. Uses include wedging structures between coil winding forms and the magnetic core; winding termination lead cable mechanical supports, and oil cooling duct spacers in large core assemblies. Recommended woods are National Hardwood Lumber Association grades of select or better evergreen magnolia or hard maple. All wood should be kiln dried and absolutely free from all knots, imperfections and bad inconsistency of grain structure.

Figures (25, 26, 27, 28) show the required oil strike and creepage spacings required for all wood composition structures. Resin impregnated chipped wood and laminated wood products must be given engineering evaluation before use due to the dielectric and mechanical effects of the impregnant.

III. Cotton Products

A. Untreated

Untreated cotton is used in tape form as a mechanical binder to mechanically retain coil insulation during winding operations and as tie strings to secure coil leads and lead cables in place. Table 12 shows the ASTM requirements for cotton tape.

B. Treated

Cotton cloth coated with either an asphaltic or oil varnish is used in tape form to wrap irregular shaped conductor configurations. It is available in wide sheets that are utilized in providing winding pad insulation. This material known as varnished cambric is infrequently used on lower voltage equipment. It is, however, used extensively in manufacturing cables and higher voltage transformers.

Table (13) lists the characteristics of commercially available varnished cloths. (Ref. 21).

IV. Silk Products

Varnish coated silk cloth is used in tape form to wrap irregular conductor configurations. This material is thinner, more flexible, and has greater dielectric strength than the varnished cambrics. It is available in sheet stock and in this form, is used as interlayer insulation or to fabricate conductor lead insulation tubing sleeves. The use of this material for interlayer insulation is usually limited to physically small transformers because of the difficulty in preventing winding conductor slippage on the smooth surface of this material.

This material is thinner, more flexible, and has greater dielectric strength than the varnished cambrics. With the advent of other fibers, the use of silk is becoming very limited.

See Table (14) for mechanical and electrical strength characteristics.

PROPERTIES OF SOLID DIELECTRICS (130°C)

I. Thermally Upgraded Cellulose Insulation

With the advent of thermally upgraded cellulose insulation, the oil cellulose system can be extended to 130°C hot spot temperature applications for 10,000 hour life.

Cellulose is thermally upgraded by one of two available methods, (1) chemically modifying the finished material by the addition of inhibiting amine compounds and (2) the chemical modification of the cellulose at the pulp stage.

The pulp modification method, (cyanoethylation)* involves the replacement or partial replacement of the water forming primary hydroxyl groups of the glucose unit of the cellulose molecule chain (see figure 22B) with acrylic nitrile groups. The reduction of the water forming radicals in the cellulose, degradation of the material is substantially reduced at higher temperatures resulting in longer insulation life at any temperature.

Figure (23) depicts the thermal life comparisons of standard and cyanoethylated kraft insulations, (General Electric Co. registered tradename - "Permalex").

Permalex cellulose kraft papers and pressboards have the same electrical properties as the respective standard kraft materials.

II. Asbestos Products

The asbestos used as electrical insulation is a fibrous form of mineral (chrysolile). Electrically, it is a relatively poor insulating material, being characterized by high dielectric losses and low dielectric strength. Non-impregnated asbestos is also highly hygroscopic, limiting its use in moist envomments.

Extensive use of this material is found in low voltage, high temperature applications where the high mechanical properties at elevated temperatures is required. Impregnation of asbestos with various resins and compounds enhances the dielectric and hygroscopic properties, usually with some degradation of the thermal properties.

*General Electric Co. patent H.F. Miller, R. G. Flowers, U.S. Patent 2,535,690

Asbestos products have high values of dielectric constant, ranging from approximately $\epsilon = 3$ to $\epsilon = 45$, depending upon the amount and type of impregnant used. These high values of dielectric constant preclude the use of asbestos for normal audio transformer applications.

One serious disadvantage of the use of asbestos for audio transformer winding insulation is its weakness in mechanical tension and its tear resistance. Table (15) lists some of the mechanical properties of asbestos products, and comparative values for dry kraft paper properties.

Table (16) shows the electrical properties of typical asbestos products.

III. Mica Products

Mica has been used as electrical insulation for many years, and it still maintains an important place because of its high dielectric strength and excellent high temperature stability. Muscovite and phlogopite are the only types of natural mica that are extensively used as electrical insulation with the muscovite accounting for 95 percent of the total use.

However, pressed sheets of natural mica are not used extensively in liquid filled transformers. Transformer oils will permeate between the laminae of pressed sheets of mica, and because of the high dielectric constant of mica ($\epsilon = 6$-8), breakdown of the interlaminae oil ensues.

This high dielectric constant also precludes the use of mica and mica products for normal audio transformer applications, because of the increased interwinding, and interlayer capacitance resulting from the higher permittivity.

Table (17) lists some of the properties of natural mica.

Synthetic mica paper products, reconstituted synthetic mica is produced from synthetic mica (fluorphlogopite) and is available in laminated thickness of 2 - 7 mils. Various binders are used with synthetic mica paper to obtain different properties.

Table (18) shows some properties of a typical synthetic mica paper.

Composite laminated mica products are available in many varied laminae combinations of mica, glass cloth, tissue paper, cotton cloth, and various resins. It is felt that the discussion of the innumerable combinations is beyond the scope of this contract.

IV. Polyester Films

A. Mylar

Mylar is the commonly referred to tradename of a condensation product of ethyleneglycol and terephthalate acid. This material is a transparent film, available in sheet and tape thicknesses of 0.25 to 10 mils. It has excellent physical electrical and thermal characteristics.

1. Electrical Characteristics
   a. High dielectric strength
   b. Low dissipation factor
   c. High surface and volume resistivity

2. Physical Characteristics
   a. Good flexibility
   b. High tensile strength

3. Thermal Characteristics
   a. Wide service range, minus 60°C to plus 150°C.

Mylar, however, is adversely affected by corona discharges with consequential lowering of the dielectric and mechanical strength properties. This film is also subject to hydrolysis. At elevated temperatures (above 100°C) the presence of moisture in a sealed system produces hydrolysis with subsequent material embrittlement. Consideration should be given to eliminate moisture and moisture forming materials if the use of this material is contemplated in a sealed system.

Table (19) lists the typical properties of mylar - (Ref. 16).

TURN INSULATION

Wire can be insulated with various enamel films, cellulosic papers, or textile coverings. Textile insulations, cotton silk, linen, etc. are relatively obsolete and, therefore, will not be discussed.

I. Standard Cellulosic Wire Covering

Both round and rectangular wire are available with paper insulation covering. Round wires usually have a covering of 1 to mils thickness helix wrapped around the wire in a butt wrap, 1/2 lap wrap, 2/3 lap wrap or 3/4 lap wrap, providing respective thicknesses of 1, 2, 3 and 4 layers of paper.

Rectangular wires are covered by spiral wrapping in a lap of 68% or 78% of the paper tape width, or by intercalation of 4 paper tapes. Both methods provide four thicknesses of paper.

A. Application of Paper Covered Wires

1. Paper covered wires are usually specified when the transformer volts per turn are high and potential enamel defects cannot be tolerated.

2. Paper is used as insulation on large diameter round wire and rectangular wires of large crossectional area, where it is difficult to suitably apply a film enamel covering.

B. Advanges Of:

1. High mechanical strength
2. High dielectric strength
3. High resistance to solvent action.

C. Disadvantages of:

1. Readily absorbs and retains moisture
2. Relatively poor space factor
3. Limited aging stability
4. Does not preclude catalytic activity of the copper wire on transformer oil oxidation.
5. Limited to 105°C hot spot temperature operation.

II. Thermally Upgraded Cellulosic Wire Covering.

Wires insulated with thermally upgraded cellulosic paper extends the use of paper covered wire to class B (130°C) operation for 10,000 hour life.

III. Film Insulations

Rectangular and round wire is available with many different film insulations. No one material excels in all characteristics, therefore, the selection of a particular film depends upon the characteristics desired. In general, film insulation should possess the following characteristics.

A. High dielectric strength
B. Resistance to mechanical abrasion
C. Flexibility
D. Resistance to mechanical cutthrough
E. Resistance to embrittlement due to heating and aging.
F. Compatibility with other construction materials.
G. Resistance to solvents, acids and alkalies.

Table (20 lists the properties of commonly used film enamels, together with comments.

It is possible to obtain wire insulations in various combinations of enamels, combinations of fibrous insulations, and combinations of both.

Table (21) shows some of the available combinations of coverings.

SELECTION OF MATERIALS AND DESIGN PARAMETERS

Insulation material selection is a process of systematic elimination. The designer must first consider the overall system requirements that must be satisfied before any attempt is made to make a choice of materials. Generally, the operating temperature of the equipment imposes a greater limitation to the selection of insulant materials than any other factor. The system thermal requirements determines the broad classification of insulations that are suitable for application.

Further material classification depends upon the properties needed to satisfy the requirements of the intended use of the materials. Mechanical properties may be of next importance because dielectric materials are available in thin flexible sheets, and as thick rigid structures with varying degrees of mechanical characteristics.

Electrical properties, however, may be of prime importance. For audio transformer applications, the permittivity value of materials are significant.

It should be apparent from preceding discussions that insulation materials should meet the following general requirements:

1. High dielectric strength
2. Low dielectric loss
3. Low dielectric constant
4. Homogenous and void free
5. Contamination free
6. Resistance to chemical and thermal degradation including oxidation, at higher temperatures.
7. Moisture free

I. Coil Winding Insulation

Cellulose products will most generall be for 105°C and 130°C (10,000 hour life).

A. Winding Support Forms

Winding support forms provide a mechanical support for the coil windings, and insulation to isolate the electrical network from the core iron.

1. Material

Kraft pressboard and adhesive
Kraft paper and adhesive
Phenolic resin bonded kraft paper

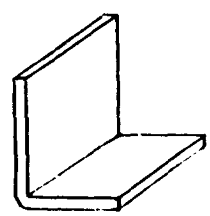
The selection of one of the above materials is dependent upon the support from physical characteristics.

2. Physical Characteristics

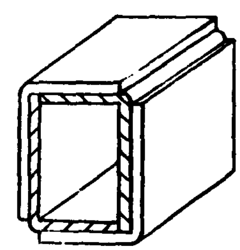
a. Cross Section

The crossectional configuration is usually rectangular or circular, depending upon the core crossection proportions.

Rectangular forms -
Rectangular forms are either wound with kraft paper with interlayer adhesive bonding or fabricated from kraft pressboard "L" shaped pieces, assembled with adhesive.



"L"
(4) REQUIRED



ASSEMBLY OF
(4) "L" PIECES

b. Length

Electrical and mechanical parameters determine the proper length of winding forms. The vertical dimension of the core window sets the maximum length of the form, however, voltage requirements may dictate the use of insulation barriers or collars at the axial ends of the coil and allowance must be made for this additional insulation.

c. Thickness

The form should have a wall dimension of sufficient thickness to limit the electrical stress in the form material to a safe level, and also to withstand the mechanical forces due to coil winding.

B. Interlayer Insulation

Interlayer insulations are thin flexible sheet or film materials used to standoff the interlayer potential between coil winding layers.

1. Materials

   Kraft paper
   Asbestos products
   Mica products
   Glass products
   Polyester films

2. Physical Characteristics

   a. Length

   Interlayer insulation length is determined from the circumferential dimension of the coil winding. In small coils, the mean length of turn of the coil is frequently used to determine the total length of the layer insulation. In large evils, the mean length of turn of radial coil sections is used as the basis of computation for individual sections.

   In instances where one thickness of insulation is used, the overlap at the insulation ends must be sufficient to meet the minimum surface creep dimensions based on the interlayer quality control test potential.

   b. Thickness

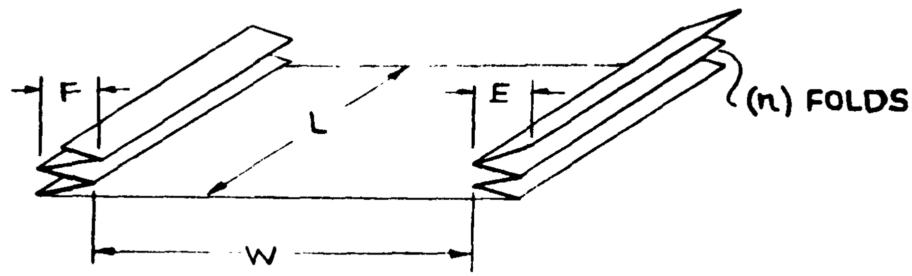
   In general, a single thickness of interleaving insulation, is not recommended because of the probability of the existance of volume imperfections in the solid, which would result in the interlayer potential being impressed entirely across the turn insulation. The use of multilayers of thin sheets in place of single thicker sheets also achieves a higher inception stress for internal discharges. If two or more sheets are used, the possibility of failure is greatly reduced.

   c. Width

   The interlayer insulation width depends on the axial length of the coil windings. Sufficient margins are required at the axial ends of the winding layers, to preclude interlayer voltage flashover under overvoltage quality control test conditions.

The developed width of the layer insulation will vary, dependent upon what method is used to mechanically retain the axial end turns of the coil winding.

Two methods of retaining end turns are in general use. (1) retaining strips and (2) folded layer insulation. Method (1) will be discussed separately. Folded layer insulation is a method that is most generally limited to cellulose papers as it does not lend itself readily to application with materials that are not easily folded. The following sketch shows the physical arrangement of this method.



Sketch of Folded Layer Insulation

L = Length of insulation
W = Width of insulation required by axial length of coil winding.
F = Required margin extensions (width of fold)
E = Required margin extensions (width of fold)
n = Number of folds

This system is primarily used with coil windings of small diameter round conductors. The number of folds (n), is determined by the relationship of the insulation thickness and the conductor diameter. To properly retain the conductor end turn, the total thickness of the folded margins should equal a minimum of 60 per cent of the conductor diameter. The developed width is determined as follows:

$$\text{Developed Width} = W + (n + 1) F + (n + 1) E$$

C. Cooling Ducts

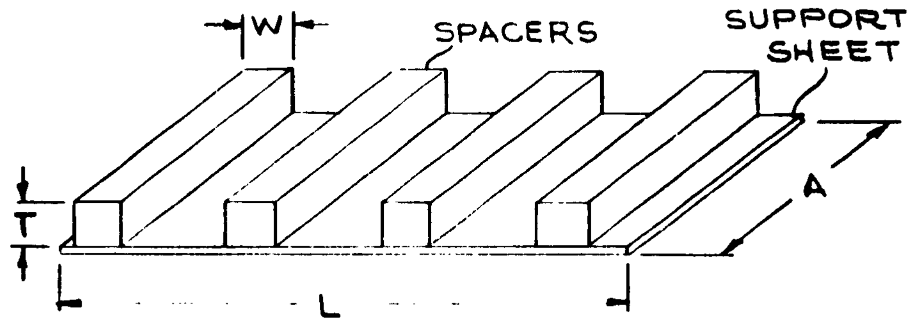
The use of cooling ducts and their location within the coil is determined by the thermal design requirements. Annular ducts are placed in the coil winding to provide a means for the axial flow of the cooling media.

Annular Ducts

1. Material

Annular ducts consist of an assembly of a support sheet, usually of the same material as the interlayer winding insulation, and rigid insulation spacer strips bonded to the support sheet.

2. Physical Characteristics



a. Length

The length (L) is determined from the peripheral dimensions of the coil at the required duct location.

b. Width

The assembly width (A) is equivalent to the axial length of the interlayer winding insulation.

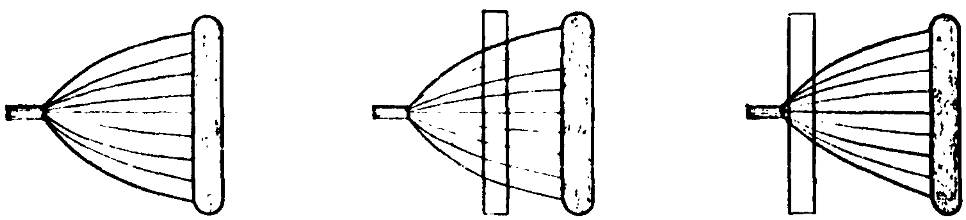
Spacer dimensions T, and W, and the required number of spacers are determined from the cooling requirements with due consideration to the effect of these parameters on the distributed capacitance of the overall structure.

D. Barriers

Many locations, external to the coil winding exist within a transformer where insulation must be maintained between parts. Various electrode configurations exist in these regions, such as smooth cables to sharp edged clamping structures. Figures 25A and 26A depict many of these electrode conditions. Rigid solid insulation barriers are used between electrodes to enhance the insulation strength of the total structure.

1. Location of Barriers Between Electrodes

The location of a barrier between electrodes has a pronounced effect on the electric strength of the structure. Placing a barrier adjacent to the electrode tends to cause a more uniform field in the dielectric liquid, thereby, increasing the corona start voltage level. The following figures illustrate this point.



A B C

No barrier is used in figure A, and a high intensity field occurs in the liquid at the rod electrode with a resultant low corona start voltage level in the liquid.

Placing a barrier between the electrodes as shown in figure B increases the overall electric strength of the system, but the dielectric liquid at the rod gap is still highly stressed. By locating this same barrier adjacent to the rod gap, the high intensity field occurs in the barrier, rather than in the liquid.

The liquid may be stressed higher with this structure, because the solid has a higher corona voltage starting point than the liquid.

TRANSFORMER DRYING AND IMPREGNATION

Drying treatments of transformer coil assemblies are for the purpose of removing moisture from the insulation structure. Moisture removal improves the dielectric strength, lowers the dielectric losses and improves the permittivity of the insulation. Moisture retained in the solid insulation will transfer from the solid to the liquid insulant during transformer operation, lowering the dielectric properties of the liquid insulant. This moisture transfer continues until a state of equilibrium is reached between the water content of the liquid and solid structures.

Shrinkage of the solids occurs with the removal of moisture during the drying treatment. The coils of larger transformers can then be mechanically packed tight after a drying process to ensure a more rigid mechanical structure.

Because of the degradation effects of higher temperatures on solid insulations, especially the cellulosic solids, the removal of moisture is not easily attained. Two drying methods are in general use; (1) circulating hot air with a vacuum break and (2) vapor phase drying treatment.

1. Circulating Hot Air With a Vacuum Break

   This method is an oven drying technique that is most generally used for relatively small, assembled transformers (15 KV and under). Drying is carried out in high air velocity ovens with air temperatures held to a maximum of 125 degrees centigrade. The air temperature is accurately controlled and drying should be continued until the coldest spot in the coil reaches a temperature of 110 degrees centigrade as determined by thermocouples affixed to the coil assembly of a representative transformer in the drying load. Open completion of the drying treatment, the transformers should be transferred to a pressure vessel for vacuum treatment. This transfer should be arranged so that the vacuum treatment can be initiated before the coil cold spot temperature drops below 100°C. Pressure in the vacuum tank is reduced to an absolute value of 1 millimeter of mercury or better within 15 minutes or less, and held for a minimum of 1 hour. Degassed and dried liquid insulant is introduced under vacuum, flood filling the dried transformers.

2. Vapor Phase Drying Treatment

   This method is used for large, high voltage transformers that have a high content of solid insulation. The vapor phase system consists of a low boiling point liquid which is allowed to condense on the transformer core and coil assemblies, using the latent heat of vaporization and condensation in transferring heat. Rapid heat transfer to the drying load is provided, and thermal gradients in the treat tank are eliminated.

   The physical system consists of an internally heated pressure tank that may also serve as the boiler for the low boiling point liquid, suitable vacuum pumps, condensers, and control devices.

   In this process, the coreand coil assemblies are placed in the treatment tank, and pressure is reduced to an absolute value of 2 millimeters of mercury or less. When the proper vacuum has been reached, the internal tank heating is turned on, and the low boiling point liquid is introduced to the bottom of the pressure tank. This liquid, which is a hydrocarbon fraction similar to kerosene, vaporizes and condenses on the colder core and coil assemblies, giving up its latent heat of vaporization, heating the coils and vaporizing the moisture in the coils.

Tank temperatures are closely controlled to preclude the coil temperature from exceeding 110 degrees centigrade. This is determined by thermocouples affixed to the top and bottom of the core and coil assemblies.

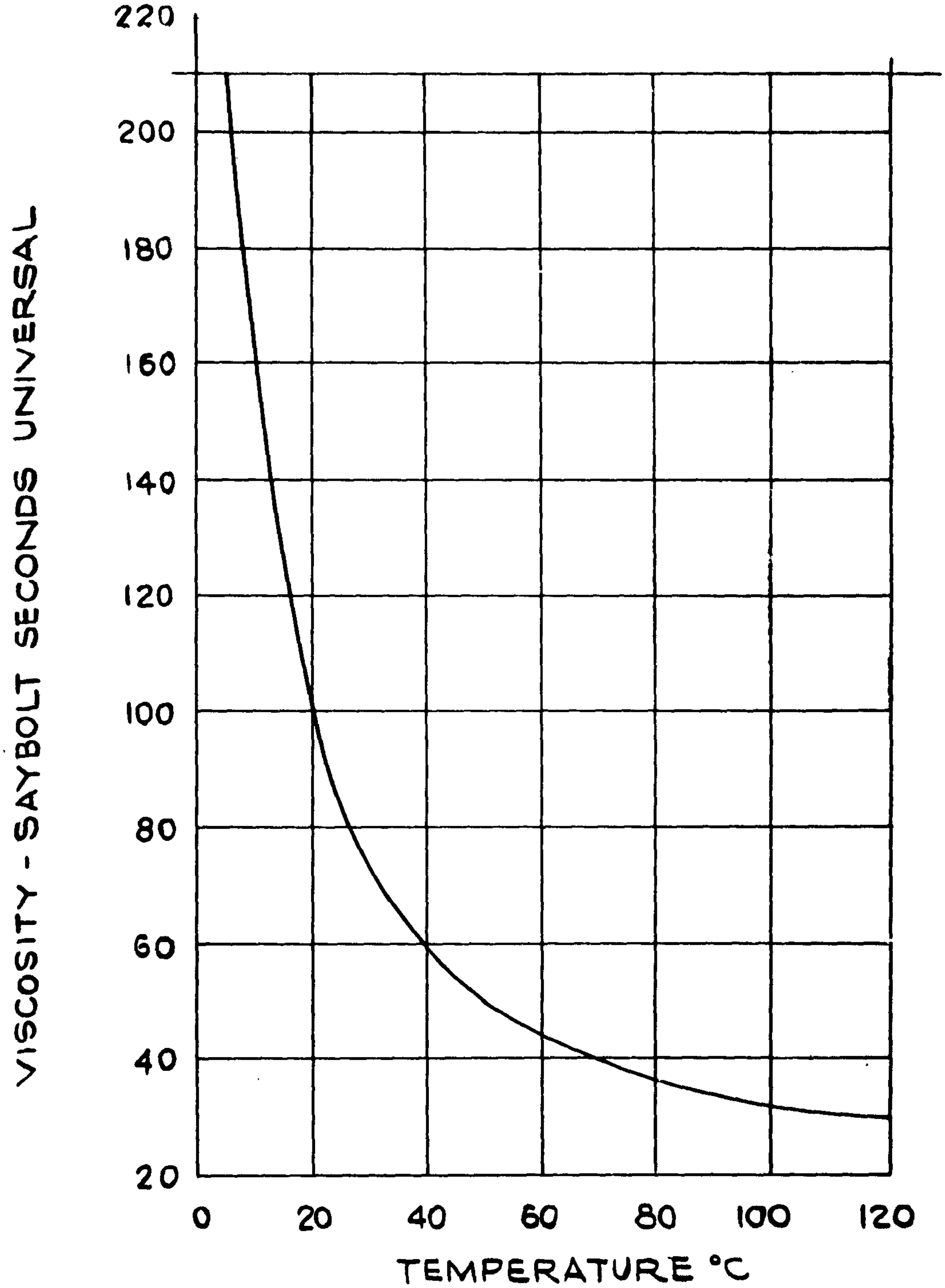
Evacuated air moisture and oil vapors are directed through appropriate heat exchangers and settling tanks. The condensed oil returns to the pressure tank to recycle. This process is allowed to continue for approximately 12 hours, after which the temperature is reduced to room temperature, and the tank vacuum is released. The vapor phase oil is then removed from the pressure tank and the values of temperature and pressure are reset to the initial values. Vacuum and heating are continued until insulation power factor measurements indicate the drying process is completed.

Flood filling of the core and coil assemblies with the impregnating liquid introduced under vacuum follows the drying process. After thorough impregnation of the system, the vacuum is released, and the assemblies are allowed to remain in the impregnate for a period of time, during which the atmospheric pressure forces the impregnate into the insulation. After completion of the soaking interval, the impregnate is drained from the treatment tank, and the core and coil assemblies are removed. After removal, the assemblies are mechanically adjusted to compensate for insulation shrinkage, after which the assemblies are tanked.

DEFINITION OF SYMBOLS

The symbols used in this milestone are defined in the following tabulation:

Symbol	Definition
ψ	Electric flux
E	Electric intensity; Voltage
ϵ_o	Permittivity of free space
ϵ_r	Relative permittivity
D	Dissipation factor; electric flux density
P.F.	Power Factor
K	Thermal conductivity in BTU-FT/FT^2-hr. °C
g	Voltage gradient; gram
V_i	Discharge inception voltage
n	Logarithm to base e
cc	Cubic centimeter
BTU	British thermal units
ω	$2\pi f$



VISCOSITY VS TEMPERATURE FOR
10 C TRANSFORMER OIL (REF. 8)

FIG. 22

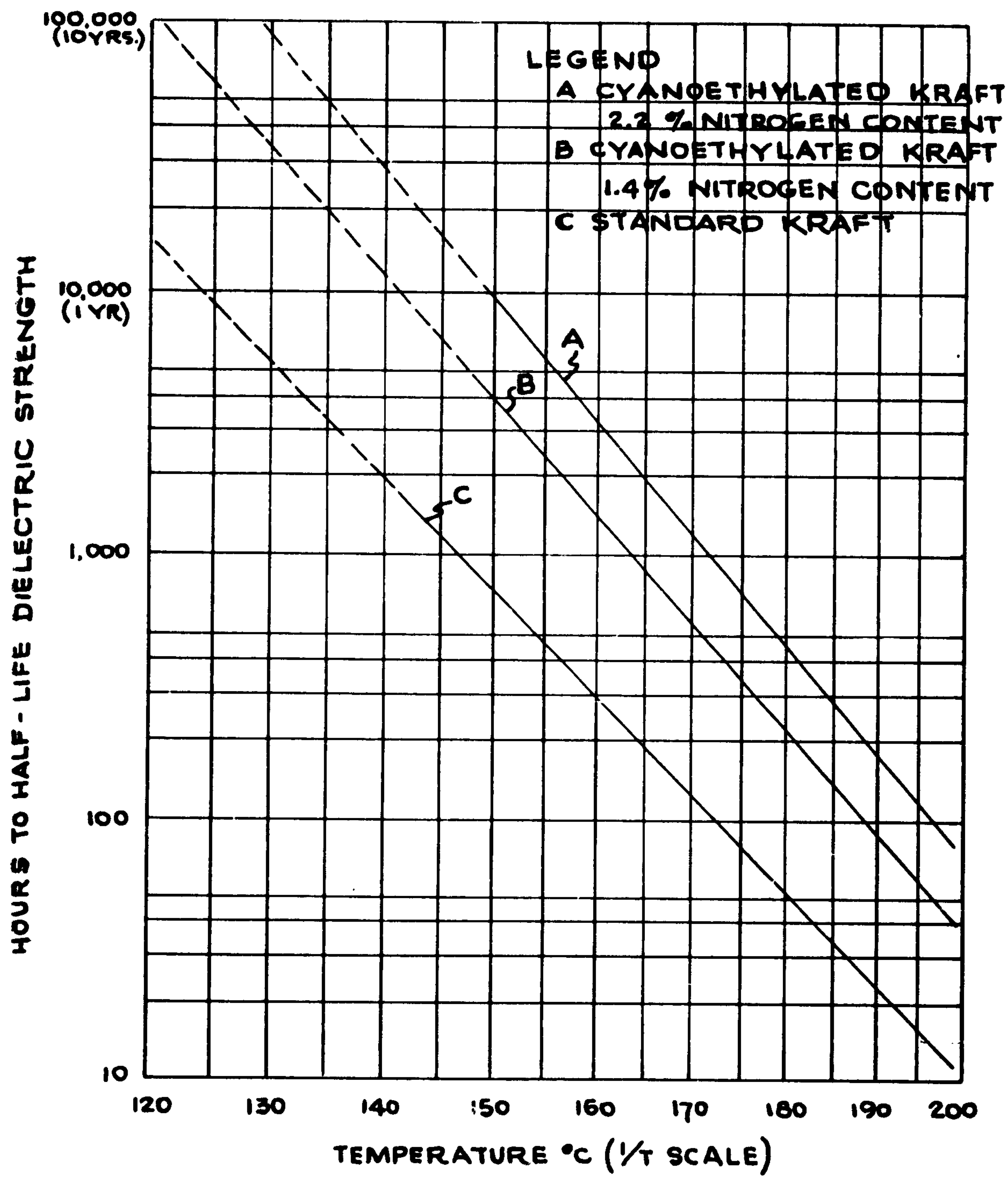


FIG. 23

Time to half life dielectric strength versus temperature for cyanoethylated and standard kraft insulations.

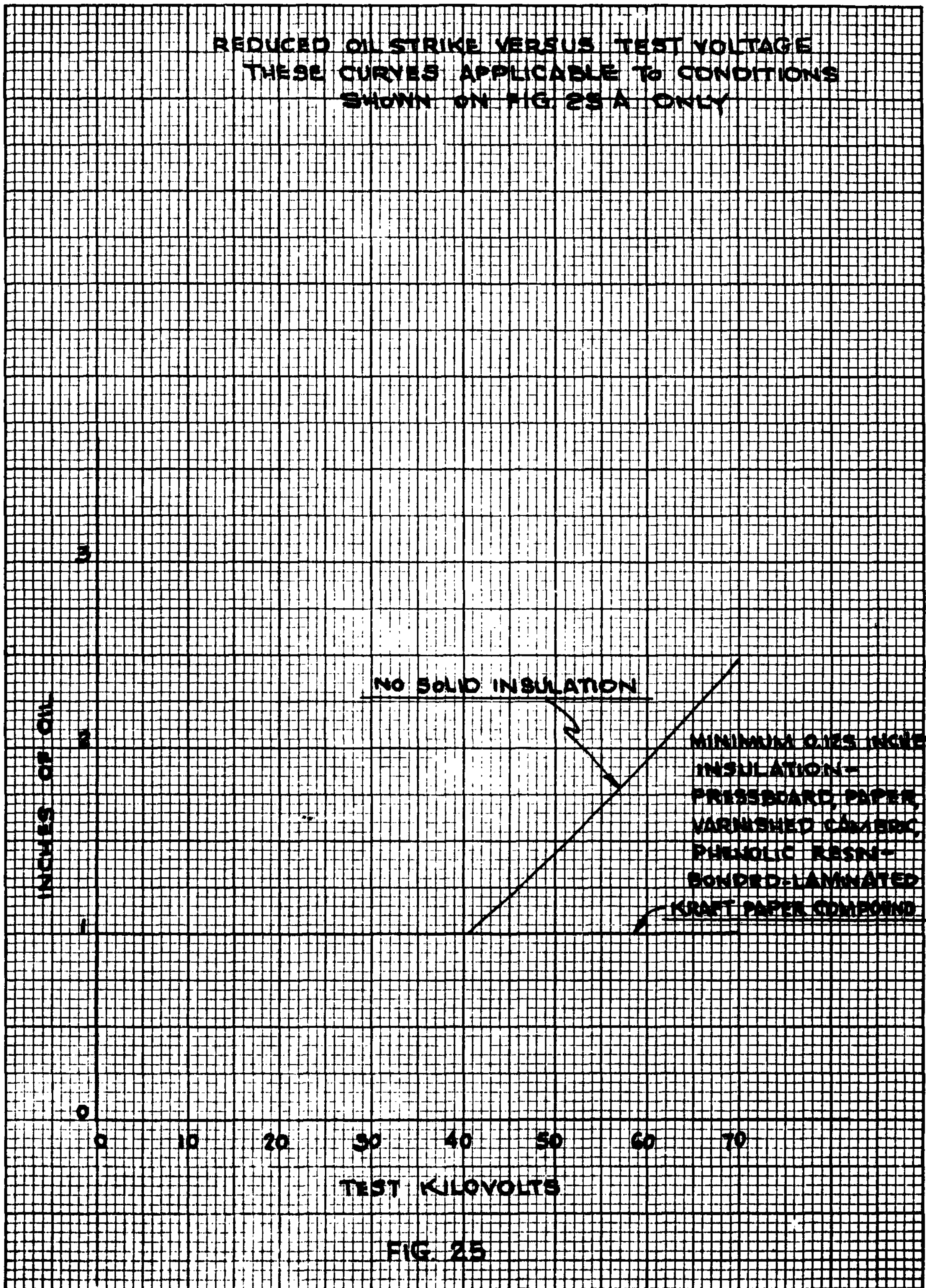

REDUCED OIL STRIKE VERSUS TEST VOLTAGE
THESE CURVES APPLICABLE To CONDITIONS
SHOWN ON FIG 25 A ONLY
NO SOLID INSULATION
MINIMUM 0.125 INCHES INSULATION- PRESSBOARD, PAPER, VARNISHED CAMBRIC, PHENOLIC RESIN-BONDED-LAMINATED KRAFT PAPER COMPOUND
INCHES OF OIL
0
1
2
3
0
10
20
30
40
50
60
70
TEST KILOVOLTS

FIG. 25

OIL STRIKE REDUCED ALLOWANCES
(USE CURVES FIG. 25 FOR THESE CONDITIONS)

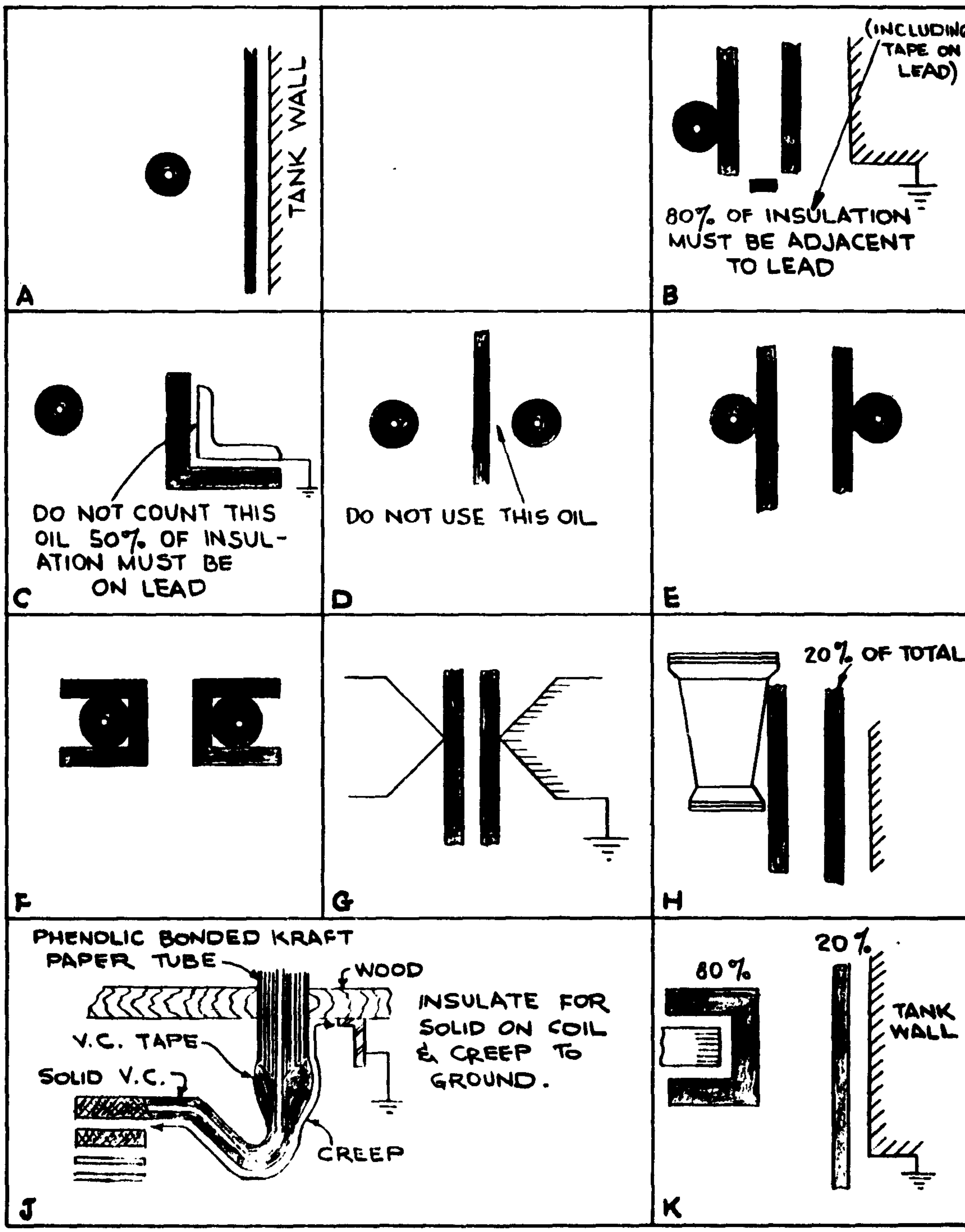


FIG. 25 A

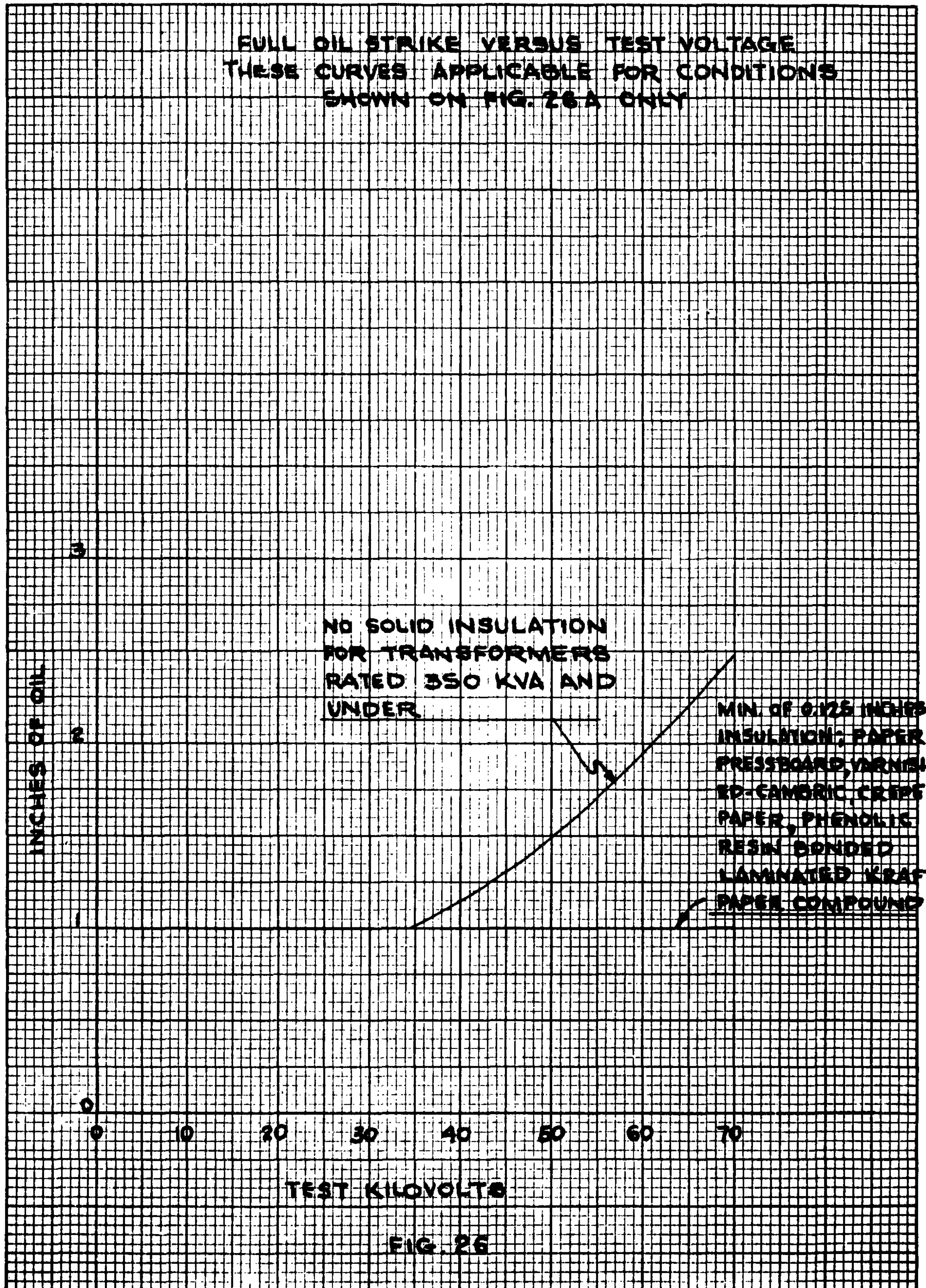

FULL OIL STRIKE VERSUS TEST VOLTAGE
THESE CURVES APPLICABLE FOR CONDITIONS
SHOWN ON FIG. 26A ONLY
NO SOLID INSULATION
FOR TRANSFORMERS
RATED 350 KVA AND
UNDER
MIN. OF 0.125 INCHES
INSULATION; PAPER,
PRESSBOARD, VARNISH-
ED-CAMBRIC, CREPE
PAPER, PHENOLIC
RESIN BONDED
LAMINATED KRAFT
PAPER COMPOUND
INCHES OF OIL
0
1
2
3
0
10
20
30
40
50
60
70
TEST KILOVOLTS

FIG. 26

OIL STRIKE FULL ALLOWANCES
(USE CURVES FIG. 26 FOR THESE CONDITIONS)

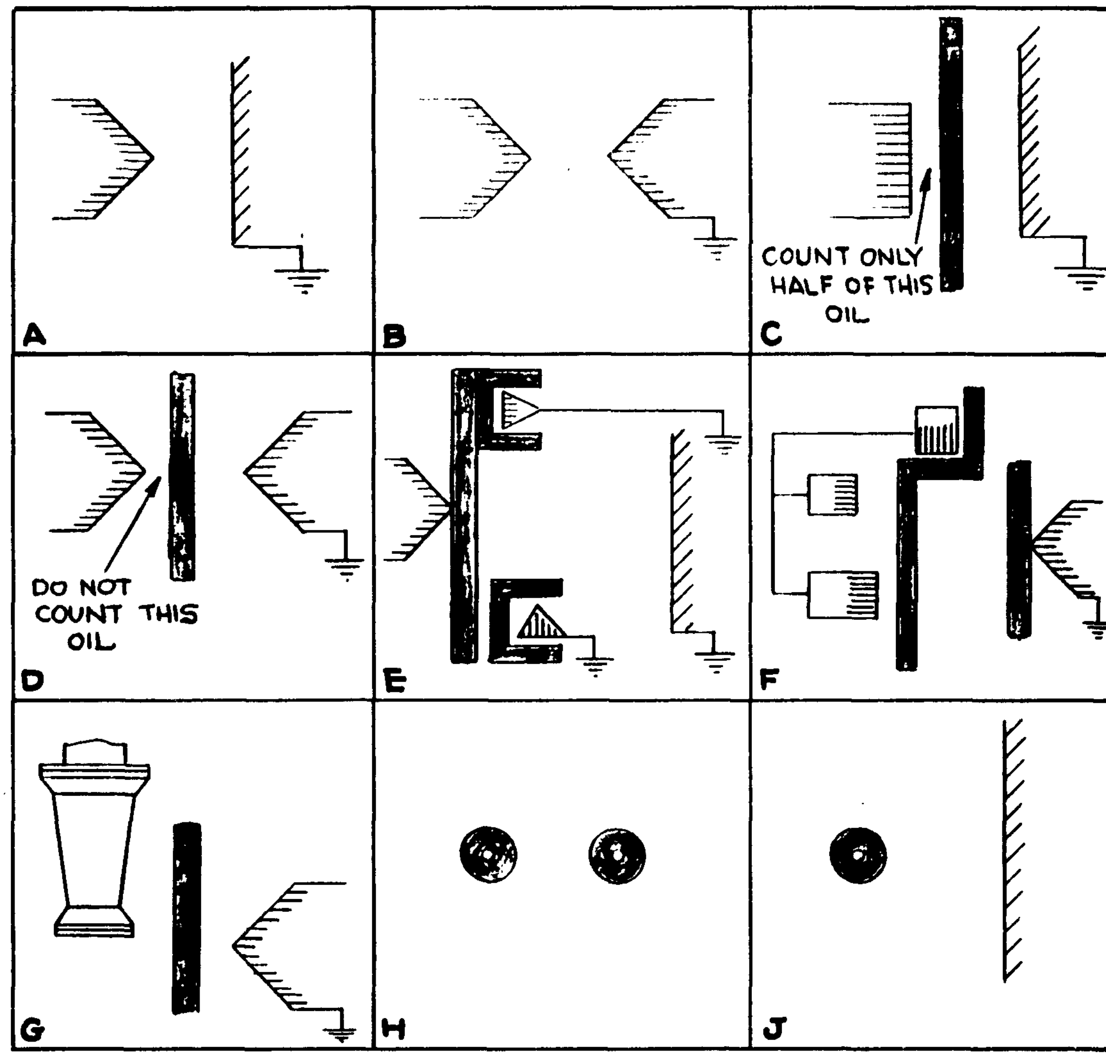


FIG. 26 A

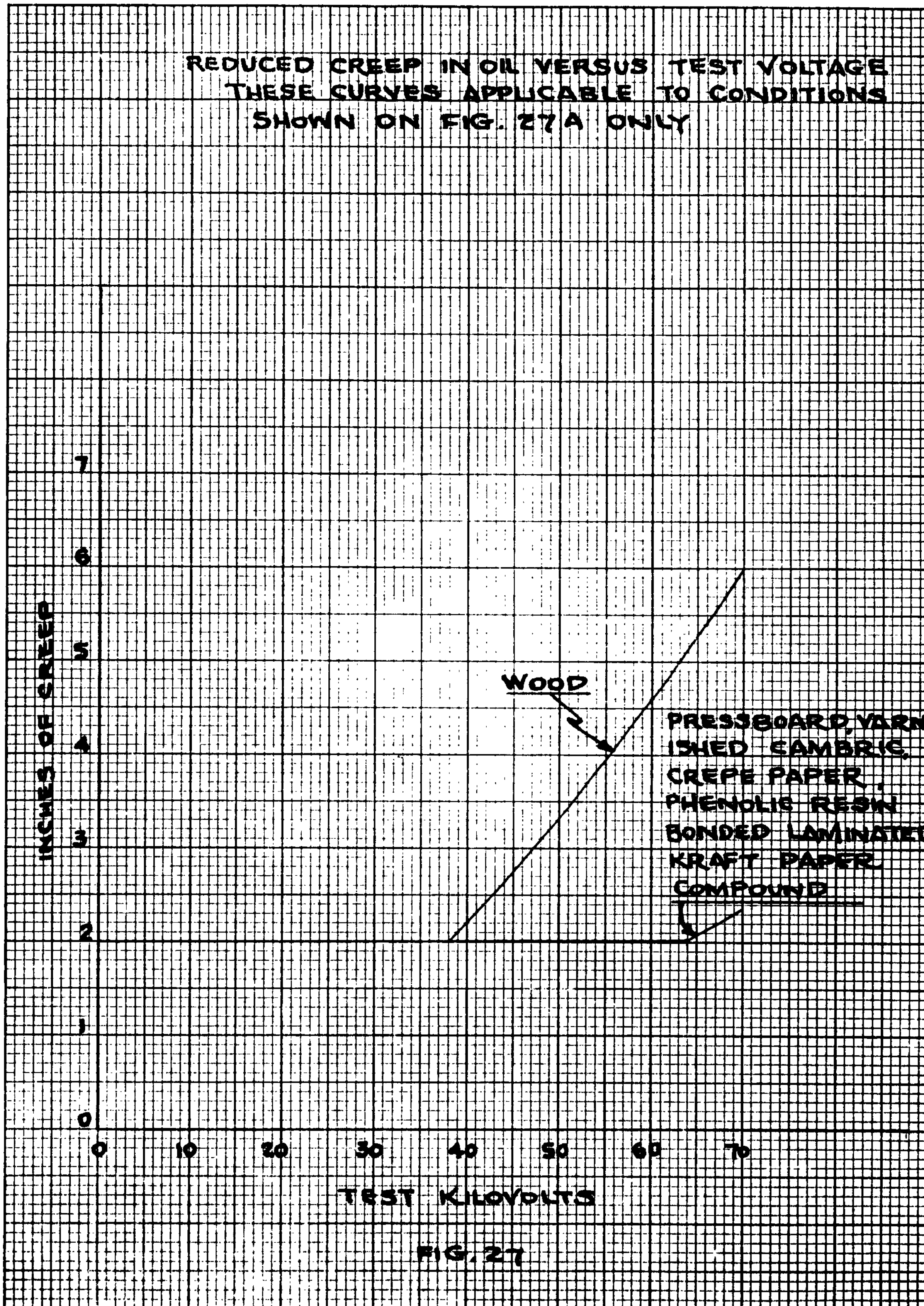
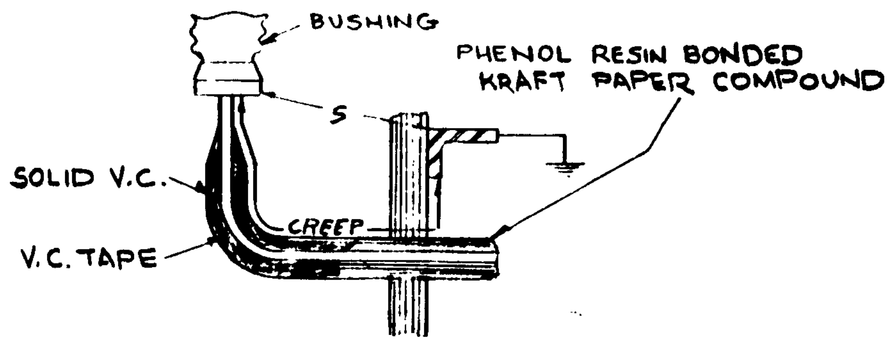

REDUCED CREEP IN OIL VERSUS TEST VOLTAGE
THESE CURVES APPLICABLE TO CONDITIONS
SHOWN ON FIG. 27A ONLY
INCHES OF CREEP
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
70
TEST KILOVOLTS
WOOD
PRESSBOARD, VARNISHED CAMBRIC, CREPE PAPER, PHENOLIC RESIN BONDED LAMINATED KRAFT PAPER, COMPOUND

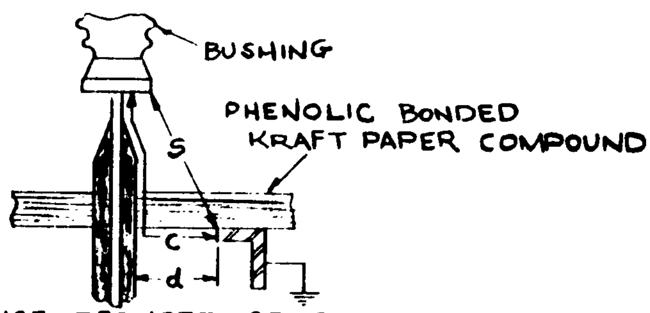
FIG. 27

REDUCED CREEP IN OIL
(USE CURVES FIG.27 FOR THESE CONDITIONS)



INSULATE FOR REDUCED CREEP FROM BUSHING TO GROUND, IF "S" IS 60% OR MORE OF CREEP.

A

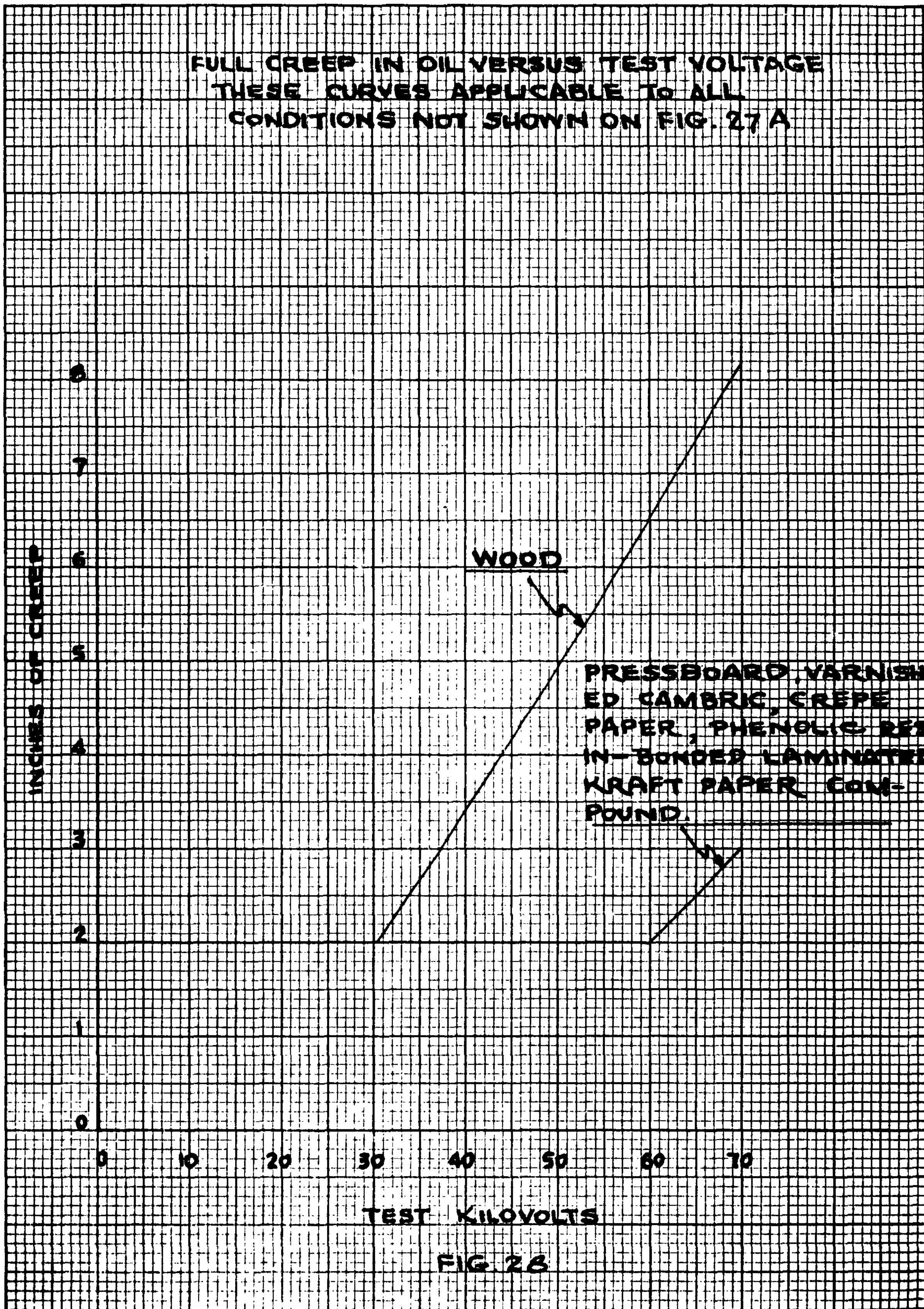


USE REDUCED CREEP ONLY IF "S" IS 60% OR MORE OF "C" (CREEP)

"d" MUST BE FULL CREEP.
IF "d" IS LESS THAN TWICE IN MINIMUM OIL FOR FULL STRIKE, "C" MUST BE FULL CREEP

B

FIG. 27 A



FULL CREEP IN OIL VERSUS TEST VOLTAGE
THESE CURVES APPLICABLE TO ALL
CONDITIONS NOT SHOWN ON FIG. 27A
INCHES OF CREEP
0
1
2
3
4
5
6
7
8
WOOD
PRESSBOARD, VARNISHED CAMBRIC, CREPE PAPER, PHENOLIC RESIN-BONDED LAMINATED KRAFT PAPER COMPOUND.
0
10
20
30
40
50
60
70
TEST KILOVOLTS

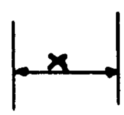
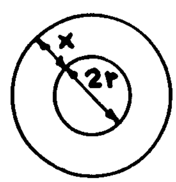
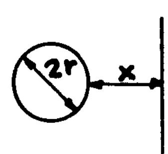
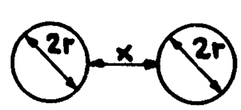
FIG. 28

The maximum voltage gradients for the most common electrode configurations are listed below:

(from "The Maximum Electrical Field Strength for Several Simple Electrode Configurations" by A. Bourvers and P. G. Cath - Philips Technical Review Sept. 1941).

TABLE 1

Maximum voltage gradient E in KV per inch or volts per mil with a potential difference V in KV between the electrodes, for different electrode configurations:

Configuration	Formula for E	Example
Two parallel plane plates 	$\frac{V}{x}$	V=100 kV, x= 2 in, E= 50 kV/in.
Two concentric spheres 	$\frac{V}{x} \cdot \frac{r+x}{r}$	V= 150 kV, r= 3 in, x = 2 in, E= 125 kV/in.
Sphere and plane plate 	$0.9\,\frac{V}{x} \cdot \frac{r+x}{r}$	V= 200 kV, r= 5 in, x = 8 in, E= 58.5kV/in.
Two spheres at a distance **x** from each other 	$0.9\,\frac{V}{x} \cdot \frac{r+x/2}{r}$	V= 200 kV, r= 5 in, x= 12 in, E= 33kV/in.

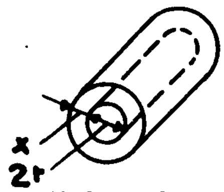
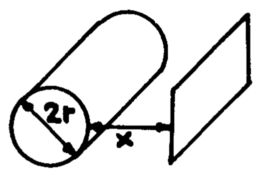
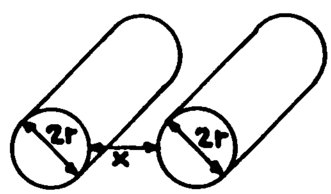
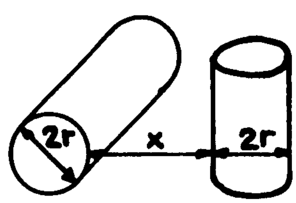
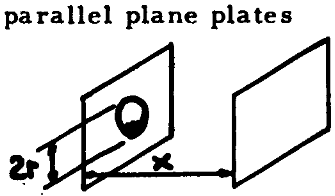
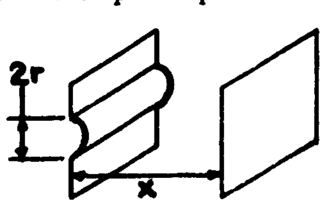
Configuration	Formula for E	Example
Two coaxial cylinders  	$\dfrac{V}{r \ln \dfrac{r+x}{r}}$	V= 100 kV, r= 5 in, x= 7 in, E= 22.9kV/in.
Cylinder parallel to plane plate  	$0.9 \dfrac{V}{r \ln \dfrac{r+x}{r}}$	V= 200 kV, r= 5 in, x= 10 in, E=32.8kV/in.
Two parallel cylinders  	$0.9 \dfrac{V/2}{r \ln \dfrac{r+x/2}{r}}$	V= 150 kV, r= 6 in, x= 20 in, E=11.5 kV/in.
Two perpendicular cylinders  	$0.9 \dfrac{V/2}{r \ln \dfrac{r+x/2}{r}}$	V= 200 kV, r= 10 in, x= 10 in, E=22.2kV/in.
Hemisphere on one of two parallel plane plates  	$\dfrac{3V}{x}$; $(x \gg r)$	V= 100 kV, x= 10 in, E= 30 kV/in.
Semicylinder on one of two parallel plane plates  	$\dfrac{2V}{x}$: $(x \gg r)$	V= 200 kV, x= 12 in, E= 33.3 kV/in.

TABLE 2

Relative Permittivities of Typical Insulation Materials

Material	Relative Dielectric Constant (permittivity) ϵ_r
Dry air (atm. pr. $0^{o}C$)	1.00058
Asphalt	2.5
Bakelite	4.5
Glass	4-10
Mica	5-7
Oil transformer	2-2.5
Askarel	4-5
Paper (dry)	2-3.5
Paper (oiled)	4-4.5
Pressboard (dry)	3
Pressboard (oiled)	4-5
Porcelain	4-9
Wood (treated)	3-3.5

TABLE (8)

Comparison of Values Found in Askarel Insulation After Various Stages of Use

	A	B	C	D	E	F
Physical Properties	New askarel	Askarel in properly* built new or rebuilt units prior to use.	Typical values after normal operation. (Survey of 50 units mostly 2-5 yrs. old-some (10)	Non-arced but slightly contaminated askarel in improperly* built units, new or slightly used.	Same fluid in column D after refining with earth & filtering.	Heavily arced askarels. Of the very few askarel failures, the majority were due to excess water-remainder due to internal electrical discrepancy.
Color	Light straw	Light straw	Light straw	Foreign shades, blue, green, red cast.	Foreign shades remain showing extraction of oil soluble color.	Black
Condition	Clear, free from particles	Clear, practically free from particles	Clear, trace of particles.	Clear, slight amount of particles.	Clear, free from particles.	Contains carbon particles.
Moisture, 25°C	30 ppm	30 ppm	10-70 ppm, all dissolved water	20-100 ppm, all dissolved water	30 ppm	near or above saturation level, 125 ppm, partially undisolved water

*A properly built unit is defined as one in which the materials of construction are chemically and electrically compatible with askarel. (REF. 18)

TABLE (8A)

Comparison of Values Found in Askarel Insulation After Various Stages of Use

	A	B	C	D	E	F
Electrical Properties	New askarel	Askarel in properly* built new or rebuilt units prior to use.	Typical values after normal operation. (Survey of 50 units mostly 2-5 yrs. old-some 10)	Non-arced but slightly contaminated askarel in improperly* built units, new or slightly used.	Same fluid in column D after refining with earth & filtering.	Heavily arced askarels. Of the very few askarel failures, the majority were due to excess water-remainder due to internal electrical discrepancy.
Dielectric strength, 25°C, 0.1-in. gap	35 kv min.	35-18 kv	35-45 kv	30-42 kv	40-45 kv	5-15 kv
Volume resistivity, 100°C, 500 V. d-c, 0.1 inch gap	100 x 10' ohm-cm min. usually 500-1500	20 x 10' ohm-cm min. usually at least 100 x 10'	15-400 x 10' ohm-cm	about 5 x 10' ohm-cm	at least 1500 x 10' ohm-cm	about 3 x 10' ohm-cm
Power Factor: 100°C, 60 cycles	2-5%	10-25%	10 to near 80%	30 to 100%	2-5%	100%
25°C, 60 cycles	0.05-0.1%	0.5-2%	0.5 to near 10%	about 7 to over 15%	0.1-0.2%	at least 25%

*A properly built unit is defined as one in which the materials of construction are chemically and electrically compatible with askarel. (REF. 18)

TABLE 9

KRAFT PAPER

Thickness (inches)	Density (g/cc)	Breaking Strength lbs/one inch Strip		Tearing Strength Grams		Short Time Dielectric Strength Volts
		MD	CMD	MD	CMD	
.005(A)	1.05-1.3	42	15	85	100	1400
.010(A)	1.05-1.3	60	35	150	300	2700
.015(A)	1.05-1.3	180	75	325	500	3500
.020(A)	1.00-1.2	220	85	400	600	3700
.025(A)	0.95-1.2	250	125	875	1000	4000
.030(A)	0.90-1.17	300	140	1000	1200	4300
.010(B)	0.78	120	30	200	300	1800
.015(B)	0.78	170	40	300	450	2400
.020(B)	0.78	210	50	450	650	3000
.030(B)	0.78	270	75	750	1100	3500
.005(C)	0.8-0.9	40	20	-	-	1000
.010(C)	0.8-0.9	80	40	-	-	1500
.015(C)	0.8-0.9	100	75	-	-	2250

A - Super calendered kraft paper - high glazed surface finish

B - Rough finished surface - minimum of calendering

C - Medium finished surface - machine calendered.

TABLE 10

KRAFT PRESSBOARD

THICKNESS (INCHES)	DENSITY (g/cc)	TENSILE STRENGTH (CBS/INCH)		SHORT TIME DIELECTRIC STRENGTH VOLTS/MIL
		MD	CMD	
.031 A	1.1-1.2	420	140	-
.040 A	1.1-1.2	500	190	-
.062 A	1.1-1.2	835	280	-
.093 A	1.0-1.1	1000	370	-
.125 A	1.0-1.1	-	-	-
.187 A	.95-1.1	-	-	-
.250 A	.95-1.1	-	-	-
.031 B	0.9-1.1	-	-	150
.062 B	0.9-1.1	-	-	-
.093 B	0.9-1.1	-	-	-
.125 B	0.9-1.1	-	-	-
.031 C	1.2-1.3	310	110	325
.062 C	1.2-1.3	620	215	300
.031 D	1.25-1.35	450	150	-
.062 D	1.25-1.35	850	275	-
.125 D	1.25-1.35	1500	500	-

A - DENSE TOUGH GRADE REASONABLE FORMABILITY

B - LOWER DENSITY GRADE MEDIUM FORMABILITY

C - ROSIN SIZED - USUALLY FOR MECHANICAL APPLICATION

D - EXTRA HIGH DENSITY - USED FOR ELECTRICAL AND MECHANICAL APPLICATIONS IN TRANSFORMERS. VERY POOR FORMABILITY - ROSIN SIZED.

TABLE 12

ASTM PHYSICAL REQUIREMENTS FOR COTTON TAPE

*ASTM Type	Thickness Inches	Width Inches	Total Ends (Warp)	Picks Per Inch (Filling)	Min. Yds. Per Lbs.	Breaking Strength Min. Lbs.	Recommended Yarn Numbers
A-1	.005	1/2 3/4 1	36 56 72	36 36 36	350 270 200	25 30 40	20/1 Warp 38/1 Filling
A-2	.007	1/2 3/4 1 1-1/4 1-1/2	36 56 72 92 108	36 36 36 36 36	290 190 140 110 90	25 30 40 50 60	20/1 Warp 30/1 Filling
A-3	.007	1/2 3/4 1 1-1/4 1-1/2	36 56 72 92 108	28 28 28 28 28	300 200 150 120 100	25 30 40 50 60	20/1 Warp 30/1 Filling
B-1	.013	1/2 3/4 1 1-1/4 1-1/2	52 76 100 135 148	40 40 40 40 40	220 150 115 85 75	40 65 85 115 130	20/1 Warp 30/1 Filling
B-2	.020	1/2 3/4 1 1-1/4 1-1/2	40 60 80 100 120	40 40 40 40 40	110 95 70 55 45	50 75 100 125 150	20/2 Warp 20/1 Filling
C-1	.030	1/2 3/4 1 1-1/4 1-1/2	60 80 100 132 150	40 40 40 40 40	110 90 70 55 45	60 75 90 115 140	20/2 Warp 20/1 Filling

*A indicates plain weave; "B" is herringbone weave (at least single point twill two up and two down); and "C" is non-elastic weave.

(Ref. 16)

TABLE 13

CHARACTERISTICS OF VARNISHED COTTON CLOTH

Black Varnished (Straight Weave)					
Thickness inches	.005	.007	.010	.012	.015
Bare cloth thickness inches	.0035	.005	.005	.005	.005
Temperature class	A(105°C)	A(105°C)	A(105°C)	A(105°C)	A(105°C)
Dielectric Strength (volts/ mil)					
After 48 hrs., 22°C, 50% RH	-	1740	1495	1655	-
After 96 hrs. at 96% RH	-	660	680	680	-
Power factor at 100°C	-	24%	18%	16%	-
Breaking Strength (lbs./inch width)	-	57	56	56	-
Gurley Stiffness (gms)					
Lengthwise	-	87	89	89	-
Crosswise	-	38	46	57	-
Black Varnished (Bias cut, 45° angle)					
Thickness inches	-	.007	.010	.012	.015
Bare cloth thickness inches	-	.0055	.0055	.0055	.0055
Temperature Class	-	A(105°C)	A(105°C)	A(105°C)	A(105°C)
Initial	-	1375	1530	1580	1900
6% elongation	-	1050	1760	1440	1300
After 96 hrs. at 96% RH	-	392	-	525	-
Power Factor 100°C	-	-	32%	15%	15%
Breaking Strength lbs/in.	-	58	58	52	52

TABLE 14

CHARACTERISTICS OF OIL VARNISHED SILK

(TEMPERATURE CLASS A-(105°C)

FINISHED MATERIAL THICKNESS INCHES	BREAKING STRENGTH (WARP DIRECTION LBS/INCH WIDTH	SHORT TIME DIELECTRIC STRENGTH-VOLTS/MIL
.002	14	1800
.003	14	1800
.005	14	1600

TABLE 15

TYPICAL MECHANICAL PROPERTIES OF ASBESTOS AND KRAFT PAPER

MATERIAL	RESIN IMPREGNATE	THICKNESS (MILS)	TEAR STRENGTH (GRAMS)		TENSILE STRENGTH (LBS./INCH OF WIDTH)	
			CMD[1]	MD[1]	CMD	MD
KRAFT PAPER	-	10	300	200	30	120
KRAFT PAPER	-	5	130	120	20	70
ASBESTOS	EPOXY (25%)	9	48	-	-	-
ASBESTOS	EPOXY (45%)	3.5	-	-	-	15.0
ASBESTOS	NONE	3.0	-	-	-	0.35
ASBESTOS	NONE	9	-	-	-	1.15
ASBESTOS	POLYVINYL ACETATE	3	-	-	-	7.0
ASBESTOS	POLYVINYL ACETATE	9	-	-	-	13.0

[1] CMD - IS IN CROSS MACHINE DIRECTION
MD - IS IN MACHINE DIRECTION

TABLE 16
(Ref. 17)

TYPICAL ASBESTOS INSULATION PROPERTIES

Resin Impregnate	Thickness Mils	Temperature Class	Dielectric Strength (VPM)	Dielectric Constant	Power Factor %
None	3	B-(105°C)	290	6	30
Silicone	3	H	290	5	25
Silicone	5.5	H	350	8	25
Epoxy (25%)	3.5	F	275	8.0	25
Epoxy (45%)	3.5	F	700	2.5	6

TABLE 17

THE PROPERTIES OF NATURAL MICA

Properties	Muscovite	Phlogopite
Specific gravity	2.8	2.8
Specific heat	0.207	0.207
Dielectric strength-VPM*	3000-6000	3000-4200
Dielectric Constant	6.5-8.7	5-6
Thermal Conductivity, Watts/in °C	.009	-

*(1-2 mils thick in air - dielectric strength decreases with increased thickness).

TABLE 18

TYPICAL PROPERTIES OF SYNTHETIC MICA PAPER

Properties	
Apparent density gm/cc	1.7-2.0
Melting point °C	1365
Tensile strength psi	(5 to 10) x 10^3
Dielectric constant	4
Dielectric strength	600

TABLE 19

TYPICAL PROPERTIES OF MYLAR

TENSILE STRENGTH, PSI	20,000 - *
TENSILE MODULUS, PSI	550,000 - *
BREAK ELONGATION, %	100 - *
BURSTING STRENGTH, MULLEN	45 LB. - *
SPECIFIC GRAVITY	1.39
DIELECTRIC STRENGTH, VPM	
25°C, 60 CPS	4,000
150°C, 60 CPS	3,150
DIELECTRIC CONSTANT	
25°C, 60 CPS	3.2
25°C, 1 KC	-
DISSIPATION FACTOR	
25°C, 60 CPS	0.002
25°C, 1 KC	0.005
SURFACE RESISTIVITY, OHMS	
25°C, 100% RH	4.8 x 10[11]
VOLUME RESISTIVITY, OHM-CM	
MOISTURE ABSORPTION, %	<0.5
MOISTURE VAPOR PERMEABILITY,	
G/100 M^2/HR/MIL	100
G/100 IN^2/24 HR/MIL	-
MELTING POINT	250-255°C
SERVICE TEMPERATURE	-60 TO 150°C

* 1.0 MIL THICKNESS

TABLE 20

PROPERTIES OF INSULATING ENAMELS FOR WIRE

Wire Film Material	MIL-W-583B Type	Maximum Temperature Class (°C)	NEMA Twisted Pairs Dielectric Strength (Volts per mil)	Dissipation Factor at 25°C, Frequency CPS 10^2	Dissipation Factor at 25°C, Frequency CPS 10^5	Film Dielectric Constant	Comments
Oleoresinous (plain)	E, E2	105	1000	.02	-	2.5	Inexpensive-Good resistance to solvent action (compatible with askarels) Limited to thin films
Phenolic modified polyvinyl formal	T,T2,T3,T4	105	1500	.005	.0195		Resistant to hydrolysis-good abrasion resistance-subject to solvent action by (askarels)
Polyamides (Nylon)	T,T2,T3,T4	105	1500	.122	.068		Susceptible to hydrolysis-poor cut through resistance-solderable without mechanical film removal-good flexibility
Polyepoxides (epoxy)	B,B2,B3,B4	130	2000	.0033	.023		Very resistant to hydrolysis-good resis. to solvent action-good thermal resis.-tough-poor flexibility if not modified.
Polyester	B,B2,B3,B4, L,L2,L3,L4	130 155	2500	.003	.025		Good thermal resistance-Very susceptible to hydrolysis-good mech. properties
Polytetrafluoroethylene (Teflon)	K,K2,K3,K4	200	1000	.0108	.0135		Good thermal resis.-Poor scrape resis-poor cut-through resistance
Polyimide (ML)	K,K2,K3,K4	200	2000	.0029	-	3.78	Excel. therm. resis-good cut thru resis-suscep. to hydrolysis-good resis. to solvent action (compatible with askarels)

TABLE 21

WIRE INSULATION COMBINATIONS AVAILABLE

Enamels	Cotton	Glass	Glass Polyester	Nylon	Paper	Sick
Polyepoxides (epoxy)	-	O R	O R	-	O R	-
Phenolic Modified Polyvinyl Formal	O R	O R	O R	O	O R	O
Polyamides (nylon)	O	-	-	O	-	-
Polyimide (ML)	-	O R	O R	-	-	-
Oleoresinous	O	O	O	O	O	O
Polyester	-	O R	O R	-	-	-

O - Indicates round wire

R - Indicates rect..gular and square wire

(Ref.16)

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    A1A12 for kraft paper
    A1A14 for kraft pressboard
    A19A2 for tubes and cylinders
    A19B1 for phenolic resin treated tubes and cylinders
    A2A1 for cotton tapes
    A22A10 for treated cloths
    A22A11 for treated cloths
    A22A13 for treated cloths
    A22A14 for treated cloths
    A13B3 for transformer insulating pyranol
    A13A3 for transformer insulating oil
    A1J6 for asbestos sheet
    A14A for mica sheet
    A14E for composite mica
    A16B17 for mylar

EXHIBIT 2

MILESTONE REPORT #5

FOR

HIGH POWER, HIGH VOLTAGE, AUDIO FREQUENCY TRANSFORMER

DESIGN MANUAL

PROCEDURE COVERING CALCULATION METHODS FOR DETERMINING FREQUENCY RESPONSE OF VARIOUS EQUIVALENT CIRCUITS

NAVY DEPARTMENT BUREAU OF SHIPS ELECTRONICS DIVISION

CONTRACT NUMBER NObsr 87721, PROJECT SERIAL NO. SR-008-08-02, TASK 9599

GENERAL ELECTRIC

HIGH VOLTAGE SPECIALTY TRANSFORMER SECTION

HOLYOKE, MASS.

PROCEDURE COVERING CALCULATION METHODS FOR DETERMINING FREQUENCY RESPONSE OF VARIOUS EQUIVALENT CIRCUITS

SCOPE

As outlined in the project schedule, the purpose of this milestone report is to:

1. Derive equations for output voltage, output voltage phase shift, and input impedance for various equivalent circuits of the transformer and its associated network.

2. Calculate dimensionless curves for these equivalent circuits and explain their use in determining frequency response.

3. Compare the calculated curves against experimental data to show the accuracy of the calculations and the feasibility of using equivalent circuits.

FREQUENCY RANGE

The frequency range to be considered under the scope of this contract is in the audio-range of 20 to 20,000 cycles per second. The band-width ratio (highest: lowest frequency) is 1000:1, and, since a wide-band transformer can be defined as a transformer spanning at least a decade of frequency, we shall be dealing mainly with wide or broad-band transformers. The narrow-band high frequency transformer, which is a simplified case of the wide-band transformer, will also be considered.

FREQUENCY RESPONSE

Transformers are normally used in amplifier circuits for impedance-matching, d-c isolation, and phase inverting. Although there are other methods of coupling, as in a resistance-coupled amplifier, the transformer still remains as the primary method of performing these functions. This is due to improvements in core materials and winding designs.

In order to be of value in a circuit, the transformer must be capable of passing the required band of frequencies for which the circuit was designed, without consuming excessive power or space, and without introducing excessive amounts of distortion.

Frequency response, measured in terms of the voltage ratio between input and output voltage of the transformer (or between output voltage and the output voltage at some mid-band frequency), and expressed in decibels over a range of frequency, is a measure of value of the transformer in maintaining a constant voltage ratio before attenuation occurs in either the upper or lower frequency range.

EQUIVALENT CIRCUITS

The behavior of the transformer in a circuit may be determined in several ways. The most accurate method is to construct the transformer and measure its response in the circuit. Another method is to build a scaled down model of the transformer and measure its response. Breadboard circuits using lumped parameters can be checked for their response characteristics and the transformer designed using these parameters. In all of these methods, the equivalent circuit is the starting point for the basis analysis of the transformer's frequency response.

A fortunate feature of wide-band transformers is that the frequency coverage may be separated into two or more nearly independent ranges for purposes of analysis. Thus, in the higher frequency range, the core impedance is sufficiently large that its effect on the high frequency response may be neglected. Similarly, in the low frequency cutoff region, the electrical parameters which determine the high frequency cut off have only negligible influence.

By using the equivalent circuit of the transformer in the network, and then analyzing the various frequency regions of the circuit, the response of the transformer and associated network can be predicted with reasonable accuracy.

EQUIVALENT CIRCUIT ANALYSIS

For purposes of analysis, three circuits have been chosen as most representative and are shown in figures 1, 4 and 7. Figure 1 is the equivalent circuit of the output transformer of an amplifier where:

E_i = voltage generated in the plate circuit of the amplifier tube.

R_p = plate resistance of amplifier tube

C_p = total primary shunt and distributed capacitance

L_p = primary leakage inductance

C_s = total secondary shunt and distributed capacitance

R_{pri} = primary winding resistance

R_e = equivalent resistance corresponding to core losses

L_e = equivalent magnetizing (exciting) inductance of primary

T_r = ideal transformer of primary to secondary turns ratio of 1:r

C_{ps} = primary to secondary capacitance (interwinding capacitance)

R_{sec} = secondary winding resistance

L_s = secondary leakage inductance

C_L = shunt capacitance of load

R_L = equivalent resistive load of amplifier

Since winding resistances are small compared with source and load resistances in well-designed transformers, R_{pri} and R_{sec} may normally be neglected. Likewise, if the coefficient of coupling is practically unity and the core losses are negligibly small (i.e. R_e is large compared with load resistance, especially if good quality core material is used) then the simplified equivalent circuit of Figure 2 gives a good approximation of the equivalent circuit of Figure I. Referring all values to the primary, the circuit elements in Figure 2 are:

L_1 = total transformer leakage inductance referred to primary
$= L_p + L_s/r^2$

L_2 = primary exciting inductance = L_e

C_1 = total shunt capacitance of load and transformer secondary as referred to the primary = $r^2 (C_s + C_L)$

C_3 = total shunt capacitance of transformer primary = C_p

C_{ps} = primary to secondary capacitance (interwinding capacitance)

R_1 = equivalent resistance load referred to primary = R_L/r^2

The effect of the interwinding capacitance, C_{ps}, is to cause a rise in the response curve at some point beyond the high-frequency cut-off. This effect is of no concern to the transformer designer except that some distortion may occur at a frequency which is one-third of this peaking frequency. Therefore, the response should be carried out far enough, normally three times the required value, to prevent distortion due to C_{ps}. Reference 12 discusses the effect of interwinding capacitance more fully. For purposes of this report, C_{ps} is neglected in the equivalent circuit analysis bearing in mind its distortion effect.

Since the analysis is to apply to transformers having wide-band characteristics, the equivalent circuit of Figure 2 can be simplified by dividing the frequency range into three sections; low, medium, and high frequency. The medium frequency region is the band over which the reactive elements have negligible effects and in which the simple circuit of Figure 3(a) holds true. At high frequencies, the effect of the series inductances and shunt capacitances are all that need to be considered and the equivalent circuit of Figure 3(b) is used. At low frequencies, the shunt inductances and series capacitances become effective and the equivalent circuit of Figure 3(c) becomes valid. These equivalent circuits now represent the transformer and circuit as relatively simple networks made up of elements of resistors, inductors, and capacitors.

In order to obtain a simple terminology for expressing the interrelationship of these elements, and to avoid the use of such frequency - dependent factors as Q (quality factor), the reactive elements of the network can be treated as elements of an artificial line of characteristic impedance Z_o which is defined by the expression $Z_o = \sqrt{L/C}$. If the circuit of Figure 3(b) is treated as an artificial line, it will have a characteristic impedance Z_{01} equal to $\sqrt{L_1/C_1}$. The circuit constants can be conveniently related to frequency by the equation for electrical resonance. Thus, for the high frequency circuit of Figure 3(b), $2\pi f_{01} = \omega_{01} = 1/\sqrt{L_1 C_1}$.

In the case of the transformer with large turns ratio where $r \gg 1$ (step-up), the secondary distributed capacitance and shunt load capacitance, C_1, may outweight C_3, the primary shunt capacitance, by such a large factor that C_3 may be neglected, resulting in the equivalent circuit of Figure 13. Similarly, if $r \ll 1$, C_1 may be omitted yielding the circuit of Figure 12.

In the equivalent circuit of the transformer-coupled modulator with shunt-feed choke shown in Figure 4:

C_c = coupling capacitance between transformer and modulation inductor.

L_L = shunt-feed inductor

and the remaining circuit elements are the same as for Figure 1. This circuit has been simplified to the circuit of Figure 5, where:

C_2 = capacitance of coupling capacitor referred to primary = r^2C_c

L_3 = inductance of shunt-feed inductor referred to primary = L_L/r^2

and L_1, L_2, C_1, C_3, and R_1 are the same elements as in Figure 2. Further breakdown into high and low frequency range yields the equivalent circuits of Figures 6(a) and (b).

Figure 7 is the equivalent circuit of an output transformer with an autotransformer across the secondary. L_A is the leakage inductance of the autotransformer. This circuit has been simplified to the one shown in Figure 8, where L_4 is the autotransformer leakage inductance referred to the primary of the output transformer = L_A/r^2. Figures 9(a) and 9(b) show the equivalent circuits at high and low frequency respectively.

Figures 10 through 16 show some of the equivalent circuits for low and high frequency analysis and give the complex equations for the voltage ratio and the input impedance. Although all of the equivalent circuits are not given, the methods of solving the circuits to obtain an expression for the voltage response, phase shift, and input impedance are given. It is up to the transformer designer, working to the transformer specifications to decide which circuit elements must be included and which ones may be neglected. If it should turn out to be a circuit other than the ones included in this report, then he must solve the circuit and using different values for the various parameters, plot curves of frequency response until one is attained which meets the desired response.

Feedback

When feedback is taken from the plate circuit of the final push-pull amplifier tubes, it is necessary that the transformer designer know the end effect of such feedback in modifying the actual plate resistance of these tubes. Feedback reduces the gain and distortion through the amplifier and also reduces the effective plate resistance, when compared to the normal plate resistance of the output tubes. If feedback is taken from the secondary of the transformer, which tends to reduce any distortion caused by the transformer, the circuit designer will have to specify the maximum allowable phase shift through the transformer in order to ensure that the feedback is degenerative and not regenerative.

SAMPLE DERIVATION OF FREQUENCY RESPONSE EQUATIONS FOR A TRANSFORMER-COUPLED MODULATOR WITH SHUNT-FEED INDUCTOR

The equivalent circuit for a transformer-coupled modulator with a shunt-feed choke at low frequency is shown in Figure 16. Since it is desired to know the attenuation of this circuit in terms of decibels, an expression for $20 \log_{10} \frac{E_{in}}{E_{out}}$ versus an independent variable of frequency is needed. Letting ω_{02} equal $1/\sqrt{L_3 C_2}$ and Z_{02} equal $\sqrt{L_3/C_2}$ gives these parameters if the attenuation in decibels is plotted against the ratio ω/ω_{02}. Note that both parameters, E_i/E_o and ω/ω_{02} are dimensionless and express only ratios; hence, families of curves may be conveniently plotted.

The solution of the low frequency equivalent circuit of Figure 16 for the ratio E_i/E_o follows, using the loop method to obtain three equations which are solved simultaneously by determinants.

Letting $I_1, I_2,$ and I_3 be the currents in loops 1, 2, and 3 respectively, the loop equations are:

$$E_i = I_1 (R_p + j\omega L_2) - I_2 (j\omega L_2)$$

$$O = -I_1 (j\omega L_2) + I_2 \left(j\omega L_2 + j\omega L_3 + \frac{1}{j\omega C_2}\right) - I_3 (j\omega L_3)$$

$$O = -I_2 (j\omega L_3) + I_3 (R_1 + j\omega L_3)$$

Since $\sqrt{L_3/C_2} = Z_{02}$ and $\frac{1}{\sqrt{L_3 C_2}} = \omega_{02}$, the expressions for L_3 and C_2 are:

$$L_3 = \frac{Z_{02}}{\omega_{02}} \qquad C_2 = \frac{1}{\omega_{02} Z_{02}}$$

Letting $L_3/L_2 = K$, then $L_2 = Z_{02}/\omega_{02}K$

Substituting these values of L_2, L_3 and C_2 in the three loop equations yields:

$$E_i = I_1 \left(R_p + j\frac{\omega Z_{02}}{\omega_{02}K}\right) - I_2 \left(j\frac{\omega Z_{02}}{\omega_{02}K}\right)$$

$$O = -I_1 \left(j\frac{\omega Z_{02}}{\omega_{02}K}\right) + I_2 \left(j\frac{\omega Z_{02}}{\omega_{02}K} + j\frac{\omega Z_{02}}{\omega_{02}} - j\frac{\omega_{02} Z_{02}}{\omega}\right) - I_3 \left(j\frac{\omega Z_{02}}{\omega_{02}}\right)$$

$$O = -I_2 \left(j\frac{\omega Z_{02}}{\omega_{02}}\right) + I_3 \left(R_1 + j\frac{\omega Z_{02}}{\omega_{02}}\right)$$

Expressing I_3 in terms of its determinant,

$$I_3 = \frac{\begin{vmatrix} R_p + j\dfrac{\omega Z_{o2}}{\omega_{o2} K} & -j\dfrac{\omega Z_{o2}}{\omega_{o2} K} & E_i \\ -j\dfrac{\omega Z_{o2}}{\omega_{o2} K} & j\left(\dfrac{\omega Z_{o2}}{\omega_{o2} K} + \dfrac{\omega Z_{o2}}{\omega_{o2}} - \dfrac{\omega_{o2} Z_{o2}}{\omega}\right) & 0 \\ 0 & -j\dfrac{\omega Z_{o2}}{\omega_{o2}} & 0 \end{vmatrix}}{\begin{vmatrix} R_p + j\dfrac{\omega Z_{o2}}{\omega_{o2} K} & -j\dfrac{\omega Z_{o2}}{\omega_{o2} K} & 0 \\ -j\dfrac{\omega Z_{o2}}{\omega_{o2} K} & j\left(\dfrac{\omega Z_{o2}}{\omega_{o2} K} + \dfrac{\omega Z_{o2}}{\omega_{o2}} - \dfrac{\omega_{o2} Z_{o2}}{\omega}\right) & -j\dfrac{\omega Z_{o2}}{\omega_{o2}} \\ 0 & -j\dfrac{\omega Z_{o2}}{\omega_{o2}} & R_1 + j\dfrac{\omega Z_{o2}}{\omega_{o2}} \end{vmatrix}}$$

Examination of the above determinant shows that the term E_i will appear in the numerator of the equation for I_3. Since $E_o = I_3 R_1$, an equation is obtainable in terms of E_o/E_i. Taking the reciprocal will give a value in complex form for E_i/E_o. For convenience in plotting the curves, the value $-20 \log_{10} \left|\frac{E_i}{E_o}\right|$ is used. Solving the determinant, substituting in the equation $E_o = I_3 R_1$ and taking the reciprocal yields the following equation:

$$\frac{E_i}{E_o} = 1 + \frac{R_p}{R_1} - \left(\frac{\omega_{o2}}{\omega}\right)^2 \left(\frac{R_p L_3}{R_1 L_2} + 1\right)$$
$$-j \frac{\omega_{o2}}{\omega}\left[\frac{Z_{o2}}{R_1} + \frac{R_p}{Z_{o2}}\left(\frac{L_3}{L_2} + 1\right) - \left(\frac{\omega_{o2}}{\omega}\right)^2 \frac{R_p}{Z_{o2}} \frac{L_3}{L_2}\right]$$

This equation describes the low frequency variation of output voltage with respect to the modulator tube EMF and frequency. The magnitude of this voltage ratio is:

$$\left|\frac{E_i}{E_o}\right| = \left\{\left[1 + \frac{R_p}{R_1} - \left(\frac{\omega_{o2}}{\omega}\right)^2 \left(\frac{R_p}{R_1}\frac{L_3}{L_2} + 1\right)\right]^2 + \left[\frac{\omega_{o2}}{\omega}\left(\frac{Z_{o2}}{R_1} + \frac{R_p}{Z_{o2}}\left\{\frac{L_3}{L_2} + 1\right\} - \left\{\frac{\omega_{o2}}{\omega}\right\}^2 \frac{R_p}{Z_{o2}}\frac{L_3}{L_2}\right)\right]^2\right\}^{1/2}$$

Values for Z_{02}/R_1, R_p/R_1 and L_3/L_2 are used as parameters.. Curves for various values of the parameters are plotted in Appendix I.

The phase of output voltage with respect to modulator tube EMF is:

$$\phi\frac{E_o}{E_1} = \frac{\tan^{-1}\frac{\omega_{o2}}{\omega}\left[\frac{Z_{o2}}{R_1} + \frac{R_p}{Z_{o2}}\left(\frac{L_3}{L_2} + 1\right) - \left(\frac{\omega_{o2}}{\omega}\right)^2 \frac{R_p}{Z_{o2}}\frac{L_3}{L_2}\right]}{1 + \frac{R_p}{R_1} - \left(\frac{\omega_{o2}}{\omega}\right)^2\left(\frac{R_p L_3}{R_1 L_2} + 1\right)}$$

Again, values for Z_{02}/R_1, R_p/R_1 and L_3/L_2 are used as the parameters and phase curves are plotted in Appendix I.

Another important characteristic of the low frequency equivalent circuit is the impedance presented to the tube by the transformer, the coupling network, and the load. This impedance, shown in Figure 17, taken with respect to the load, R_1, may be plotted against the independent variable ω/ω_{o2} to show how the impedance characteristic varies with frequency.

The equation for Z_p is:

$$Z_p = \frac{\left(\frac{j\omega L_3 R_1}{R_1 + j\omega L_3} + \frac{1}{j\omega C_2}\right)\left(j\omega L_2\right)}{\frac{j\omega L_3 R_1}{R_1 + j\omega L_3} + \frac{1}{j\omega C_2} + j\omega L_2}$$

Substituting the values of $L_3 = Z_{02}/\omega_{o2}$, $C_2 = 1/\omega_{o2} Z_{02}$ and $L_2 = Z_{02}/\omega_{o2}K$, which were derived in the preceding section, gives:

$$Z_p = \frac{\left(\dfrac{j \dfrac{\omega Z_{02} R_1}{\omega_{02}}}{R_1 + j \dfrac{\omega Z_{02}}{\omega_{02}}} - j \dfrac{\omega_{02} Z_{02}}{\omega} \right) \left(j \dfrac{\omega Z_{02}}{\omega_{02} K} \right)}{\dfrac{j \dfrac{\omega Z_{02} R_1}{\omega_{02}}}{R_1 + j \dfrac{\omega Z_{02}}{\omega_{02}}} + j \left(\dfrac{\omega Z_{02}}{\omega_{02} K} - \dfrac{\omega_{02} Z_{02}}{\omega} \right)}$$

Simplifying this equation by rationalization and dividing both sides by R_1 yields:

$$\frac{Z_p}{R_1} = \frac{\dfrac{Z_{02}}{R_1} + \dfrac{R_1}{Z_{02}} \left[\left(\dfrac{\omega_{02}}{\omega} \right)^2 - 1 \right] + j \dfrac{\omega}{\omega_{02}}}{\dfrac{L_3 R_1}{L_2 Z_{02}} + j \left[\dfrac{\omega_{02}}{\omega} \left(\dfrac{L_3 R_1^2}{L_2 Z_{02}^2} - \dfrac{L_3}{L_2} + \dfrac{R_1^2}{Z_{02}^2} \right) - \left(\dfrac{\omega_{02}}{\omega} \right)^3 \dfrac{L_3 R_1^2}{L_2 Z_{02}^2} + \dfrac{\omega}{\omega_{02}} \right]}$$

A family of curves may be plotted when actual values are substituted for the parameters Z_{02}/R_1 and L_3/L_2 as the ratio ω/ω_{02} is varied. Curves of this type are included in Appendix I. It should be noted that large dips in impedance within the normal operating range are to be avoided since this tends to increase the distortion in the associated amplifier tubes. A large variation in impedance occurring at either or both ends of the pass-band can be tolerated. By judicious use of the response curves for impedance and those of the voltage ratio, a compromise may be made in determining the best ratio of characteristic impedance, Z_{02}, to the load resistance, R_1.

The derivation of the equations for the voltage ratio, phase shift and input impedance for the high frequency equivalent circuit of the transformer-coupled modulator with shunt-feed choke could be accomplished in the same manner as the low frequency network analysis, i.e., using determinants, but in order to avoid repetition and to show its value in solving filter networks, matrices will be used.

Referring to Figure 18, which is the high frequency equivalent circuit of the transformer-coupled modulator with shunt-feed choke, the input to output response in terms of the ABCD constants is:

$$E_i = A E_o + B I_o$$

$$I_i = C E_o + D I_o$$

and since $I_o = O$, the ratio of input to output voltage is:

$$\frac{E_i}{E_o} = A$$

Therefore, it is only necessary to find the A constant of the network in order to know the voltage response and the phase shift.

To find the A constant for the network, the matrices of the fundamental network components are displayed as follows:

$$\begin{bmatrix} E_i \\ I_i \end{bmatrix} = \begin{bmatrix} 1 & R_p \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ j\omega C_3 & 1 \end{bmatrix} \begin{bmatrix} 1 & j\omega L_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{1}{R_1} + j\omega C_1 & 1 \end{bmatrix} \begin{bmatrix} E_o \\ I_o \end{bmatrix}$$

The multiplication of the square matrices is performed in the following steps:

$$\begin{bmatrix} E_i \\ I_i \end{bmatrix} = \begin{bmatrix} 1 & R_p \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ j\omega C_3 & 1 \end{bmatrix} \begin{bmatrix} 1 + j\frac{\omega L_1}{R_1} - \omega^2 L_1 C_1 & j\omega L_1 \\ \frac{1}{R_1} + j\omega C_1 & 1 \end{bmatrix} \begin{bmatrix} E_o \\ I_o \end{bmatrix}$$

$$\begin{bmatrix} E_i \\ I_i \end{bmatrix} = \begin{bmatrix} 1 & R_p \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 + j\frac{\omega L_1}{R_1} - \omega^2 L_1 C_1 & j\omega L_1 \\ j\omega C_3 - \frac{\omega^2 L_1 C_3}{R_1} - j\omega^3 L_1 C_1 C_3 + \frac{1}{R_1} + j\omega C_1 & -\omega^2 L_1 C_3 + 1 \end{bmatrix} \begin{bmatrix} E_o \\ I_o \end{bmatrix}$$

Since we are interested in only the A constant of the network, the B, C, and D constants may be dropped in the final step of multiplication, yielding:

$$\begin{bmatrix} E_i \\ I_i \end{bmatrix} = \begin{bmatrix} 1 + j\frac{\omega L_1}{R_1} - \omega^2 L_1 C_1 + j\omega C_3 R_p - \frac{\omega^2 L_1 C_3 R_p}{R_1} - j\omega^3 L_1 C_1 C_3 R_p + j\omega C_1 R_p + \frac{R_p}{R_1} & B \\ C & D \end{bmatrix} \begin{bmatrix} E_o \\ I_o \end{bmatrix}$$

Rearranging terms of the A constant and expressing the voltage ratio,

$$\frac{E_i}{E_o} = A = 1 + \frac{R_p}{R_1} - \omega^2 L_1 C_1 - \frac{\omega^2 L_1 C_3 R_p}{R_1} + j\left[\frac{\omega L_1}{R_1} + \omega C_3 R_p + \omega C_1 R_p - \omega^3 L_1 C_1 C_3 R_p\right]$$

Having found the expression for the input to output voltage ratio, it is now necessary to express the equation in terms of $Z_{01} = \sqrt{L_1/C_1}$ and $\omega_{01} = 1/\sqrt{L_1 C_1}$. Substituting the following values of

$$\frac{L_1}{C_1} = Z_{01}^2 \;, \quad L_1 C_1 = \frac{1}{\omega_{01}^2} \;, \quad L_1 = \frac{Z_{01}}{\omega_{01}} \;, \text{ AND } C_1 = \frac{1}{\omega_{01} Z_{01}}$$

in the voltage equation yields:

$$\frac{E_i}{E_o} = 1 + \frac{R_p}{R_1} - \left(\frac{\omega}{\omega_{01}}\right)^2 \left(\frac{R_p C_3}{R_1 C_1} + 1\right) + j\frac{\omega}{\omega_{01}}\left[\frac{Z_{01}}{R_1} + \frac{R_p}{Z_{01}}\left(\frac{C_3}{C_1} + 1\right) - \left(\frac{\omega}{\omega_{01}}\right)^2 \frac{R_p C_3}{Z_{01} C_1}\right]$$

This complex equation describes the high frequency variation of output voltage with respect to the modulator EMF and frequency. The magnitude of the voltage ratio is:

$$\left|\frac{E_1}{E_o}\right| = \left\{\left[1 + \frac{R_p}{R_1} - \left(\frac{\omega}{\omega_{01}}\right)^2 \left(\frac{R_p C_3}{R_1 C_1} + 1\right)\right]^2 + \left[\frac{\omega}{\omega_{01}}\left(\frac{Z_{01}}{R_1} + \frac{R_p}{Z_{01}}\left\{\frac{C_3}{C_1} + 1\right\} - \left\{\frac{\omega}{\omega_{01}}\right\}^2 \frac{R_p C_3}{Z_{01} C_1}\right)\right]^2\right\}^{1/2}$$

Values of Z_{01}/R_1, R_p/R_1, and C_3/C_1 are used as parameters. Curves are plotted in Appendix II for various values of these parameters.

The phase of the output voltage with respect to the modulator tube EMF is:

$$\phi\frac{E_o}{E_1} = \tan^{-1}\frac{\frac{\omega}{\omega_{01}}\left[\frac{Z_{01}}{R_1} + \frac{R_p}{Z_{01}}\left(\frac{C_3}{C_1} + 1\right) - \left(\frac{\omega}{\omega_{01}}\right)^2 \frac{R_p C_3}{Z_{01} C_1}\right]}{1 + \frac{R_p}{R_1} - \left(\frac{\omega}{\omega_{01}}\right)^2 \left(\frac{R_p C_3}{R_1 C_1} + 1\right)}$$

Curves of the phase function are also plotted in Appendix II for various high frequency equivalent circuits.

The solution of the equation for input impedance for the high frequency equivalent circuit is similar to that of the low frequency circuit and, therefore, omitted. The final equation can be found in Figure 14.

COMPARISON OF CALCULATED FREQUENCY RESPONSE TO MEASURED RESPONSE

For the purpose of checking the accuracy of using equivalent circuits with lumped parameters to calculate frequency response, one of the coils used in Milestone Report #3 (to check leakage inductance calculations) was measured to check its actual frequency response. The winding diagram of the test coils is shown in Figure 19.

In this winding arrangement, the windings are divided into two equal sections, wound into separate coils, and placed on opposite core legs. The secondary windings are connected in parallel and the half-primary windings are transposed to obtain balanced leakage inductance from each half-primary to secondary. This arrangement will have some capacitance unbalance because of the different voltage gradients as described in the Third Milestone Report. The coils have a step-up turns ratio of 1:2, there being 200 turns on each half-primary and 400 turns on the secondary. The measured leakage inductance from each half-primary to secondary was 1.76 millihenries, referred to the secondary, and the calculated distributed capacitance of the secondary was 393 picofarads, referred to the secondary, when grounded at terminals S_2 and P_{ct}.

The high frequency voltage response of the transformer was measured in the circuit shown in Figure 20, using two Hewlett-Packard VTVM's and a General Radio RF oscillator.

Since this is a step-up transformer with resistive load shunted by a capacitance, the equivalent circuit of Figure 21 should give a close approximation of the high frequency response. L_1 is the leakage inductance from half-primary to secondary and C_1 is the total shunt capacitance of the load and the transformer.

All the parameters of the equivalent circuit are now known or can be calculated from known values. Referring all parameters to the secondary:

$R_p \quad = [175\,\Omega + 12\,\Omega \text{(winding resistance)}]\ 4 \ = 748 \text{ ohms}$

$L_1 \quad = 1.76 \times 10^{-3}$ henry

$C_1 \quad = 393 \text{ pf} + 400 \text{ pf} = 793 \times 10^{-12}$ farads

$R_1 \quad = 1500$ ohms

$$Z_{01} = \sqrt{L_1/C_1} = \sqrt{\frac{1.76 \times 10^{-3}}{793 \times 10^{-12}}} = 1490 \text{ ohms}$$

$$\omega_{01} = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{1.76 \times 10^{-3} \times 793 \times 10^{-12}}} = 847,500 \ \frac{\text{radians}}{\text{sec.}}$$

$$f_{01} = \omega_{01}/2\pi = 847,500/6.283 \doteq 135 \text{ Kilocycles}$$

$$Z_{01}/R_1 = \frac{1490}{1500} \approx 1$$

$$R_p/R_1 = \frac{748}{1500} \approx .5$$

$$\frac{R_p}{Z_{01}} = .5$$

If these values are substituted in the equation for the magnitude of the voltage ratio for the equivalent circuit of Figure 13,

$$\left|\frac{E_1}{E_o}\right| = \left\{ \left[1 + \frac{R_p}{R_1} - \left(\frac{\omega}{\omega_{01}}\right)^2 \right]^2 + \left[\frac{\omega}{\omega_{01}} \left(\frac{R_p}{Z_{01}} + \frac{Z_{01}}{R_1} \right) \right]^2 \right\}^{1/2}$$

and the values obtained for the voltage ratio as the frequency ω is varied are plotted in decibels, the calculated curve of Figure 22 is obtained.

In the test circuit of Figure 20, the input voltage was held constant as the frequency was varied. The output voltage is plotted in Figure 22 in decibels calculated from the expression:

$$D_b = 20 \log_{10} \frac{E_o}{E_o \text{ at } 20 \text{ KC}}$$

The voltage of 20 KC is used as a reference since at this center frequency the response is flat and the reactive components of the circuit have little effect on the response. The calculated curve has been shifted 3.522 db so that it has the same voltage reference, E_p in Figure 21, as the measured curves.

A comparison of the calculated and measured response curves shows that the actual response of the test coils fell off at a lower frequency than was calculated by 7% and 11% at the -1 db level. Since the equivalent circuit is not an exact method, some error can be expected between the actual and calculated response. The response of the two half primaries shows some difference since the parameters L_1 and C_d of the half-primaries are never exactly the same.

Specifications

The following is an outline of essential specifications which the circuit designer should provide the transformer designer to adequately describe the circuit in which the transformer is to be used and the over-all performance required. These specifications have been taken directly from Ref. 1.

Individual Characteristics of Circuit and Transformer

CIRCUIT CHARACTERISTICS

Load:

Equivalent load resistance
Total value of shunt capacitances
Required maximum audio power into load
Component of direct current into load

Power Source:

For a line or cable

Characteristic impedance

For an amplifier

Single-ended; Push-pull Class A, Class AB, or Class B.

Minimum average plate resistance; this should include the effect of feedback in modifying the actual plate resistance.

Plate current at zero signal and maximum signal; maximum unbalance if push-pull.

Peak plate current.

Direct current plate supply voltage.

Peak-to-peak plate voltage swing.

TRANSFORMER CHARACTERISTICS

Secondary:

Maximum allowable winding resistance.
Direct current component of voltage to ground.
Peak-to-peak voltage swing or RMS value of alternating current current component of voltage.

Primary:

Maximum allowable winding resistance.

Normal value of impedance presented to power source with load connected.

Efficiency:

Minimum allowable.

Over-all Performance of Transformer and Circuit

FREQUENCY RESPONSE CHARACTERISTICS

Load Voltage:

Amplitude versus frequency

Phase versus frequency, when required.

Primary Impedance:

Minimum allowable within operating range, as percent of normal.

Signal Amplitude:

Maximum required input signal in percent of normal as a function of frequency.

HARMONIC DISTORTION

Maximum allowable attributable to the transformer, excluding that caused by impedance effects.

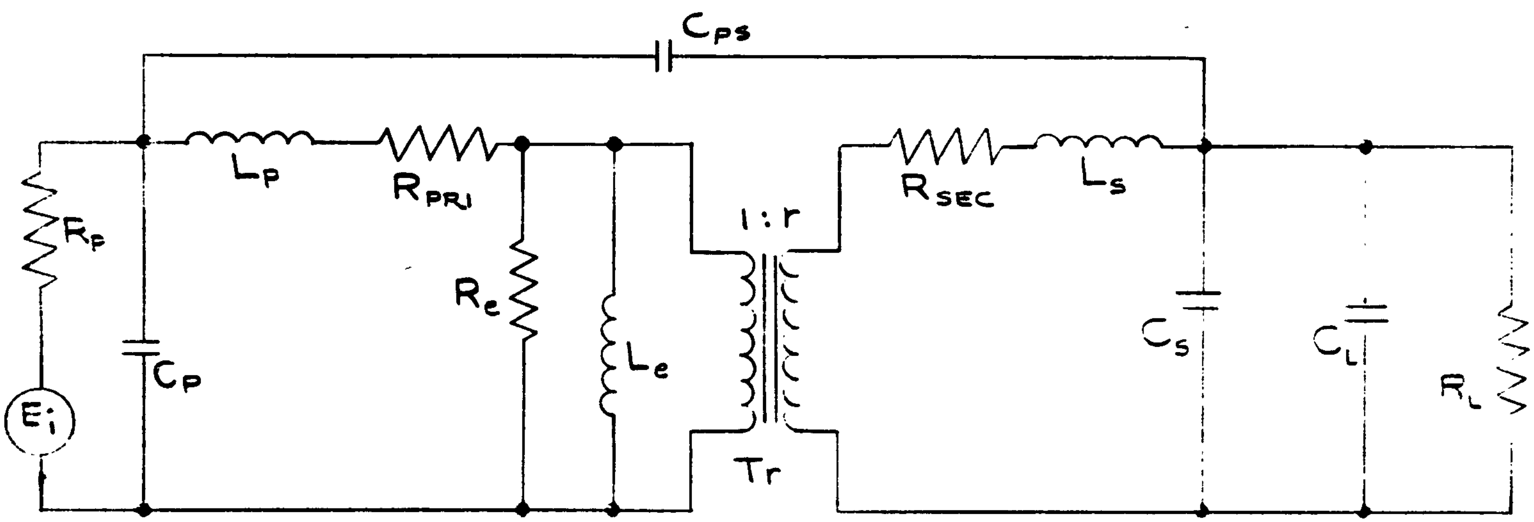
DESIGN PROCEDURE

A design procedure is fairly straightforward when based upon the generalized response curves and a suitable set of specifications covering the transformer and circuit performance requirements. First, the required transformer turns ratio 1:r of the primary to secondary is calculated from the specified transformer ratings and used to determine an equivalent value for the resistive component of the load as reflected to the primary. Then, the ratio of this reflected load resistance to the average effective plate resistance of the amplifier tube, as given by the specifications, provides the information needed to select the generalized frequency response curve to be used at each end of the pass band. These two curves are then employed to determine values for the magnetizing inductance, the total leakage inductance, and the allowable shunt capacitances.

For illustrating this procedure, assume the transformer is coupled to the load through a shunt feed inductor and coupling capacitor. The low frequency equivalent circuit is shown in Figure 6 (b). Referring to Figure 11 of Appendix 1, the curve for $Z_{02} = 1.25\ R_1$ appears to give the best value of primary impedance. Assume the reflected load resistance, R_1, is 10,000 ohms, the effective plate resistance, R_p, is 20,000 ohms, and it is desired that the output voltage must be no more than one decibel down at 50 cycles. From the curve of Figure 9, Appendix 1, for the ratio $R_p/R_1 = 2$, the response curve is down one decibel from the center frequency value of -9.5 db when $\omega/\omega_{02} = 0.72$. Then $\omega_{02} = 2\pi 50/0.72 = 436$ radians/sec. Since $Z_{02} = 1.25\ R_1$, $Z_{02} = 12,500$ ohms. The expressions $Z_{02} = \sqrt{L_3/C_2}$ and $\omega_{02} = 1/\sqrt{L_3C_2}$ can be combined to give the expressions $L_3 = Z_{02}/\omega_{02}$ and $C_2 = 1/Z_{02}\omega_{02}$. Therefore, the value of $L_3 =$ 12,500/436 = 28.7 henries and is the reflected value for the shunt-feed inductor. Since the ratio $L_3/L_2 = 1$ is one of the parameters for the response curve of Figure 9, Appendix 1, it is desirable that the transformer magnetizing inductance be equal to this same value of 28.7 henries. The actual value for the shunt-feed choke will be $r^2 \times 28.7$ henries. The reflected value for the coupling capacitor will be $C_2 = 1/12,500 \times 436 =$ 0.1835 microfarads. The required value will be $0.1835/r^2$ microfarads.

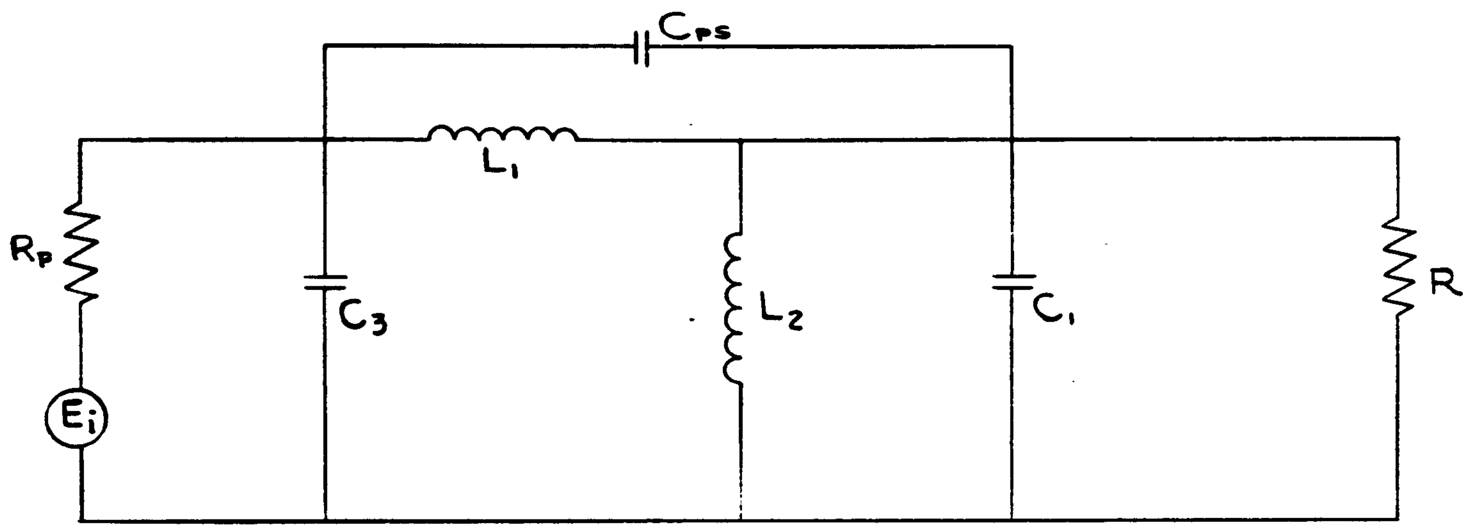
If we assume a step-up transformer, the primary capacitance is small and, therefore, can be neglected. In this case, Figure 14 of Appendix 2 can be used to determine the total equivalent primary leakage inductance and total allowable secondary and load shunt capacitance. The curve for $R_p/R_1 = 2$ shows the output voltage is down one decibel from the mid-frequency value of -9.5 decibels at $\omega/\omega_{01} = 0.88$. If this point is assumed to be specified as the 10 kilocycle point in the overall frequency response characteristic, then $\omega_{01} = 2\pi(10,000)/0.88 = 7.14 \times 10^4$ radians/sec. Therefore, the total equivalent primary leakage inductance, L_1, should be $12,500/7.14 \times 10^4 = 0.175$ henry and the total reflected secondary and load capacitance, C_1, should be $1/12,500 \times 7.14 \times 10^4 = 1120$ picofarads.

All of the transformer design constants which affect the frequency response have now been determined. The problem now becomes one of designing a transformer which will have these constants and which will have sufficient core area and copper cross section to handle the power level as specified for certain frequency ranges within the passband. In general, the core area is determined by the low frequency requirements; so the transformer is first designed with sufficient core area and coil turns to satisfy the power conditions at the low frequency end of the passband and with the required value of magnetizing inductance. The coil configuration and arrangement of windings are then varied to obtain the required value of leakage inductance. Finally, the distributed and shunt capacitances are calculated. In order to obtain a satisfactory low value of capacitance without an increase in leakage inductance caused by increasing the spacings between layers and/or windings, it may be necessary to start a new design using a larger core area.



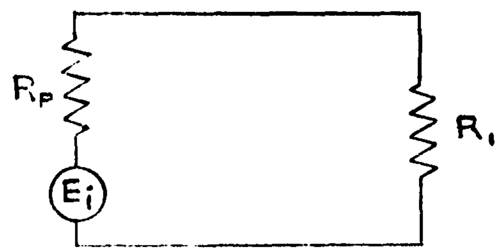
EQUIVALENT CIRCUIT OF AN AMPLIFIER TRANSFORMER

FIG. 1



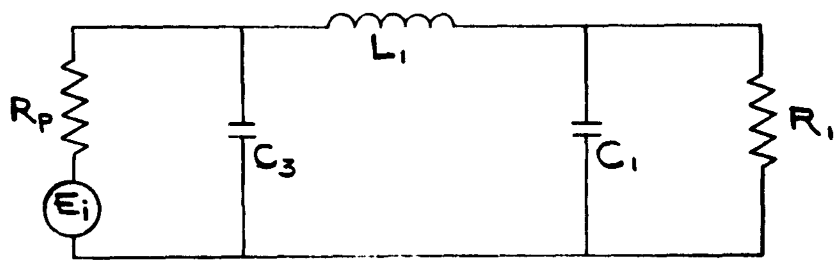
SIMPLIFIED EQUIVALENT CIRCUIT OF FIG. 1

FIG. 2



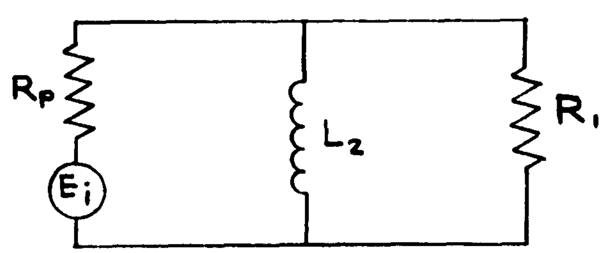
EQUIVALENT CIRCUIT AT MEDIUM FREQUENCY

(a)



EQUIVALENT CIRCUIT AT HIGH FREQUENCY

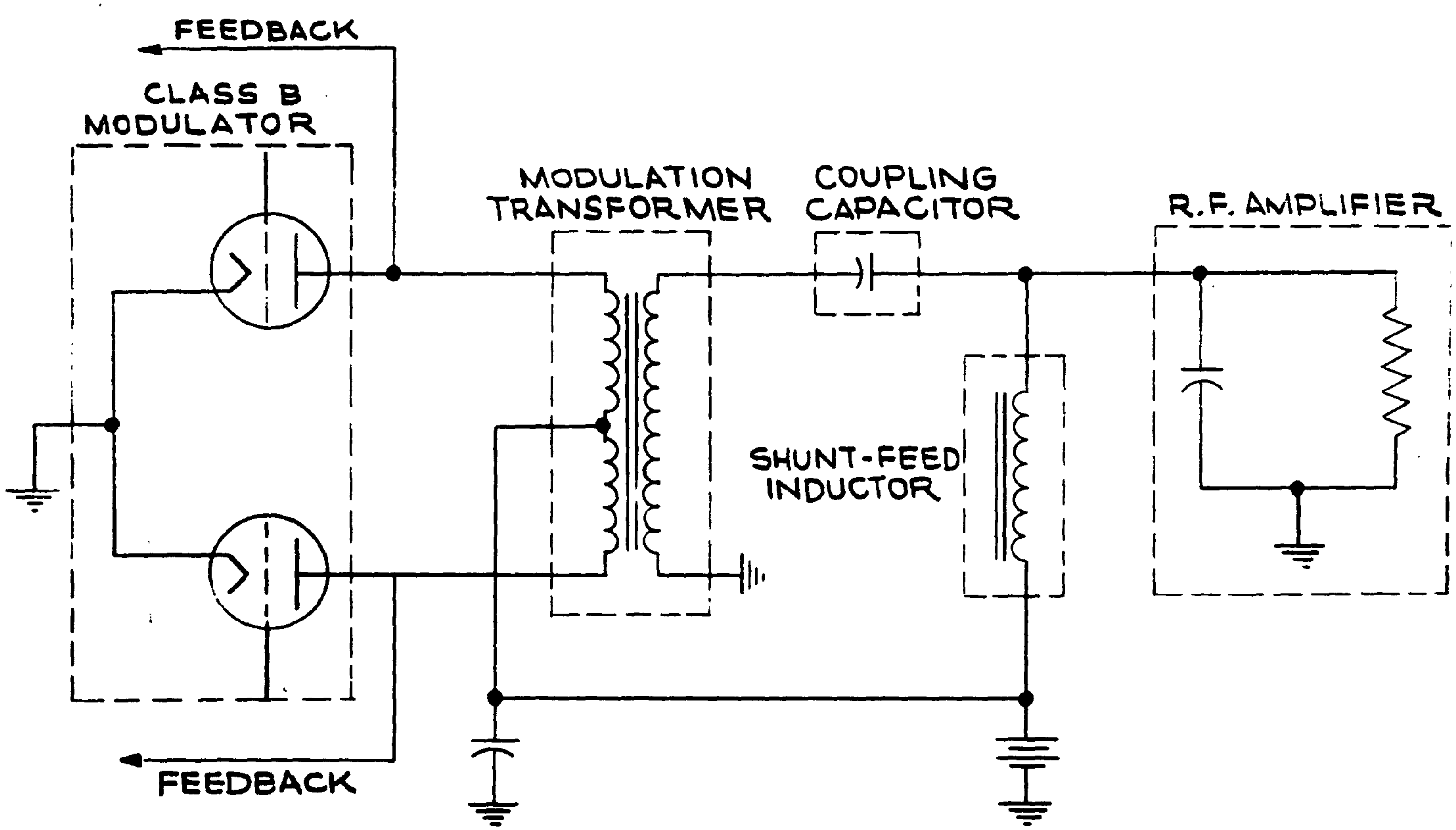
(b)



EQUIVALENT CIRCUIT AT LOW FREQUENCY

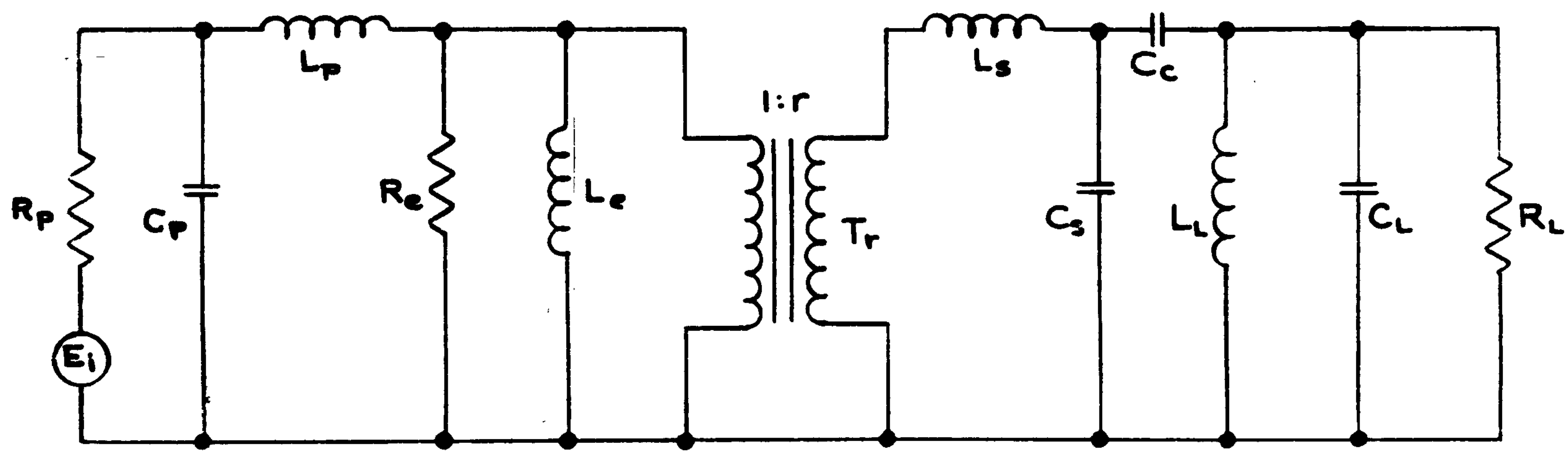
(c)

FIG. 3



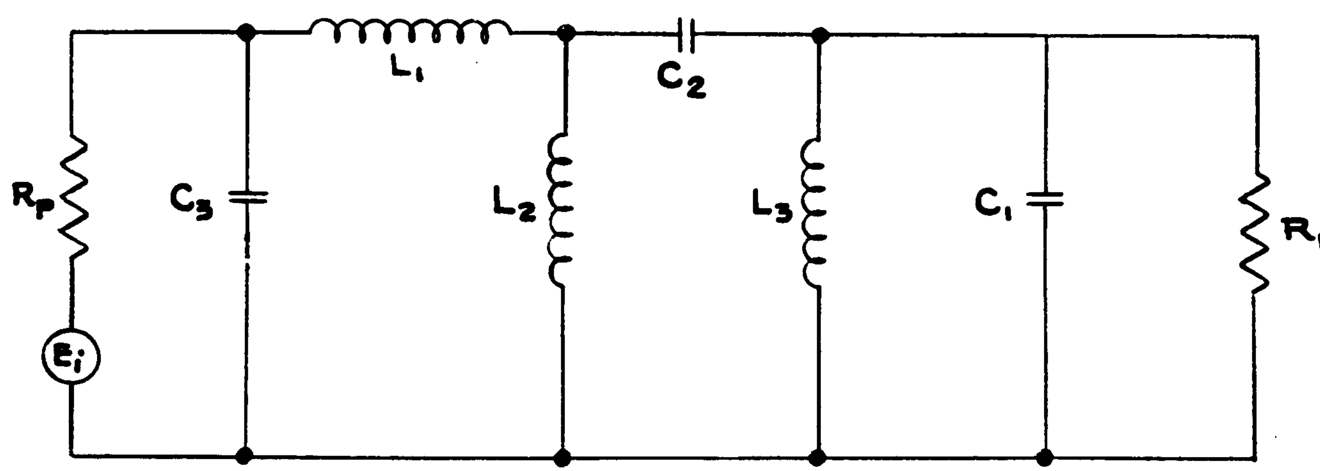
CIRCUIT DIAGRAM OF TYPICAL ANODE MODULATION SYSTEM

FIG. 4 A



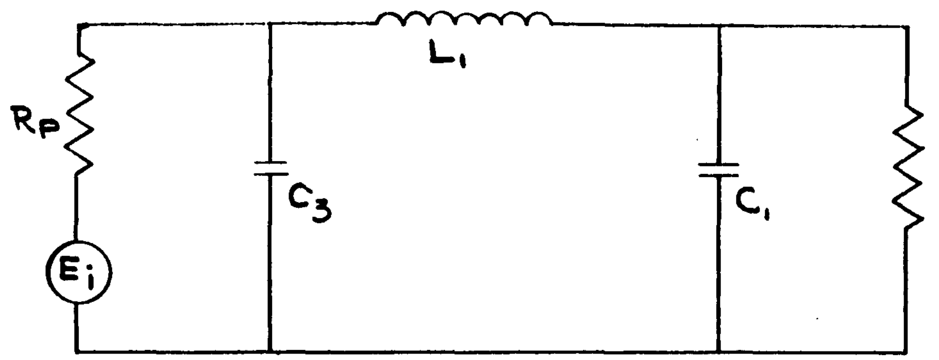
EQUIVALENT CIRCUIT OF TRANSFORMER - COUPLED MODULATOR
WITH SHUNT-FEED INDUCTOR

FIG. 4



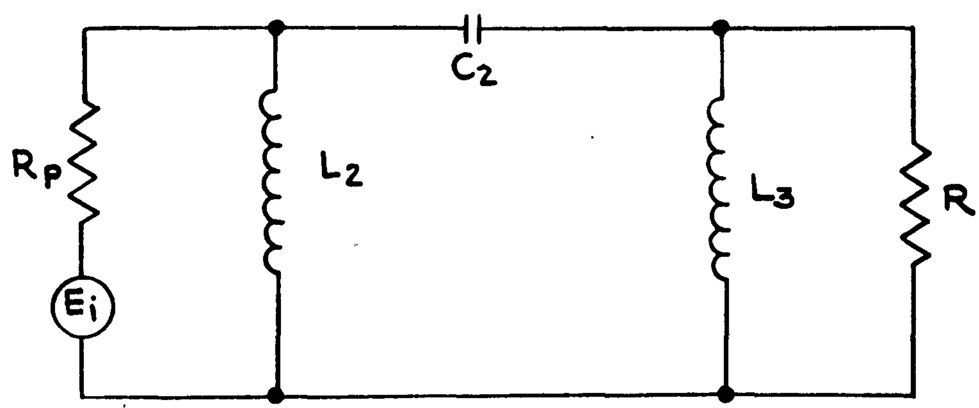
SIMPLIFIED EQUIVALENT CIRCUIT OF FIG.4

FIG. 5



EQUIVALENT CIRCUIT AT HIGH FREQUENCY

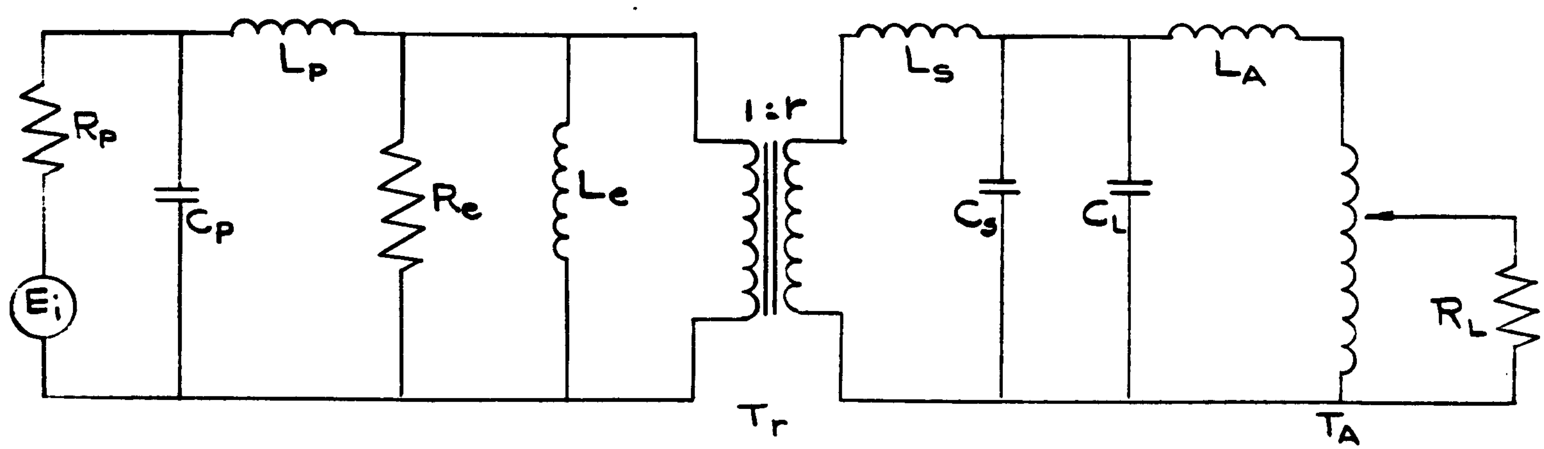
(a)



EQUIVALENT CIRCUIT AT LOW FREQUENCY

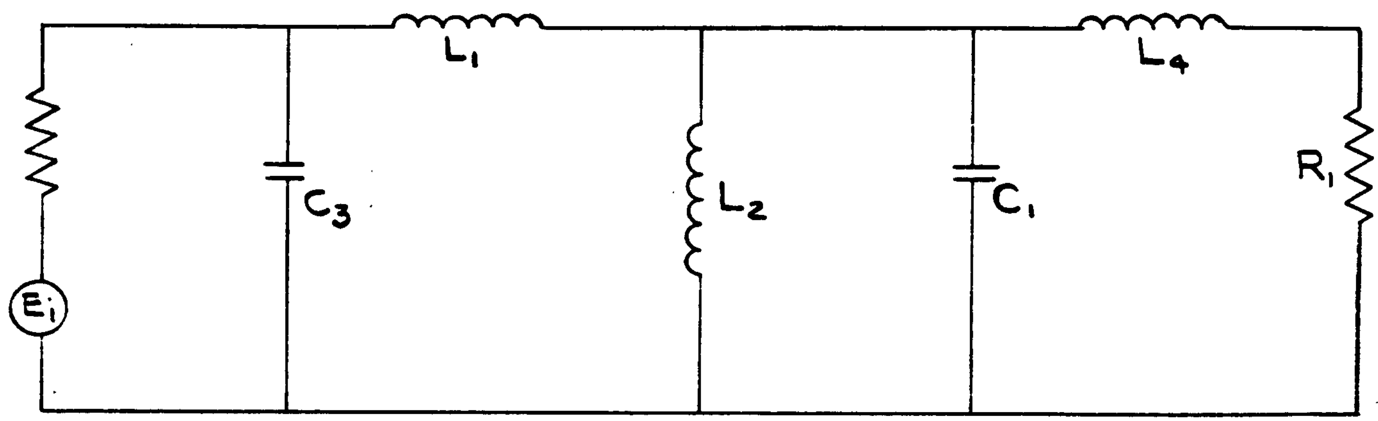
(b)

FIG. 6



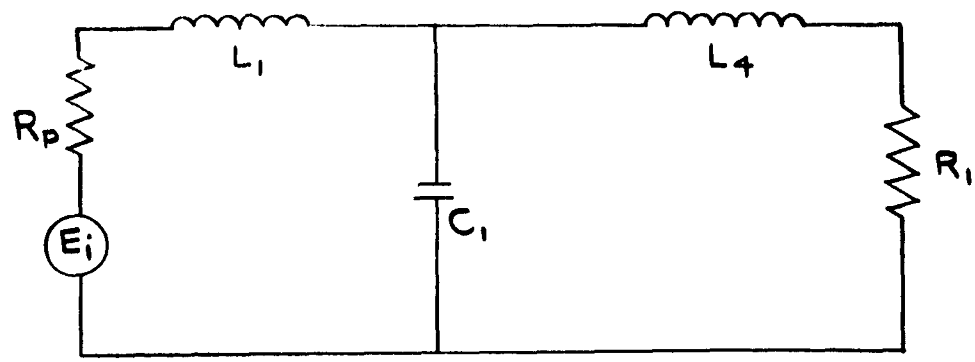
EQUIVALENT CIRCUIT OF AN AMPLIFIER TRANS-
FORMER DRIVING AN AUTO TRANSFORMER

FIG. 7



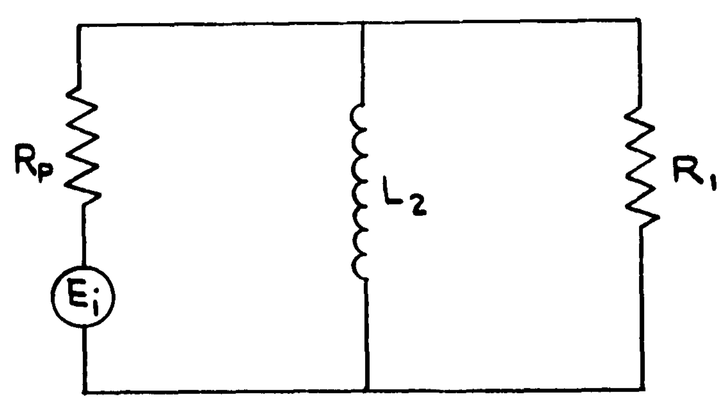
SIMPLIFIED EQUIVALENT CIRCUIT OF FIG. 7

FIG. 8



EQUIVALENT CIRCUIT AT HIGH FREQUENCY

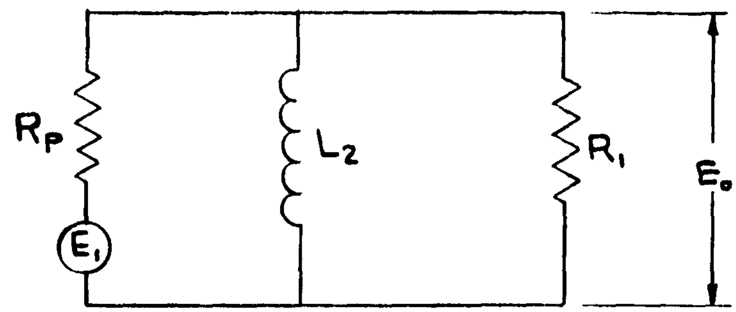
(a)



EQUIVALENT CIRCUIT AT LOW FREQUENCY

(b)

FIG. 9



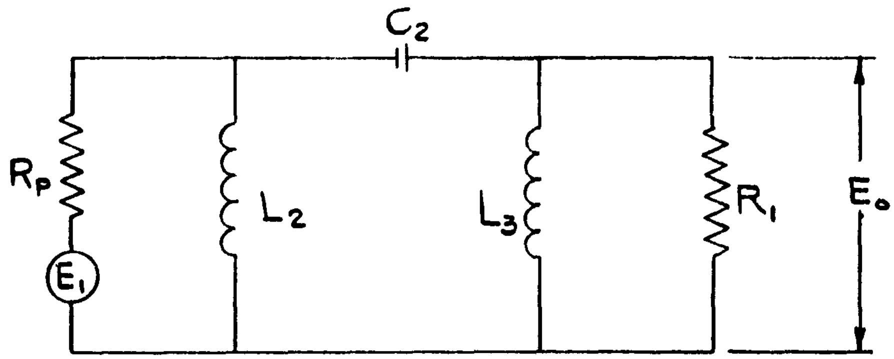
$$\omega_{o2} = \frac{R_1}{L_2}$$

LOW FREQUENCY EQUIVALENT CIRCUIT

$$\frac{E_i}{E_o} = \frac{R_P}{R_1} + 1 - j\,\frac{\omega_{o2}}{\omega}\frac{R_P}{R_1}$$

$$\frac{Z_P}{R_1} = \frac{1 + j\,\frac{\omega_{o2}}{\omega}}{1 + \left(\frac{\omega_{o2}}{\omega}\right)^2}$$

FIG. 10



$$\omega_{02} = \frac{1}{\sqrt{L_3 C_2}} \qquad Z_{02} = \sqrt{\frac{L_3}{C_2}}$$

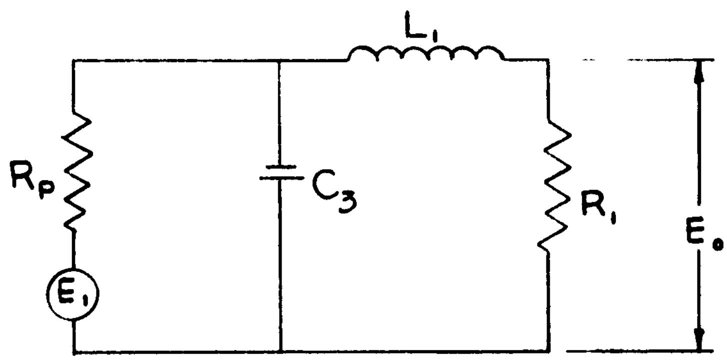
LOW FREQUENCY EQUIVALENT CIRCUIT

$$\frac{E_1}{E_0} = 1 + \frac{R_P}{R_1} - \left(\frac{\omega_{02}}{\omega}\right)^2 \left(\frac{R_P}{R_1}\,\frac{L_3}{L_2} + 1\right)$$

$$- j\,\frac{\omega_{02}}{\omega}\left[\frac{Z_{02}}{R_1} + \frac{R_P}{Z_{02}}\left(\frac{L_3}{L_2} + 1\right) - \left(\frac{\omega_{02}}{\omega}\right)^2 \frac{R_P}{Z_{02}}\,\frac{L_3}{L_2}\right]$$

$$\frac{Z_P}{R_1} = \frac{\dfrac{Z_{02}}{R_1} + \dfrac{R_1}{Z_{02}}\left[\left(\dfrac{\omega_{02}}{\omega}\right)^2 - 1\right] + j\,\dfrac{\omega}{\omega_{02}}}{\dfrac{L_3 R_1}{L_2 Z_{02}} + j\left[\dfrac{\omega_{02}}{\omega}\left(\dfrac{L_3 R_1^2}{L_2 Z_{02}^2} - \dfrac{L_3}{L_2} + \dfrac{R_1^2}{Z_{02}^2}\right) - \left(\dfrac{\omega_{02}}{\omega}\right)^3 \cdot \dfrac{L_3 R_1^2}{L_2 Z_{02}^2} + \dfrac{\omega}{\omega_{02}}\right]}$$

FIG. 11



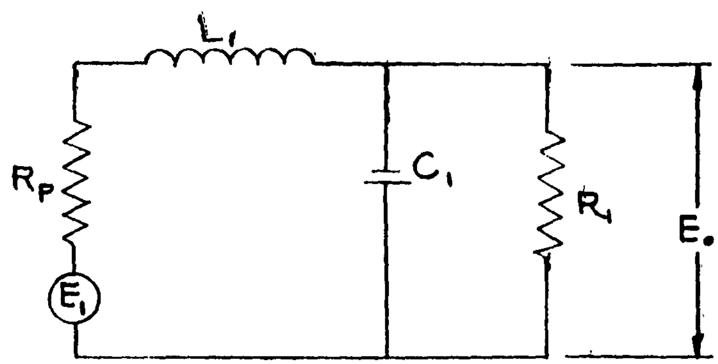
$$\omega_{01} = \frac{1}{\sqrt{L_1 C_3}} \qquad Z_{01} = \sqrt{\frac{L_1}{C_3}}$$

HIGH FREQUENCY EQUIVALENT CIRCUIT

$$\frac{E_1}{E_0} = 1 + \frac{R_p}{R_1}\left[1 - \left(\frac{\omega}{\omega_{01}}\right)^2\right] + j\,\frac{\omega}{\omega_{01}}\left[\frac{R_p}{Z_{01}} + \frac{Z_{01}}{R_1}\right]$$

$$\frac{Z_p}{R_1} = \frac{1 + j\,\frac{\omega}{\omega_{01}}\left[\frac{Z_{01}}{R_1} - \frac{R_1}{Z_{01}} - \left(\frac{\omega}{\omega_{01}}\right)^2 \frac{Z_{01}}{R_1}\right]}{\left[1 - \left(\frac{\omega}{\omega_{01}}\right)^2\right]^2 + \left(\frac{\omega}{\omega_{01}}\right)^2\left(\frac{R_1}{Z_{01}}\right)^2}$$

FIG. 12



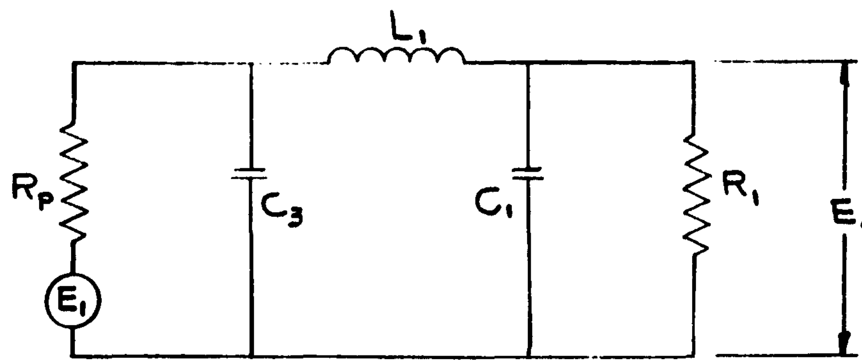
$$\omega_{01} = \frac{1}{\sqrt{L_1 C_1}} \qquad Z_{01} = \sqrt{\frac{L_1}{C_1}}$$

HIGH FREQUENCY EQUIVALENT CIRCUIT

$$\frac{E_1}{E_o} = 1 + \frac{R_P}{R_1} - \left(\frac{\omega}{\omega_{01}}\right)^2 + j\,\frac{\omega}{\omega_{01}}\left(\frac{R_P}{Z_{01}} + \frac{Z_{01}}{R_1}\right)$$

$$\frac{Z_P}{R_1} = \frac{1 + j\,\dfrac{\omega}{\omega_{01}}\left[\dfrac{Z_{01}}{R_1} - \dfrac{R_1}{Z_{01}} + \left(\dfrac{\omega}{\omega_{01}}\right)^2 \dfrac{R_1}{Z_{01}}\right]}{1 + \left(\dfrac{\omega}{\omega_{01}}\right)^2 \left(\dfrac{R_1}{Z_{01}}\right)^2}$$

FIG. 13



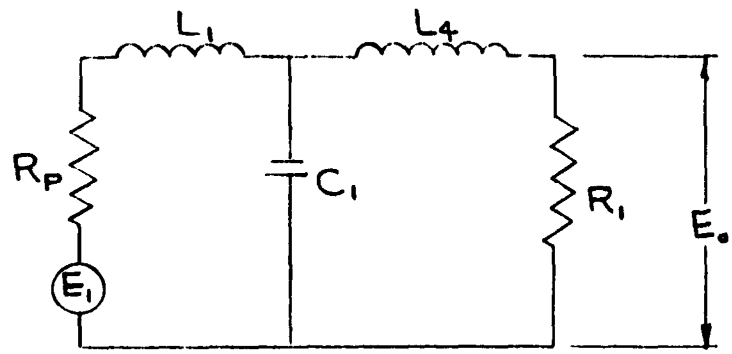
$$\omega_{01} = \frac{1}{\sqrt{L_1 C_1}} \qquad Z_{01} = \sqrt{\frac{L_1}{C_1}}$$

HIGH FREQUENCY EQUIVALENT CIRCUIT

$$\frac{E_1}{E_0} = 1 + \frac{R_p}{R_1} - \left(\frac{\omega}{\omega_{01}}\right)^2 \left(1 + \frac{C_3 R_p}{C_1 R_1}\right)$$
$$+ j\,\frac{\omega}{\omega_{01}} \left[\frac{R_p}{Z_{01}} + \frac{C_3 R_p}{C_1 Z_{01}} + \frac{Z_{01}}{R_1} - \left(\frac{\omega}{\omega_{01}}\right)^2 \left(\frac{C_3}{C_1}\,\frac{R_p}{Z_{01}}\right)\right]$$

$$\frac{Z_p}{R_1} = \frac{\dfrac{Z_{01}}{R_1} + j\left[\dfrac{\omega}{\omega_{01}}\left(\dfrac{Z_{01}^2}{R_1^2} - 1\right) + \left(\dfrac{\omega}{\omega_{01}}\right)^3\right]}{\dfrac{Z_{01}}{R_1} + \left(\dfrac{\omega}{\omega_{01}}\right)^2\left(\dfrac{C_3 R_1}{C_1 Z_{01}} - \dfrac{C_3 Z_{01}}{C_1 R_1} + \dfrac{R_1}{Z_{01}}\right) - \left(\dfrac{\omega}{\omega_{01}}\right)^4 \dfrac{C_3 R_1}{C_1 Z_{01}} + j\,\dfrac{\omega C_3}{\omega_{01} C_1}}$$

FIG. 14



$$\omega_{01} = \frac{1}{\sqrt{L_1 C_1}} \qquad Z_{01} = \sqrt{\frac{L_1}{C_1}}$$

HIGH FREQUENCY EQUIVALENT CIRCUIT

$$\frac{E_1}{E_0} = 1 + \frac{R_P}{R_1} - \left(\frac{\omega}{\omega_{01}}\right)^2 \left(\frac{R_P}{R_1} \frac{L_4}{L_1} + 1 \right)$$
$$+ j \left[\frac{\omega}{\omega_{01}} \left(\frac{R_P}{Z_{01}} + \frac{Z_{01}}{R_1} + \frac{L_4}{L_1} \frac{Z_{01}}{R_1} \right) - \left(\frac{\omega}{\omega_{01}}\right)^3 \frac{L_4}{L_1} \frac{Z_{01}}{R_1} \right]$$

$$\frac{Z_P}{R_1} = \frac{1 + j \left\{ \frac{\omega}{\omega_{01}} \left[\frac{Z_{01}}{R_1} \left(\frac{L_4}{L_1} + 1 \right) - \frac{R_1}{Z_{01}} \right] + \left(\frac{\omega}{\omega_{01}}\right)^3 \left[\frac{L_4}{L_1} \frac{Z_{01}}{R_1} \left(\frac{\omega^2}{\omega_{01}^2} \frac{L_4}{L_1} - 2 - \frac{L_4}{L_1} \right) + \frac{R_1}{Z_{01}} \right] \right\}}{\left(\frac{\omega}{\omega_{01}}\right)^2 \left(\frac{R_1}{Z_{01}}\right)^2 + \left[\left(\frac{\omega}{\omega_{01}}\right)^2 \frac{L_4}{L_1} - 1 \right]^2}$$

FIG. 15

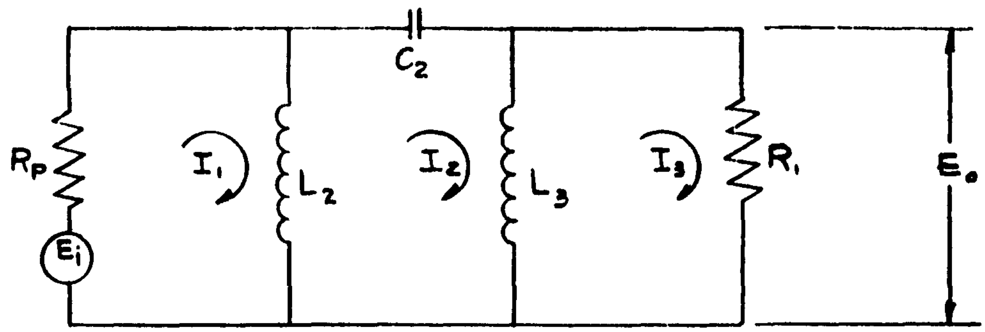


FIG. 16

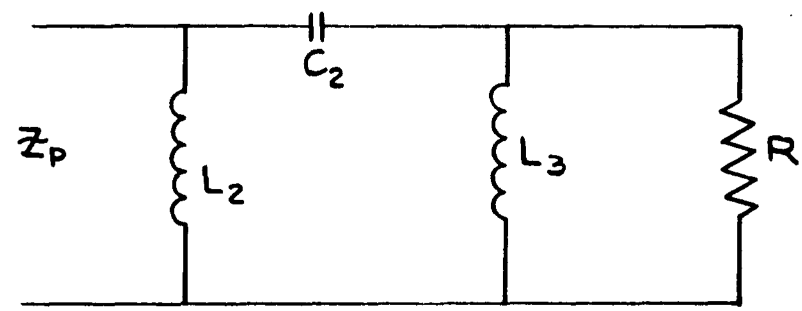


FIG. 17

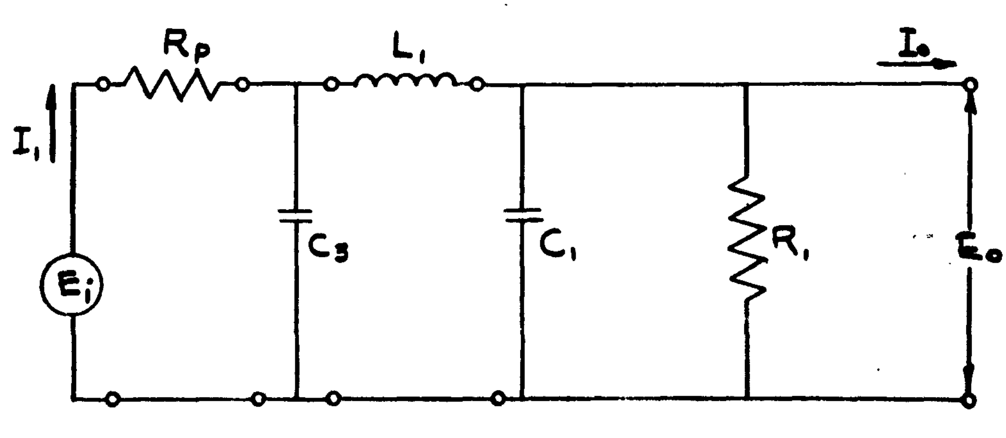


FIG. 18

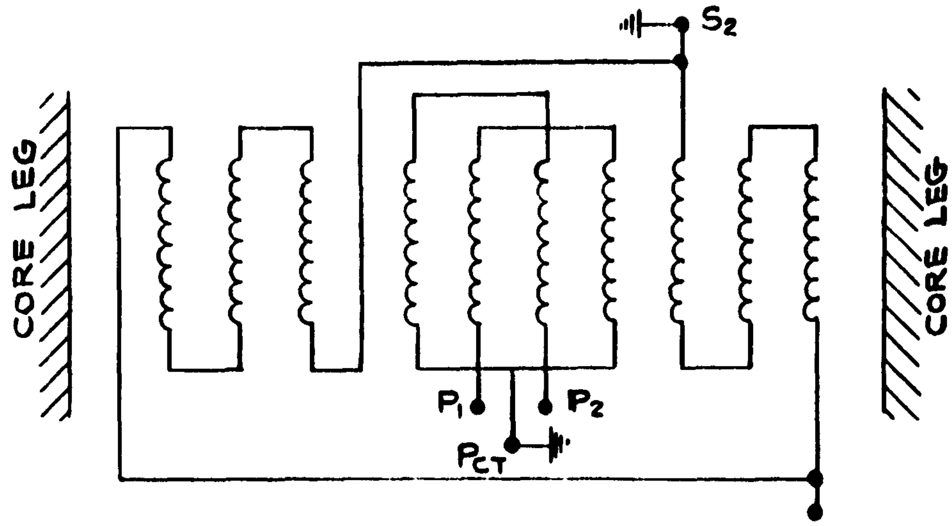


FIG. 19

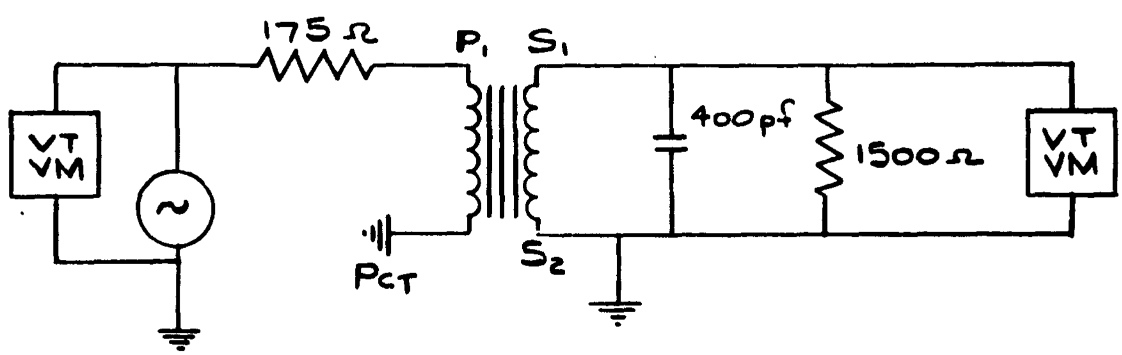


FIG. 20

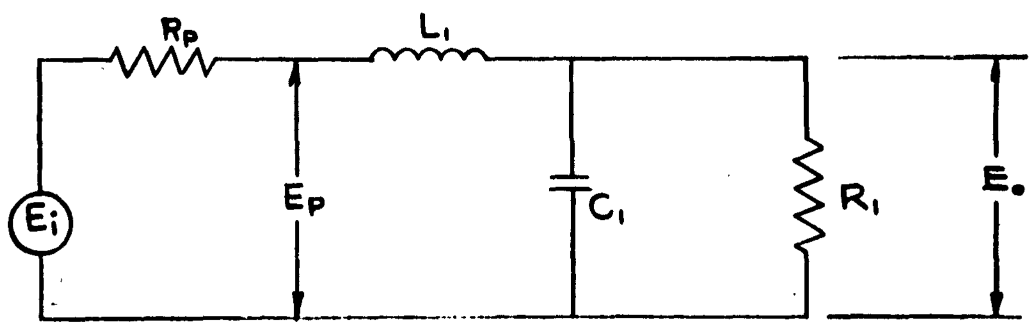
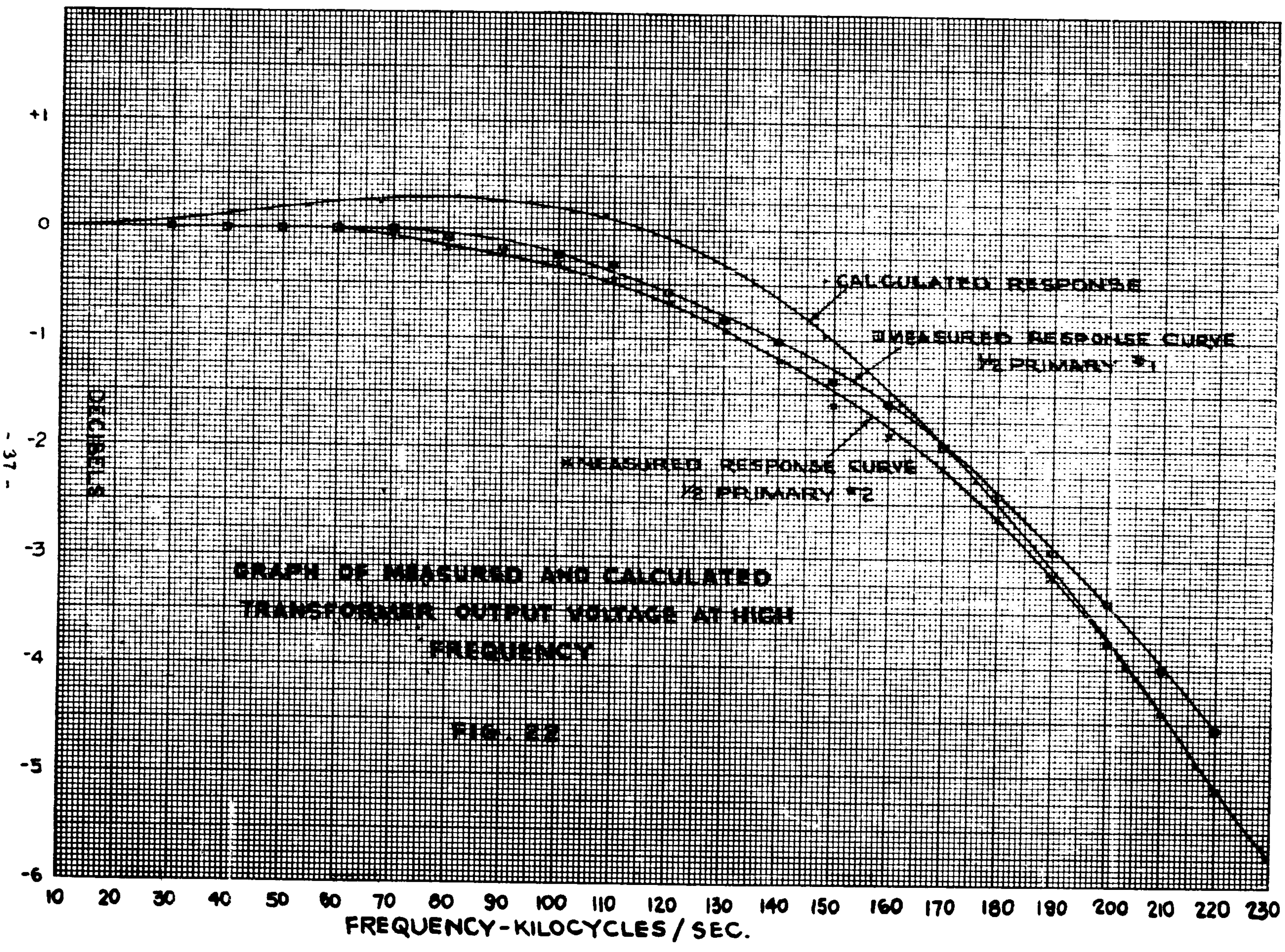


FIG. 21



+1
0
-1
-2
-3
-4
-5
-6
DECIBELS
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230
FREQUENCY-KILOCYCLES / SEC.
CALCULATED RESPONSE
MEASURED RESPONSE CURVE ½ PRIMARY #1
MEASURED RESPONSE CURVE ½ PRIMARY #2
GRAPH OF MEASURED AND CALCULATED TRANSFORMER OUTPUT VOLTAGE AT HIGH FREQUENCY
FIG. 22

REFERENCES

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2. "Transformer Engineering," Blume, Boyajian, Camilli, Lennox, Minneci, and Montsinger, John Wiley &Sons, Inc., New York, N.Y., 1951.

3. "Electronic Transformers and Circuits, " R. Lee, John Wiley & Sons, Inc., New York, N.Y., 1955.

4. "Radio Engineering," F. Terman, McGraw-Hill, Inc., New York, N.Y. 1947.

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6. "Wide-Band Transformers and Associated Coupling Networks," T. O'Meara, Electro-Technology, Sept., 1962.

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8. "A Distributed-Parameter Approach to the High-Frequency Network Representation of Wide-Band Transformers," T.O'Meara, Trans. IRE, March, 1961.

9. "A Comparison of Thin Tape and Wire Windings for Lumped-Parameter, Wide-Band, High Frequency Transformers," T. O'Meara, Trans. IRE, June, 1959.

10. "Design of Audio-Frequency Amplifier Circuits Using Transformers," P. Klipsch, Proc. IRE, Vol. 24, 1936.

11. "Output Transformer Response," F. Terman and R. Ingebretsen, Electronics, Vol. 9, January, 1936.

12. "Analysis and Synthesis with the 'Complete' Equivalent Circuit for the Wide-Band Transformer," T. O'Meara.

13. "The Specification of Control System Transformers Using a Dynamic Response Criterion," D. Pidhayny.

14. "Electrical Engineering Circuits," H. H. Skilling, John Wiley & Sons, Inc. New York, N.Y., 1957.

APPENDIX I

MILESTONE REPORT #5

LOW FREQUENCY RESPONSE CURVES FOR

VARIOUS EQUIVALENT CIRCUITS

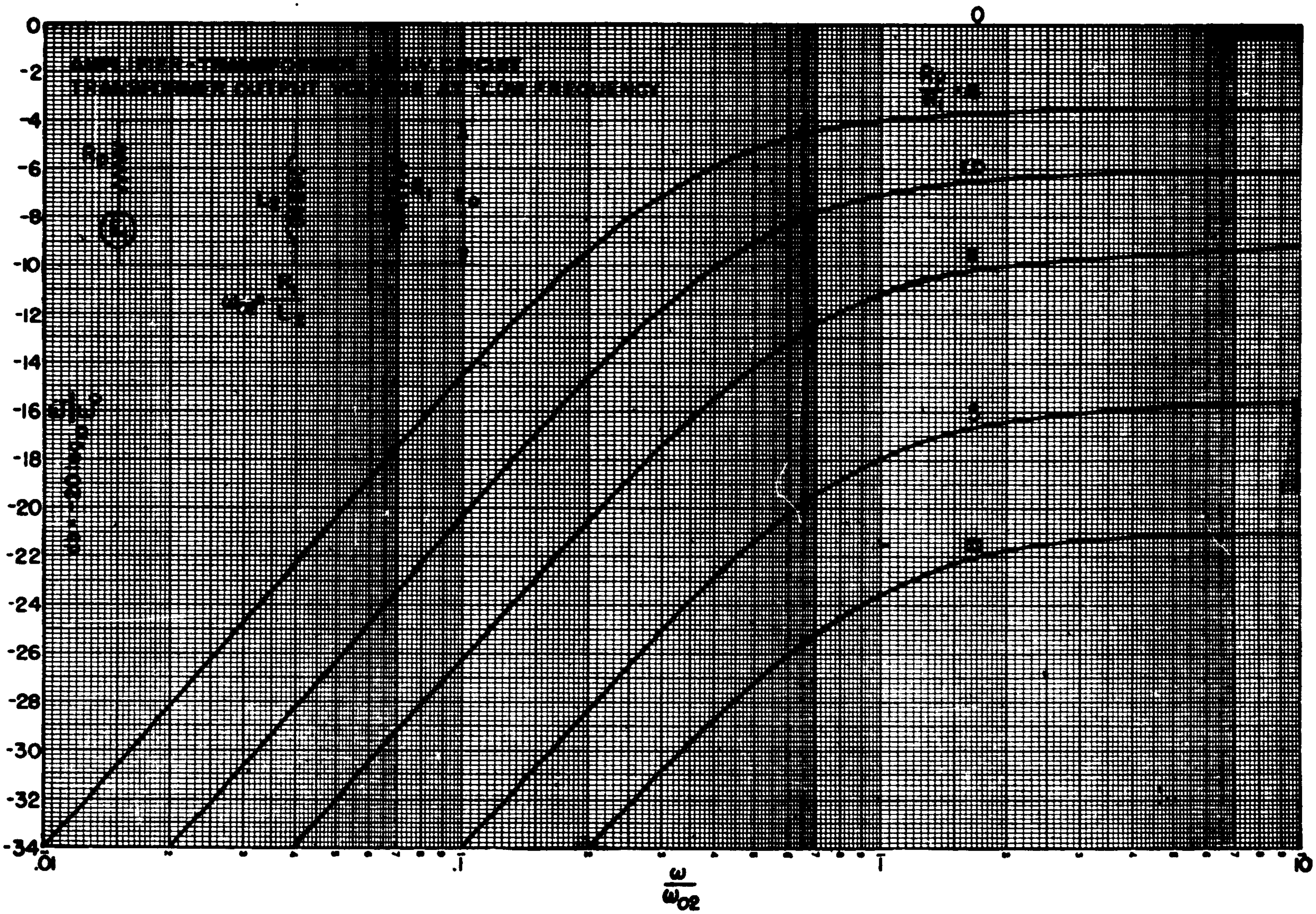

0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
.01
.1
1
10
$\frac{\omega}{\omega_{o2}}$

FIG. 1

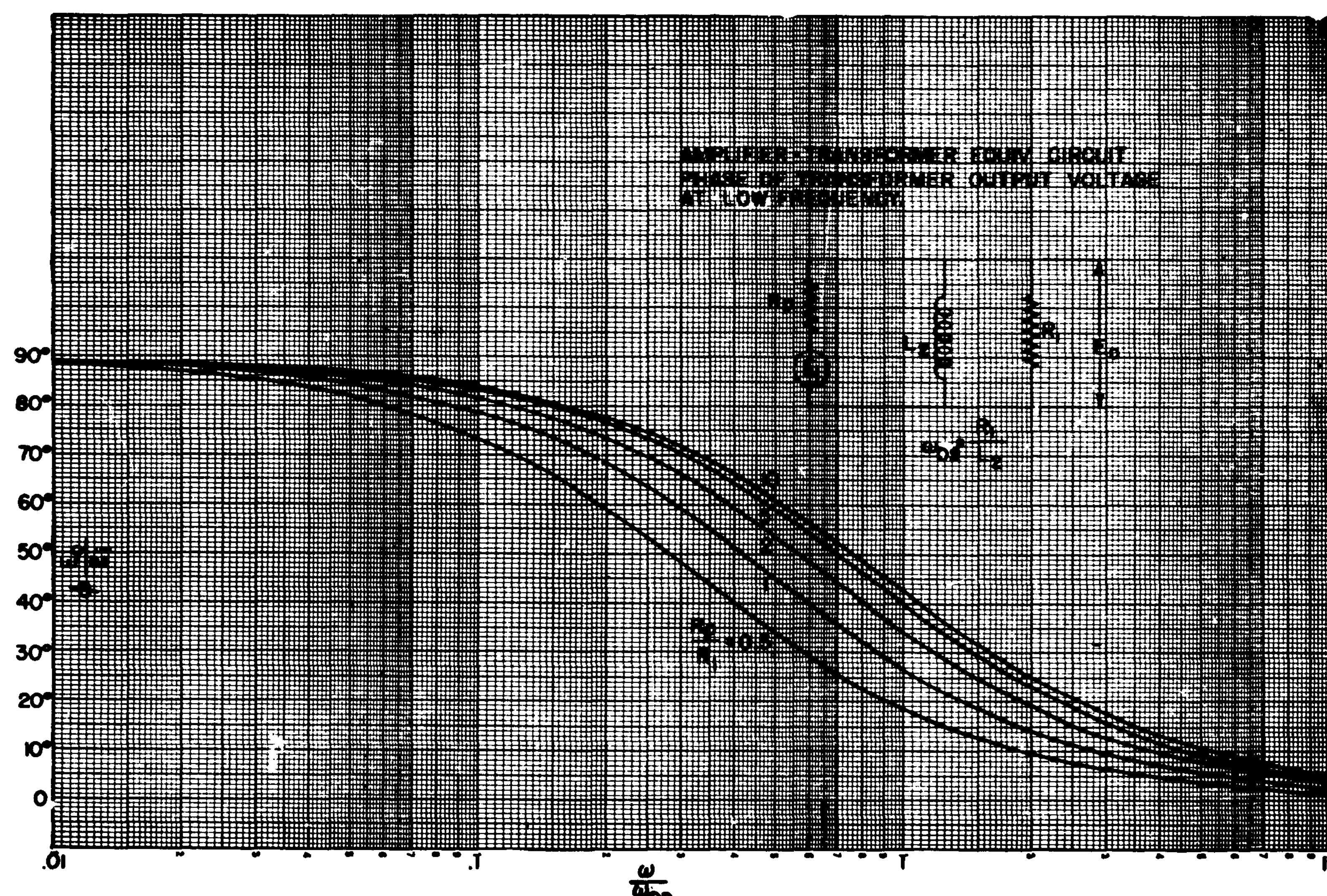

AMPLIFIER - TRANSFORMER EQUIV. CIRCUIT
PHASE OF TRANSFORMER OUTPUT VOLTAGE
AT LOW FREQUENCY
90°
80°
70°
60°
50°
40°
30°
20°
10°
0
.01
.1
1
10
ω / ω02

FIG. 2

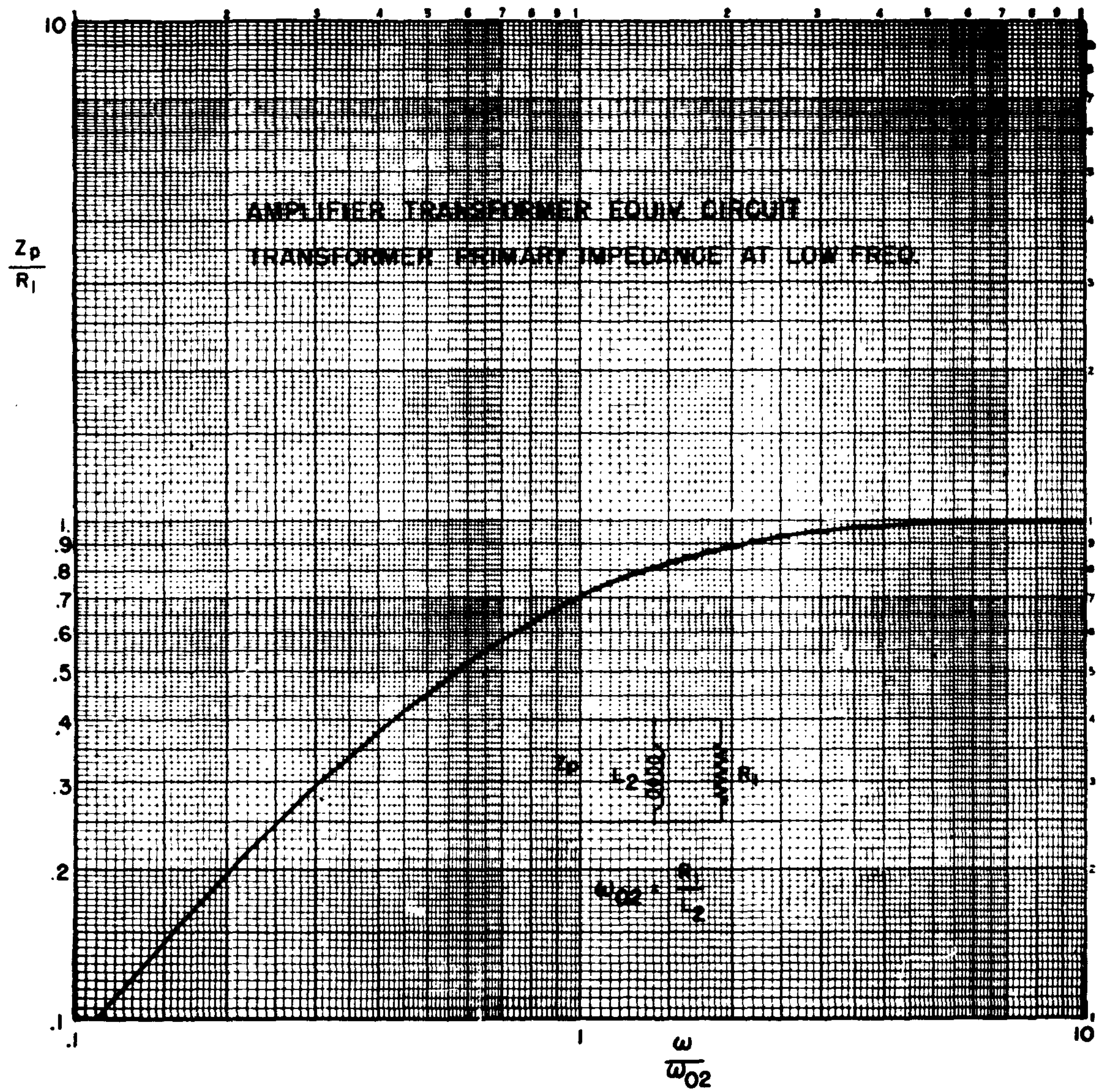

AMPLIFIER TRANSFORMER EQUIV. CIRCUIT
TRANSFORMER PRIMARY IMPEDANCE AT LOW FREQ.
Zp
R1
Zp
L2
R1
ω02 = R1/L2
ω
ω02
10
1.
.9
.8
.7
.6
.5
.4
.3
.2
.1
.1
1
10

FIG. 3

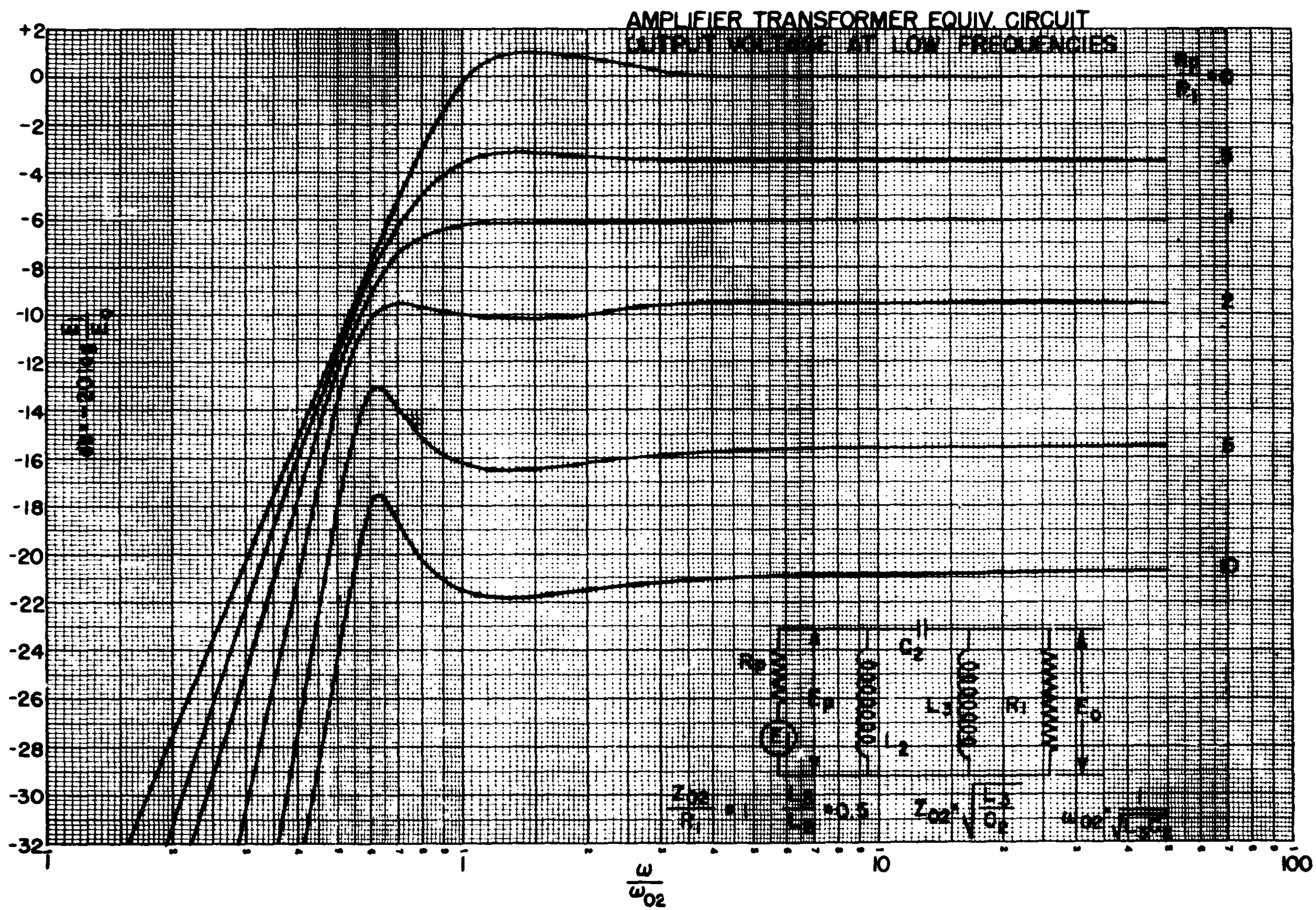

AMPLIFIER TRANSFORMER EQUIV. CIRCUIT
OUTPUT VOLTAGE AT LOW FREQUENCIES
+2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
1
10
100
ω/ω02
C2
Rp
Cp
L2
L3
R1
E0
Z02/R1 = 1
Z02 = √(L3/C2)

FIG. 4

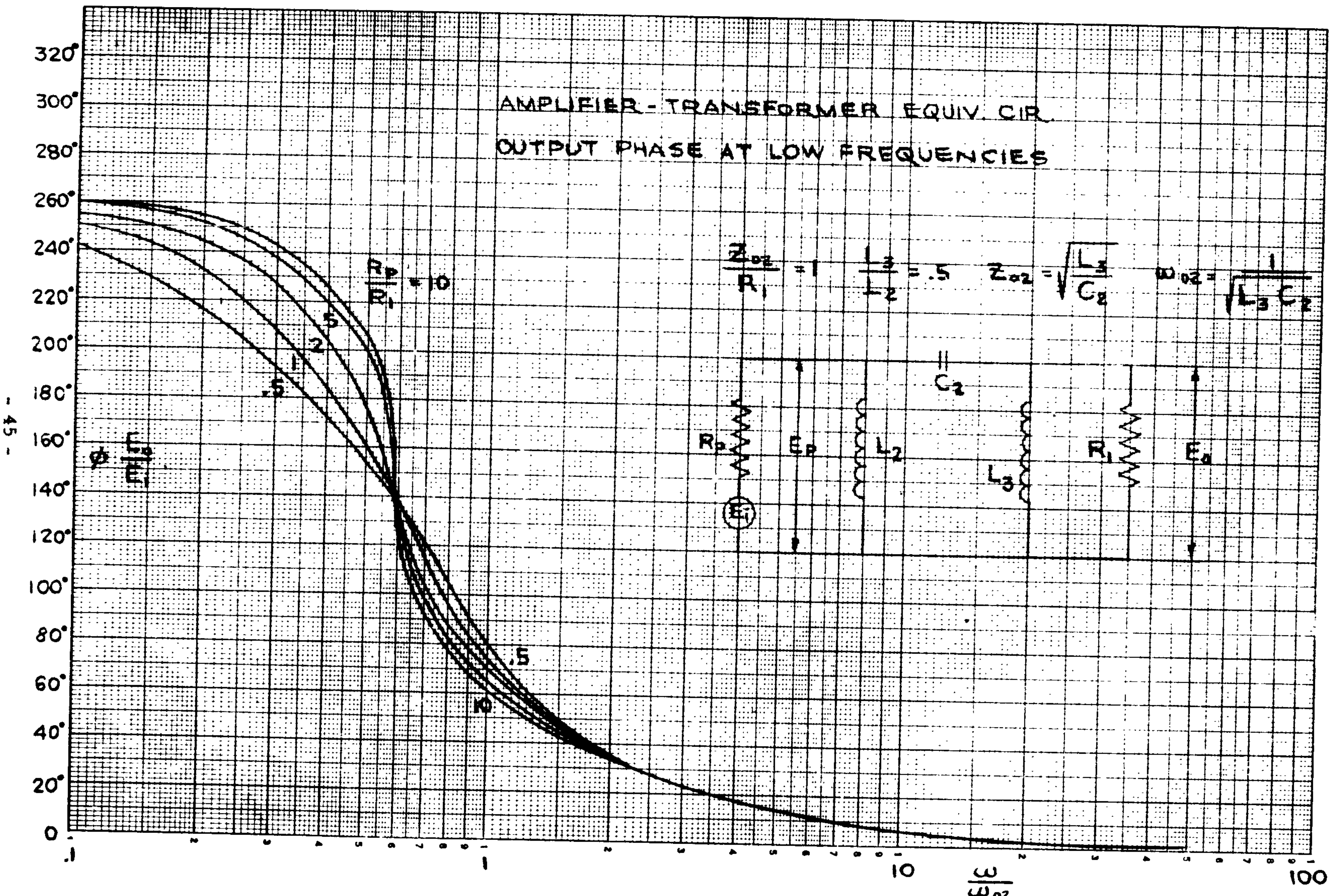

AMPLIFIER - TRANSFORMER EQUIV. CIR.
OUTPUT PHASE AT LOW FREQUENCIES
$\frac{Z_{o2}}{R_1} = 1$ $\frac{L_3}{L_2} = .5$ $Z_{o2} = \sqrt{\frac{L_3}{C_2}}$ $\omega_{o2} = \frac{1}{\sqrt{L_3 C_2}}$
$\frac{R_p}{R_1} = 10$
5
2
1
.5
10
$\phi \frac{E_o}{E_1}$
R_p
E_1
E_p
L_2
C_2
L_3
R_1
E_o
320°
300°
280°
260°
240°
220°
200°
180°
160°
140°
120°
100°
80°
60°
40°
20°
0
.1
1
10
100
$\frac{\omega}{\omega_{o2}}$

FIG. 5

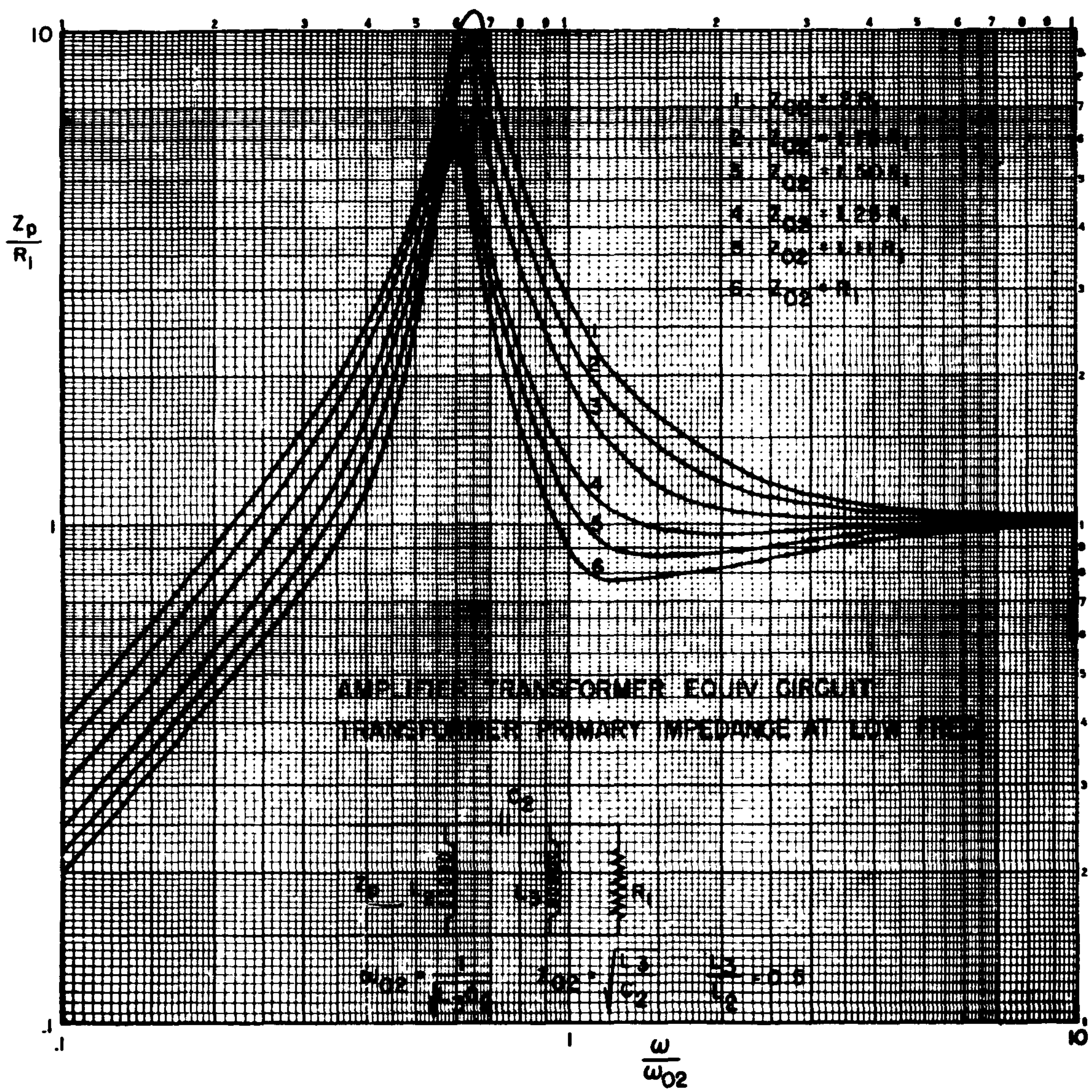

AMPLIFIER TRANSFORMER EQUIV CIRCUIT
10
1
.1
10
$\frac{Z_p}{R_1}$
$\frac{\omega}{\omega_{02}}$

FIG. 6

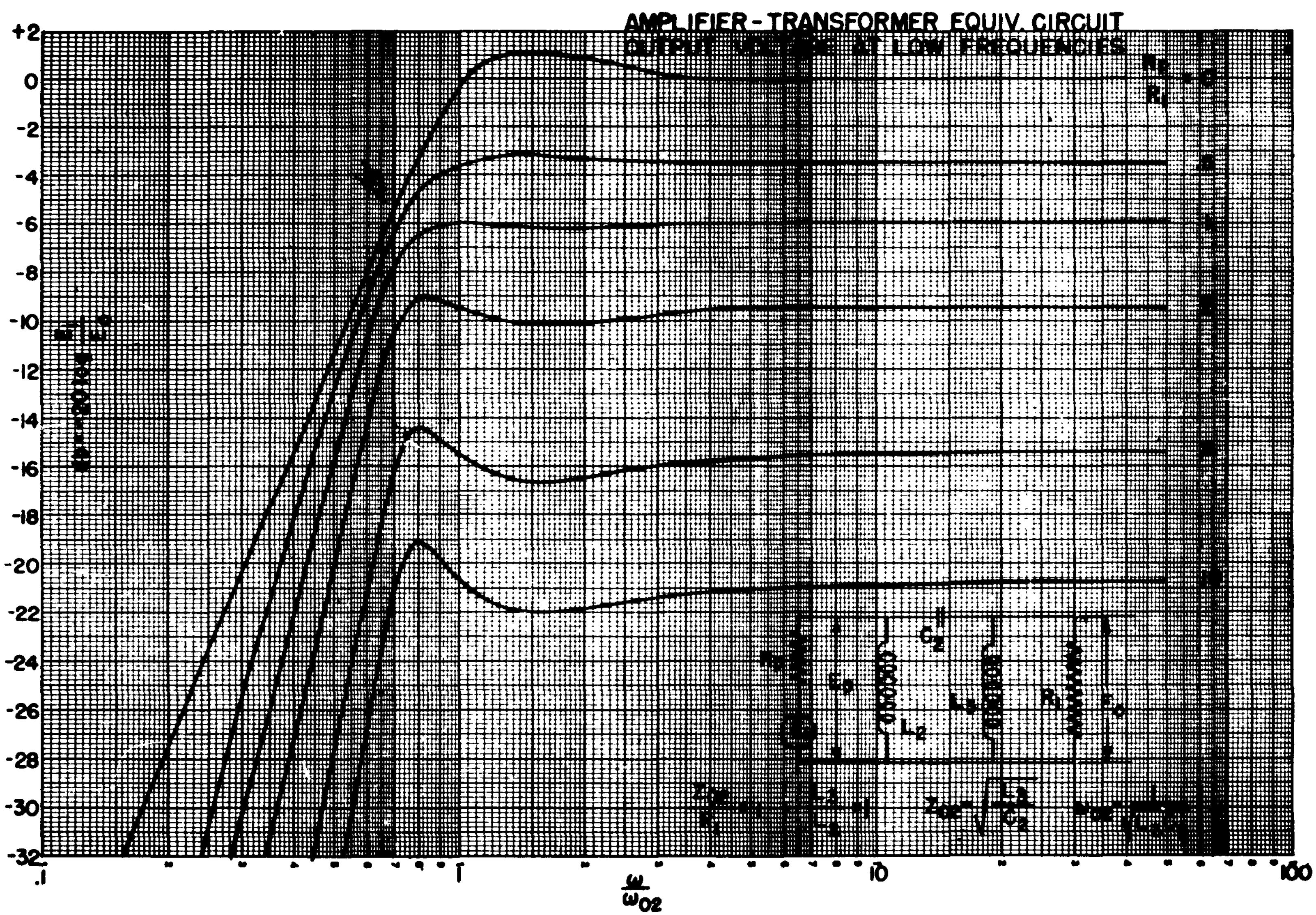
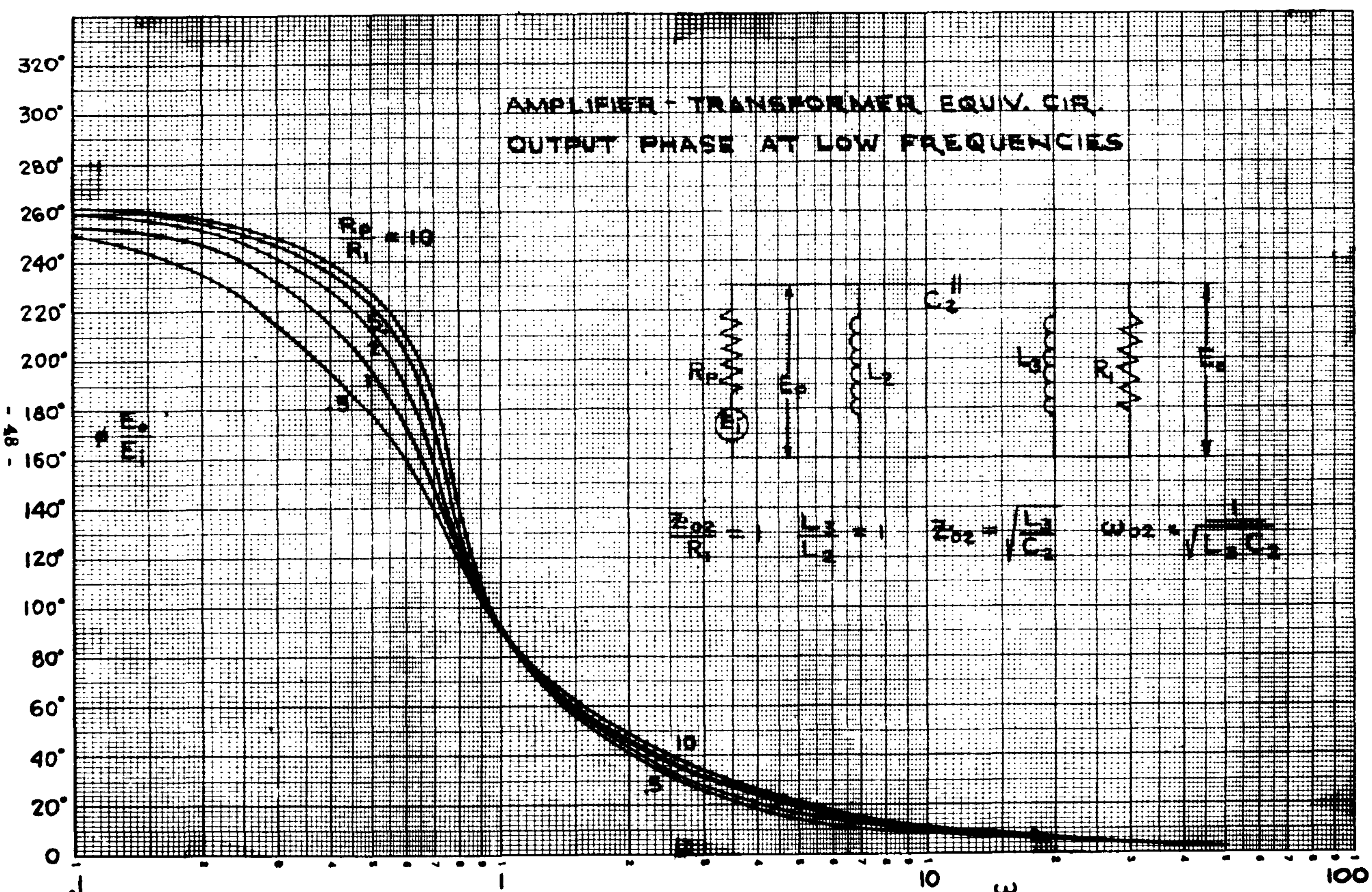

AMPLIFIER - TRANSFORMER EQUIV. CIRCUIT
OUTPUT VOLTAGE AT LOW FREQUENCIES
+2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
.1
1
10
100
ω / ω02
C_2
L_2
R_1

FIG. 7



AMPLIFIER - TRANSFORMER EQUIV. CIR.
OUTPUT PHASE AT LOW FREQUENCIES
$\frac{R_P}{R_1} = 10$
5
R_P
E_1
E_p
L_2
C_2
L_3
R_1
E_2
$\frac{Z_{02}}{R_1} = 1$
$\frac{L_3}{L_2} = 1$
$Z_{02} = \sqrt{\frac{L_3}{C_2}}$
$\omega_{02} = \frac{1}{\sqrt{L_3 C_2}}$
10
5
320°
300°
280°
260°
240°
220°
200°
180°
160°
140°
120°
100°
80°
60°
40°
20°
0
$\phi \frac{E_0}{E_1}$
.1
1
10
100
$\frac{\omega}{\omega_{02}}$

FIG. 8

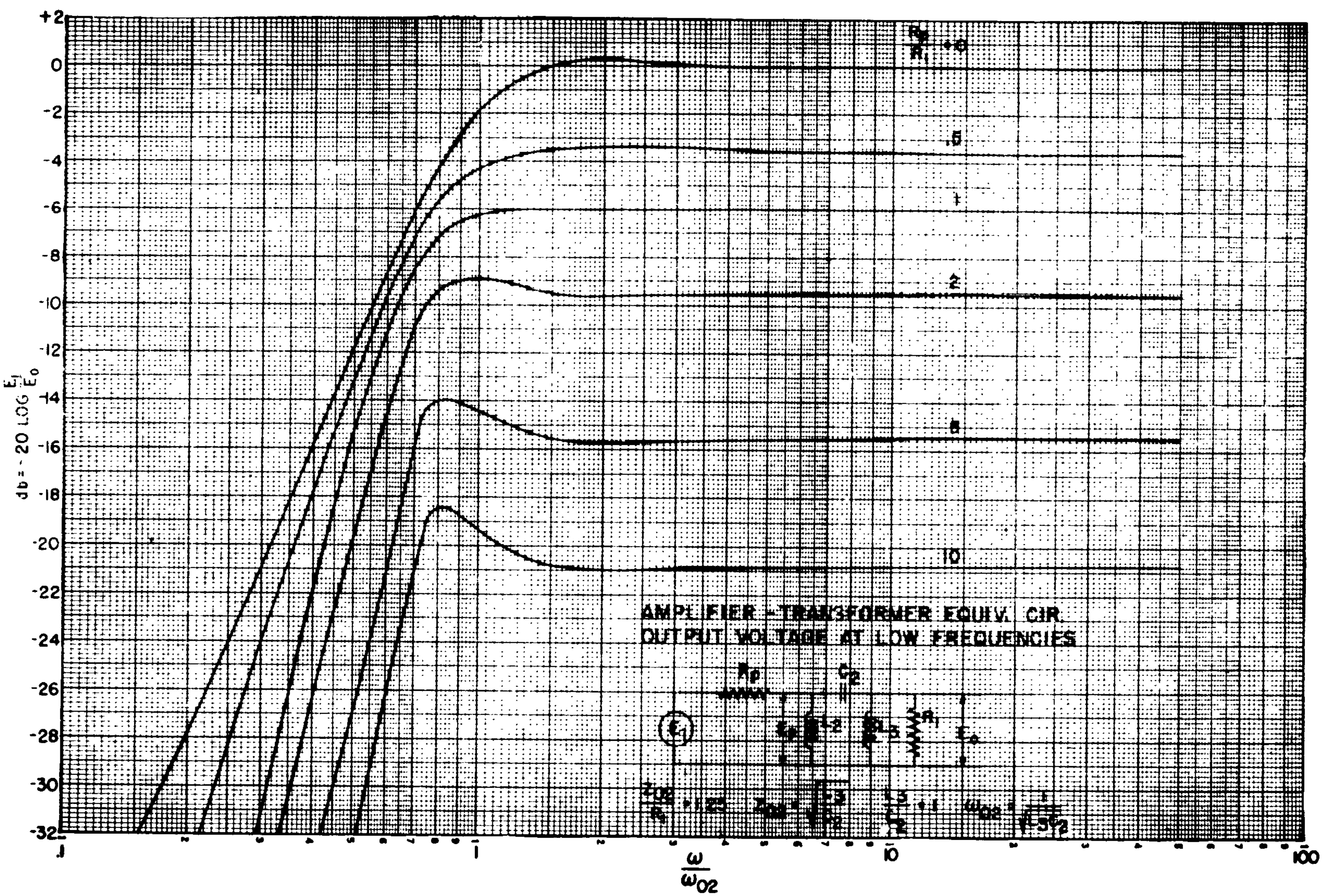
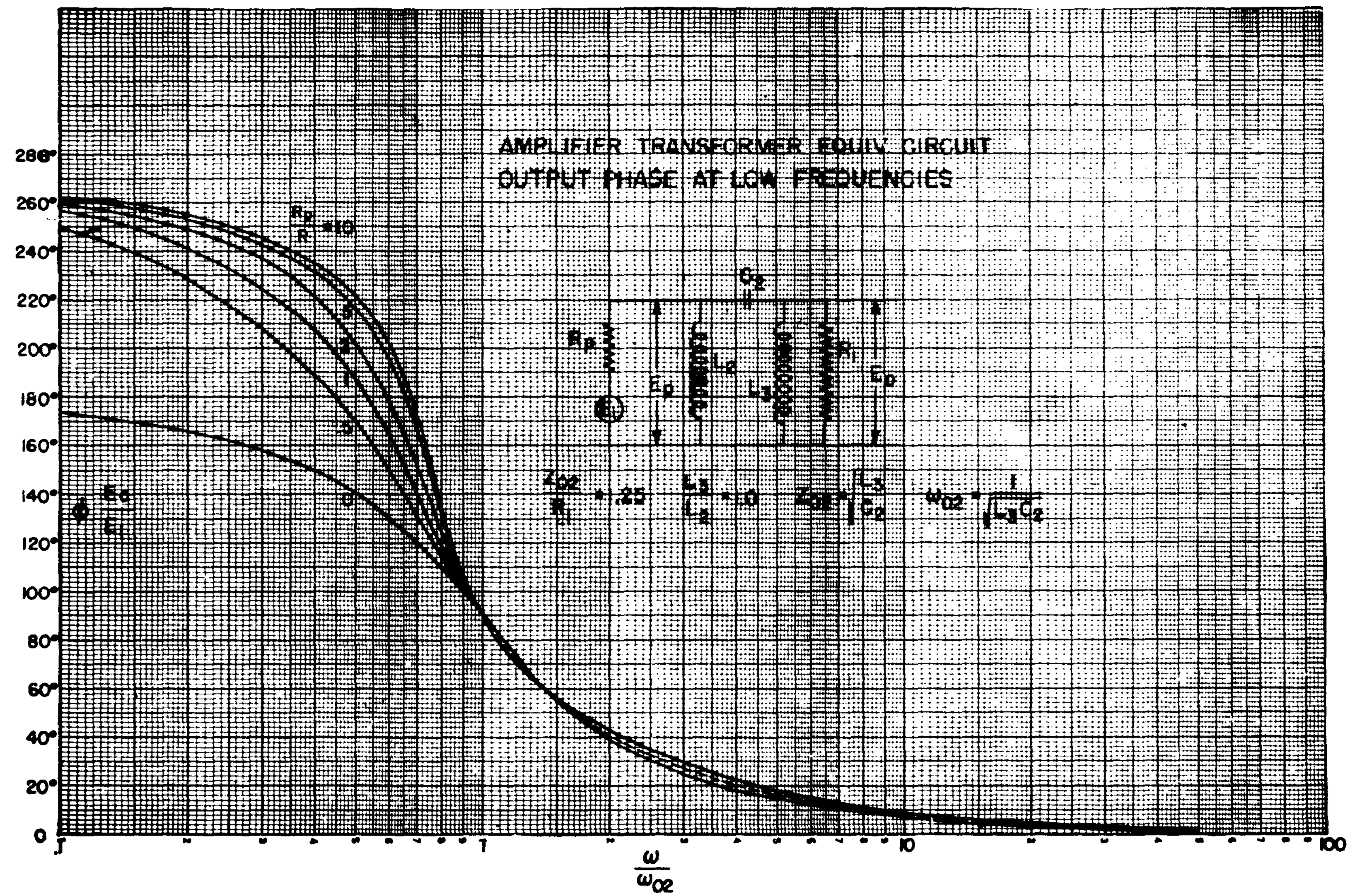

AMPLIFIER - TRANSFORMER EQUIV. CIR.
OUTPUT VOLTAGE AT LOW FREQUENCIES
.5
1
2
5
10
+2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
.1
1
10
100
$\frac{\omega}{\omega_{02}}$
$db = -20 \log \frac{E_1}{E_0}$

FIG. 9



AMPLIFIER TRANSFORMER EQUIV. CIRCUIT
OUTPUT PHASE AT LOW FREQUENCIES
$\frac{R_p}{R} = 10$
5
2
1
.5
0
C_2
R_p
E_p
L_2
L_3
R_1
E_o
$\frac{Z_{02}}{R_1} = .25$
$\frac{L_3}{L_2} = 10$
$Z_{02} = \sqrt{\frac{L_3}{C_2}}$
$\omega_{02} = \frac{1}{\sqrt{L_3 C_2}}$
$\Phi \frac{E_o}{E_i}$
280°
260°
240°
220°
200°
180°
160°
140°
120°
100°
80°
60°
40°
20°
0
.1
1
10
100
$\frac{\omega}{\omega_{02}}$

FIG. 10

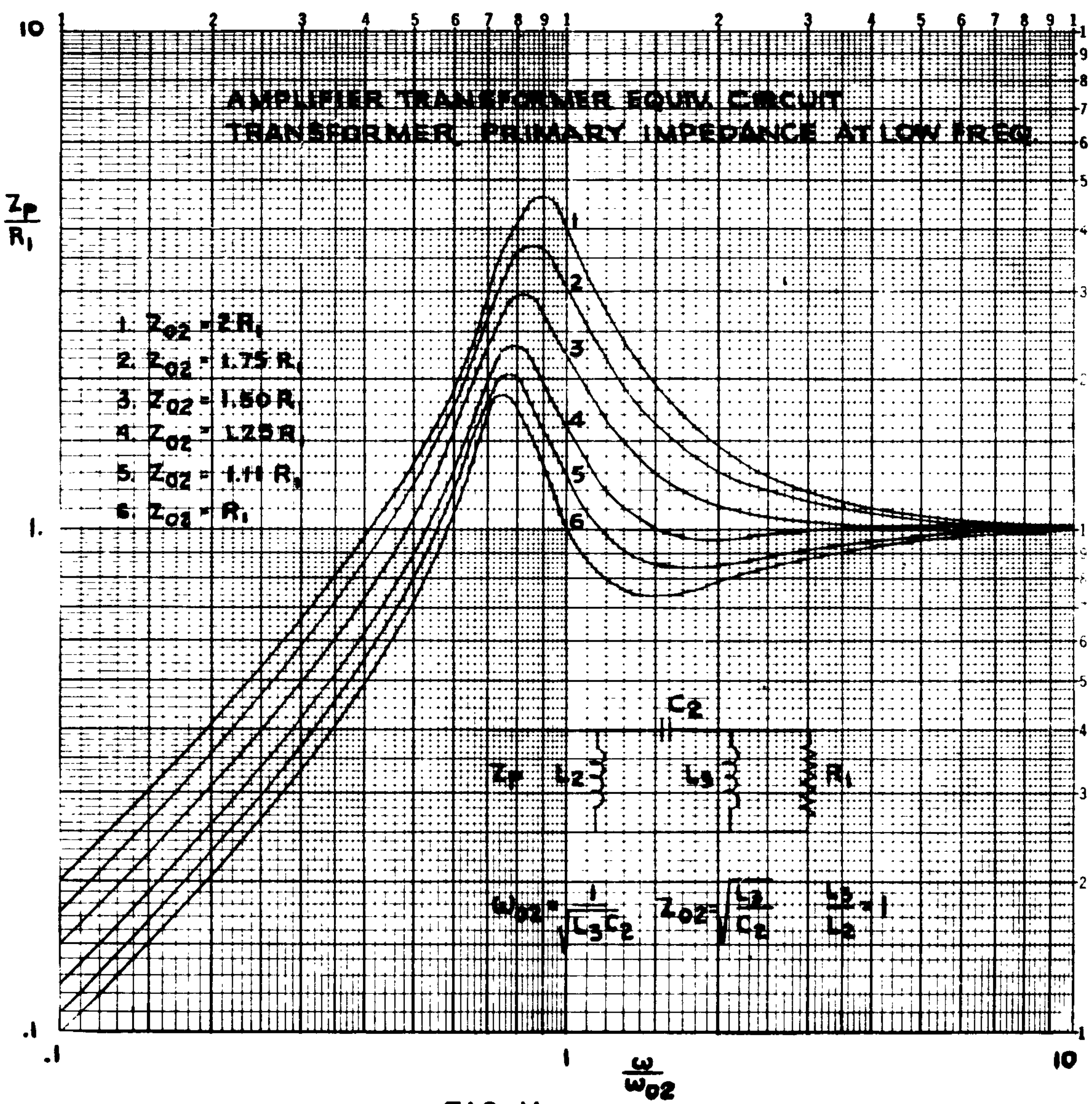

AMPLIFIER TRANSFORMER EQUIV. CIRCUIT
TRANSFORMER PRIMARY IMPEDANCE AT LOW FREQ.
$\frac{Z_P}{R_1}$
1. $Z_{02} = 2R_1$
2. $Z_{02} = 1.75 R_1$
3. $Z_{02} = 1.50 R_1$
4. $Z_{02} = 1.25 R_1$
5. $Z_{02} = 1.11 R_1$
6. $Z_{02} = R_1$
C_2
Z_P
L_2
L_3
R_1
$\omega_{02} = \frac{1}{\sqrt{L_3 C_2}}$
$Z_{02} = \sqrt{\frac{L_2}{C_2}}$
$\frac{L_3}{L_2} = 1$
$\frac{\omega}{\omega_{02}}$

FIG. 11

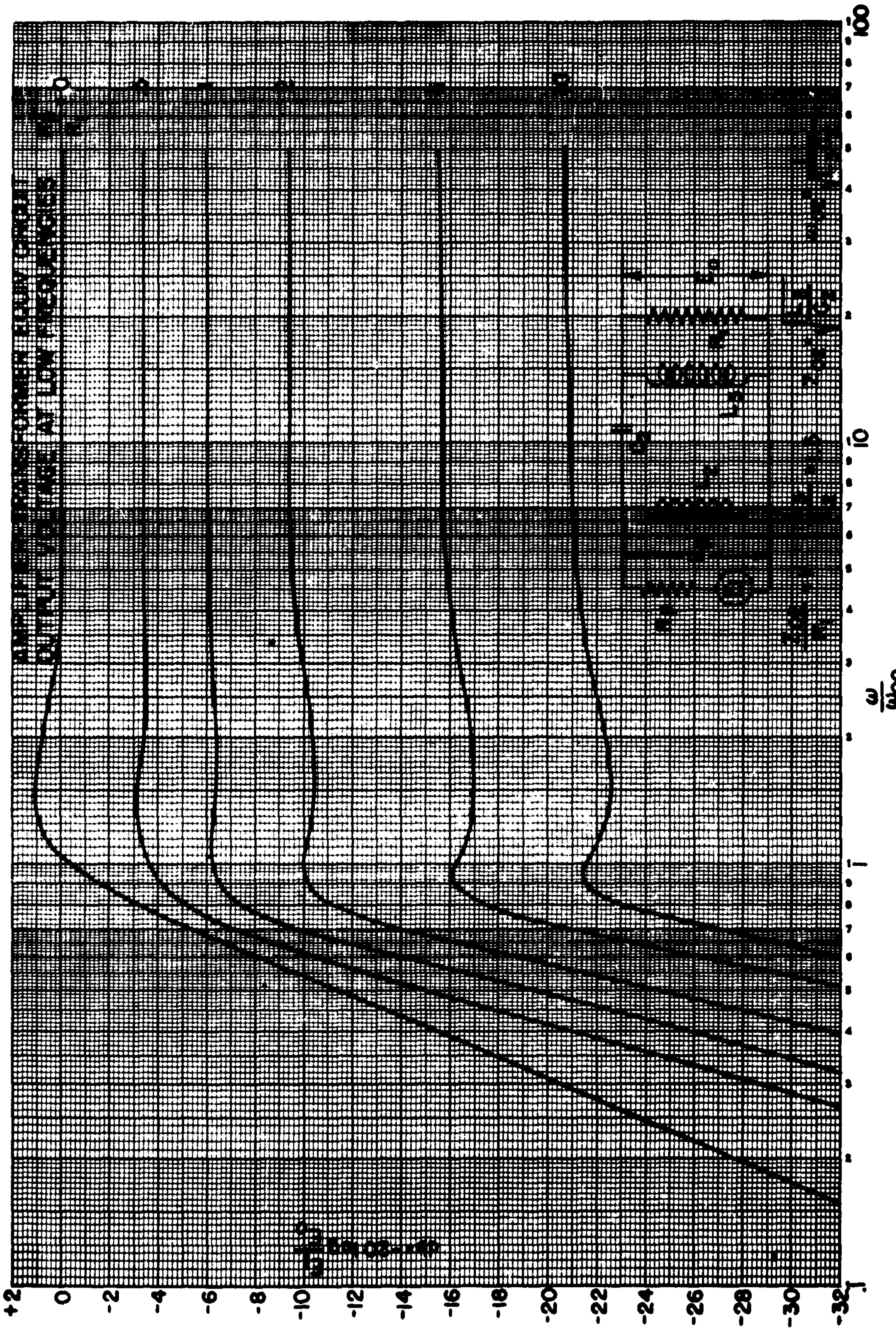


FIG. 12

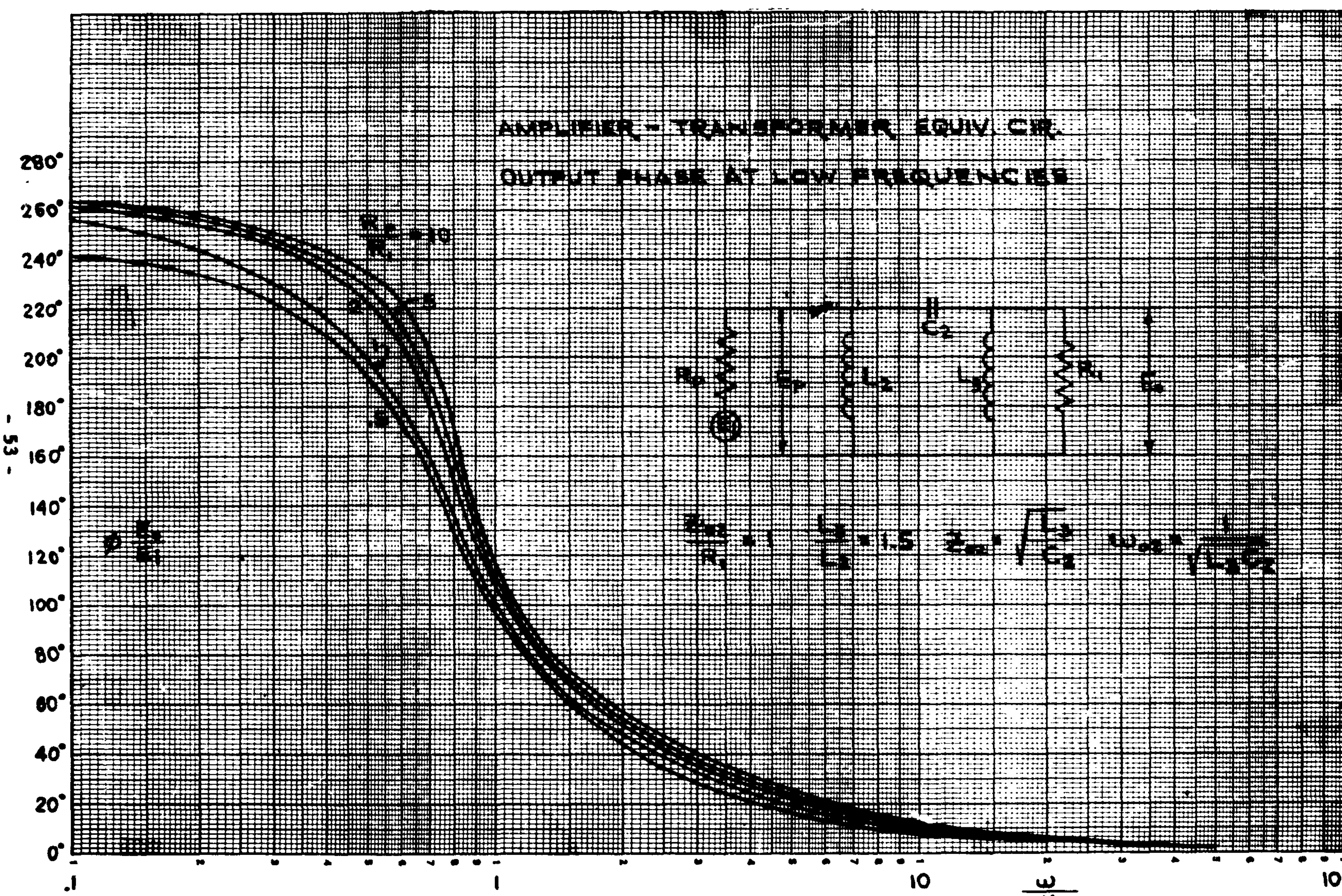

AMPLIFIER - TRANSFORMER EQUIV. CIR.
OUTPUT PHASE AT LOW FREQUENCIES
280°
260°
240°
220°
200°
180°
160°
140°
120°
100°
80°
60°
40°
20°
0°
.1
1
10
100
ω / ω02

FIG. 13

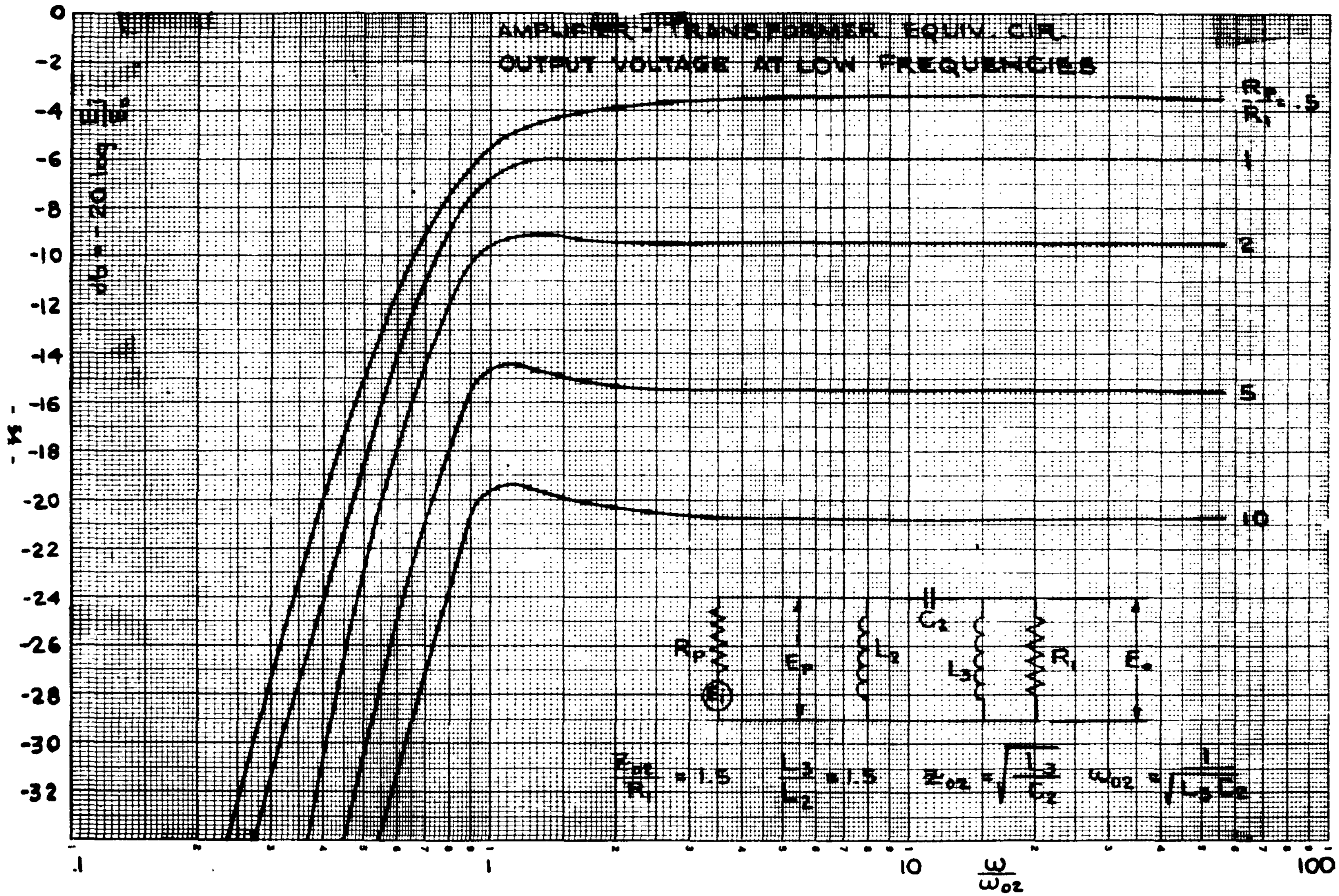

AMPLIFIER - TRANSFORMER EQUIV. CIR.
OUTPUT VOLTAGE AT LOW FREQUENCIES
$db = -20 \log \frac{E_i}{E_o}$
$\frac{R_P}{R_1} = .5$
1
2
5
10
R_P
E_i
E_P
L_2
C_2
L_3
R_1
E_o
$\frac{Z_{o2}}{R_1} = 1.5$
$\frac{L_3}{L_2} = 1.5$
$Z_{o2} = \sqrt{\frac{L_3}{C_2}}$
$\omega_{o2} = \frac{1}{\sqrt{L_3 C_2}}$
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
.1
1
10
100
$\frac{\omega}{\omega_{o2}}$

FIG. 14

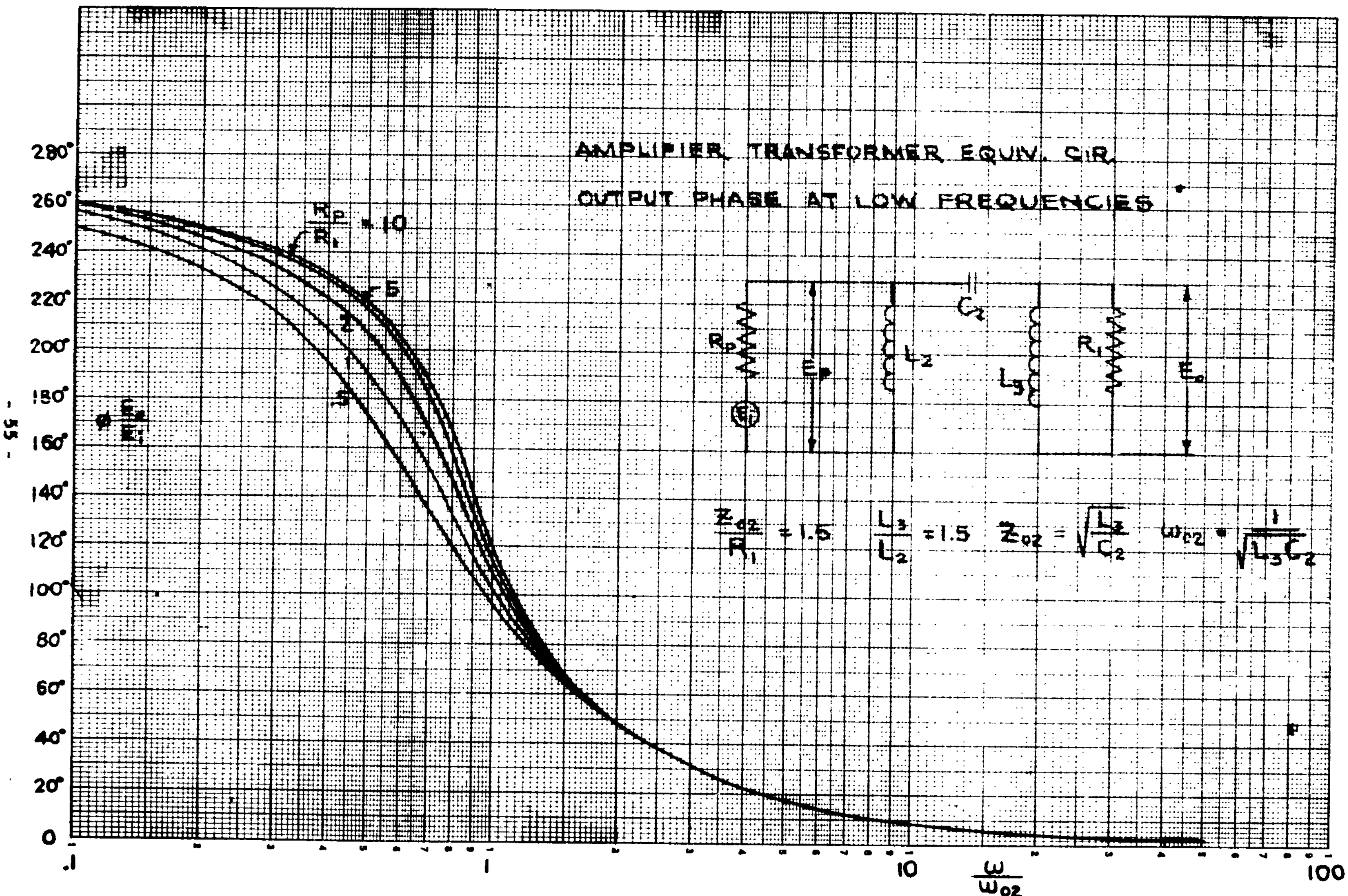
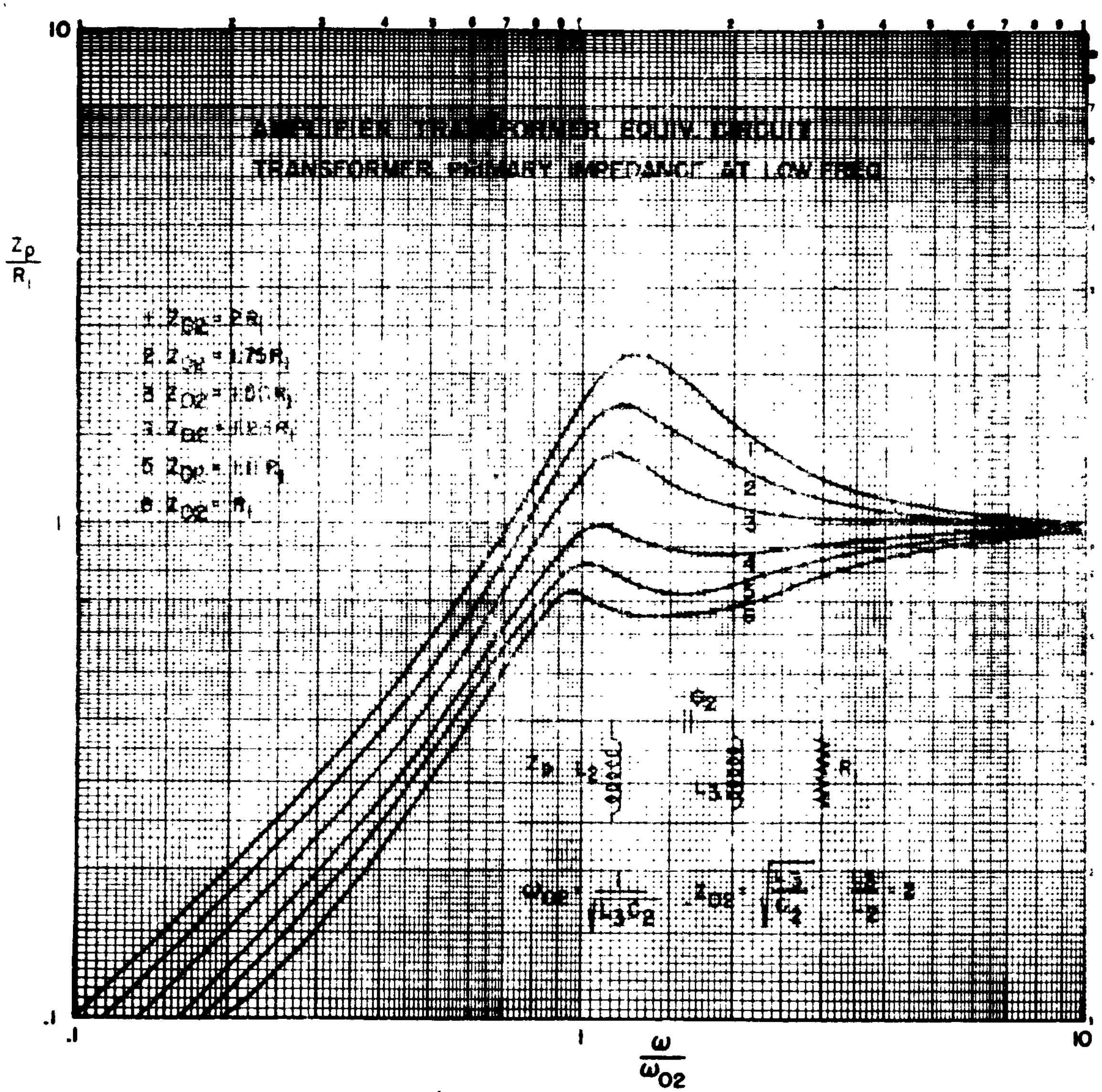

AMPLIFIER TRANSFORMER EQUIV. CIR.
OUTPUT PHASE AT LOW FREQUENCIES
$\frac{R_p}{R_1} = 10$
5
2
1
R_p
E_p
L_2
C_2
L_3
R_1
E_o
$\frac{Z_{o2}}{R_1} = 1.5$ $\frac{L_3}{L_2} = 1.5$ $Z_{o2} = \sqrt{\frac{L_3}{C_2}}$ $\omega_{o2} = \frac{1}{\sqrt{L_3 C_2}}$
$\phi \frac{E_o}{E_i}$
280° 260° 240° 220° 200° 180° 160° 140° 120° 100° 80° 60° 40° 20° 0
.1 1 10 100
$\frac{\omega}{\omega_{o2}}$

FIG. 15



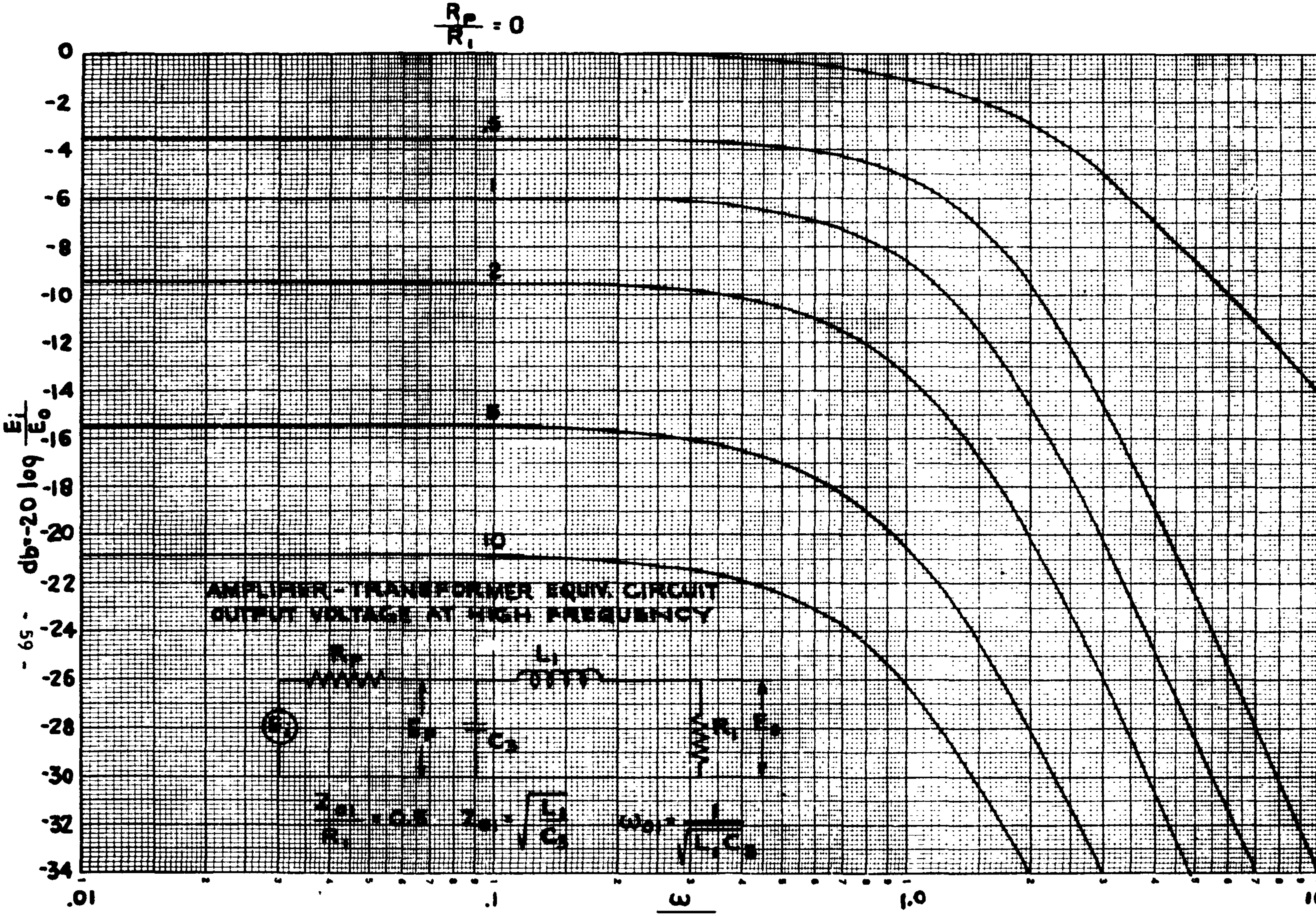
TRANSFORMER PRIMARY IMPEDANCE AT LOW FREQ.
10
1
.1
10
$\frac{Z_p}{R_1}$
$\frac{\omega}{\omega_{02}}$

FIG.16

APPENDIX II

MILESTONE REPORT #5

HIGH FREQUENCY RESPONSE CURVES FOR VARIOUS EQUIVALENT CIRCUITS



$\frac{R_P}{R_1} = 0$
.5
1
2
5
10
AMPLIFIER - TRANSFORMER EQUIV. CIRCUIT
OUTPUT VOLTAGE AT HIGH FREQUENCY
R_P
L_1
C_S
R_1
E_0
$\frac{Z_{01}}{R_1} = 0.5$
$Z_{01} = \sqrt{\frac{L_1}{C_S}}$
$\omega_{01} = \frac{1}{\sqrt{L_1 C_S}}$
$db = 20 \log \frac{E_i}{E_o}$
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
.01
.1
1.0
10
$\frac{\omega}{\omega_{01}}$

FIG. 1

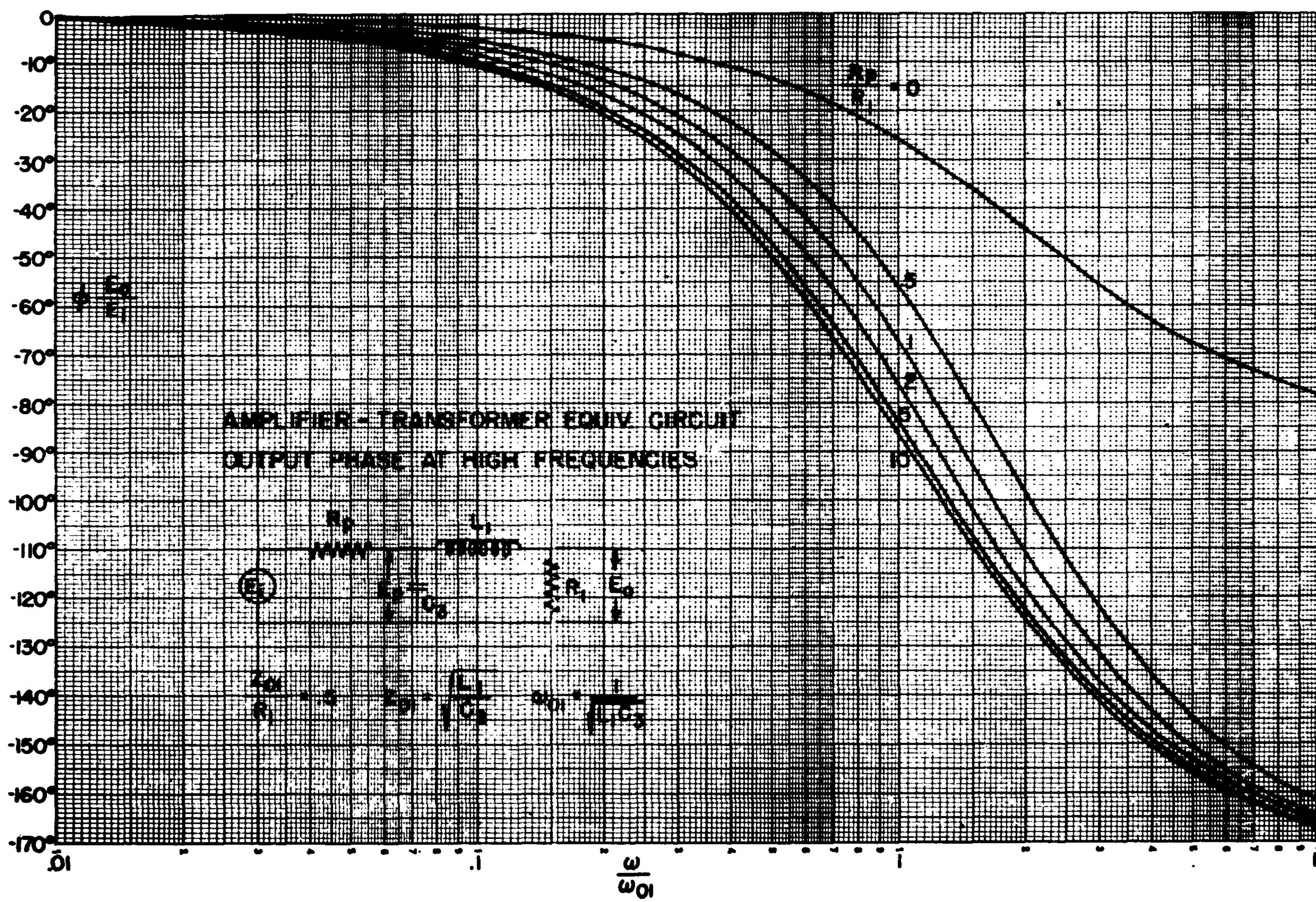
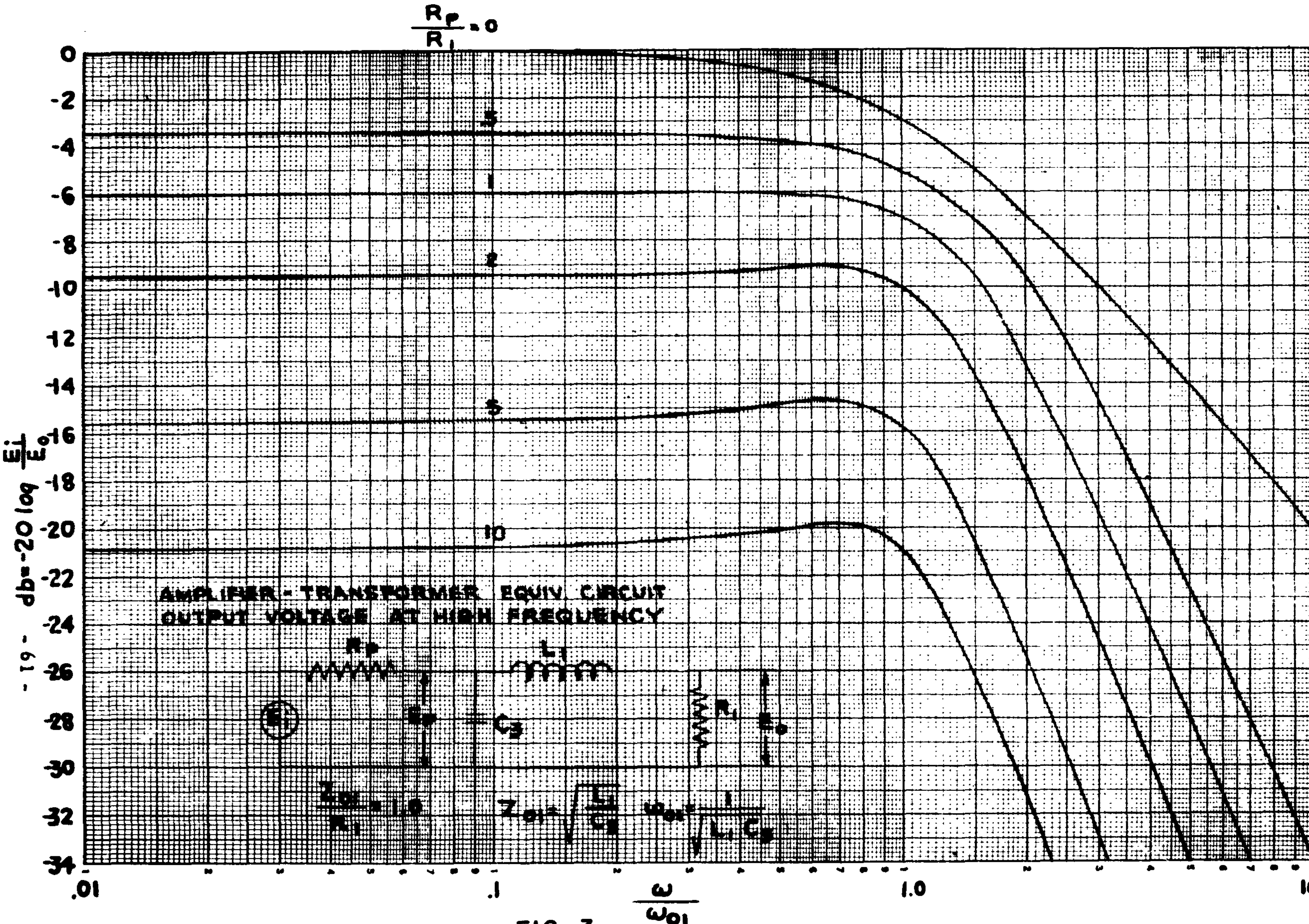
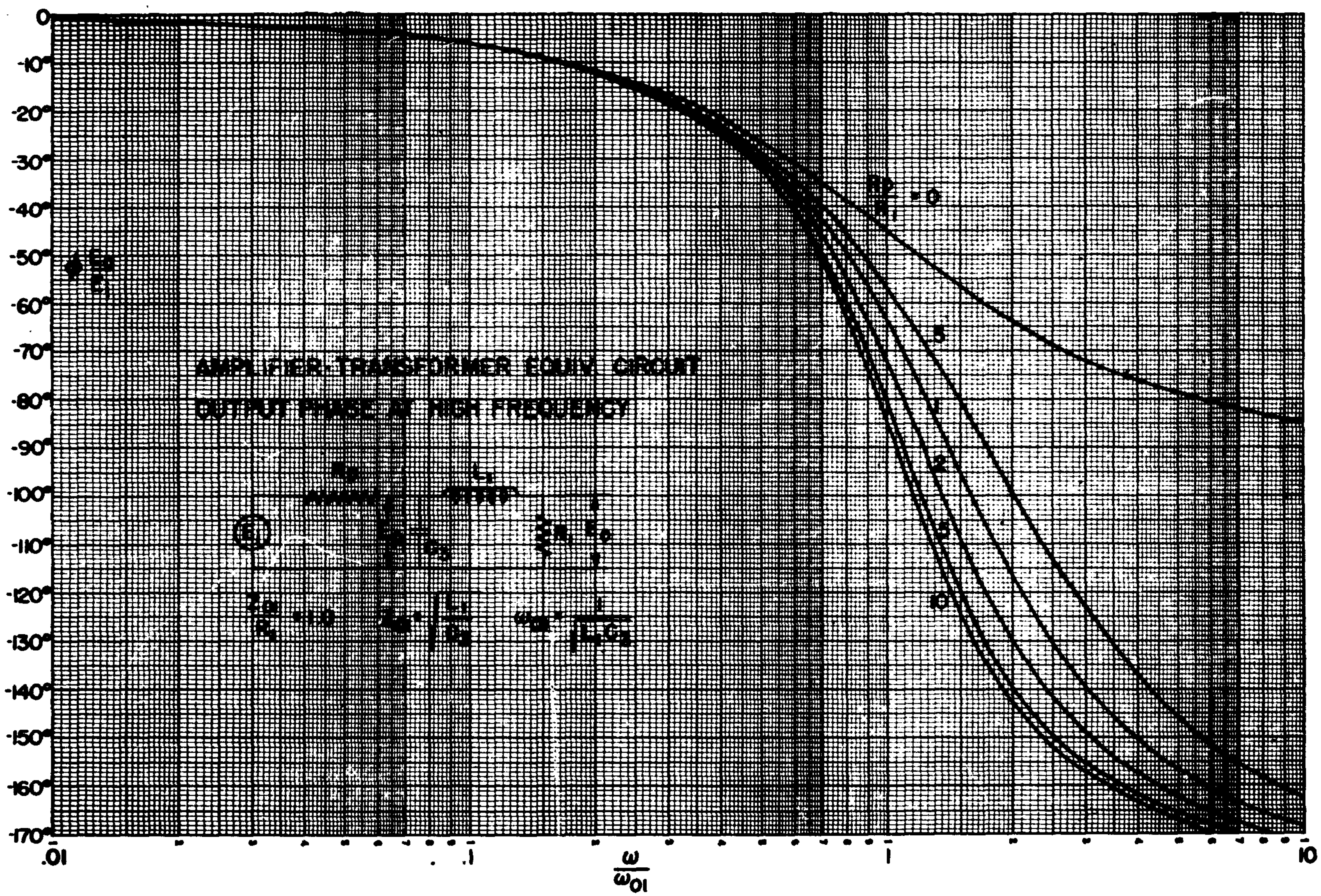

AMPLIFIER - TRANSFORMER EQUIV. CIRCUIT
OUTPUT PHASE AT HIGH FREQUENCIES
0
-10°
-20°
-30°
-40°
-50°
-60°
-70°
-80°
-90°
-100°
-110°
-120°
-130°
-140°
-150°
-160°
-170°
.01
.1
1
10
ω/ω01
.5
1
2
5
10

FIG. 2



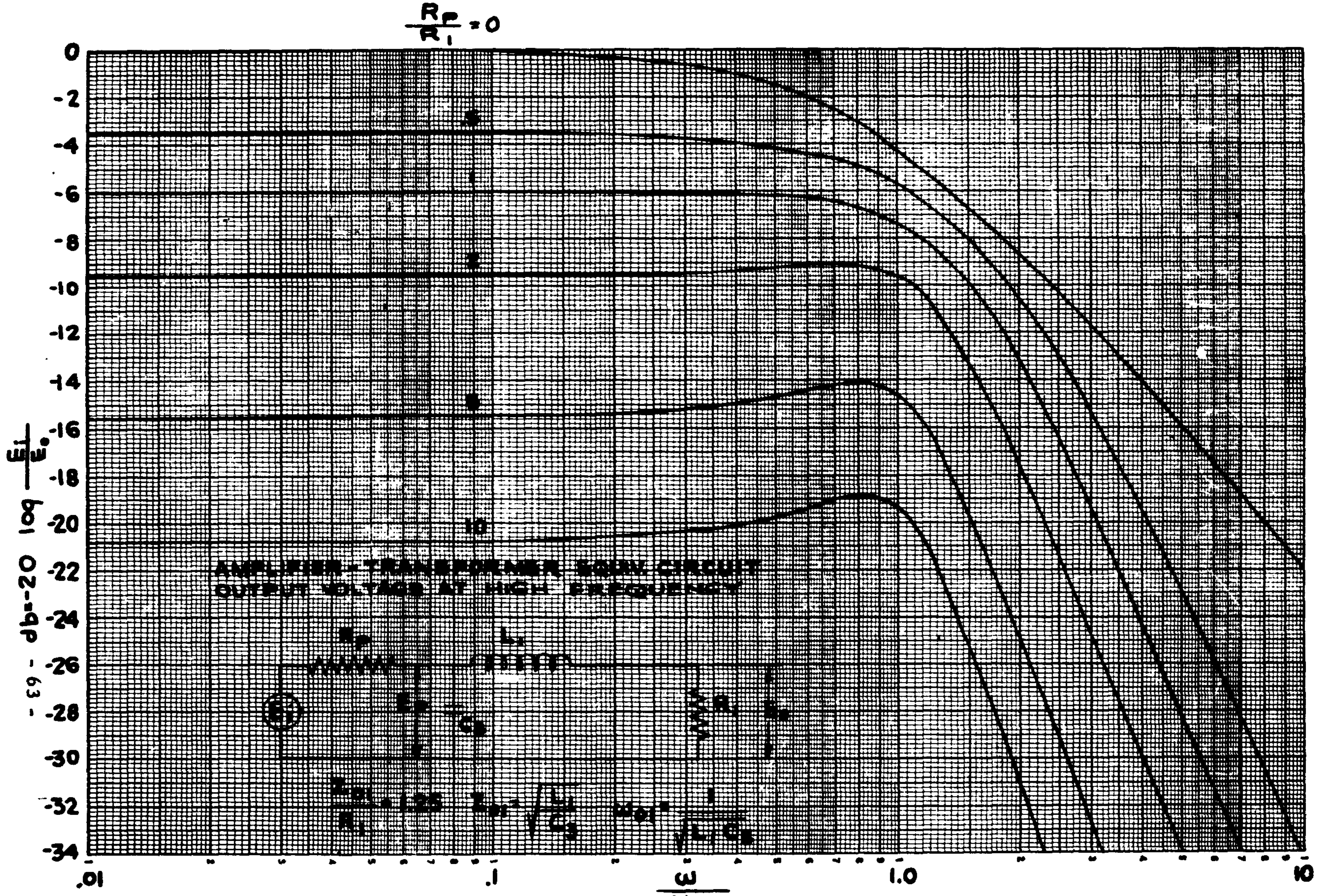
$\frac{R_p}{R_1} = 0$
.5
1
2
5
10
AMPLIFIER - TRANSFORMER EQUIV CIRCUIT
OUTPUT VOLTAGE AT HIGH FREQUENCY
R_p
L_1
E_i
E_p
C_S
R_1
E_o
$\frac{Z_{01}}{R_1} = 1.0$
$Z_{01} = \sqrt{\frac{L_1}{C_S}}$
$\omega_{01} = \frac{1}{\sqrt{L_1 C_S}}$
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
$db = -20 \log \frac{E_i}{E_o}$
.01
.1
1.0
10
$\frac{\omega}{\omega_{01}}$

FIG. 3



AMPLIFIER-TRANSFORMER EQUIV. CIRCUIT
OUTPUT PHASE AT HIGH FREQUENCY
0
-10°
-20°
-30°
-40°
-50°
-60°
-70°
-80°
-90°
-100°
-110°
-120°
-130°
-140°
-150°
-160°
-170°
.01
.1
1
10
ω/ω01

FIG. 4



$\frac{R_P}{R_1} = 0$
10
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
$db = 20 \log \frac{E_i}{E_o}$
AMPLIFIER - TRANSFORMER EQUIV. CIRCUIT
OUTPUT VOLTAGE AT HIGH FREQUENCY
.01
.1
1.0
10
$\frac{\omega}{\omega_{01}}$

FIG. 5

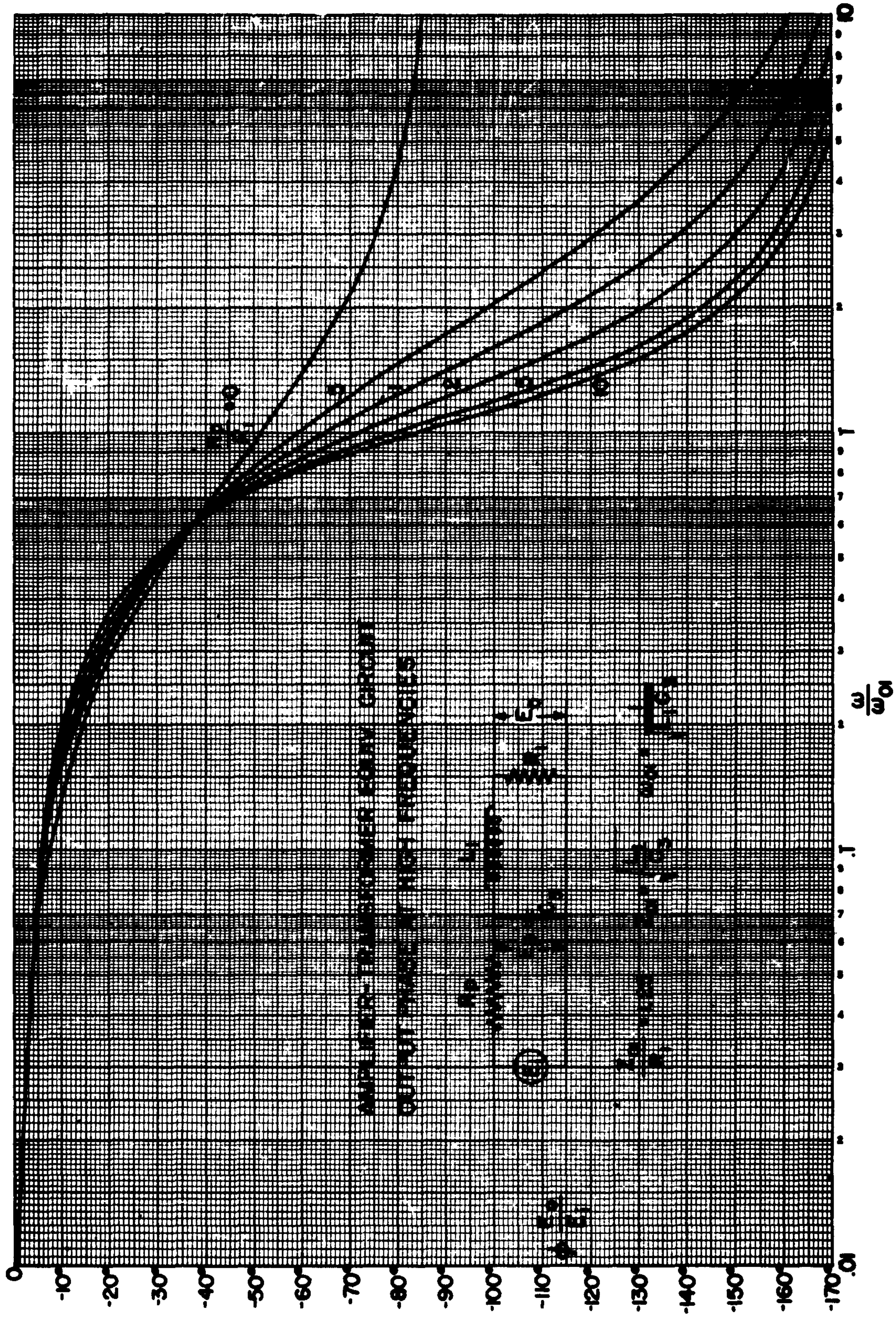

AMPLIFIER-TRANSFORMER EQUIV. CIRCUIT
OUTPUT PHASE AT HIGH FREQUENCIES
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
-170
.01
.1
1
10

FIG. 6

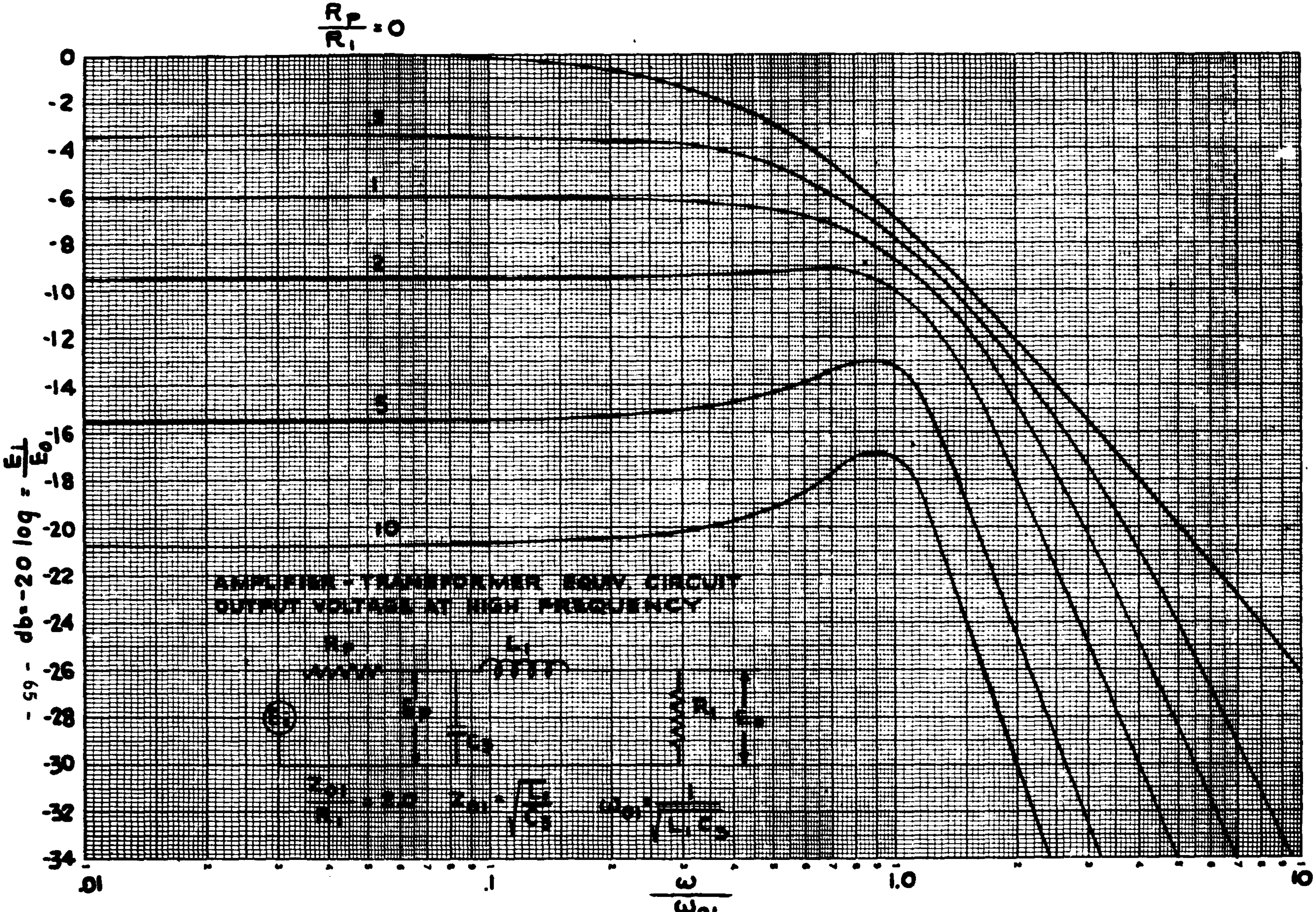
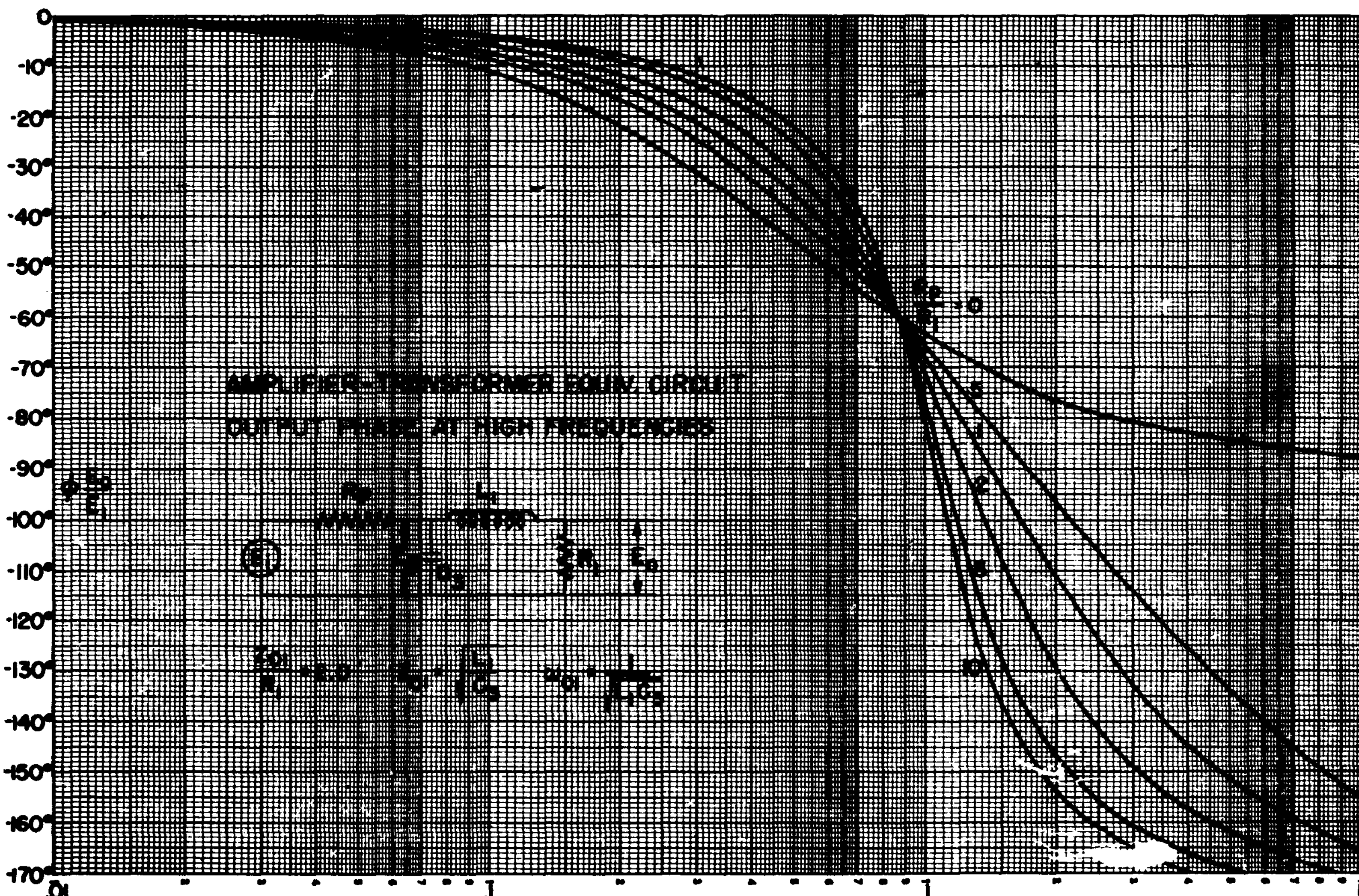

$\frac{R_P}{R_1} = 0$
.5
1
2
5
10
AMPLIFIER - TRANSFORMER EQUIV. CIRCUIT
OUTPUT VOLTAGE AT HIGH FREQUENCY
db = -20 log = $\frac{E_1}{E_0}$
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
.01
.1
1.0
10
$\frac{\omega}{\omega_{01}}$

FIG. 7



$\frac{\omega}{\omega_{01}}$

FIG. 8

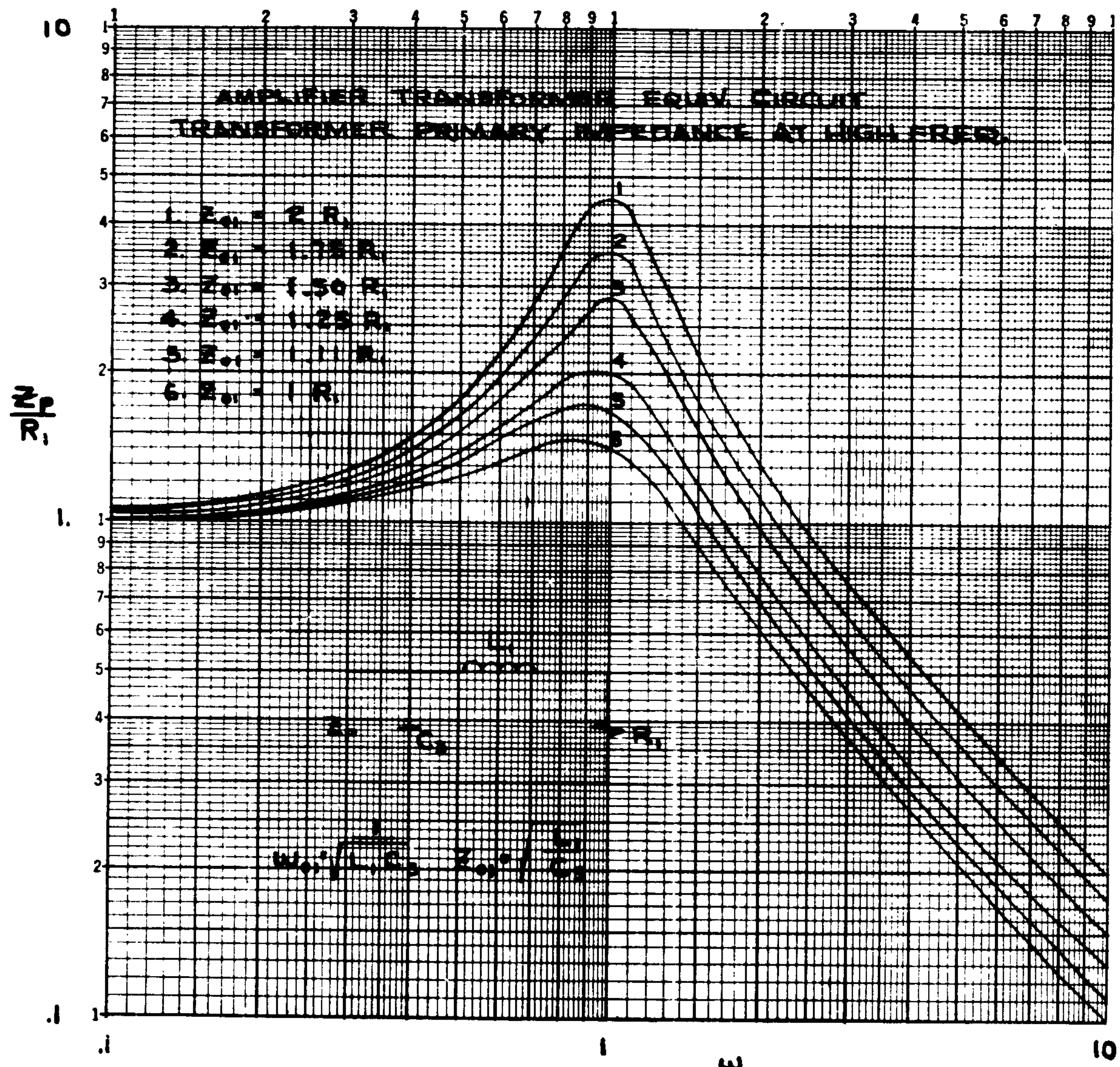

AMPLIFIER TRANSFORMER EQUIV. CIRCUIT
TRANSFORMER PRIMARY IMPEDANCE AT HIGH FREQ.
1. $Z_{01} = 2\ R_1$
2. $Z_{01} = 1.75\ R_1$
3. $Z_{01} = 1.50\ R_1$
4. $Z_{01} = 1.25\ R_1$
5. $Z_{01} = 1.11\ R_1$
6. $Z_{01} = 1\ R_1$
$\frac{Z_p}{R_1}$
$\frac{\omega}{\omega_{01}}$
10
1.
.1
10

FIG. 9

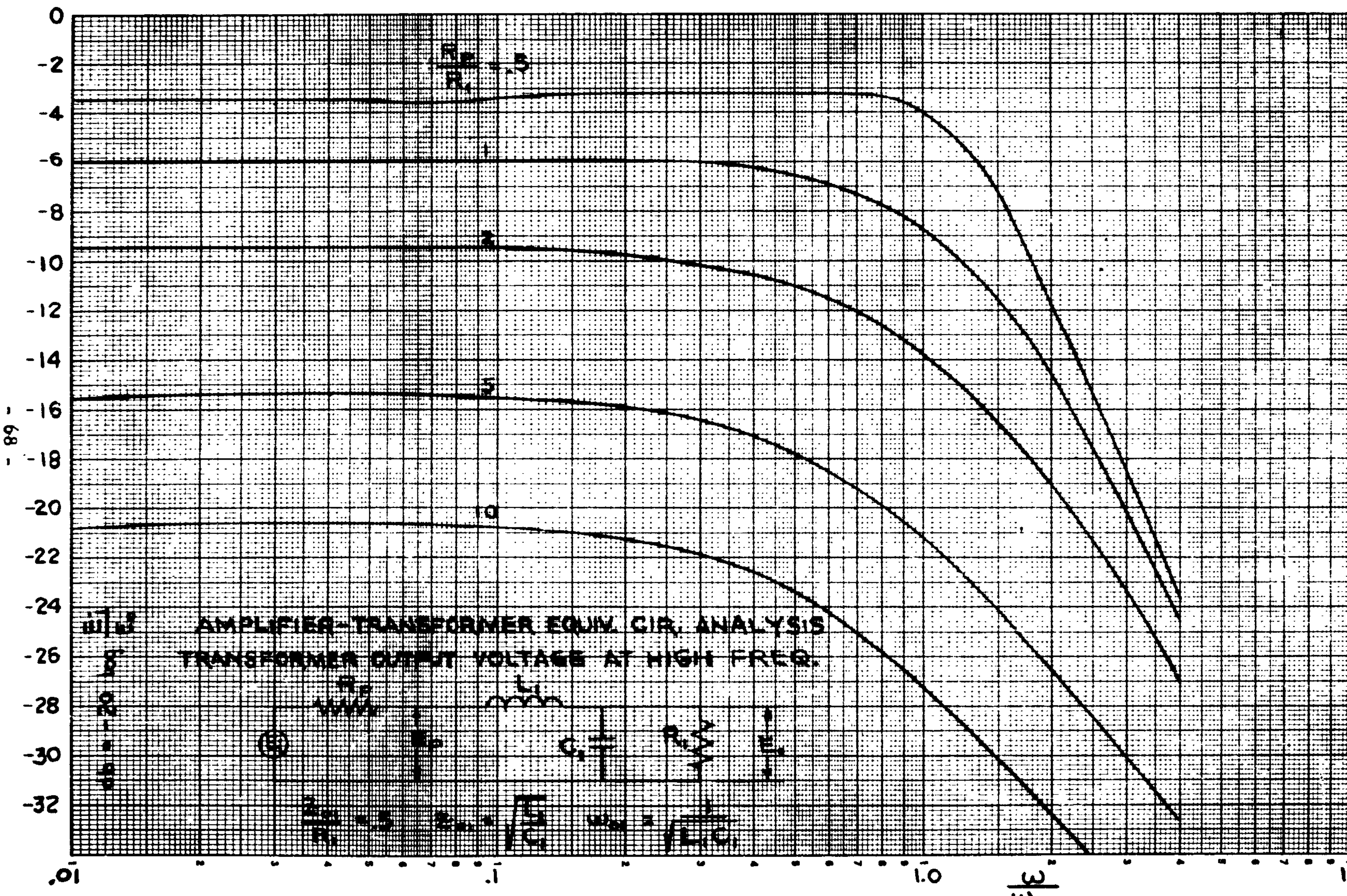

AMPLIFIER-TRANSFORMER EQUIV. CIR. ANALYSIS
TRANSFORMER OUTPUT VOLTAGE AT HIGH FREQ.
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
.01
.1
1.0
10
ω / ω01
1
2
5
10

FIG. 10

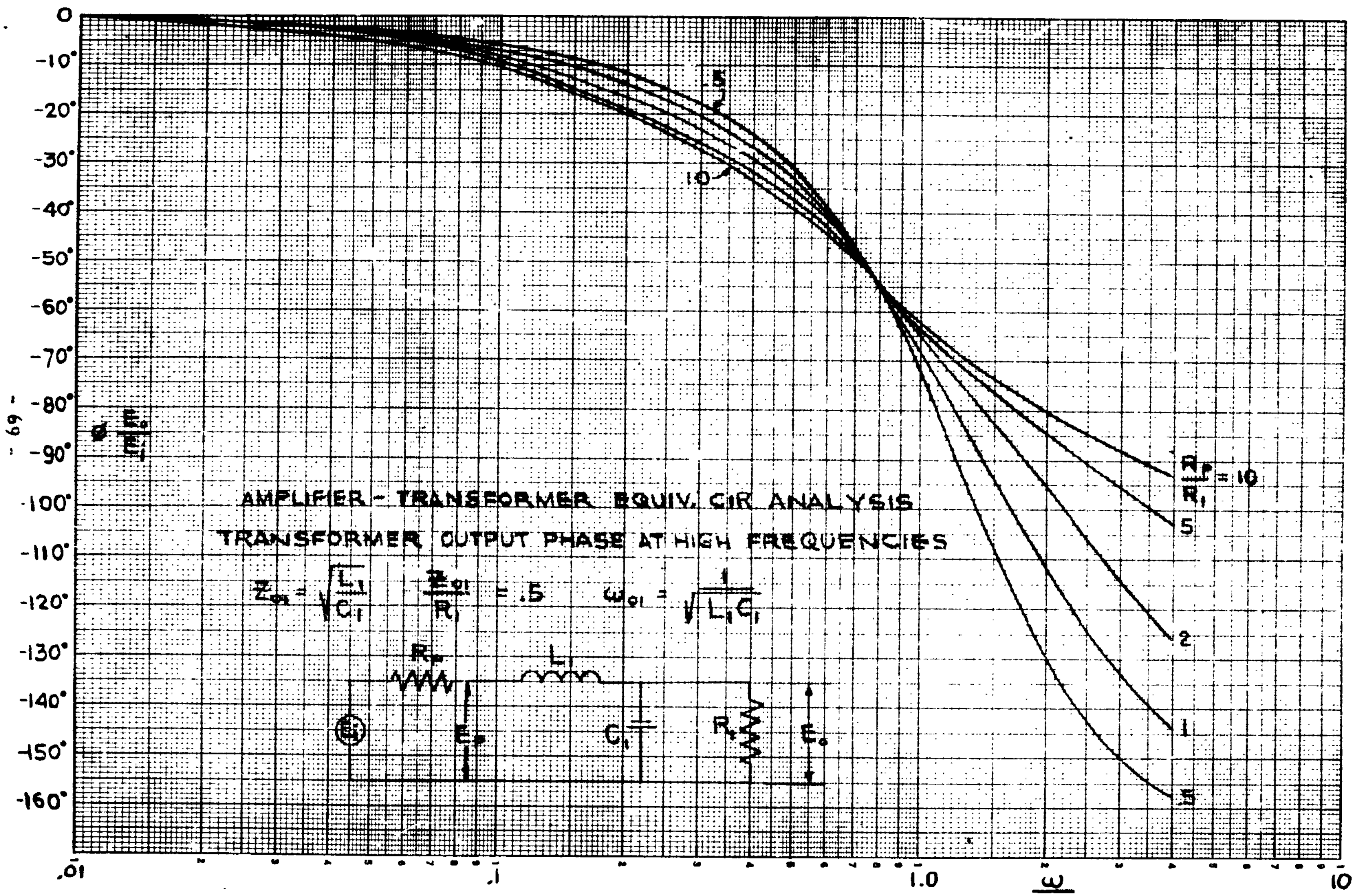

AMPLIFIER - TRANSFORMER EQUIV. CIR ANALYSIS
TRANSFORMER OUTPUT PHASE AT HIGH FREQUENCIES
$Z_{01} = \sqrt{\frac{L_1}{C_1}}$ $\frac{Z_{01}}{R_1} = .5$ $\omega_{01} = \frac{1}{\sqrt{L_1 C_1}}$
$\frac{R_P}{R_1} = 10$
$\phi \frac{E_o}{E_i}$
$\frac{\omega}{\omega_{01}}$
0
-10°
-20°
-30°
-40°
-50°
-60°
-70°
-80°
-90°
-100°
-110°
-120°
-130°
-140°
-150°
-160°
.01
.1
1.0
10

FIG. 11

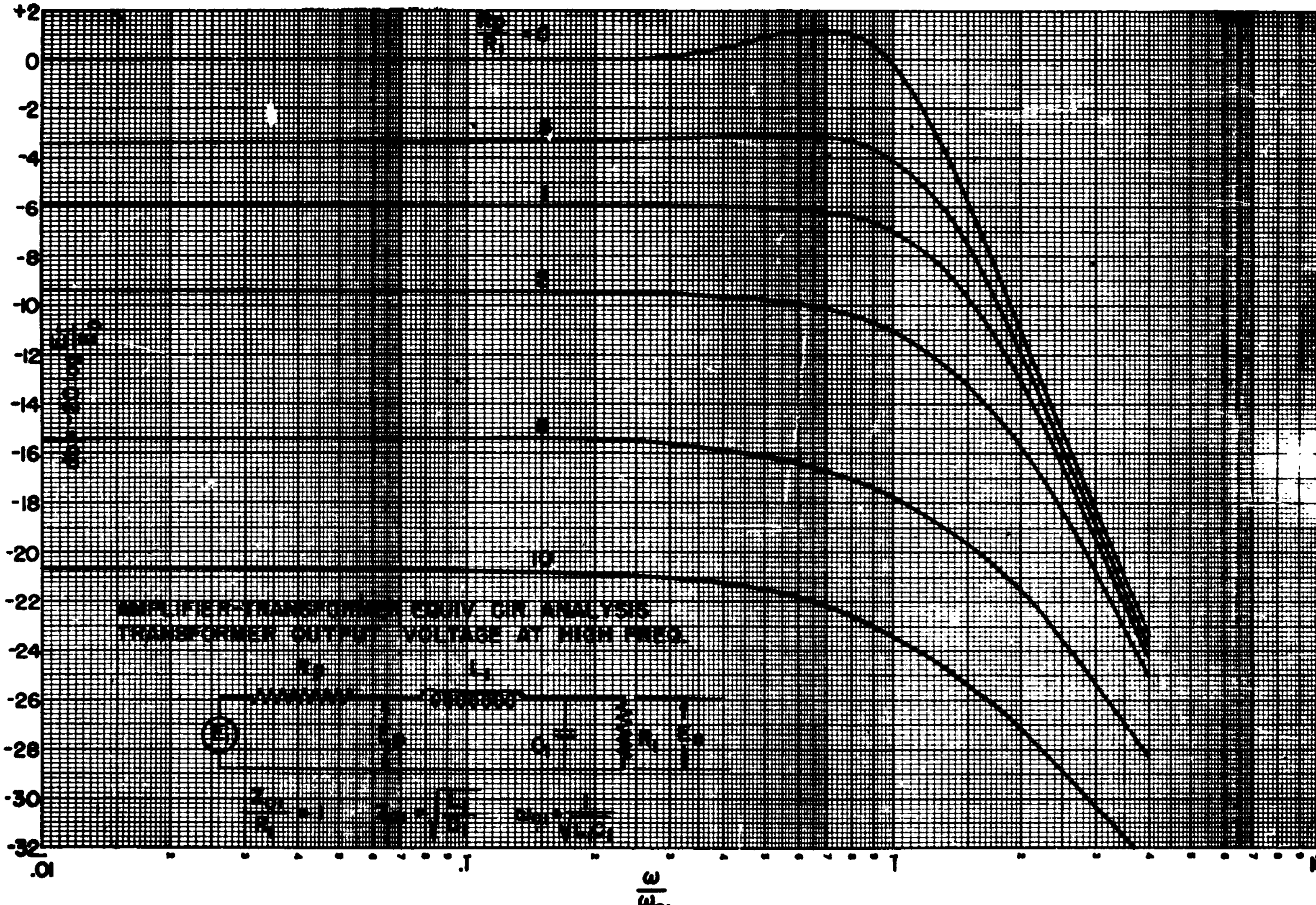

AMPLIFIER-TRANSFORMER EQUIV. CIR. ANALYSIS
TRANSFORMER OUTPUT VOLTAGE AT HIGH FREQ.
+2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
.01
.1
1
10
$\frac{\omega}{\omega_{01}}$

FIG. 12

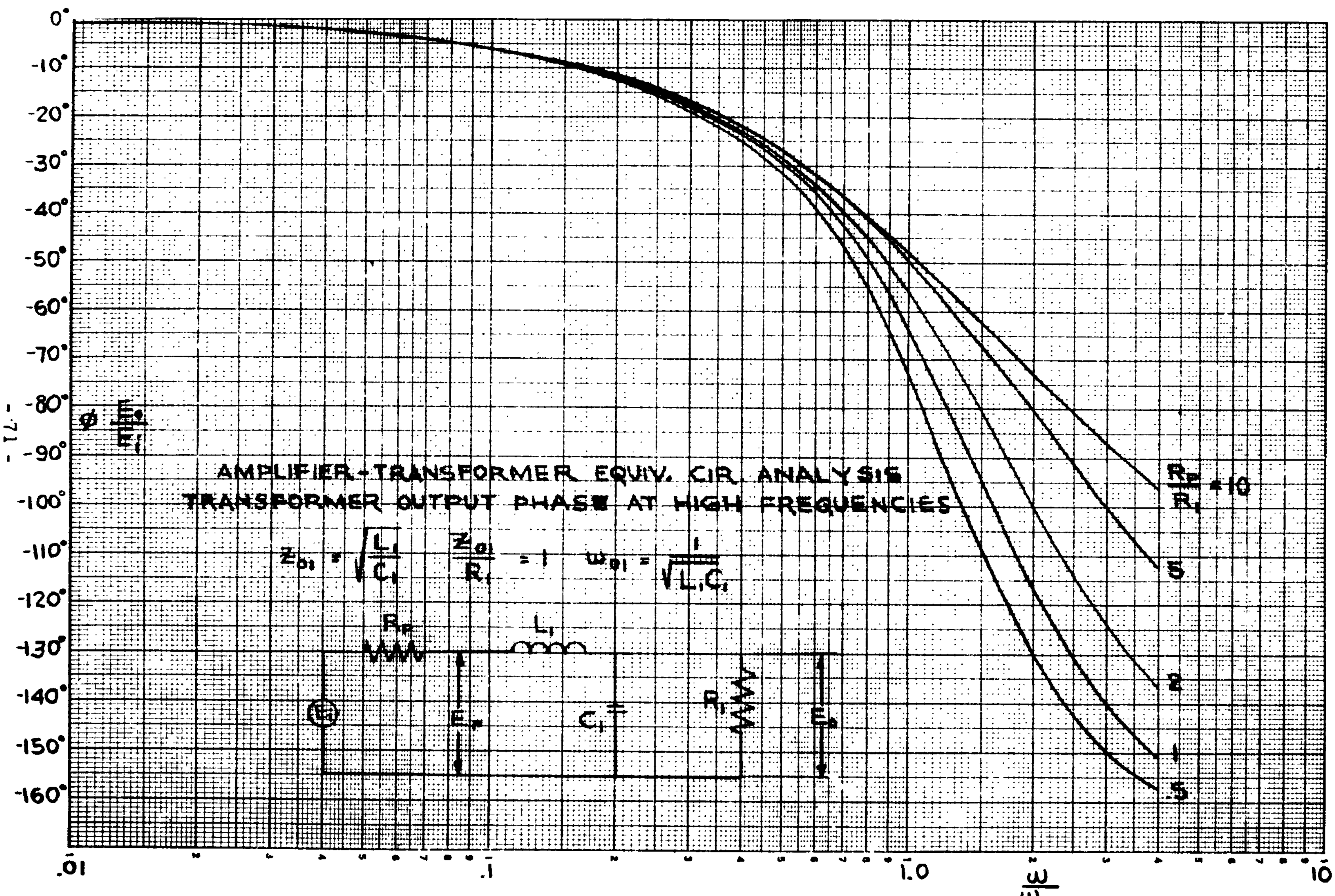
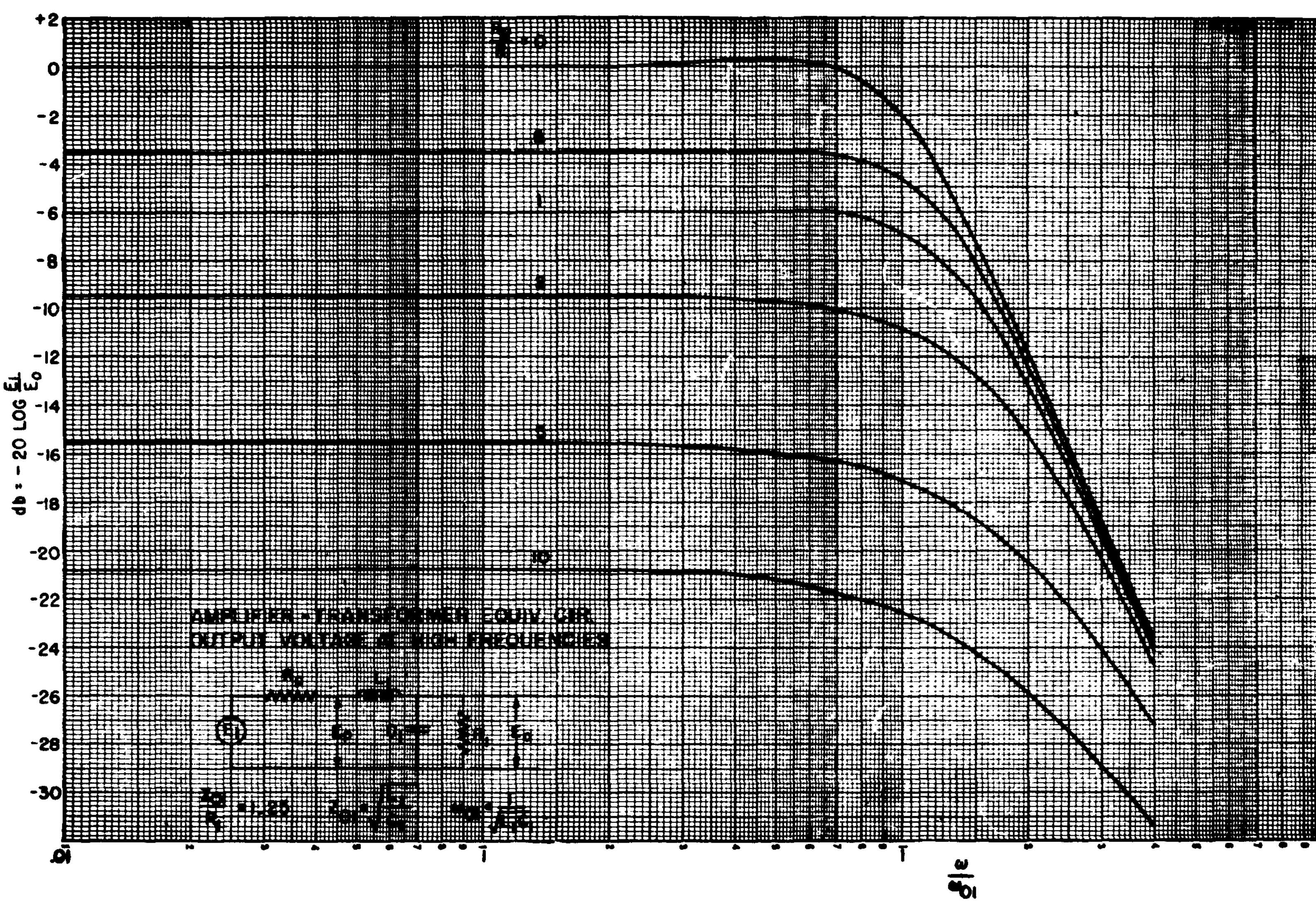

AMPLIFIER - TRANSFORMER EQUIV. CIR. ANALYSIS
TRANSFORMER OUTPUT PHASE AT HIGH FREQUENCIES
$Z_{01} = \sqrt{\frac{L_1}{C_1}}$ $\frac{Z_{01}}{R_1} = 1$ $\omega_{01} = \frac{1}{\sqrt{L_1 C_1}}$
$\frac{R_P}{R_1} = 10$
5
2
1
.5
$\phi \frac{E_0}{E_1}$
$\frac{\omega}{\omega_{01}}$
R_P
L_1
C_1
R_1
E_1
E_P
E_0
0°
-10°
-20°
-30°
-40°
-50°
-60°
-70°
-80°
-90°
-100°
-110°
-120°
-130°
-140°
-150°
-160°
.01
.1
1.0
10

FIG. 13



AMPLIFIER - TRANSFORMER EQUIV. CIR.
OUTPUT VOLTAGE AT HIGH FREQUENCIES
db = - 20 LOG $\frac{E_L}{E_0}$
$\frac{\omega}{\omega_{01}}$

FIG. 14

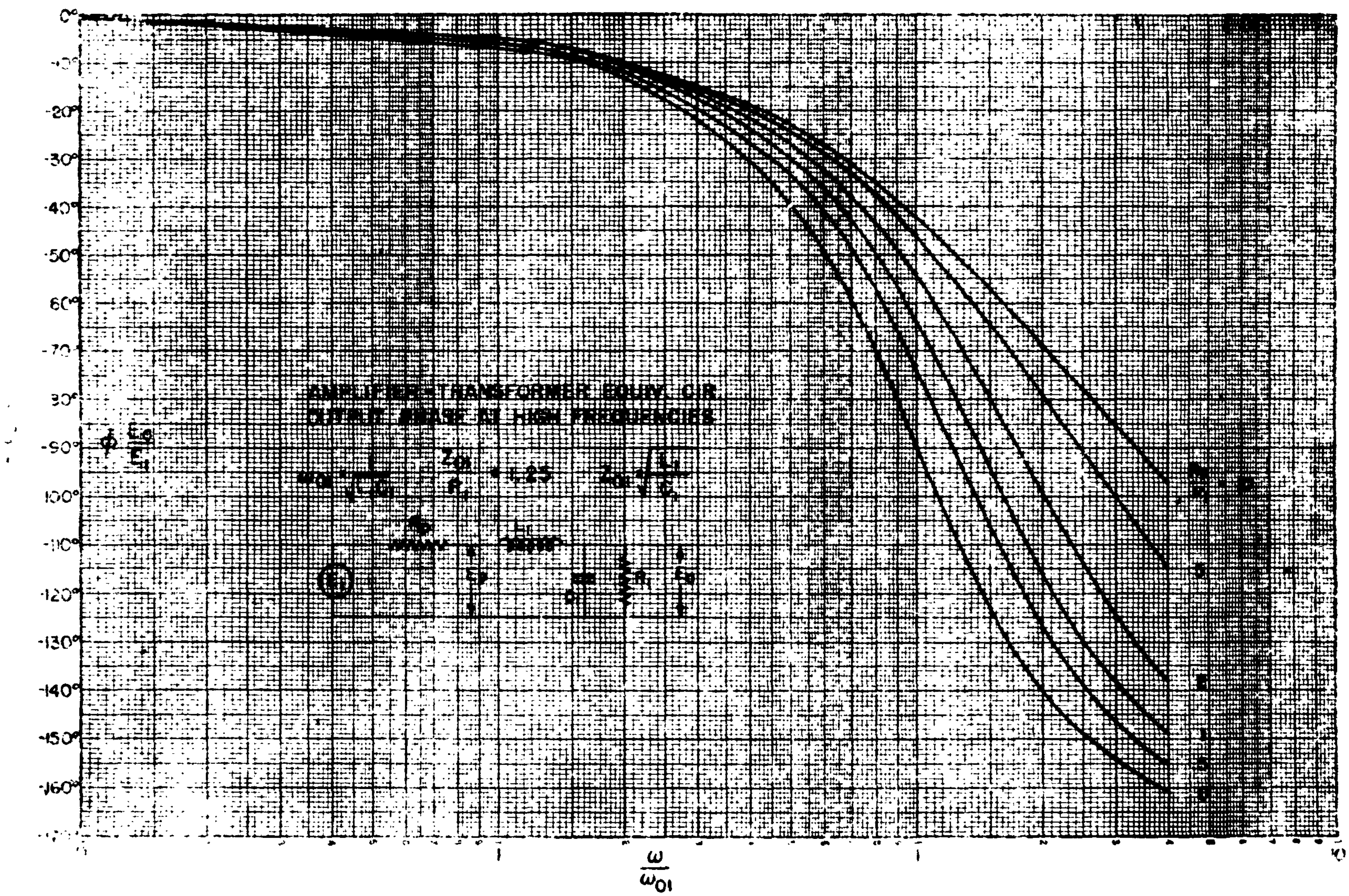

0°
-20°
-30°
-40°
-50°
-70°
-90°
100°
-110°
-120°
-130°
-140°
-150°
-160°
AMPLIFIER-TRANSFORMER EQUIV. CIR.
OUTPUT PHASE AT HIGH FREQUENCIES
1
1
10
ω/ω01

FIG. 15

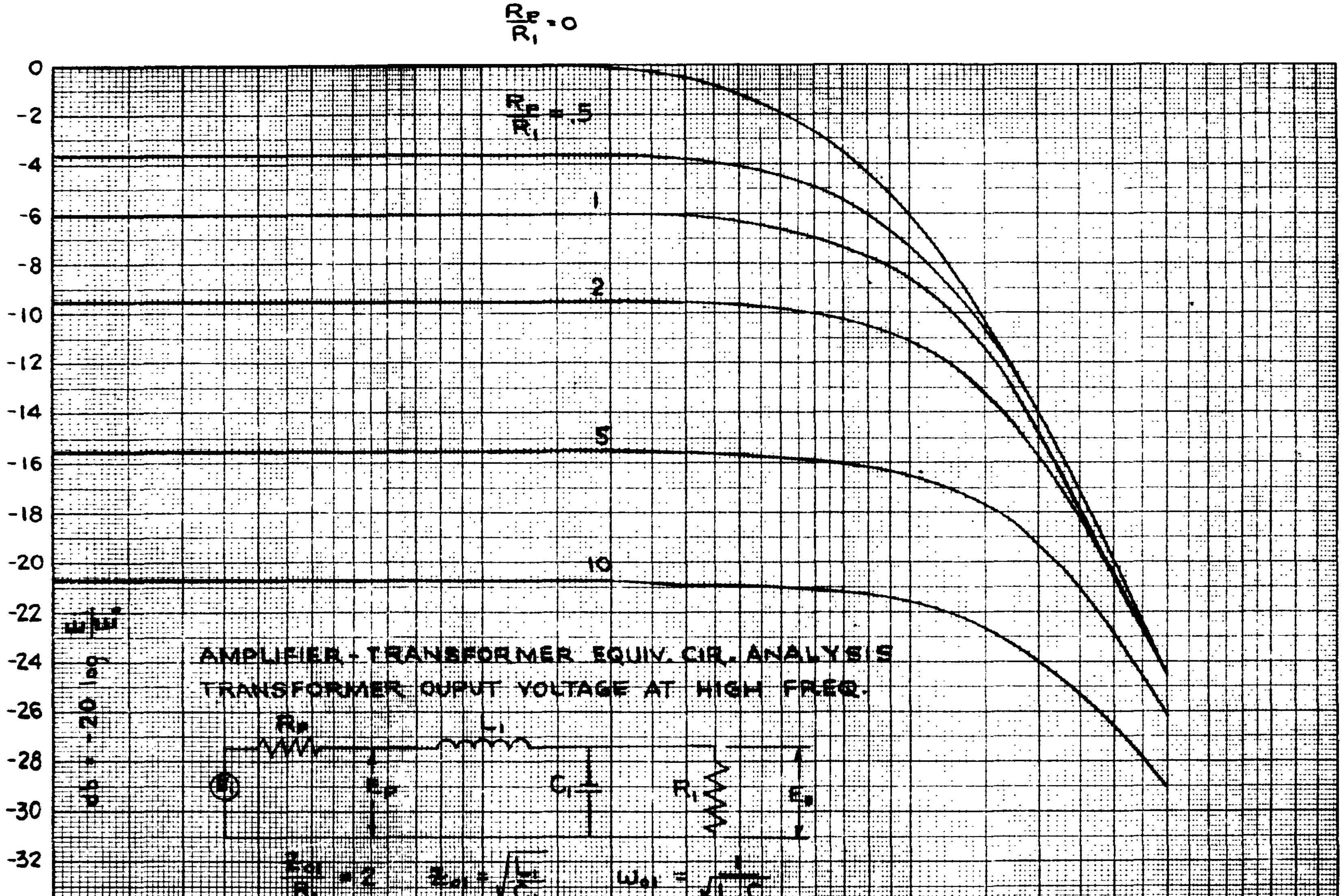

$\frac{R_P}{R_1} = 0$
$\frac{R_P}{R_1} = .5$
1
2
5
10
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
$db = -20 \log \frac{E}{E_1}$
AMPLIFIER - TRANSFORMER EQUIV. CIR. ANALYSIS
TRANSFORMER OUPUT VOLTAGE AT HIGH FREQ.
R_P
L_1
E_P
C_1
R_1
E_2
$\frac{Z_{01}}{R_1} = 2$
$Z_{01} = \sqrt{\frac{L_1}{C_1}}$
$\omega_{01} = \frac{1}{\sqrt{L_1 C_1}}$
.01
.1
1.0
10
$\frac{\omega}{\omega_{01}}$

FIG. 16

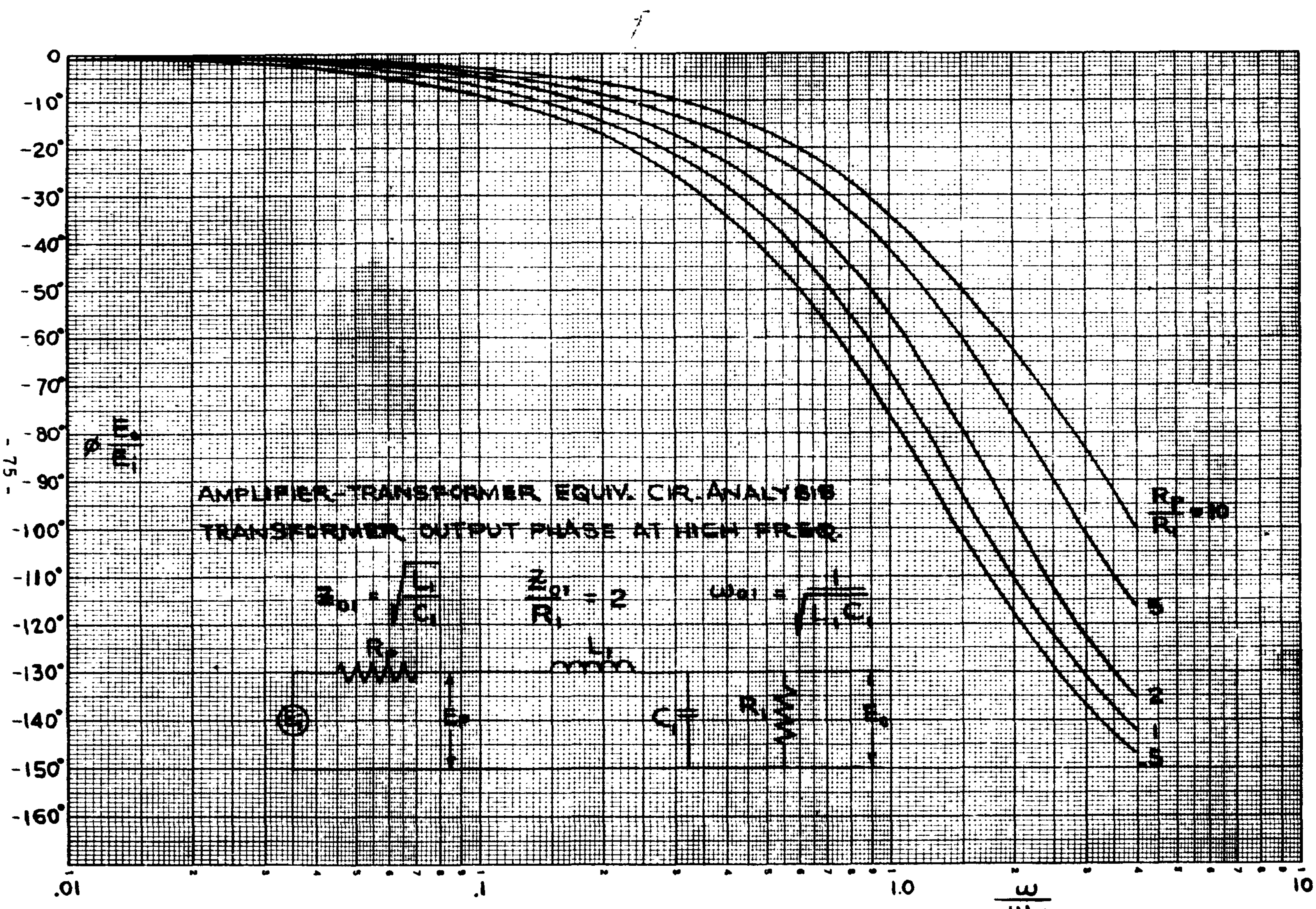

AMPLIFIER-TRANSFORMER EQUIV. CIR. ANALYSIS
TRANSFORMER OUTPUT PHASE AT HIGH FREQ.
$Z_{01} = \sqrt{\frac{L_1}{C_1}}$
$\frac{Z_{01}}{R_1} = 2$
$\omega_{01} = \frac{1}{\sqrt{L_1 C_1}}$
$\frac{R_p}{R_1} = 10$
5
2
1
.5
R_p
L_1
C_1
R_1
E_p
E_0
$\phi \frac{E_0}{E_1}$
$\frac{\omega}{\omega_{01}}$
0
-10°
-20°
-30°
-40°
-50°
-60°
-70°
-80°
-90°
-100°
-110°
-120°
-130°
-140°
-150°
-160°
.01
.1
1.0
10

FIG. 17

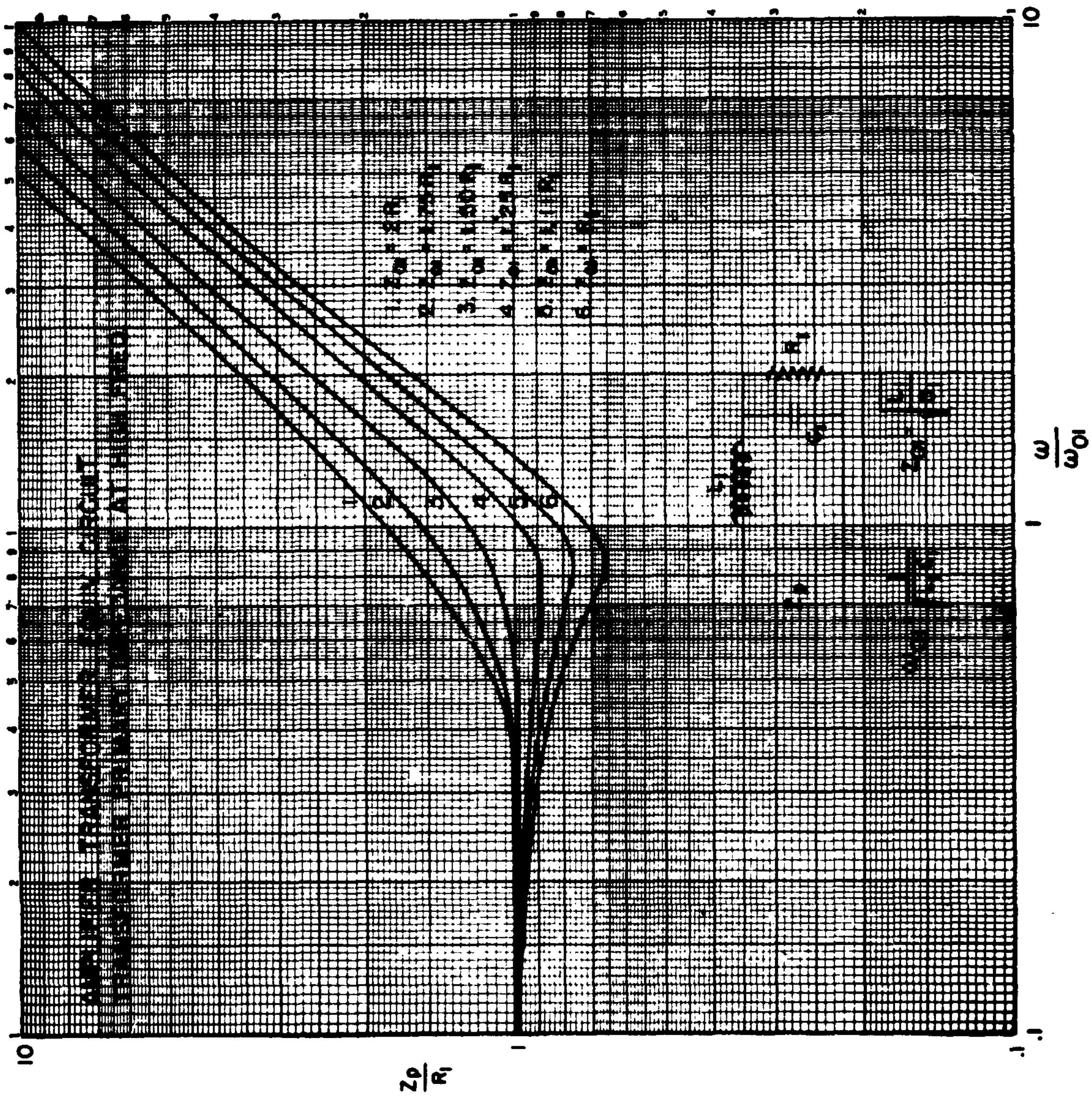
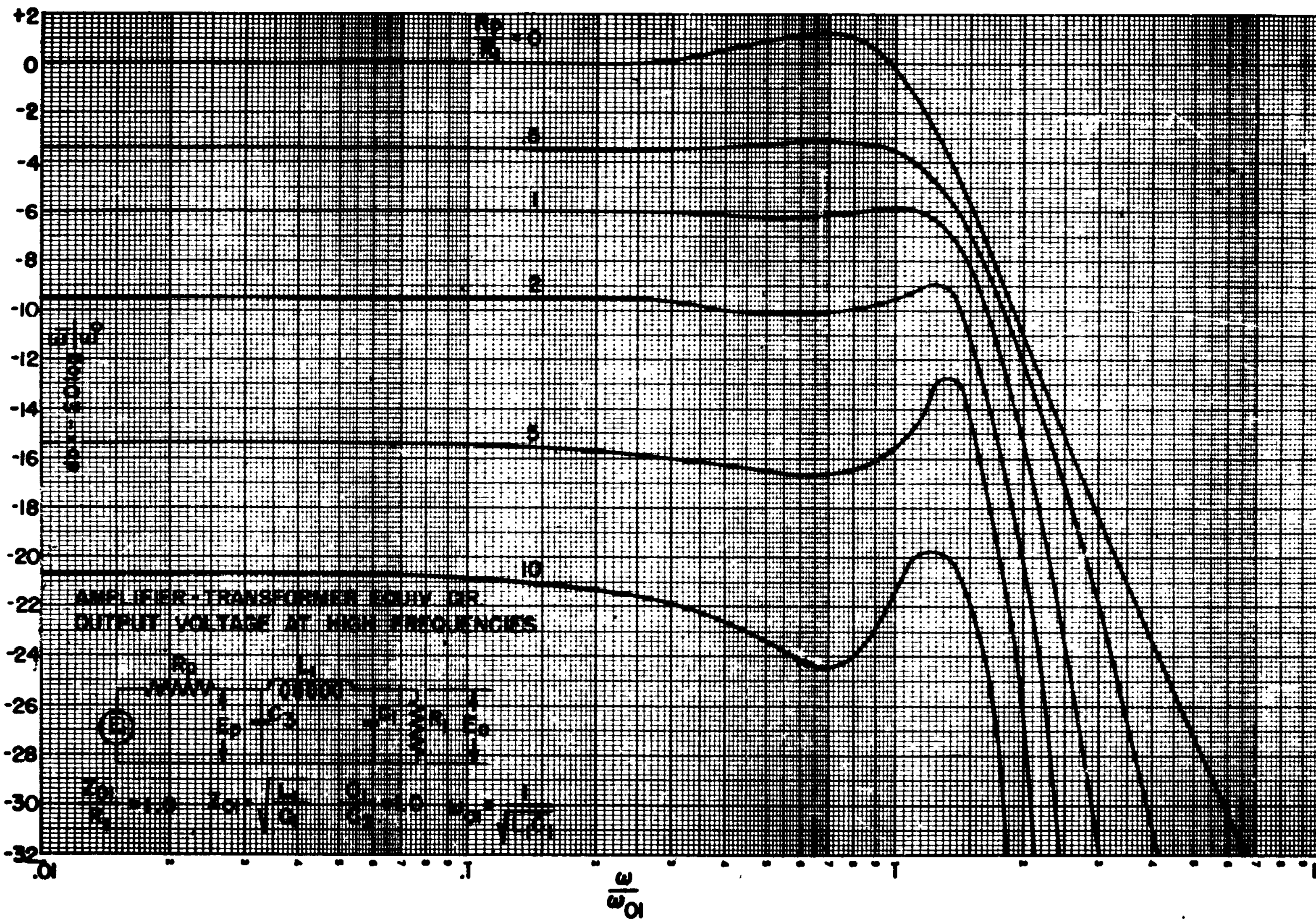


FIG. 18



AMPLIFIER - TRANSFORMER EQUIV. CIR.
OUTPUT VOLTAGE AT HIGH FREQUENCIES

FIG. 19

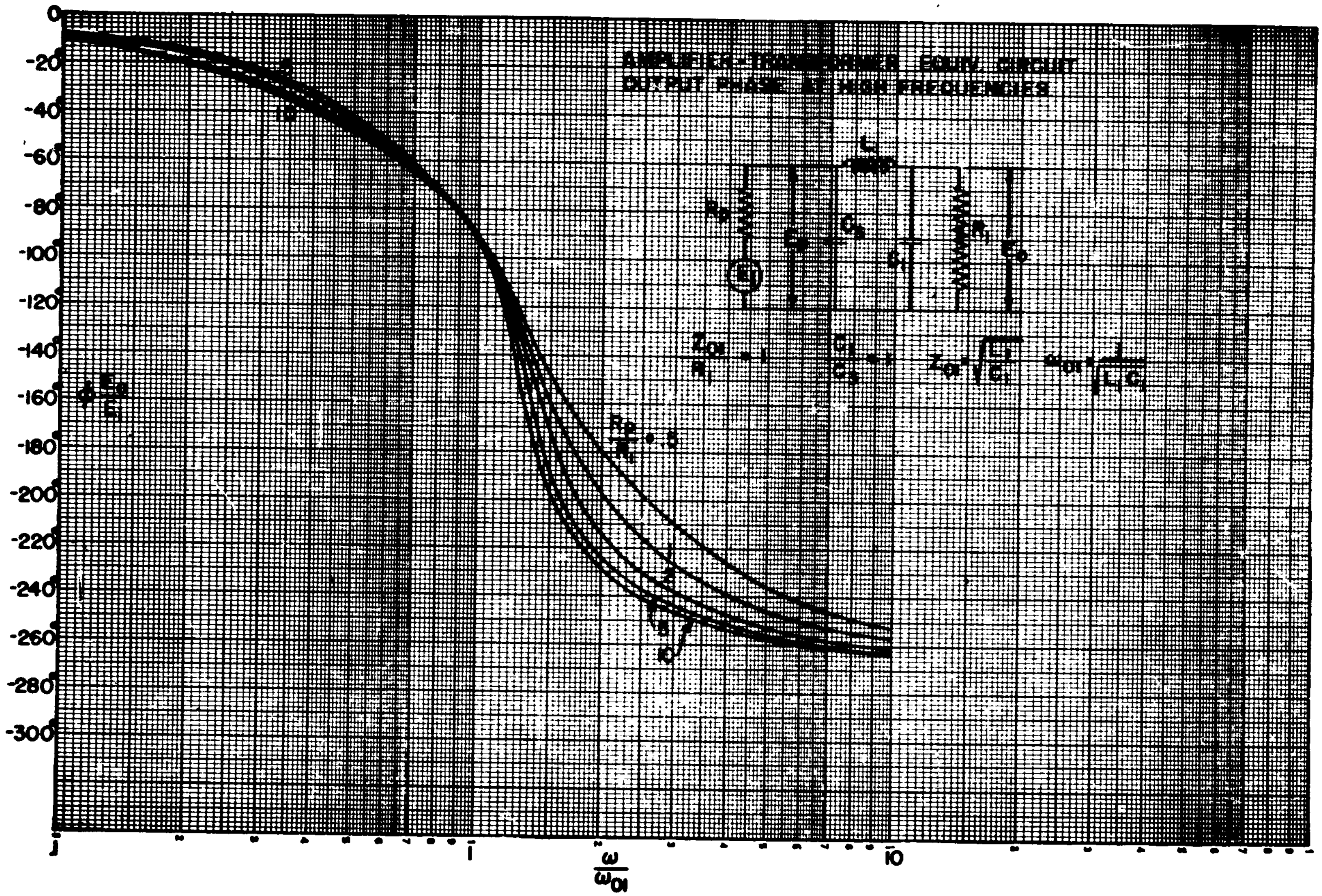

AMPLIFIER - TRANSFORMER EQUIV. CIRCUIT
OUTPUT PHASE AT HIGH FREQUENCIES
0
-20°
-40°
-60°
-80°
-100°
-120°
-140°
-160°
-180°
-200°
-220°
-240°
-260°
-280°
-300°
1
10
ω/ω01

FIG. 20

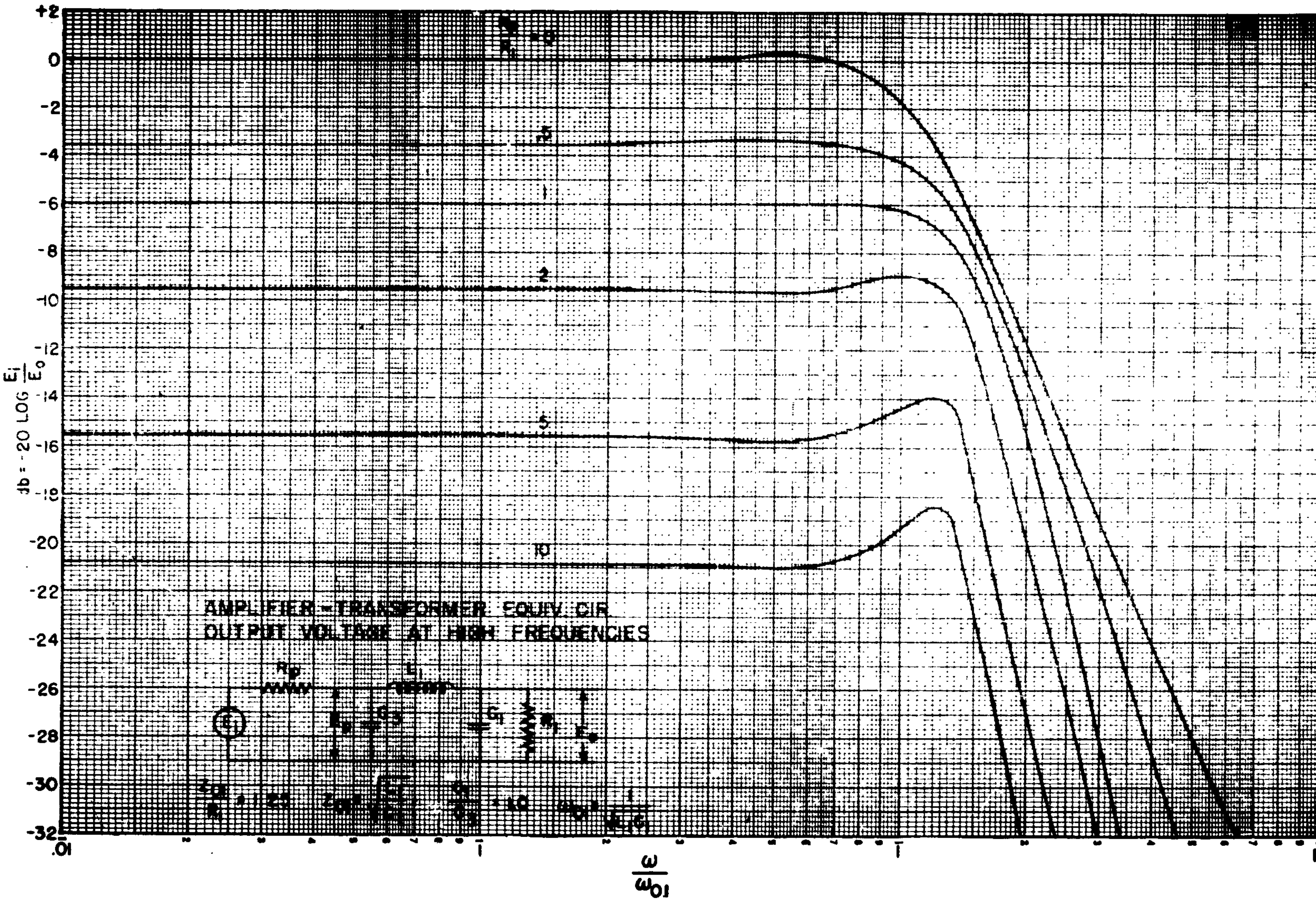
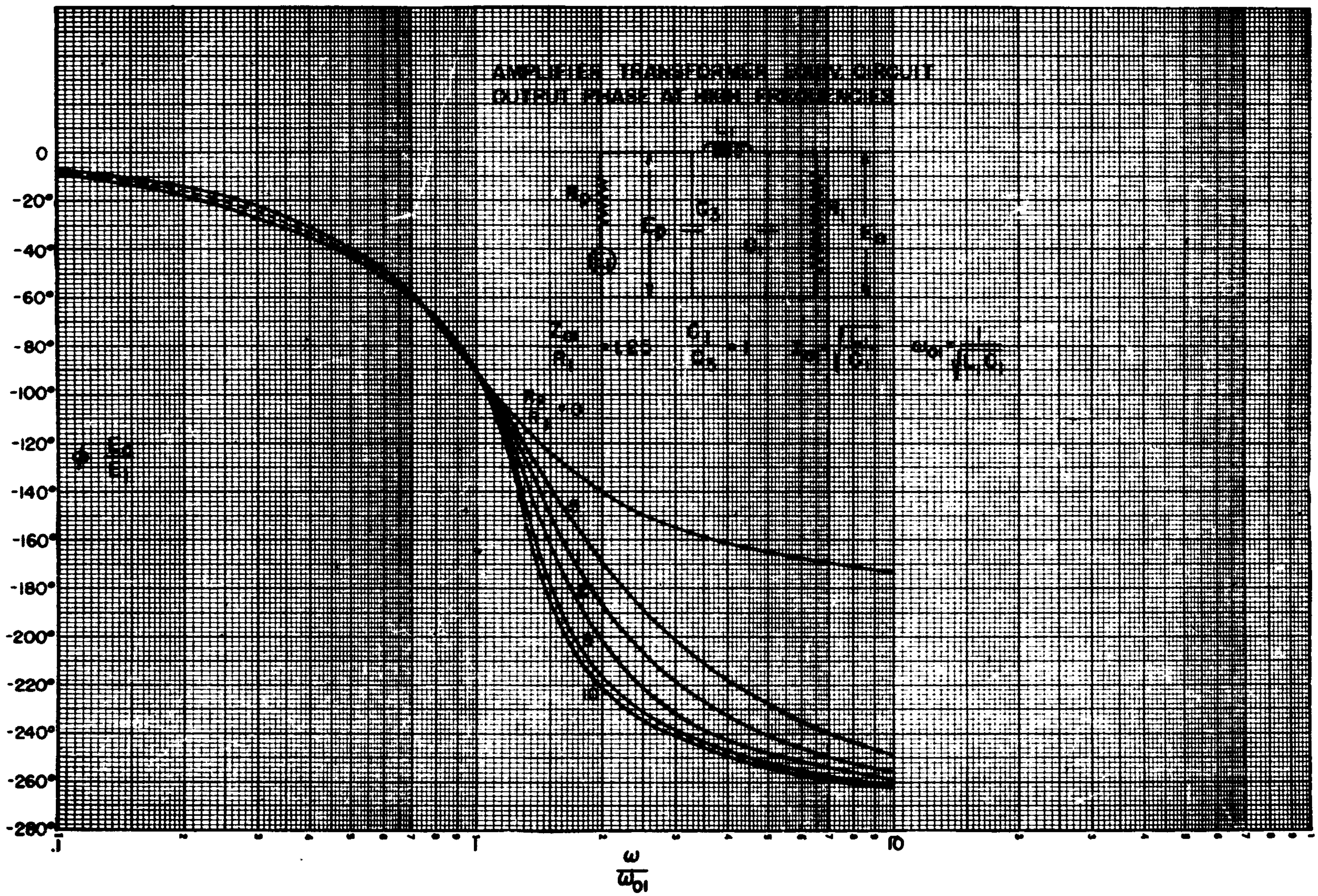
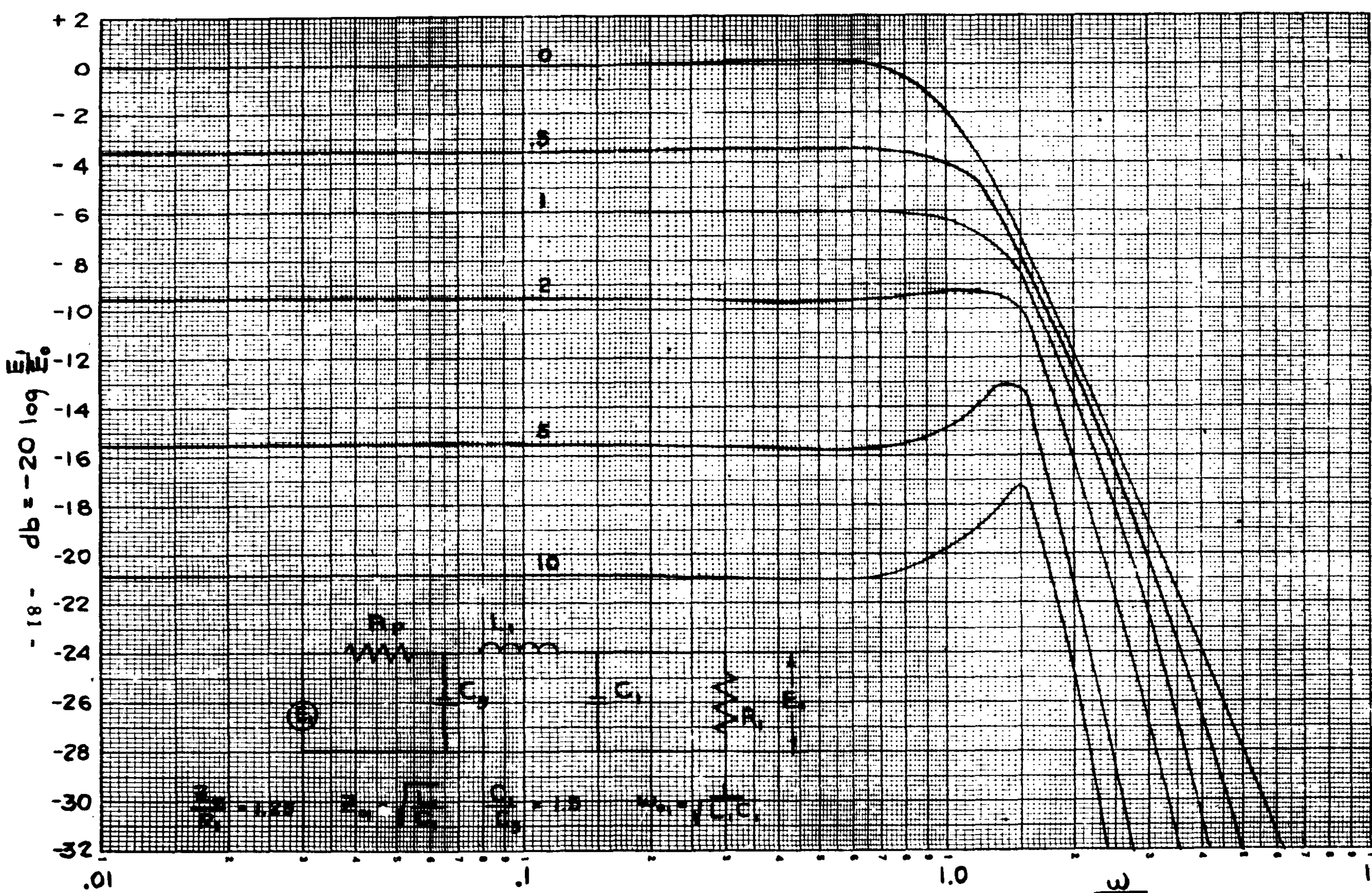

AMPLIFIER - TRANSFORMER EQUIV CIR
OUTPUT VOLTAGE AT HIGH FREQUENCIES
.5
1
2
5
10
+2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
db = -20 LOG $\frac{E_i}{E_o}$
.01
.1
1
10
$\frac{\omega}{\omega_{01}}$

FIG. 21



AMPLIFIER TRANSFORMER EQUIV. CIRCUIT
OUTPUT PHASE AT HIGH FREQUENCIES
0
-20°
-40°
-60°
-80°
-100°
-120°
-140°
-160°
-180°
-200°
-220°
-240°
-260°
-280°
.1
1
10
ω
ω01

FIG. 22



+2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
.01
.1
1.0
10
0
.5
1
2
5
10
$\frac{\omega}{\omega_{01}}$

FIG. 23

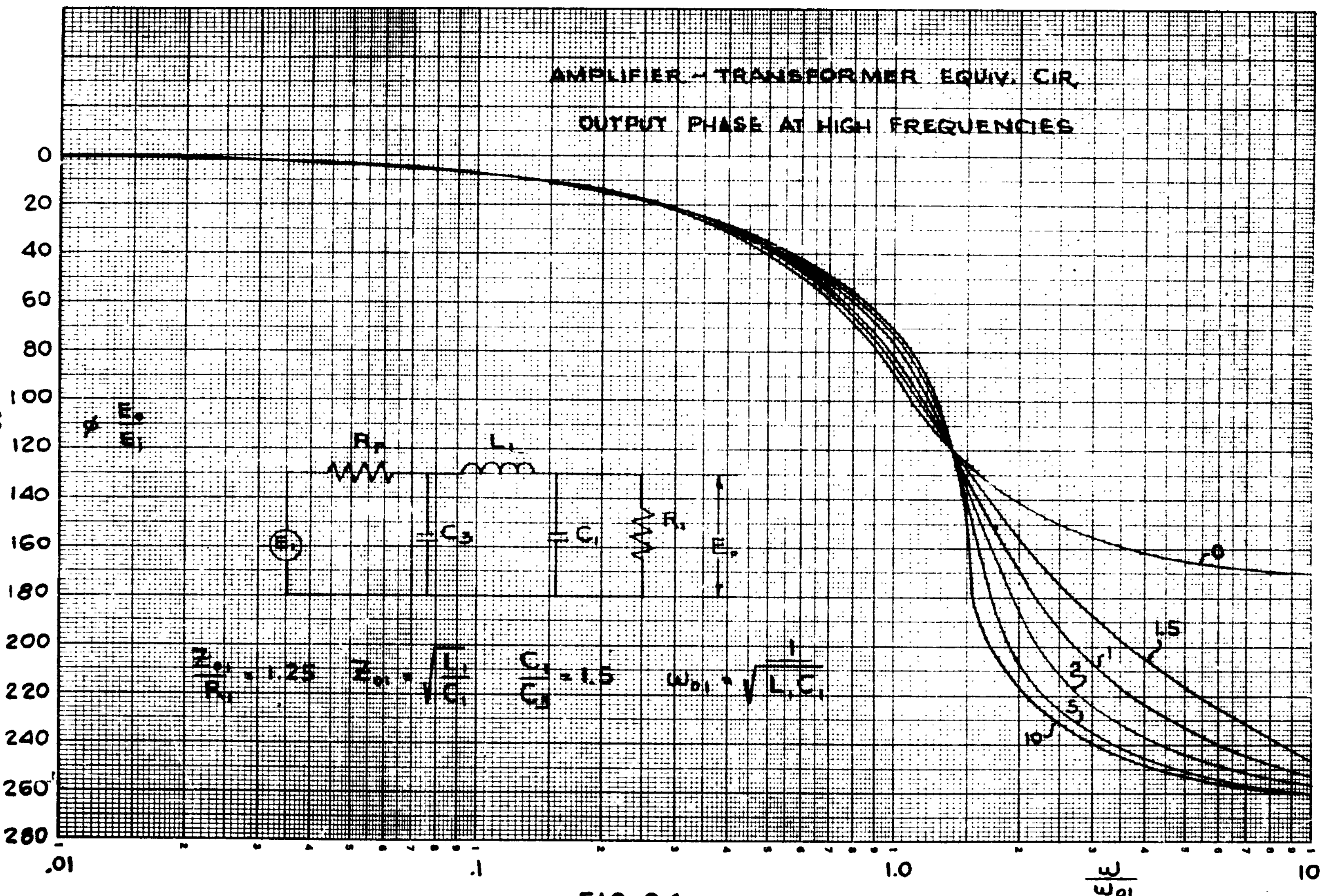

AMPLIFIER – TRANSFORMER EQUIV. CIR.
OUTPUT PHASE AT HIGH FREQUENCIES
$\phi \frac{E_o}{E_i}$
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
.01
.1
1.0
10
$\frac{\omega}{\omega_{01}}$
R_p
L_1
E_i
C_3
C_1
R_1
E_o
$\frac{Z_{01}}{R_1} = 1.25$
$Z_{01} = \sqrt{\frac{L_1}{C_1}}$
$\frac{C_1}{C_3} = 1.5$
$\omega_{01} = \sqrt{\frac{1}{L_1 C_1}}$
r = 0
1.5
r = 1
2
5
10

FIG. 24

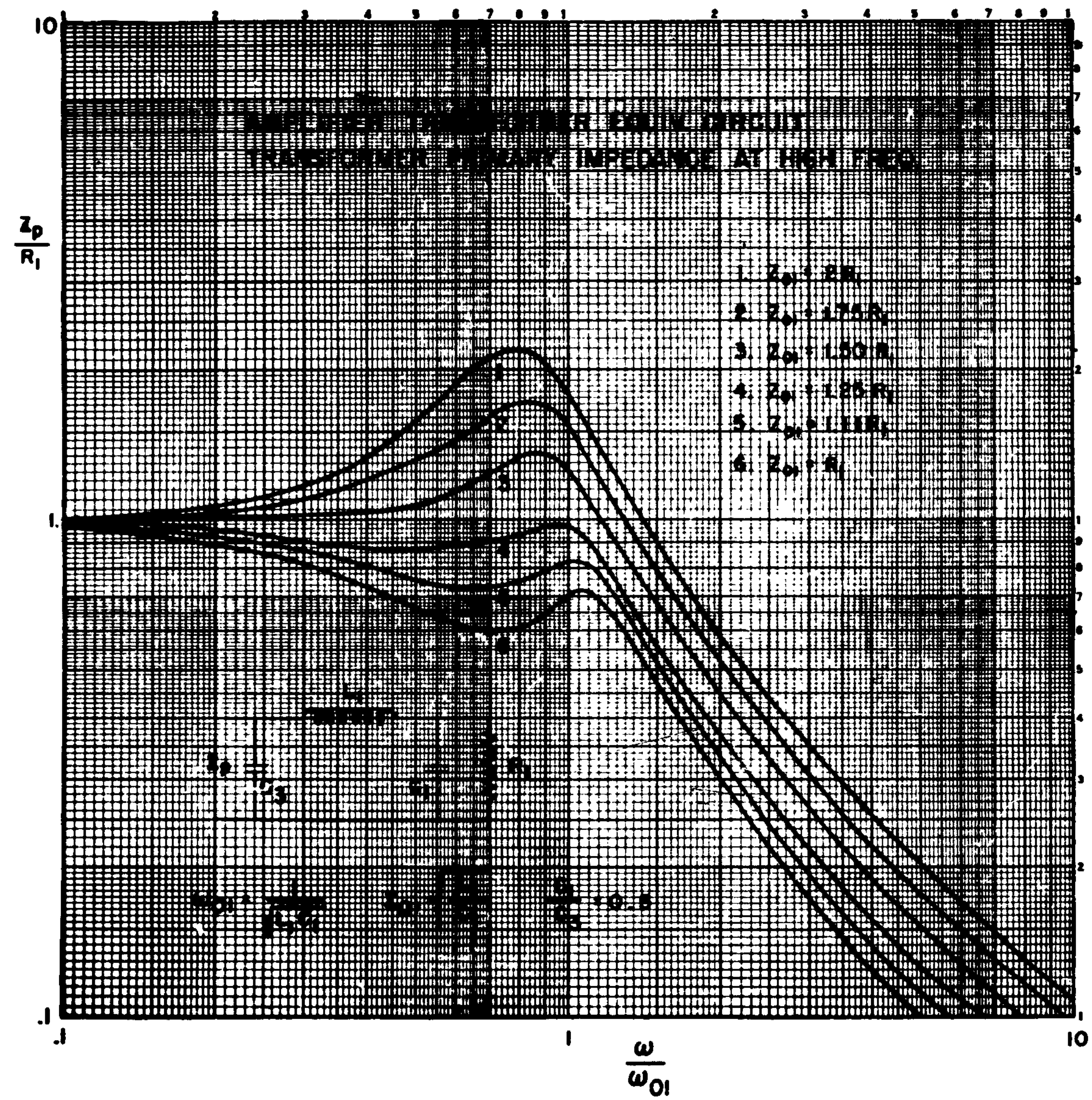
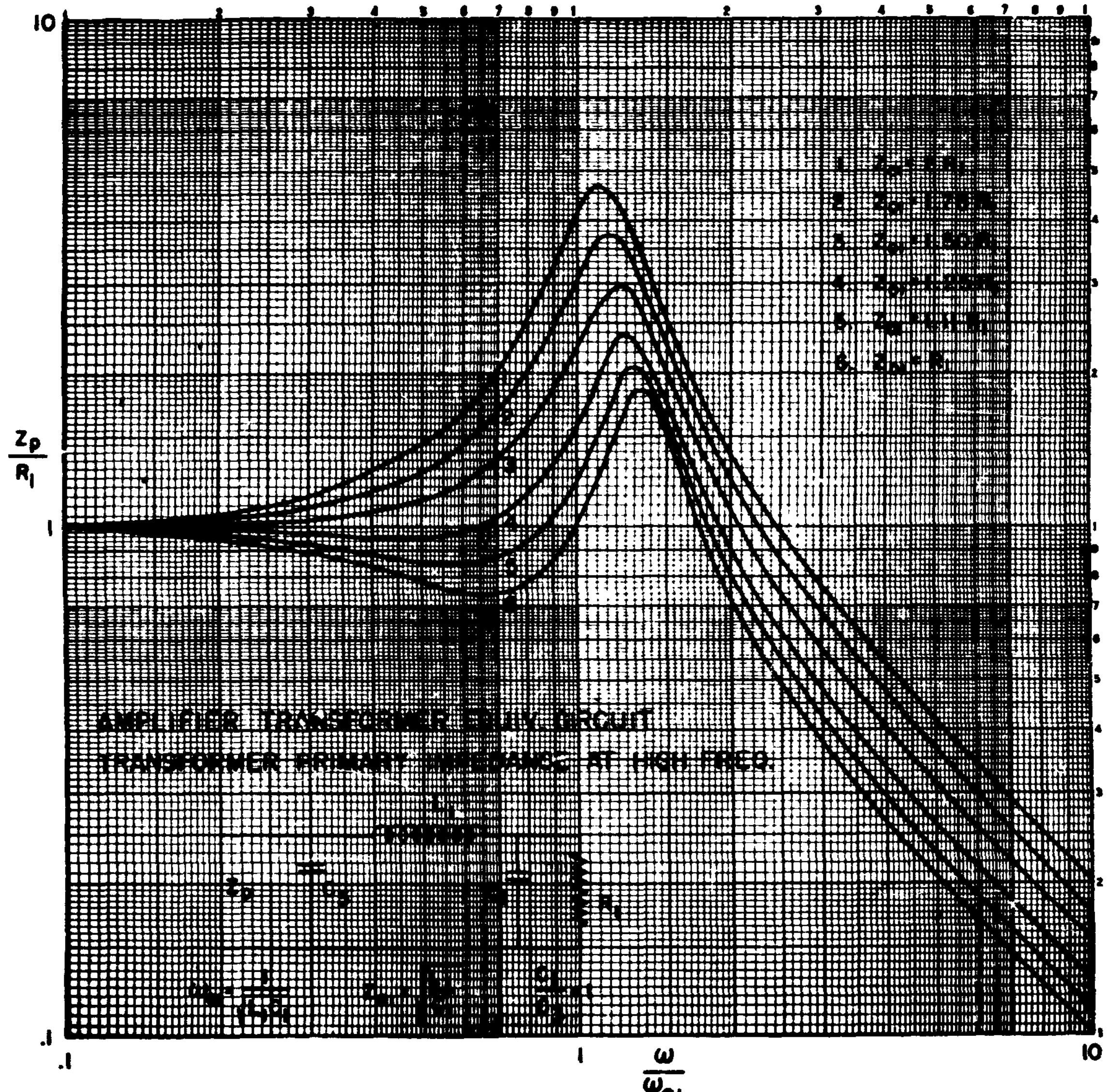

TRANSFORMER PRIMARY IMPEDANCE AT HIGH FREQ.
1. $Z_{p1} = 2R_1$
2. $Z_{p1} = 1.75 R_1$
3. $Z_{p1} = 1.50 R_1$
4. $Z_{p1} = 1.25 R_1$
6. $Z_{p1} = R_1$
$\frac{Z_p}{R_1}$
$\frac{\omega}{\omega_{01}}$
10
1.
.1
.1
1
10

FIG. 25



AMPLIFIER TRANSFORMER EQUIV. CIRCUIT
TRANSFORMER PRIMARY IMPEDANCE AT HIGH FREQ.
$\frac{Z_p}{R_1}$
$\frac{\omega}{\omega_{01}}$

FIG. 26

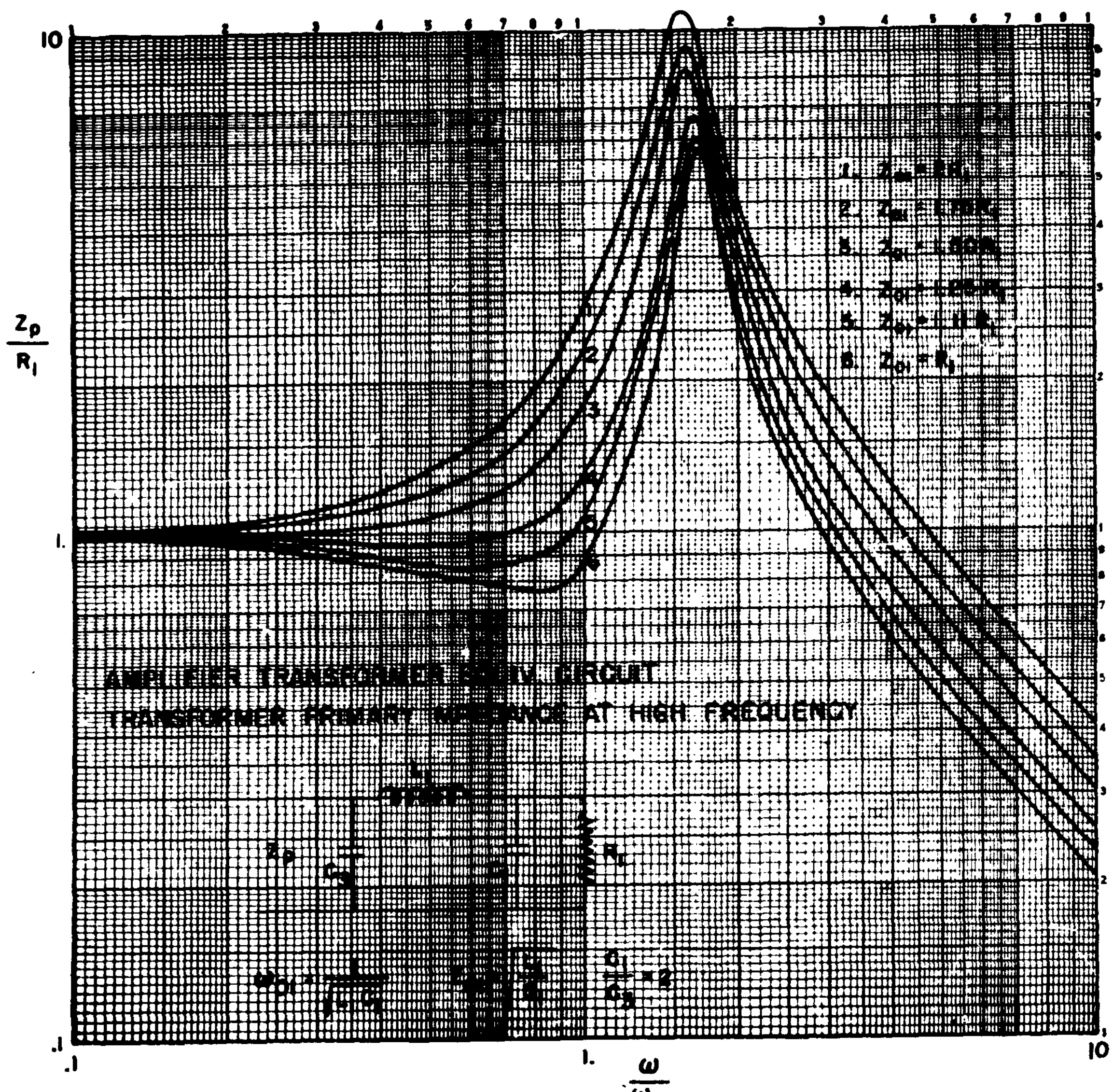

10
1.
.1
$\frac{Z_p}{R_1}$
.1
1.
10
$\frac{\omega}{\omega_{01}}$
TRANSFORMER PRIMARY
AT HIGH FREQUENCY
R_1

FIG. 27