SOME PROBLEMS
IN RADIO INTERFERENCE

A STUDY OF SOME PROBLEMS IN RADIO INTERFERENCE

A Thesis presented to

The Faculty of Graduate Studies and Research

McGill University

In partial fulfillment of conditions
required for admission to the degree
Master of Engineering

by

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Montréal, Can.
May 10, 1935.

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Preface

In the early days of wireless reception the sheer idea was so novel, so apparently miraculous that its many imperfections were taken as a matter of course, if not unnoticed. A transmission and reception process was highly successful if the listener reported the voices as clearly distinguishable.

Whether it is the approach to perfection in all the other mechanisms of our modern life or the intensified competition experienced during depression years by all manufacturers of commodities not essential to human existence or yet the fact that the novelty has worn off man's most recent toy -- the state of affairs now exists where Mr. Householder will not pay his good fifty dollars for anything that will not bring to his fireside everything offered by the B.B.C. or C.R.C. in aural perfection. As a result the modern receiver is the acme of beauty and convenience instead of the former incongruous mass of equipment with perverse operating tendencies. The listener can now receive weaker signals and reproduce them with tremendously greater power and fidelity than was conceivable a few years ago.

Unfortunately, our receivers like the rest of our robots possess no power of discrimination. Their function is to reproduce exactly the energy contained in the electromagnetic waves travelling in space. The fact that the electromagnetic field is not wholly composed of emanations from broadcasting stations but contains also extraneous fields, gives rise to the problem rightly termed Interference. Due to modern demands for increased power and fidelity of reception together with the intensified electrification of our communities in general, the condition of Interference to Radio Reception has become aggravated to a degree prohibitive, in certain locations, to enjoyment or use of the receiver.

It is with some aspects of this condition that this paper is concerned.

CHAPTER I

The sounds coming from the loudspeaker driven by any radio receiver, whether it be a domestic set, a police auto radio or an aircraft receiver may be classified by their sources.

A. Useful, desirable sound

  a. Voice, music, code, picture transmission.

B. Interfering sound

  a. Internal Receiver Noise

  b. Atmospherics

  c. 'Man-made' Interference

In spite of misapprehensions, the sound classed as A may be distinguished from those sounds under B in that they are purposefully produced. Class B sounds occur simultaneously with the former and are wholly undesirable.

a. Internal Receiver Noise.[1,2] This is that sound which is present in the output when there is no signal input and the power supply is perfectly smooth direct potential. It is a soft hiss and is due to one or more of several conditions.

A phenomenon known as Shot Effect[2] may give rise to internal receiver noise. It originates in the inter-electrode space of the tubes and is due to the fact that the space current is not a continuous flow but consists in a number of individual electrons arriving at the plate in much the same manner as raindrops falling on a roof. Since the arrival is entirely haphazard there exist irregularities from instant to instant which result in irregular current that gives rise to noise in the output of a receiver. This, together with smaller effects as erratic and incidental secondary emission, can be minimized by a copious space charge and the net result is a nearly complete elimination of shot effect noise.

The more serious cause of internal receiver noise is Thermal Agitation.[2] This originates in resistors, particularly grid resistors, by virtue of the fact that they are at a temperature above absolute zero. That is, they have a heat content which is a molecular motion. Since the motion of the molecules, ions or atoms as the case may be, is haphazard, their mean distribution varies from instant to instant. This means a conductivity that is not absolutely uniform which gives rise to potential and current variations that appear as noise in the receiver's output.

The magnitude of internal receiver noise, that is, thermal agitation chiefly, can be calculated from

$$E^2 = \int_{f_1}^{f_2} 4kT\,R(f)\,df.$$

where E = Thermal Agitation voltage between the limits of integration shown.

k = Boltzman's Constant.

R(f) = a resistance function. (Incl. Set gain)

T = the absolute temperature.

This indicates that the internal noise is governed by the gain of the set, the input resistance and the selectivity of the receiver. This value of internal noise is important in that it dictates the minimum signal that can be received with intelligence. A signal must be above the internal noise level in order that it convey its message. Terman[2] estimates the noise voltage from a half megohm resistor over a five kilocycle band to be six and one half microvolts.

b. Atmospherics.[2] While internal receiver noise is characterized by a continuous hiss, independent of the position in the spectrum, atmospherics are irregular series of crashes that have peculiar frequency, meteorological, seasonal and diurnal characteristics.

Briefly Atmospherics are the highly damped powerful electromagnetic waves set up by and radiated from magnetic storms. These storms may or may not be accompanied by the usual thunder and lightning effects of an "electrical" storm. They may be within a hundred miles or they may be tropical disturbances. While the disturbance is present over the whole spectrum, it is much more severe in the longer wavelengths. The intensity of the noise is also greater in summer than in winter and darkness seems to aggravate the condition. These are merely general statements which apply for most of this part of this hemisphere. The problem is not as cut and dried as it would appear.

No "Static Eliminator" has been successful because Interference is an electromagnetic wave just as the broadcast carriers are. One cannot reject the one wave without rejecting them all. Two palliatives are available. By having a receiver as selective as possible, the quantity of Interference received is a minimum, since the Interference is blanketed over the whole spectrum. Secondly, to use a directive antenna for east to west reception when atmospherics from tropical storms to the south are most severe.

A suggestion receiving some attention is that of super power broadcasting. The idea is to completely override the Interference with a tremendously strong signal so that ample volume may be obtained from a receiver so insensitive that the worst Interference would not be audible.

c. Man-made Static. This type of Interference will receive particular treatment in later chapters.

CHAPTER II

Some Definitions

At this stage it is fitting to define some terms which will be used in the discussion which follows. These terms are frequently used without discrimination by laymen and even engineers. The definitions given here are not necessarily standard ones though they are correct in the opinion of the writer.

Interference is any undesired occurrence. It shall be limited here to mean Interference to Radio signal reception. It may be applied to an electromagnetic field or to the sound produced by its passage through the processes of a radio receiver. The term makes no distinction between the methods used for the propagation of the disturbance, viz. conduction, induction or radiation.

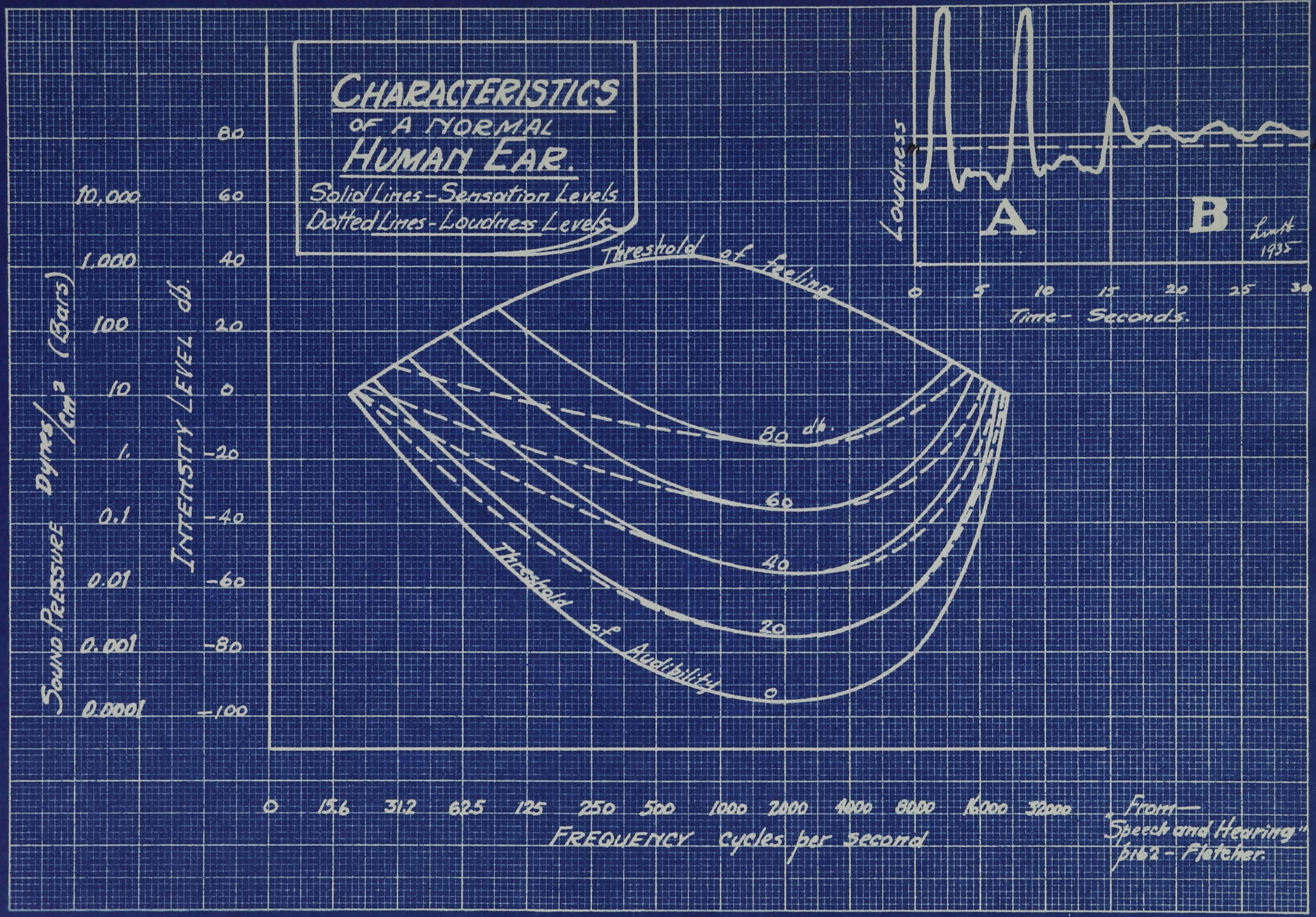
Static. Objection is here made to any use of this term. Colloquially it means no more than is implied by "Interference" and technically its use is fallacious. It will be demonstrated in Chapter III that no static condition whatsoever is capable of producing interference. The term is avoided herein.

Noise is a sound which is unpleasant to the human ear. One distinction between noises and tones is the lack of recurrent periodicity in the pressure oscillations of the former. This is very nearly correct though noise is an aggravating, unpleasant sound which we wish to eliminate and this cannot be said of all non-recurrent periodic pressures such as the consonants of our spoken language.

Loudness of a Noise in fact, is the degree of unpleasantness caused by the noise. This is not the same as the loudness of a tone. To enunciate the unpleasantness of anything in terms of concrete parameters is an imposing if not impossible task. Consequently one must be satisfied with the definition of loudness of a tone applied to noise considerations.

Loudness of a Tone[4] is a complex function of the frequency and amplitude of the pressure oscillations. Figure 1 shows the levels of equal loudness in terms of sound intensity or pressure level. It is noticed that loudness levels and sensation levels are not the same throughout. The former is a hearing phenomenon and the latter is a question of feeling.

In applying this to a noise the difficulty arising is evident from considering Figure 1A, 1B. The curves are for two hypothetical types of noise. Both have the same average loudness level. Though A has very high peaks it drops to low values in between while B maintains an even average value. According to the definition concerning tones they are equally loud; yet a program of loudness level mn would not be heard at all with B and would be heard intermittently with A. On the other hand the ear can become accustomed to a noise as at B and never notice it whereas intermittent, irregular shocks are always unpleasant.


CHARACTERISTICS
OF A NORMAL
HUMAN EAR.
Solid Lines - Sensation Levels
Dotted Lines - Loudness Levels
Threshold of feeling
Threshold of Audibility
80 db.
60
40
20
0
Sound Pressure Dynes/cm² (Bars)
10,000
1,000
100
10
1.
0.1
0.01
0.001
0.0001
Intensity Level db.
80
60
40
20
0
-20
-40
-60
-80
-100
0
15.6
31.2
62.5
125
250
500
1000
2000
4000
8000
16000
32000
FREQUENCY cycles per second
Loudness
A
B
1935
0
5
10
15
20
25
30
Time - Seconds.
From — "Speech and Hearing" p162 - Fletcher.
FIG. 1

CHAPTER III

Electromagnetic Waves

Since the whole question is one of the behavior of electromagnetic waves, it is proper to review briefly some principles involved rather than attempting the solution in any haphazard manner. Part I will deal with the propagation of electromagnetic waves through space. Part II will concern itself with their propagation along a conducting system.

PART I

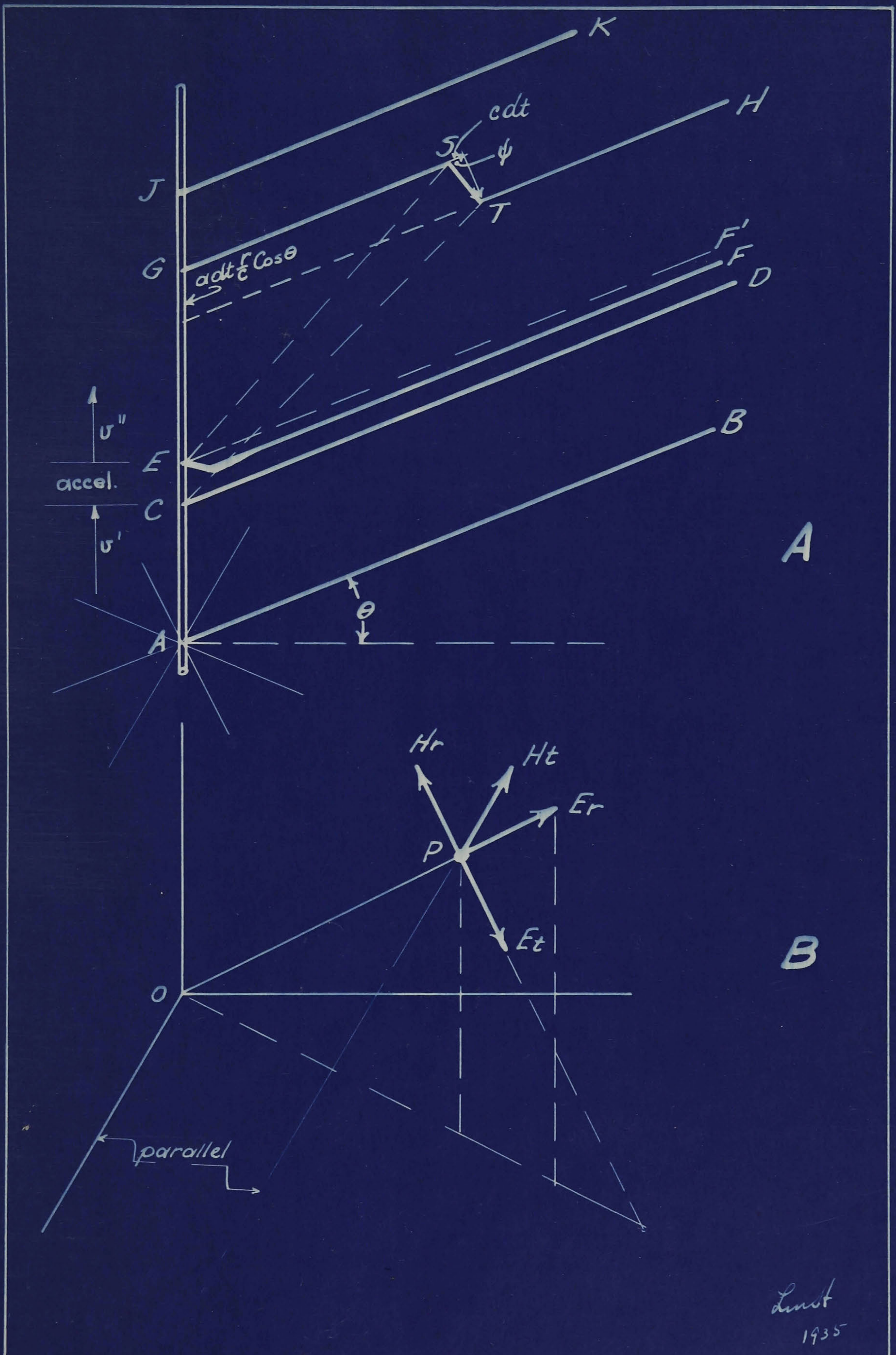
In this discussion the writer, preferring concretion to sublimity, employs the simplest conception of this phenomenon consistent with adequate, useful results.[5,6,7]

Modern conception of current flow is that of the movement of a large constant number of free electrons along the conductor. The current density is a measure of their velocity and their number. Since the net phenomenon is the additive result of all the electrons present, we may simplify the discussion by considering a single one of these entities.

In Figure 2A the electron is stationary, as far as any longitudinal drift is concerned, at A. That is, there is no current flowing. Radially from the electron there are lines of electric flux by virtue of its charge, a physical constant which can be denoted by e. Since all the lines are similar except for direction we may consider any one of them alone, say AB making an angle θ with the normal to the conductor.

Introducing now a constant electromotive force into the system causes the electron at A together with all its fellows to move along the wire with a constant velocity V'.

FIG. 2



K
H
cdt
S
ψ
J
T
G
adt $\frac{r}{c}$ Cosθ
F'
F
D
v''
E
accel.
C
v'
B
A
θ
A
Hr
Ht
Er
P
Et
B
O
parallel
1935

The lines of flux including AB follow the electron as it moves and at some place C the flux line will be in the position CD, nearly parallel to AB. If it were exactly parallel to AB it would mean that the flux line is capable of establishing itself in its radial position with infinite speed for every new position of the electron. This is erroneous since it is a physical fact that the electric field establishes itself with a finite velocity equal in air to the universal constant C, the speed of light. Knowing, however, that v' will not ever exceed one centimeter per second, it is quite negligible compared to C and we may consider the flux lines to be straight, radial and moving parallel to themselves provided the velocity v' is <u>uniform.</u>

Suppose now the electron receives a uniform acceleration 'a' which lasts for a time 'dt' during which the electron travels from C to E with increasing velocity. At E the acceleration ceases and the electron continues its migration to G, J, etc. with the new velocity.

$$v'' = v' + adt.$$

During the acceleration period the flux line proceeds to establish itself in its normal radial position parallel to AB but is unable to do it with sufficient rapidity compared to dt to maintain a continuous radial position. In fact only at J is the flux line adjusted to the new velocity within the limits of the sketch, while at G the part of the flux line TH is still insensible to any change since T is as far as the disturbance has travelled from the conductor at that moment. Obviously the figure is exaggerated in scale for actually AJ is very much less than GS.

Consider the flux line in the position GSTH. It is, in spite of the kink, an intact flux line. Anywhere along it there must be a radial flux density given by

$$F = \frac{e}{4\pi r^2}$$

where r is measured from the generating electron. Since a flux line IS a line of force, the kink at ST must be due to an additional flux density acting perpendularly to the radial density. That is, the effect of the acceleration is to add a tangential component to the existing radial flux density. Referring to them as Ft and Fr, the sketch yields

$$F_r = \frac{e}{4\pi r^2}$$

$$F_t = \frac{e}{4\pi r^2} \tan\psi = \frac{e a \cos\theta}{4\pi r c^2}$$

It is seen that the radial component is independent of accelerations to the electron. It attenuates rapidly with distance from the conductor and moves with a velocity of v cos θ The tangential component on the other hand is the result of and is dependent on accelerations of the electron. It attenuates slowly with distance and moves outward with a velocity c.

The components of electric field resulting from these densities are

$$E_r = 4\pi F_r = \frac{e}{r^2}$$

$$E_t = 4\pi F_t = \frac{e a \cos\theta}{r c^2}$$

Then by electrodynamic conceptions a moving electric field has associated with it a magnetic field given by

$$H_r = \frac{E_r \times Vel.}{c} = \frac{ev \cos\theta}{cr^2}$$

$$H_t = \frac{E_t \times Vel.}{c} = \frac{e\alpha \cos\theta}{c^2 r}$$

It is noticeable that Ht and Et are apparently identical. Actually they differ by a factor 300, due to different Units and they are in space quadrature.

Finally, the completed picture of the electromagnetic wave is that of a spherical shell, Figure 2B whose radius is increasing with a velocity c. The shell is composed of electric and magnetic stresses. Each has two components, a tangential component representing radiated energy and a radial component representing normal flux of self-inductance present in any circuit. The electric vectors are in space quadrature with each other and with their associated magnetic vectors. The radiation (ie tangential) vectors are in space quatrature, in time phase and mutually perpendicular to the direction of propagation.

To make the above expressions applicable to actual figures, consider a straight conductor of length l, cross sectional area s, carrying a direct current of i amperes. Let e represent now the total charge present in the section of conductor then

Current density $= \frac{e}{ls} v$

current $= \frac{ev}{l} \times \frac{1}{3 \times 10^9} = i$

whence v $= \frac{3 \times 10^9 il}{e}$ and

$$a = \frac{dv}{dt} = 3 \times 10^9 \frac{l}{e} \frac{di}{dt}.$$

Using ea and ev from these expressions the total field present at r, is

$$H_{total} = \left[\frac{3 \times 10^9 \, i l \, Cos\theta}{r^2 C} + \frac{3 \times 10^9 \, l \frac{di}{dt} Cos\theta}{r C^2} \right] \text{dynes per unit mag. pole.}$$

$$E_{total} = 300 \left(H_{total} \right) \text{ Volts/cm.}$$

Suppose the conductor is 1000 centimeters long and carries 10 amperes. If the current jumps to 11 amperes in one one thousandth of a second we may calculate the voltage that would be induced in another conductor one meter long and located various distances away. Figure below shows the results.

r	Radiation μVolts	Induction μVolts
10^2	10^2	3×10^6
10^5	10^{-1}	3
10^8	10^{-4}	3×10^{-6}

The noticeable points in this discussion are:

(i) The induction (radial) field predominates near the conductor but the radiation (tangential) field persists to a greater distance.

(ii) The waves travel from the moving charge. This is not necessarily the direction of the source of excitation voltage.

(iii) No mention is made of a spark, or arc. These may increase or decrease the intensity of the wave. The only necessary condition for radiation is a <u>change of current flow</u>.

(iv) The magnitude of the fields is dependent upon

(a) the current flowing

(b) the rate of change of current flow

(c) the distance from the current

(d) the length of the conductor.

PART II

Propagation along a conducting system.

When an electromotive force is impressed at any point in a given conducting system, conditions of current flow and potential are established in a manner governed by and predeterminable from the nature of the applied voltage and the configuration of the system. The solution is possible by two methods.

A. Classical Method of linear equations.[8,9]

B. Operational Method of Heaviside.[10,11]

The classical method employs the original differential equations governing dynamic equilibrium in all electric circuits, viz.

$$\frac{dV}{dx} = L\frac{di}{dt} + Ri$$

$$\frac{di}{dt} = C\frac{dV}{dt} + GV$$

Where L, R, C, G are the inductance, resistance, capacitance and leakance respectively per unit length of the elongated circuit in which we are interested. V and 'i' are the instantaneous values of voltage and current at a distance 'x' from some dimensional reference point.

By assuming a solution in an exponential form and substituting in the original equations, the solution is verified for the coefficients present. The complete solution containing the Particular Integral, or steady state solution and the Complimentary Function, or transient solution is not easily obtained with the constants of integration assigned their proper values fitting boundary conditions. This is particularly true of the transient solution. The steady state solution yields to the method and the standard well-known formulae for voltage, current, attenuation, phase shift and velocity result.

To obtain an expression for the voltage or current in its complete form for any condition selected at will with respect to time or position it is often advisable to employ the Operational Method propounded by Heaviside and extended by Carson.[10,11] Briefly, the method is concerned with the derivation and evaluation of the function A(t). This function is referred to as an "Indicial Admittance" or a "Unit Function" and represents exactly the current flowing at any position 'x' in a system and at any time 't' in response to a unit 'd.c.' voltage impressed at time 't = o' at any given point in the circuit. From this the current due to any other type of voltage is directly deducable. That is, the function A(t) completely specifies the behavior of the system under all types and conditions of applied voltages and circuit arrangements.

Carson[10] has applied this function to various types of elongated circuits among them a transmission line with distributed values of R, L, C and G as above. The steps of the derivation need not be included here, save the final expressions for voltage and current Unit Functions. They are

$$i = 0 \quad \text{for } t < \frac{x}{v}$$

$$= e^{-pt}\sqrt{\frac{C}{L}}\, I_0\left(\sigma\sqrt{t^2 - \frac{x^2}{v^2}}\right) + vG\int_{\frac{x}{v}}^{t} e^{-pt} I_0\left(\sigma\sqrt{t^2 - \frac{x^2}{v^2}}\right) dt \quad \text{for } t \geqq \frac{x}{v}$$

$$e = 0 \quad \text{for } t < \frac{x}{v}$$

$$= e^{-\frac{p}{v}x} + \frac{\sigma}{v}x\int_{x/v}^{t} \frac{e^{-pt} I_1\left(\sigma\sqrt{t^2 - \frac{x^2}{v^2}}\right) dt}{\sqrt{t^2 - \frac{x^2}{v^2}}} \quad \text{for } t \geqq \frac{x}{v}$$

where

$$v = \frac{1}{\sqrt{LC}}$$

$$p = \frac{R}{2L} + \frac{G}{2C}$$

$$\sigma = \frac{R}{2L} - \frac{G}{2C}$$

From these equations it is seen that, for any point at distance 'x', the voltage and current is zero until '$t = \frac{x}{v}$' when the current suddenly jumps to $\sqrt{\frac{C}{L}}\, e^{-\frac{p}{v}x}$ and the voltage to $e^{-\frac{p}{v}x}$. At all times after this the current and voltage are chiefly dependent upon the integral terms which contain the Bessel functions I_1 and I_0. To obtain a picture of the wave front it is necessary to calculate and plot the current and voltage functions.

This may appear quite involved but in the solution of a similar case by classical method[8] the voltage summation

$$e = \frac{4}{\pi} e^{-\mu t} \sum_{0}^{\infty} \frac{\sin(2n+1)\tau \ \cos(2n+1)\psi}{n+1}$$

has to be carried to 6670 terms to obtain an accurate point on the voltage wave at 'x'= 1500 meters or 5 microseconds after the 'd.c.' voltage is impressed upon the line.

However, irrespective of one's mathematical propensities, there is sufficient data available for the present purpose. For instance, Steinmetz[4] has calculated the wave front data for the charge or discharge of a system composed of a single copper conductor of size 00 B. and S. placed 30 ft. above the ground. He has repeated the process for iron wire, smaller copper wire and smaller spacing. From such an analysis the following are the conclusions:

1. The size of the conductor has, within practical limits, no effect upon the steepness or propagation of the wave front.

2. The steepness of the wave front <u>is</u> decreased by wider spacing of the outgoing and return conductors.

3. The steepness in any case decreases inversely proportional to the square root of the distance (or time of travel).

4. The frequency components of the travelling wave are those of the natural frequency of the line together with the harmonics thereof.

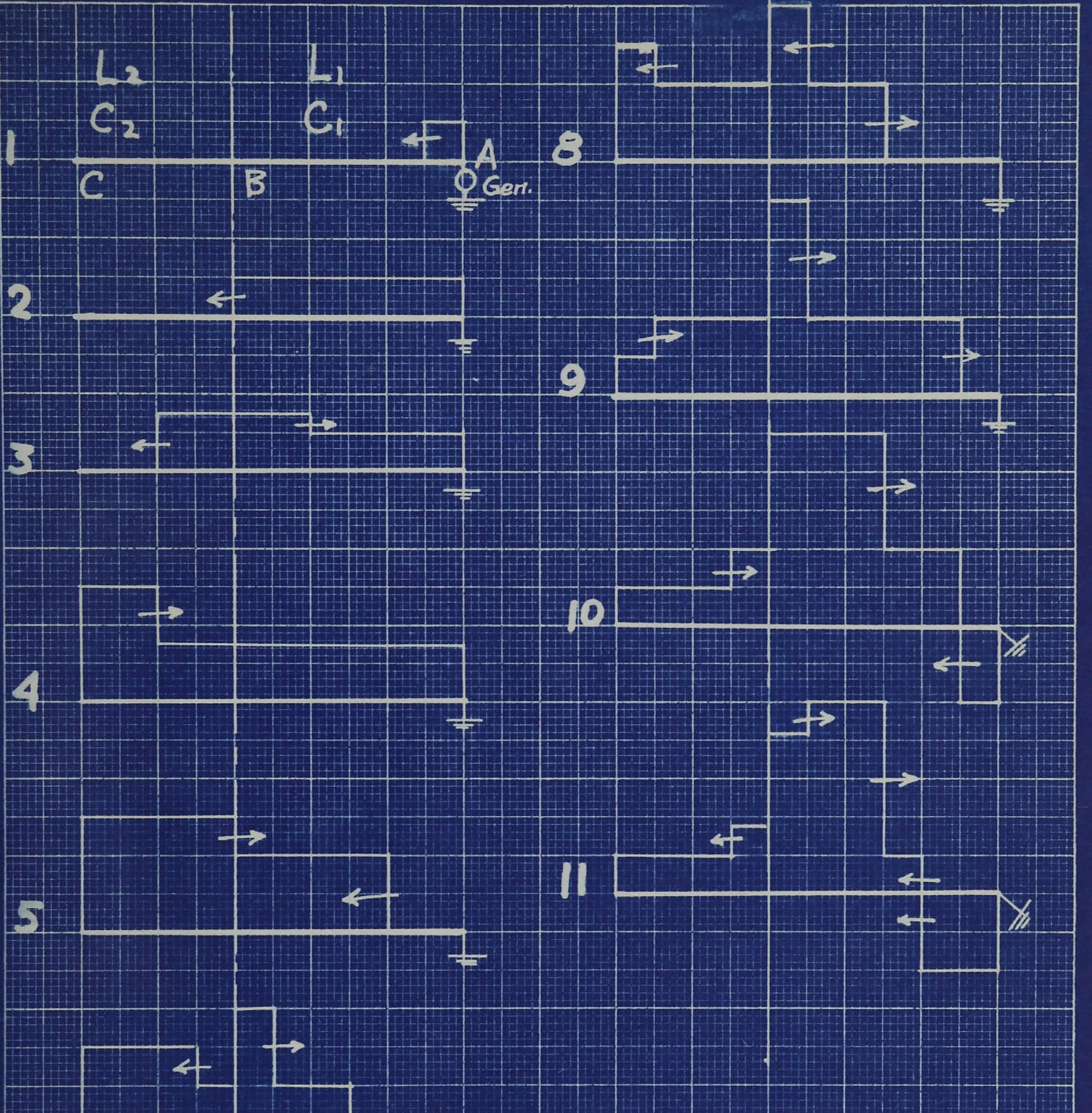
5. The higher frequency components are attenuated most rapidly though much distance may be covered meanwhile. For instance a 00 copper conductor 30 ft. high has a natural frequency of 60 kilocycles. An impulse upon that line will have

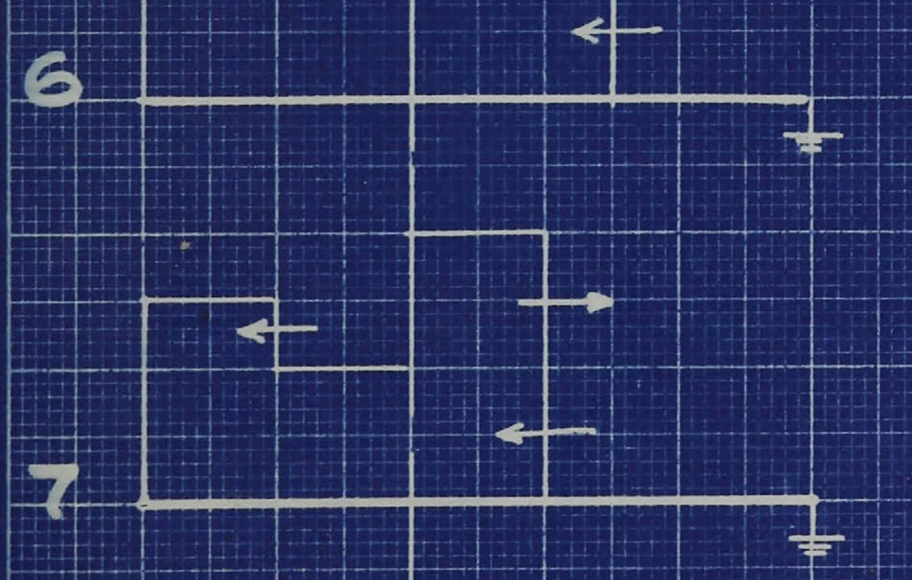
61 components effective after 1/4 miles of travel
45 " " " 1/2 " " "
3 " " " 19 " " "

6. The total attenuation is small. The peak of the wave has decreased only 7% after 19 miles of travel and 60% of peak remains after 65 miles of travel!

Remembering that, when a positive travelling wave reaches an open circuit in a line, it is reflected with its sign unchanged and when it reaches a short circuit it is reflected with its sign changed, it is possible to construct a series of diagrams representing the wave in various stages of its travel. Figure 3 represents such a condition with the added complexity of a parametrical discontinuity at B. At such a place the incident wave is divided such that the sum of the incident and reflected waves of voltage equals the voltage of the transmitted wave. Also the sum of the reflected and transmitted voltage waves divided by $\sqrt{\frac{L_2}{C_2} \cdot \frac{C_1}{L_1}}$ equals the voltage of the incident wave. These facts are proven in several texts such as Steinmetz. The figure referred to shows how a small surge may reach tremendous instantaneous values by superposition of the reflected, transmitted and incident waves. The figure illustrates about a quarter of a cycle of such interactions. Subsequent to picture 11 the magnitude of the peaks would decrease to zero, then go negative and so back to zero and on to subsequent cycles until the attenuation and leakage has reduced the surge to zero.

FIG. 3





REFLECTION, REFRACTION

TRAVELLING VOLTAGE WAVE

ON A LINE THAT IS
GROUNDED AT A
DISCONTINUOUS AT B
OPEN AT C
Where

$$\sqrt{\frac{L_2}{C_2} \cdot \frac{C_1}{L_1}} = 2$$

$$R = G = 0$$

Lauf... Apl 10/35

CHAPTER IV.

The Present Position.

With the preceding chapters as background it is now fitting to analyse the previous and contemporary efforts made toward the suppression of Interference. The sources of interference may be classified as follows:

Man-made Interference

Minor Sources

A. Small motors

B. Automatic telephone equipment, Buzzers.

C. Poor contacts in any electric circuit.

D. Automobile ignition.

E. Amateur radio transmitters.

H. Miscellaneous.

Major Sources

F. Power Transmission Systems.

G. Electric railways.

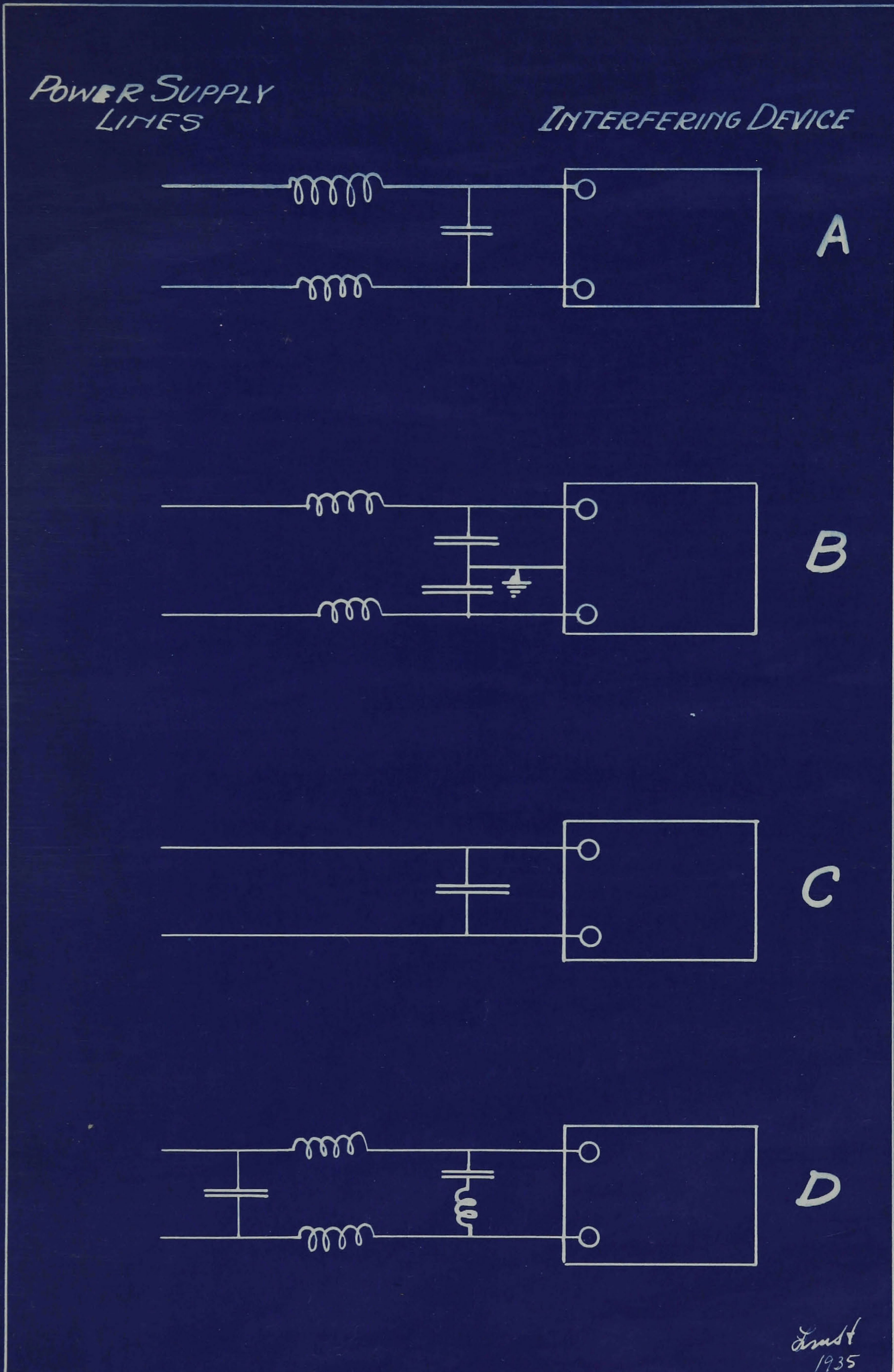
Class A includes the multitude of fractional horse-power motors which supply power to washing machines, refrigerators, vacuum cleaners and a host of other home appliances. They are invariable commutator types; they run at tremendous speeds and receive no electrical care. As a result commutator interference often occurs. The remedy applied is universal in principle but may be one of several forms. In general it is a high pass filter connected directly at the terminals of the machine intended to provide a path of low impedance for the high frequency components of the surges. If the supply lines also have a low impedance (capacitive) to higher frequencies a low pass filter is inserted in series with the supply lines in addition to the high pass filter. In its simplest form it is a condenser-choke arrangement shown in Figure 4 A. The choke coils may not be necessary and Figure 4 C is a solution. Also tieing the system to ground as at Figure 4 B. is often helpful provided the grounding lead is short and of low impedance, otherwise it may become an efficient interference. Where the characteristics of the interfering device are such that certain disturbing frequencies are preeminently present, band pass filters can be used. Figure 4 D represents one of a number of such arrangements. The whole problem is to keep the high frequency currents flowing in a localized circuit, instead of allowing it to spread throughout the distribution system where it may radiate with greater ease. This type of interference is dealt with by Merriman (See Reference 12).

Class B, telephones, buzzers, etc. is the same problem except for the hair-splitting distinction that the current rupture is unavoidable though unnecessary in small motors but quite necessary to the functioning of these apparata. A small condenser across the dial or buzzer contacts usually remedies the situation at once.

Class C is the result of poor workmanship, faulty operation of equipment or dangerously ramshackle devices. Radio interference from the erratic operation of such equipment will vanish with the correction of the faulty wiring or appliances as required for safety by the Canadian Electrical Code.

Class D, Automobile Ignition, is a recent aggravation brought to the front by the introduction and public acceptance

FIG. 4



of auto radio receivers and particularly short wave sets. The problem is handled quite satisfactorily by the use of resistors and suppressors designed for the purpose. The resistor is placed in the high tension lead to each spark plug, right at the plug, its effect being to dampen the oscillatory nature of the spark after the first impulse passes the gap. The condenser fulfils its usual bypass function when connected across the breaker points. IRC, Aerovox,[13] Erie, and other manufacturers have bulletins available on such equipment.

Class E is an inexcusable type of interference well under the control of authorities and the individual Amateur Operator.

Class H includes a host of heterogeneous equipment such as flashing signs, diathermy and therapeutic equipment, neon signs, etc. Canada uniquely has staff and equipment to successfully treat such interference.

Class F and Class G represent sources of interference no solution for the suppression of which is available. Three reasons for this are apparent. Firstly, the offending eqipment is itself an elongated circuit with beautiful radiating and propagating properties. Secondly, the quantities involved are so large that surgetraps where feasible may be impossible. Thirdly, the mechanical arrangements of apparatus in the course of their normal functioning are such as to preclude the application of any filter circuit. While the problem of the Transmission System[14] and that of the Tramway[15] have many similar aspects, this paper will refer specifically to the Tramway Problem in subsequent text.

Methods of Investigation Employed

1. Portable Receiver equipped with

    (a) Aural indication

    (b) Graphic indication

    (c) Oscillographic observation

    (d) Directive antenna

    (e) Probe antenna

2. Trial and Error Method.

3. Public Questionnaire.

The third method is, obviously, a dismal failure from the standpoint of obtaining reliable data on the question. It does however, add a little balm to a very sore spot upon the position of the Investigator in the good will of John Public and this is the aim of the mercenary offending corporation in many cases.

The second method, the path of least resistance, while successful in the case of the minor sources of interference has not contributed anything to the solution of the Tramway Problem. It is a method that has a rightful place in Engineering Investigation but its usefulness has been exhausted as far as this question concerns Street Railway Interference.

A portable receiver with pickup and output refinements is a useful tool in the study. It must, however, be used with intelligence and its indications properly interpreted. For instance, a directive loop indicates the direction of travel of the electromagnetic wave. This is taken as the direction of the source when the distance of the loop from the source is great compared to the dimensions of the source as in ship to shore direction finding. <u>But</u> it is entirely erroneous to place a loop twenty feet say from a trolley wire that extends for miles in various directions thereabouts, rotate it for maximum signal, then point in the indicated direction as the source of interference. What <u>is</u> indicated is that the direction of travel of the maximum magnetic vector of the existing complex induction (not radiation) field is as indicated by the loop. Even this makes the assumption that the various magnetic components among which the loop selected, are equally modulated. This is true enough since the radiation and induction is due to a rapid series of shock excitations together with their reflected and refracted waves surging back and forward over the system, being attenuated by distance and being increased by newly generated waves. Consequently the directive indication is meaningless since we know the wave travels perpendicularly from the trolley wire except where the field is distorted by other metal masses or conductors in the field.

The probe antenna of the straight rod type is non-directive, indicating simply the field at the point and that is, like the loop, simply a measure of seriousness of the interference, no more.

Aural indication of the output is scarcely satisfactory. It may be sufficient for rough comparison purposes if the differences of output are great. Also it proves of use where sounds to be segregated have characteristic pitch such as synchronous machinery or accelerating commutator noise, arc light sputter, etc. Even these must be carefully accepted since there are many commutators running at any one time and an arc sputter may be street light or it may be trolley wheel and many such ambiguities.

In the Use of Graphic indication one must remember that the meter is being used as a ballistic instrument and records taken with one instrument are not comparable with those of another save by correction by the ratio of the decrements of the two instruments. However, referring all inferences to one meter, the system may have considerable value.

Conclusions of Investigators.

All investigators agree that improper maintenance of track, trolley and car aggravates the interference. This is obvious and reasonable since the poorer the condition of trolley wire, trolley wheel, car wheel and rail, the more irregular will be the rolling contact above and below and the oftener will circuit ruptures take place. A circuit rupture is, of course, the source of the impulse wave that creates interference as it travels along the system and through space.

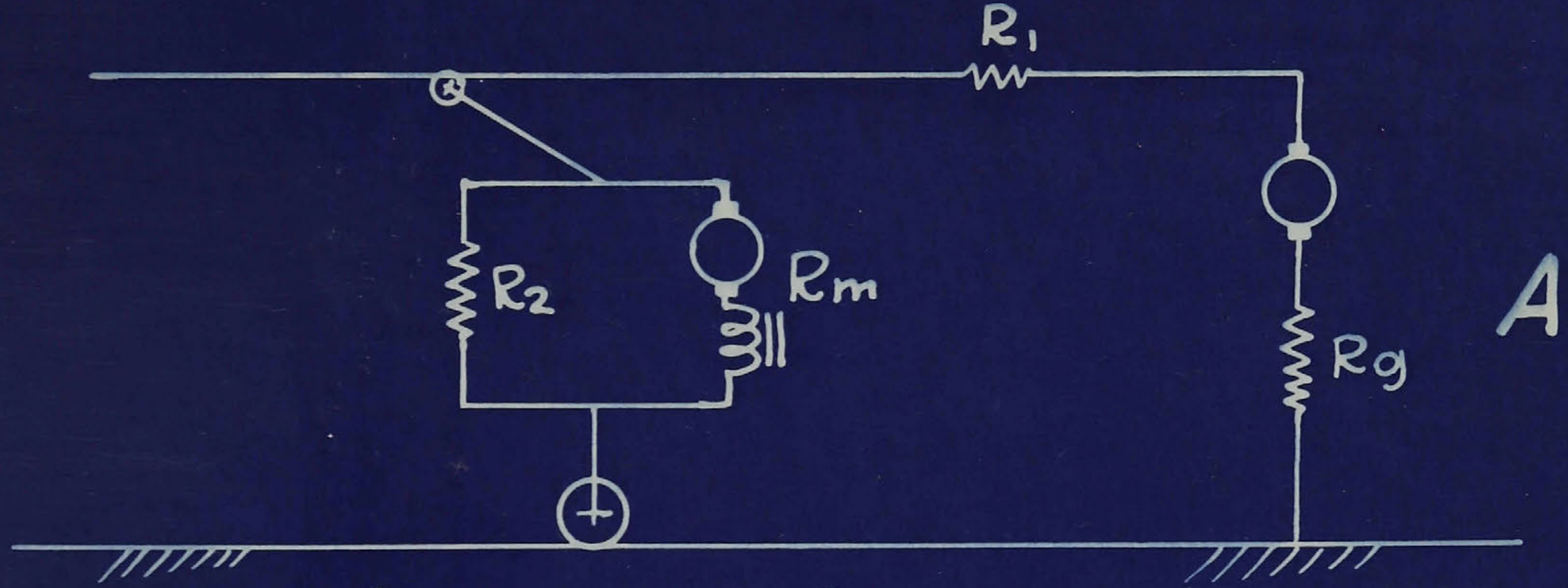
The power supply station has been blamed for originating interference. Filter units have been installed where necessary and the trouble eliminated.

Street car motors, both the traction and compressor motors have been found guilty of producing interference. Transposing the series fields to the trolley side (where the insulation permits) was found to be beneficial in Manchester and Leeds and some Canadian cities. A condenser of 0.1 to 6 mfd. has been added by Lille, Utrecht[15] and Montreal[15] with questionable success. Mechanical difficulties seem to be prohibitive and the cost excessive compared to the improvement.

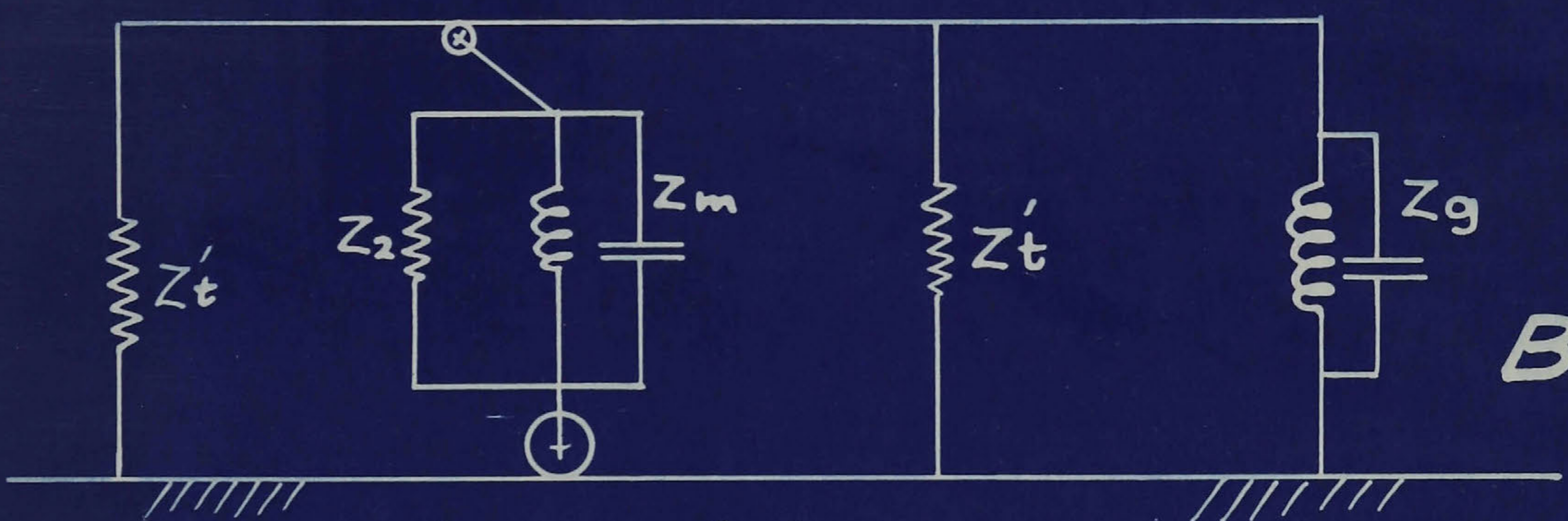
Consider Figure 5 to see, if possible, what this juggling of constants is actually doing in the electrical circuit. Figure 5 A shows the d.c. circuit as it exists and in it there is no interest. In B the motor of the car is shown to have certain impedance 'Zm'; that it is composed of resistance, inductance and shunt capacity is quite certain. 'Z't' represents the impedance of the trolley system looking each way from X. The equivalent circuit is shown at C. 'Zt is the impedance of the whole overhead system and power station. The whole problem is to keep high frequency currents from flowing through Zt. Z2 is the auxiliary car circuits and Zm as before, the motor circuit. Zt and Z2 have been determined by the writer and are presented later. Zm is more difficult to determine since it varies with the speed of the machine.

There are five places where it is possible to break the circuit as denoted by the letters a,b,c,d,e. 'a' is the commutator, 'b' is the controller, 'c' is auxiliary circuit switches, 'd' is the trolley contact and 'e' is the rail contact. What actually happens when a 'd.c.' circuit is broken is that a resistance is suddenly put in. If the circuit is completely broken the resistance is infinite or if a very heavy arc is drawn the resistance equivalent is nearly zero, and similarly for intermediate values. By the Compensation Theorem[16] the addition of a resistance to a circuit is exactly equivalent to inserting an 'e.m.f.', at that point equal to -IR where R is the inserted Resistance and I, the current flowing in the circuit previous to the change. So if our trolley circuit is broken instantaneously it is

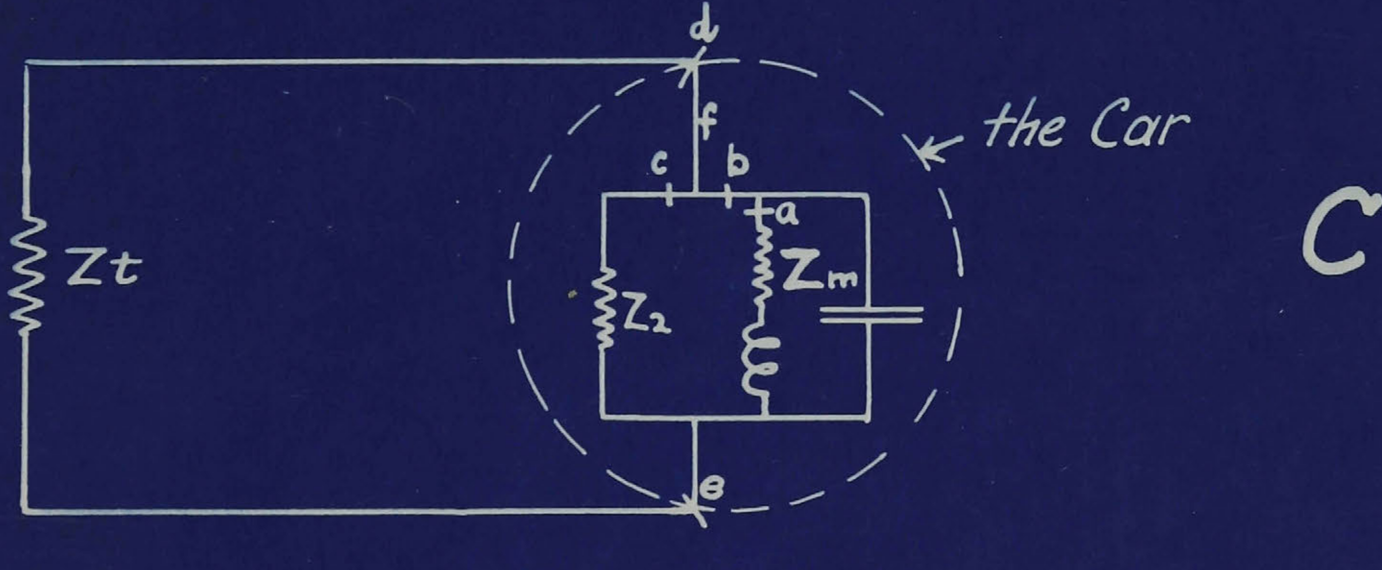
FIG. 5



ACTUAL D.C. CIRCUIT



ACTUAL A.C. CIRCUIT



EQUIVALENT A.C. CIRCUIT

1935

equivalent to inserting an infinite 'd.c.' voltage. The practical existent form of this extreme is a more or less slowly broken circuit which was carrying various currents. To summarize, the magnitude of any one frequency component of an impulse of voltage equivalent to a circuit rupture is dependent directly upon

1. The rapidity of the break, and
2. The magnitude of the current flowing, inasmuch as it does not affect inversely the rapidity of the break.

This appears to contradict the universal observation of investigators that a car drawing small current causes more interference than a heavily loaded one. However, the rapidity of the circuit break as controlled by the size of the current is a governing factor in the 'e.m.f.' produced to the negligibility of the actual magnitude of the current as a factor.

Returning to Figure 5 C, imagine a circuit rupture occurring at 'a'. So a voltage placed in the circuit will cause a current to flow. Its path will be that of lowest impedance. If a condenser is shunted across the motor in addition to its own self capacity it certainly will tend to localize the trouble if the capacity is sufficiently large. Again, the value of the impulse voltage is indeterminate and if 90% of it is bypassed by the condenser and the motor self capacity there is still the possibility that the remaining 10% is sufficient to cause interference when flowing through Zt. This is the case or else the motor is not causing interference judging from Manchester's[15] estimated improvement of only 40%. After reviewing conditions in Europe M. Peridier[15] states

> "Speaking generally, condensers are not sufficient in themselves, as their impedance is too high to drain away disturbances".

Perhaps the most successful treatment applied to the condition is the use of 'Choke' coils in the main trolley circuit upon the tramcar roof. The coil may or may not be tuned to a given frequency. Its object in either case is to provide a high impedance to currents of radio frequency. If the coil is acting as an impedance, the high frequency waves of voltage and current will suffer attenuation through the coil and this is exactly what is wanted. But suppose the coil is tuned, either naturally or by added capacity to parallel resonance with the object of increased impedance at a particular frequency, then one has a new set of conditions existent. Here there is a parallel resonant circuit in series with other impedances all of which have low ohmic resistance. Into this circuit is inserted a series of impulse voltages by circuit breaks. These impulses will keep the resonant circuit in a perpetual state of damped oscillation and consequently Edinburgh and Brussels report varied results, Stuttgart have had satisfactory results and London United have had no success![15]

It appears to the writer that the only method of using such a scheme is to apply normal filter principles as shown in the Figure below (p. 10).

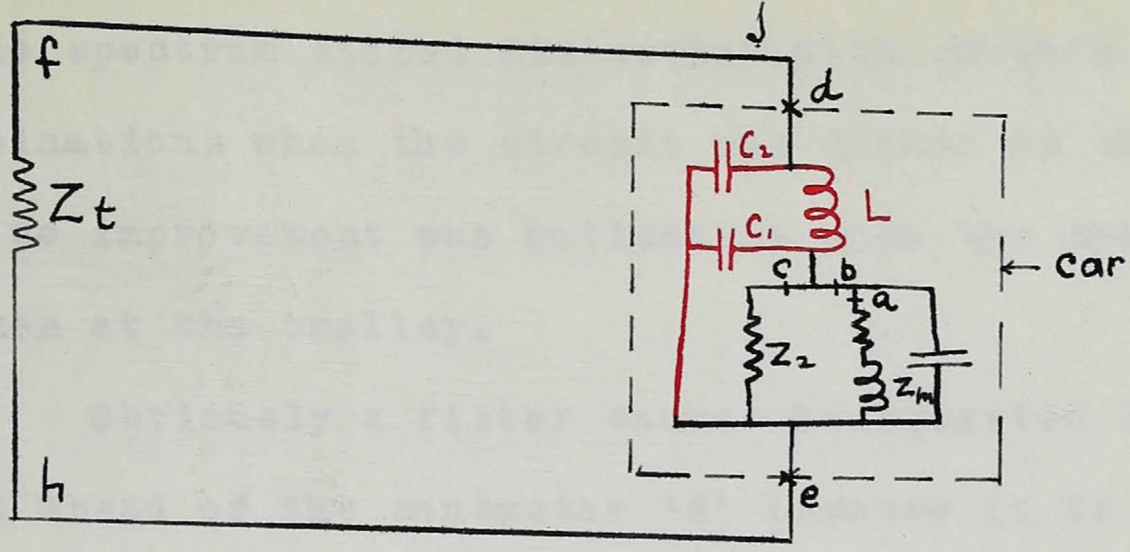
Characteristics of Choke Coils

used by

Canadian Department of Marine

in Tests at Montreal April 1935

	#1 Coil Pancake	#1 Coil Pancake	#2 Coil Pancake	#3 Coil Solenoid
Mounting	Iron Clamp	Wood Clamp	Wood clamp	Wood core
Turns	19	19	45	
True Inductance uh	14	11	30	81
Self Capacitance uut	355.	36.5	70	40
Resonant frequency m.c.	2.25	2.57	3.48	2.82



L is an inductance with low distributed capacity, ie. high resonant frequency. C1 and C2 are high capacity condensers, chosen to avoid serious resonance with L. It is simply a low pass filter to localize all high frequency currents resulting from circuit ruptures within the car.

This point must be noticed -- that no device discussed so far in this chapter is of any value when considering current breaks outside the car, that is, at trolley 'd' and track 'e'. This condition exists since no circuit element or combination of elements inserted in the car (dotted square, Figure above) can influence the generation or propagation along 'dfh' of an impulse originated by a rupture at 'd'. The same is true for a break at 'e', though the latter is, for mechanical reasons, not so prevalent, or serious, when it does occur due to ground absorption. As far as one can tell from the literature, this fact is not fully recognized by investigators. That it is not a theoretical pipe dream was demonstrated early in April of this year by the Canadian Department of Marine officials at Montreal. At that time various coil-condenser combinations were inserted in the main trolley lead on the car roof and a car circuit automatically interrupted first within the car, then secondly at the trolley. Interference measured throughout the whole radio spectrum showed diminution with certain coil-condenser combinations when the circuit was broken at the controller but no improvement was noticeable when the same circuits were broken at the trolley.

Obviously a filter cannot be inserted in the supply line ahead of the contactor 'd' because it is moving physically. Consequently, to eliminate the circuit break is the next idea that was exploited. This, largely a mechanical problem, gave rise to a sliding shoe (Berlin, Leige, Detroit) to replace the wheel. Also larger trolley wheels and greater contact pressure were tried at Copenhagen and Hamburg. Brussels conducted experiments with a compound wheel system in a caterpillar arrangement. Pantograph collectors have been investigated. And the net result of the whole affair is that these devices are merely palliatives and no arrangement economically possible can keep the trolley wire and collector in perfect continuous contact.

Since a heavy arc is noticed to have produced less interference than a small arc, the idea springing therefrom is to add some element to the car circuit to fatten the arc. Increased load would be wasteful and costly. The addition of a heavy choke (several henrys) undoubtedly does prolong the arc as the circuit is broken, but the moment the current tends to increase the choke has the opposing effect and the net result is questionable.

In any case, the aggravation of an electric arc in the interests of minimizing radio interference is a doubtful procedure. An arc <u>never</u> is electrically quiet. Even an arc drawn between two clean hard, stationary electrodes energized from a low voltage battery generates, without amplification, a continuous hiss in a headphone. Certainly the same arc drawn between moving dirty electrodes supplied by rippled direct voltage is going to produce much more sound. And where there are resonant circuits present, as a street car (See Chapter V) or the system itself (Chapter VII) the presence of an arc has unlimited interference producing possibilities.

Improvement of the condition has been noticed in wet weather over dry weather in some Canadian cities. London reports no difference. Both may be correct if the proper cause could be assigned, viz. one or all of

1. The wave of water ahead of the moving trolley wheel.
2. The improvement in conductivity of the ground plane.
3. The improvement in conductivity of all the objects in the field of the system -- wood buildings, stone structures, etc.

Improvement during the night over daytime conditions, was noticed but the supporting evidence is questionable.

Finally, the writer is inclined to agree with M.Peridier[15] when he writes

> "Despite the interesting nature of these experiments, it can be concluded that in the present state of technical development and so far as trolley buses are concerned there is no practical solution to the problem of protection against radio interference caused by overhead current collectors nor is there also for electric tramways."

CHAPTER V

Tramcar Characteristics

There are three links in the chain, three elements in the circuit, which are indeterminate as yet.

1. The street car circuits, Z2 (Figure 5C)
2. The over head system } Zt
3. The return system }

It is the purpose of this and succeeding chapters to throw some light upon the behavior of these circuits, particularly at high frequency.

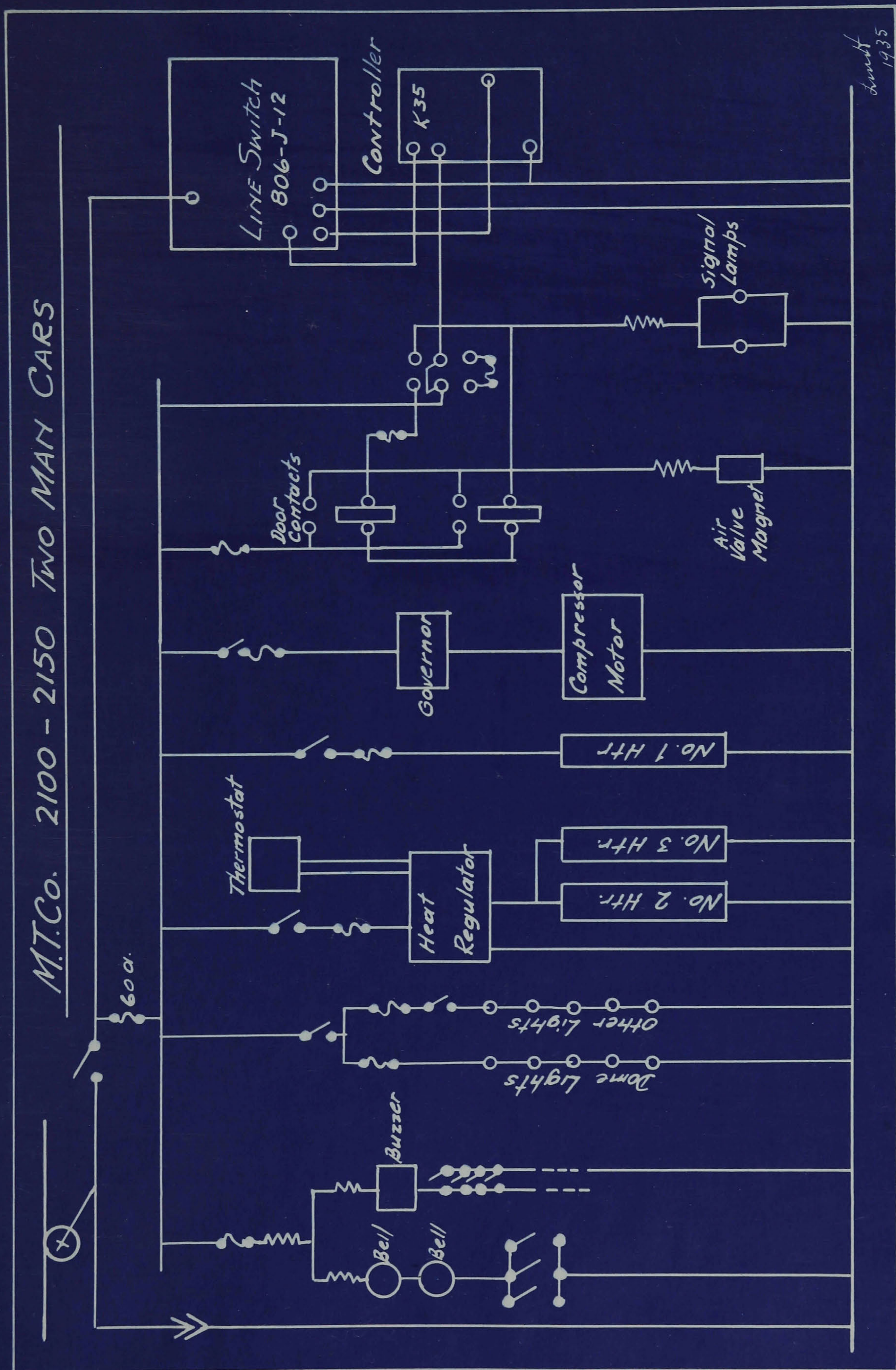
....

The circuits of Figures 6 and 8 are quite typical streetcar arrangements. They are the quantities effective at 600 volts d.c. and are not at all the impedances that would be present in the same circuit impressed with high frequency voltage. Calculation of such quantities is impossible so the writer conducted measurements to determine the high frequency characteristics of the street car as whole.

An oscillator (Appendix A) was set up in the rear window of the streetcar as shown in the photograph of Figure 15 In this position the oscillator was within five feet each of the trolley wheel and rail. Accordingly connections were made from the rail (not the metal body of the car!) and from the trolley wheel which was pulled down from the trolley wire. These leads came to am ammeter and pickup coil at the oscillator. The circuit is shown at the bottom of Figure 8B

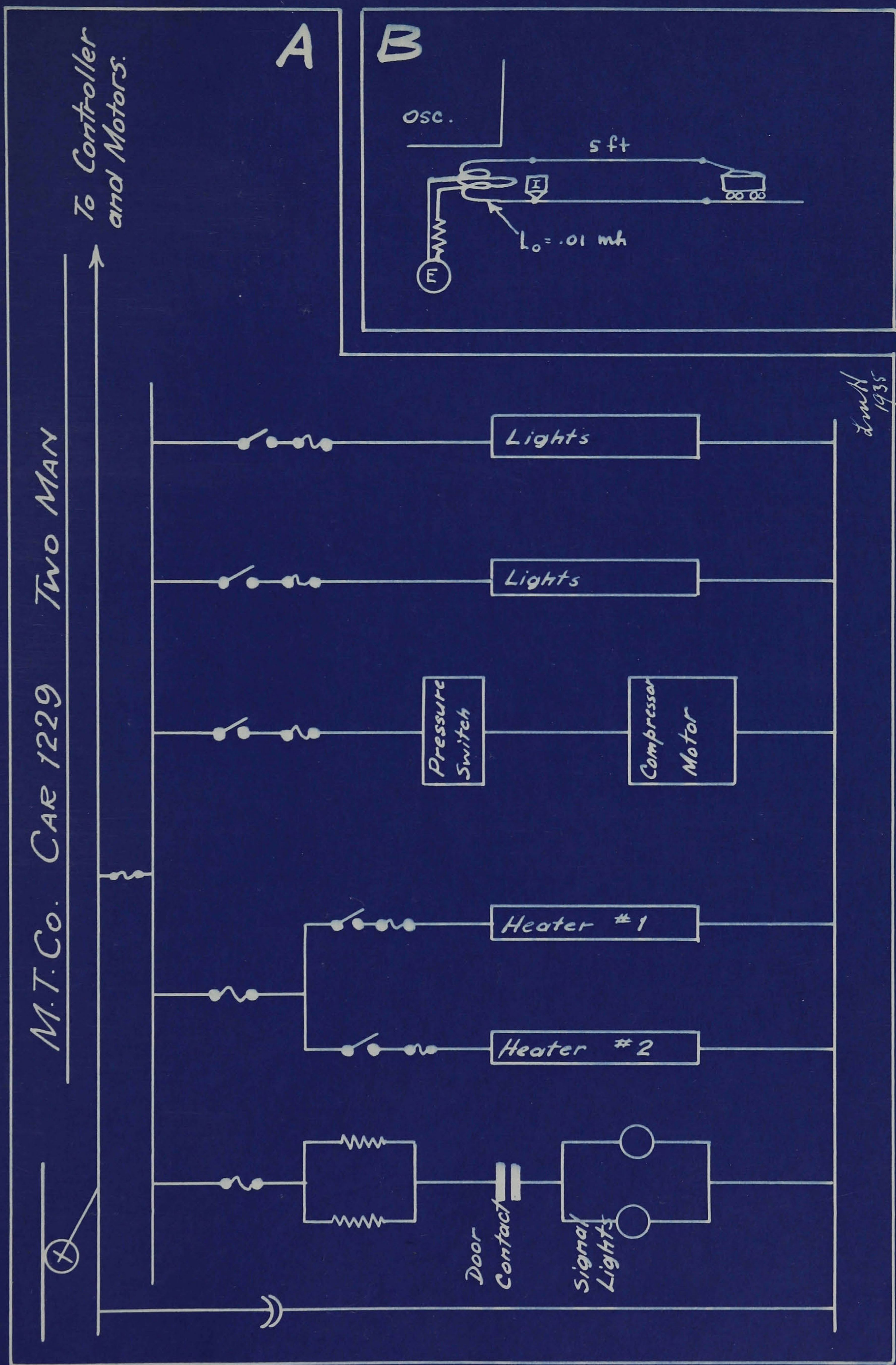
Keeping the R.F. voltage constant, the frequency is varied over wide limits and the current (ie admittance) is read. Figure 9 shows the characteristics of car 1229 of the Montreal Tramways System. It is noticed that

FIG. 6



M.T.Co. 2100 - 2150 Two Man Cars
Line Switch 806-J-12
Controller
K35
Signal Lamps
Door Contacts
Air Valve Magnet
Governor
Compressor Motor
No. 1 Htr
Thermostat
No. 3 Htr.
No. 2 Htr.
Heat Regulator
600a.
Other Lights
Dome Lights
Buzzer
Bell
Bell
1935

FIG. 8


A
B
osc.
5 ft
I
$L_0 = .01$ mh
E
To Controller and Motors.
M.T.Co. CAR 1229 TWO MAN
Lights
Lights
Pressure Switch
Compressor Motor
Heater #1
Heater #2
Door Contact
Signal Lights
1935

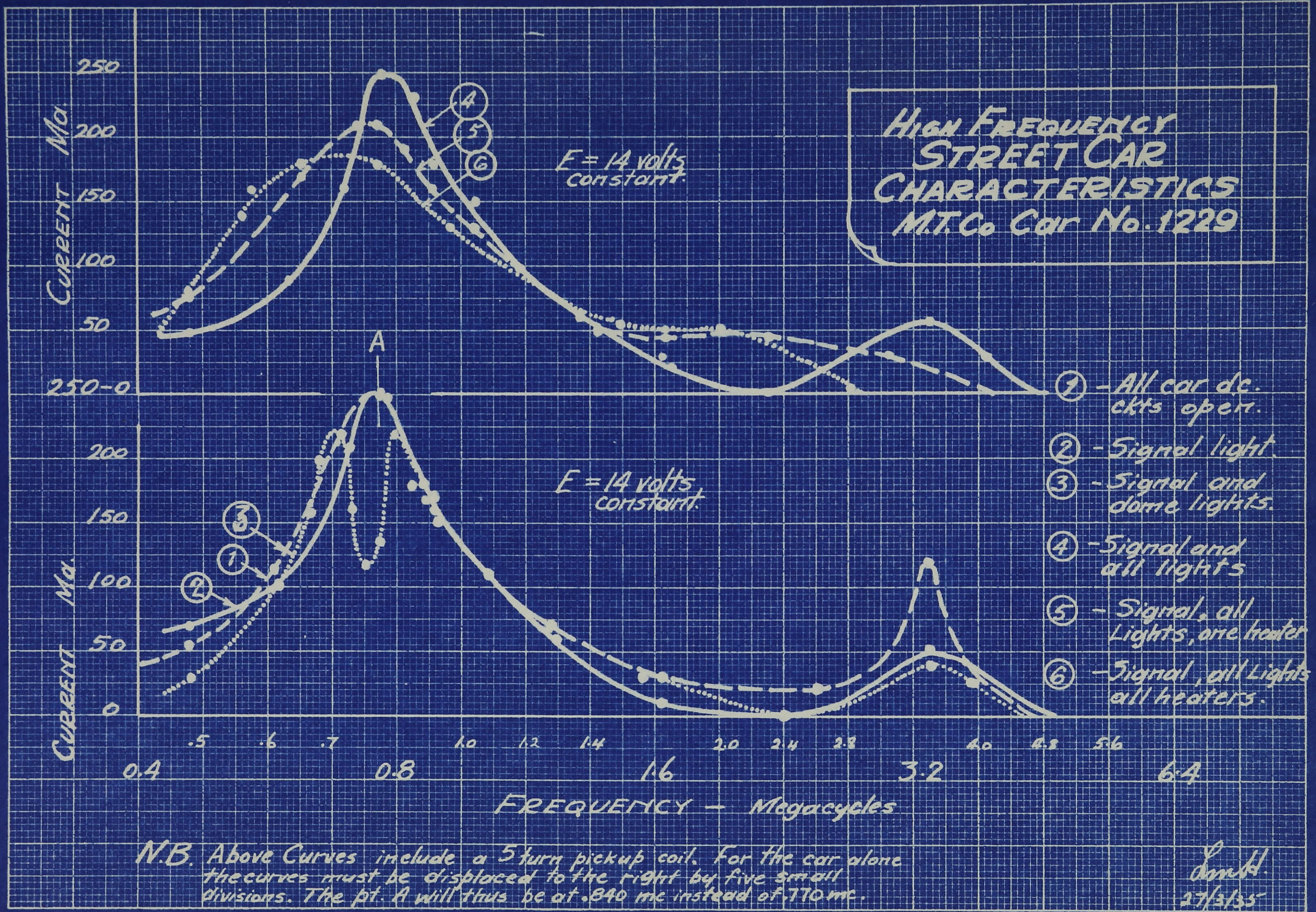

HIGH FREQUENCY STREET CAR CHARACTERISTICS M.T.Co Car No. 1229
E = 14 volts constant.
E = 14 volts constant.
A
CURRENT Ma.
CURRENT Ma.
250
200
150
100
50
250-0
200
150
100
50
0
.5
.6
.7
1.0
1.2
1.4
2.0
2.4
2.8
4.0
4.8
5.6
0.4
0.8
1.6
3.2
6.4
FREQUENCY - Megacycles
1 - All car dc. ckts open.
2 - Signal light.
3 - Signal and dome lights.
4 - Signal and all lights
5 - Signal, all Lights, one heater
6 - Signal, all Lights all heaters.
N.B. Above Curves include a 5 turn pickup coil. For the car alone the curves must be displaced to the right by five small divisions. The pt. A will thus be at .840 mc instead of 770 mc.
27/3/35

FIG. 9

a. The car has harmonic resonances characteristic of an elongated circuit.

b. The position of the resonance appears substantially independent of the circuit or circuits connected.

c. The height and flatness of the peaks depend to some extent upon the circuit connected but not appreciably.

d. The fundamental peak is in the middle of the broadcast band.

....

The only absolute values obtainable from these curves is the resistance, by dividing voltage (Appendix B) by current. To verify the rather unique method of measuring the voltage, the resistance was remeasured by the Substitution Half Current Method and the agreement shown in the table below is satisfying. It is also noticeable that the d.c. values are meaningless when considering radio frequencies.

TABLE II

Resistance of Car 1229

Method	Car on Open Circuit	Signal Only	Signal and 15 Lights	Signal and 30 Lights	Signal and 10 heaters and 30 lights	Signal and 15 heaters and 30 lights
D.C.Bridge	∞	1443	56	28	15	10
From Figure 775 Kc.	56	56	66	56	69	75
Half Current Method 775 Kc.	54	50	64	54	63	70
Net Average (less 10 for ammeter and 02 for leads)	44	40	54	44	53	60

A further test is required to give sufficient data for the effective Inductance and Capacity present. To do this the Capacity Substitution Method was successfully employed. The detailed values appearing below are averages of many readings.

TABLE III

Street Car Inductance and Capacity

Resonant Frequency mc.	Substitution Capacity uuf.	Car Capacity uuf.	Car Inductance uh.	Circuit
.725 1.135	--- 975	1300	27	Open Car
.730 1.135	--- 975	1300	27	Signal Only
.675 1.130	--- 975	1650	24	Signal 15 lights
.762 1.140	--- 975	1150	28	Signal 30 lights
.670 1.030	--- 975	1300	33	Signal 30 lights and 10 heaters
.590 1.120	--- 975	2300	22	Signal 30 lights and 25 heaters

This further indicates that one or more circuits added to a car do not alter its radio frequency characteristics appreciably.

....

Figure 7 is the characteristics of Car 2235, indicating the effect of adding various combinations of choke coils and condenser on the roof of the car when a given circuit was closed within the car. Table I, Chapter IV,gives the constants of the coils used.

The normal curve of car 2235 is similar to that of Car 1229 except that the first and third harmonic resonances are at 0.4 and 1.6 megacycles for the former car rather than at 0.8 and 3.2 megacycles for the latter car. The effect of adding the choke coil - condenser combination is simply that of superimposing its resonant frequency upon that of the car and the circuit as a whole acts as a band pass filter whose pass frequency is largely determined by the coil-condenser.

Summarizing these findings, one may say that the car has a resonant frequency in or near the broadcast band that is unaffected in position or size by the circuits, if any, that are connected in the car. Also the addition of choke coil-condenser combinations merely change the position of the resonances in the spectrum.

It must be remembered that this is strictly from an <u>external</u> point of view. That is, the quantities looking into the car circuit from the trolley wheel and rail are considered. As mentioned in the previous chapter, the car characteristics and coil-condenser effect may be quite different when viewed from a break in the controller circuit, for instance. But when considering circuit breaks at the trolley wheel, all one is

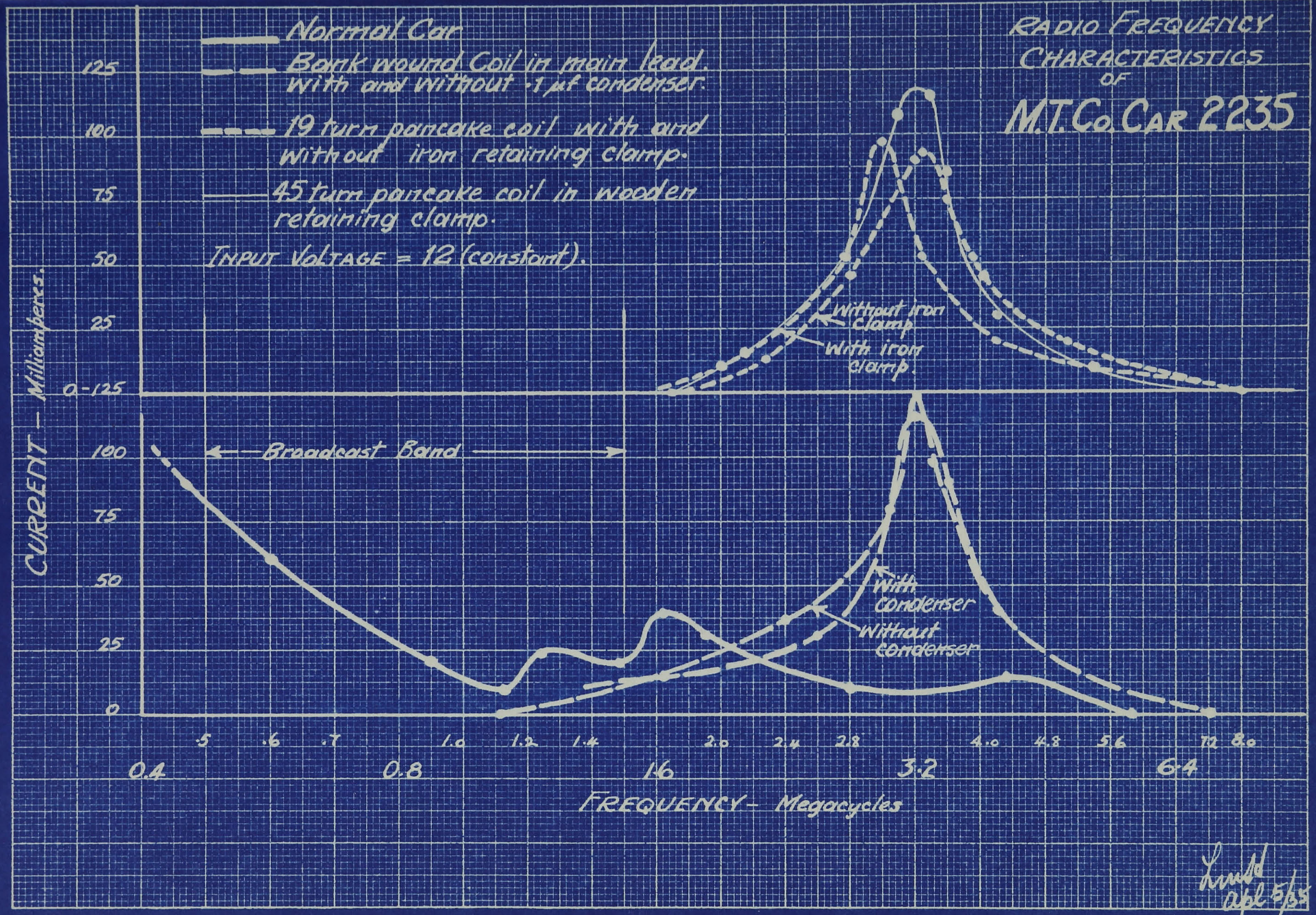

RADIO FREQUENCY CHARACTERISTICS OF M.T.Co. CAR 2235
Normal Car
Bank wound Coil in main lead. With and without ·1 μf condenser.
19 turn pancake coil with and without iron retaining clamp.
45 turn pancake coil in wooden retaining clamp.
INPUT VOLTAGE = 12 (constant).
Without iron Clamp
With iron Clamp
With condenser
Without condenser
Broadcast Band
CURRENT – Milliamperes.
125
100
75
50
25
0-125
100
75
50
25
0
.5
.6
.7
1.0
1.2
1.4
2.0
2.4
2.8
4.0
4.8
5.6
7.2
8.0
0.4
0.8
1.6
3.2
6.4
FREQUENCY – Megacycles
Apl 5/35

FIG. 7

interested in is the car circuit as a whole such as is imposed between trolley wheel and rail.

CHAPTER VI

The Overhead Trolley System

First, the overhead system will be considered in relation to a perfect return path. That is, the rails and ground will form a perfectly conducting, flat plane. The actual return circuit conditions may be considered separately.

....

Any distribution system possesses distributed resistance, inductance and capacity. The values of these arguments change with the type of current flowing, ie, its periodicity and distribution over the conductor's cross section and along its length. The ideal method would be to set up one's apparatus in the middle of the street and measure these constants directly as one would do for an antenna or a transmission line. Such a procedure is obviously impossible. Traffic cannot be held up due to 'killing' the trolley system or to the presence of the investigator and his apparatus in the thoroughfare. Also power cannot be obtained for the instruments. And what is the biggest difficulty is that the overhead system of Montreal is all tied together through underground and overhead feeders to the substation bus bars. A measurement in one place would, then, include the whole system and would not be representative of the overhead trolley wire. For instance, a capacitance measurement near the corner of St. Denis and Belle Chasse would include the capacity of a quarter mile of underground cable, ten times that of the neighboring overhead system.

Consequently, with direct measurement prohibited, two other methods of determination were employed.

1. Computation

2. Method of Models

The latter method proved to be of such power that it will be discussed in the following chapter. Computations were made as follows.

A section of the Montreal Tramways System was selected for study. The branch chosen is the section of line from Montreal East Substation out to Bout de L'Ile together with a spur line down to Reparation Chapel. The section is as simple as possible in configuration, yet contains every type of construction used through the system. In addition the system is flanked by telephone and power systems of many sorts and above all tramcars on that section are known definitely to cause interference. In fact, Car 1229 referred to in the previous chapter is of the type used in summer upon this line.

The types of construction represented in this section are

1. Single 4/o trolley, feeder, wood poles.

2. Single 2/o trolley, no feeder, wood poles.

3. Double 4/o trolley, feeder, steel poles. Distances, configurations and details of the general layout are made self explanatory in Figures 10 and 11 . Conductor specifications are as follows.

TABLE IV

Conductor	Area Circ.mils.	Diameter Inches	Diameter Cm.	Resistivity D.C. Ω/ft.
4/o Trolley	211,600	0.460	1.168	48.1×10^{-6}
2/o Trolley	133,000	0.365	0.927	76.5×10^{-6}
Feeder Cable	500,000	0.814	2.065	21.6×10^{-6}

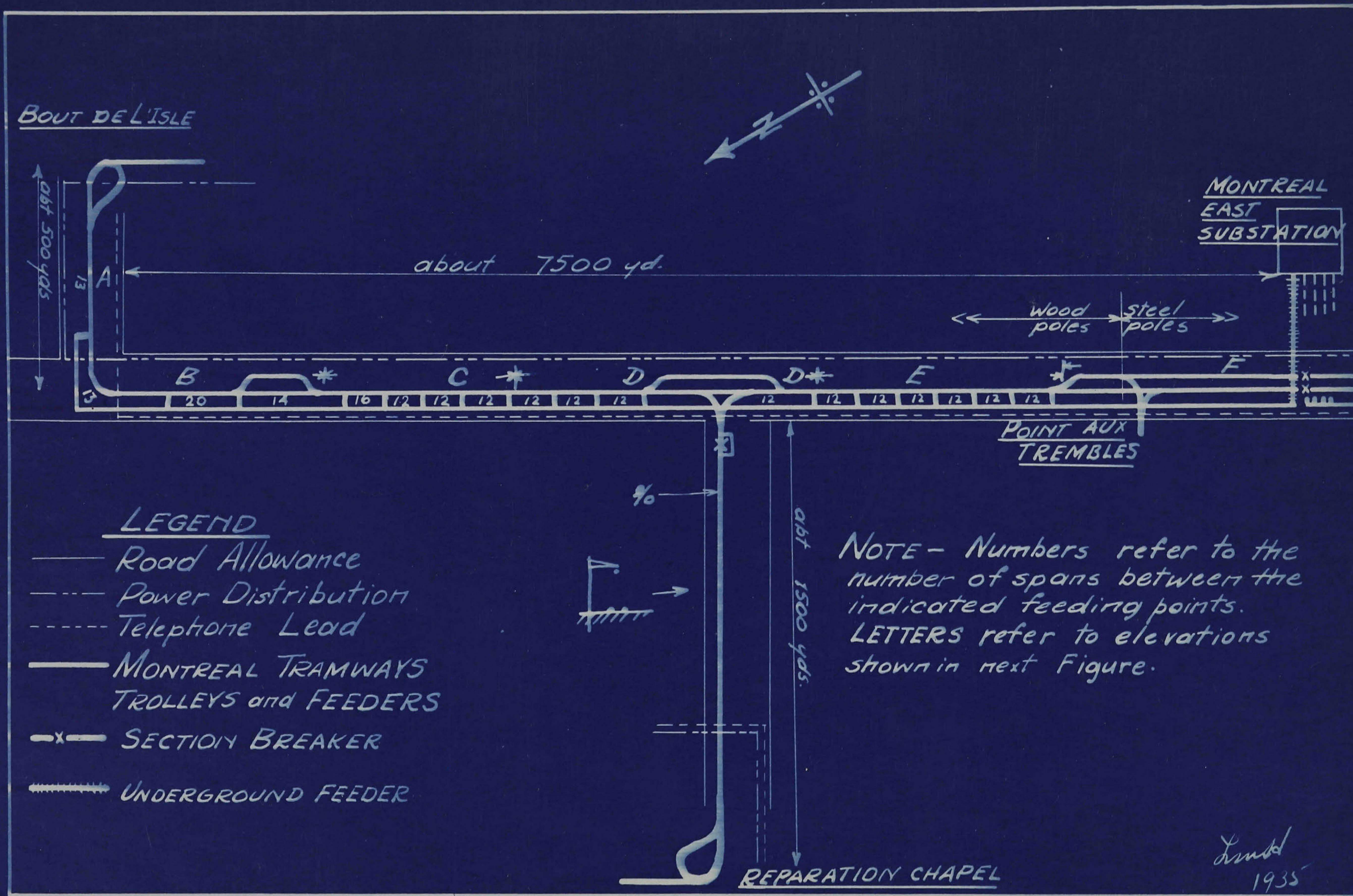
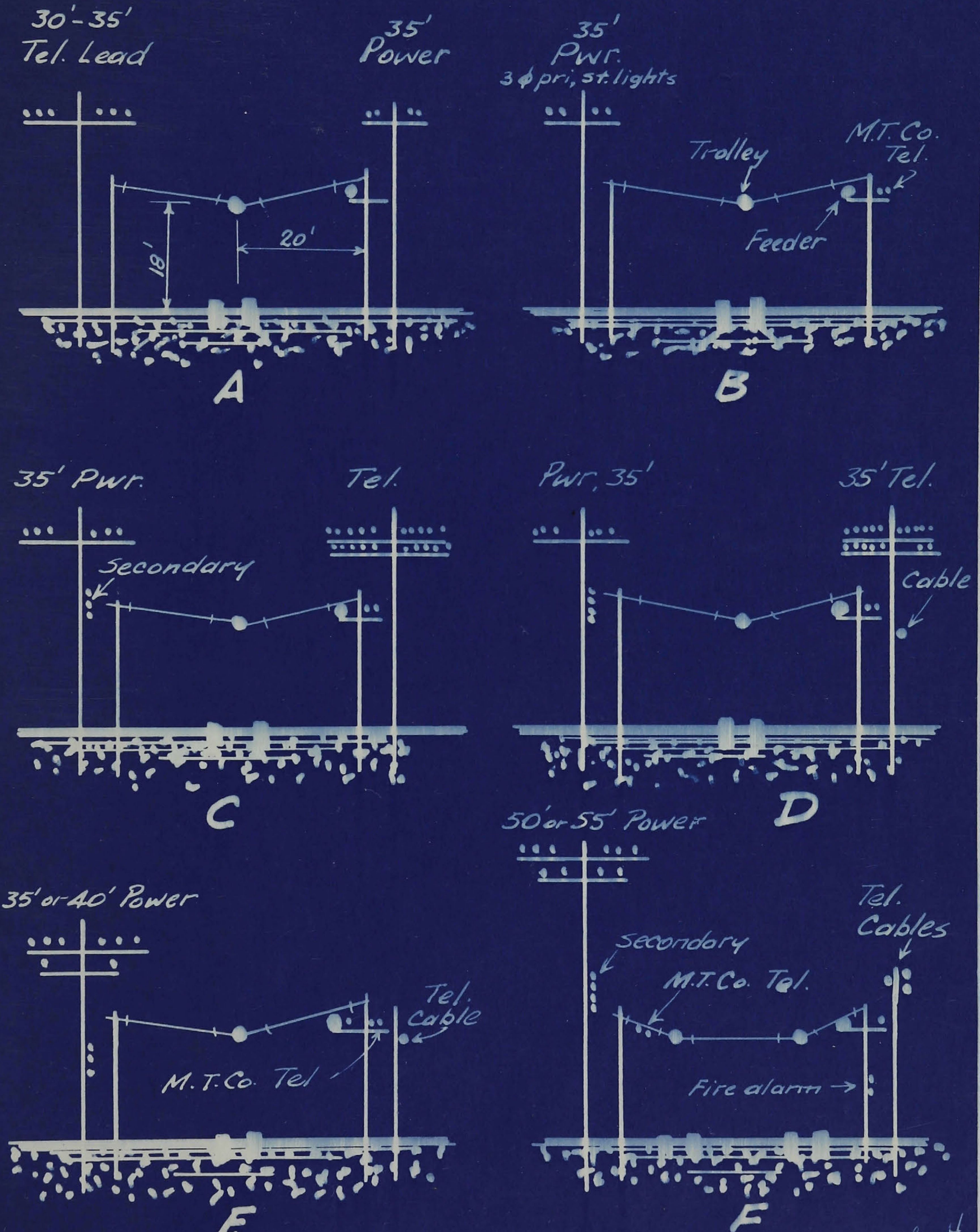

BOUT DE L'ISLE
N
MONTREAL EAST SUBSTATION
abt 500 yds
about 7500 yd.
wood poles
steel poles
A
B
C
D
D
E
F
13
13
20
14
16
12
POINT AUX TREMBLES
abt 1500 yds.
LEGEND
Road Allowance
Power Distribution
Telephone Lead
MONTREAL TRAMWAYS TROLLEYS and FEEDERS
SECTION BREAKER
UNDERGROUND FEEDER
NOTE - Numbers refer to the number of spans between the indicated feeding points. LETTERS refer to elevations shown in next Figure.
REPARATION CHAPEL
1935

FIG. 10

FIG. 11

ELECTRICAL CIRCUITS. NOTRE DAME E.



All views facing South-West (downtown)

LmH
1935

Consider the single 4/o trolley with feeder and wood poles, the type used throughout the greater length of the spur. Its computation will be sketched hereunder.

A. Inductance

The system is virtually a two wire flat top and any of the usual formulae may be applied. The results from various forms are in substantial agreement. That from Morecroft[20] is

$$L = \frac{L' + M}{2}$$

where L' is the inductance of one conductor
M is their mutual inductance

given by

$$L' = \left[2 \log_e \frac{2h}{r} + \frac{1}{4}\right] 10^{-9} \quad hy/cm.$$

$$M = \log_e \left(\frac{d^2 + 4h^2}{d^2}\right) 10^{-9} \quad hy/cm.$$

where h = height above ground in cm.

d = separation of conductors in cm.

r = conductor radius in cm.

Numerical evaluation gives

$L = 0.25 \times 10^{-3}$ mh. per foot

This assumes uniform current distribution and perfect ground plane. The effect of the current distribution non-uniformly is given by Rosa and Grover.[21] By the use of their tables and formulae the percentage error in the above, or static, value over that at 1000 kilocycles is given by

$$\frac{\Delta L}{L_{dc}} = -0.035 \quad \text{or} \quad -3.5\%$$

This is quite negligible in these calculations, and represents an average error. The maximum shown in Grover's examples is 8%.

B. Capacity

Here again, some four or five formulae were applied with agreeing results. A typical one is quoted by Tykociner[23] is

$$C = \frac{nk}{2\log_e \frac{2^n h^n}{r(nd)^{n-1}} + \frac{n-1}{3}\left(\frac{nd}{2h}\right)^2} \quad \mu\mu f/ft.$$

where n = number of wires in flat top (2)

K = units conversion factor.

Upon evaluation this gives

C = 4.45 uuf per foot

The correction for high frequency is indistinguishable where there are no standing waves. In the latter case, the capacity may be reduced to nearly half depending upon the pattern of the waves.

C. Resistance

The increase in resistance due to frequency is given in the form of curves by Morecroft[20] and tables by Rosa and Grover.[21] Using a resistivity of 10.4 ohms per mil-foot these formula may be combined into a relation like

$$R_{ac} = 0.165 \times 10^{-6} \frac{l}{r}\sqrt{f}$$

where l = length of conductor in inches

r = radius of conductor in inches

f = frequency in cycles per second

Otherwise it may be more convenient to use

$$\frac{R_{ac}}{R_{dc}} = 0.0455\sqrt{f}$$

This gives the numerical values of Feeder resistance at

1000 kc = 0.955×10^{-3} ohms per ft.

4/o trolley resistance at

1000 kc = 2.19×10^{-3} ohms per ft.

The resistance of the two in parallel then becomes

$R = 0.665 \times 10^{-3}$ ohms per foot

Applying these formulae to all types of system, one may summarize the results as follows:

TABLE V

Type	Inductance mh/ft	Capacity uuf/ft	D.C. Resistance ohms/ft	1000 k.c. Resistance ohms/ft
Single 4/o and feeder	0.25×10^{-3}	4.45	0.015×10^{-3}	0.66×10^{-3}
Single 4/o	0.475×10^{-3}	2.245	0.048×10^{-3}	2.19×10^{-3}
Single 2/o	0.488×10^{-3}	2.18	0.076×10^{-3}	3.46×10^{-3}
Double 4/o and feeder wood poles	0.20×10^{-3}	6.15	0.012×10^{-3}	0.51×10^{-3}
Double 4/o and feeder steel poles	0.20×10^{-3}	6.67	0.012×10^{-3}	0.51×10^{-3}

It is noticed in the above table that the presence of steel poles makes some difference in the capacity. This comes from the consideration that at the supporting spans the following capacitances exist.

Ear	-	100 uuf.
Pin Insulator	-	25 uuf.
Strain Insulator	-	15 uuf.

The trolley wires in Montreal being triple insulated on each side makes the capacity to ground equal to

For Feeder	-	25 uuf.
For Trolleywire	-	14 uuf.

Since the supporting spans are about 75 feet apart, one must add 0.52 uuf per foot to the trolley wire capacitance to take care of the insulation at the supporting spans. Strictly speaking this is a lumped capacity, but in view of its small size and the fact that there are over 75 lumps per mile, one can call it distributed with ease.

....

The value of these constants lies in the fact that one can, with them, determine the behavior of the line under all conditions. Only two of the usual transmission characteristics are of interest here, ie, the distance attenuation constant and the characteristic impedance. They are respectively

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}}$$

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

Since $WL \gg R$ and $WC \gg G$ (the latter being assumed zero) these expressions simplify to

$$Z_o = \sqrt{\frac{L}{C}}$$

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} = \frac{R}{2Z_o}$$

also $$f = \frac{1}{4s\sqrt{LC}}$$

the natural period of the circuit extended over 's' feet, may be of interest. One may take S = 900 ft., the approximate distance between feeder taps and assemble the following table:

TABLE VI

Type	Attenuation Constant	Characteristic Impedance	Fundamental Natural Frequency
Single 2/o	4.64×10^{-6}	473	269 k.c.
Single 4/o	2.38×10^{-6}	460	268
Single 4/o and feeder	1.40×10^{-6}	237	263
Double 4/o wood poles and feeder	1.42×10^{-6}	180	250
Double 4/o steel poles and feeder	1.48×10^{-6}	173	240

This affirms the observation of Steinmetz[8] that the natural period of an elongated circuit depends only upon the length. Size, number, height and spacing make no substantial difference.

To grasp the significance of these figures consider the 1000 kc. component of a voltage impulse. If it has an initial value of one volt it will travel 29 miles on the Single 2/o line or 90 miles on the double 4/o trolley with feeder and steel poles before it is diminished to one half a volt. When it has reached one tenth of a volt it has travelled 115 or 360 miles on the two systems respectively. These distances may be in a straight course if such exists or they may be made up of multitudinous reflections and transmissions through line discontinuities.

Due to the finite impedance of the ground, these attenuation constants are undoubtedly low, yet the cumulative effect of reflections noticed in a previous chapter is not considered here.

Again, take the above case of the double trolley reducing the wave to 10% of its initial value in 360 miles. If the car is 10 miles from the open end of the line, the wave will make 36 traverses of the distance and the time required will be about one five hundredth of a second. This means a modulation frequency well within the audible range. And since the natural frequency of the line depends only upon its length, the car has only to travel a short distance along a straight section of track before the natural frequency of the line or some of its harmonics have swept through the complete radio spectrum.

CHAPTER VII

Model System

After all, Chapter VI is merely a mathematical corroboration of a serious interference condition that is no news to anybody, certainly to no receiver owner between Montreal East and Bout de L'Ile. To extend one's computations to include the effects of metal objects, wet objects, telephone leads, power systems, trees in the field of the trolley system, is a formidable business quite beyond the scope of an engineer - or the writer. However, an ingenious method of investigation proposed at some length by Tykociner[23] is capable of solving these and many other problems concerning this interference question.

The idea involved is to construct a model of the system reducing all dimensions by a chosen factor, say 'p'. It can then be shown by substitution the following relations exist. The subscript 'm' refers to the model and 'a' refers to the actual system.

$$C_m = \frac{C_a}{p}$$ (Capacity)

$$L_m = \frac{L_a}{p}$$ (Inductance)

$$R_m = R_a\sqrt{p}$$ (Resistance)

$$S_m = S_a$$ (Radiation Resistance)

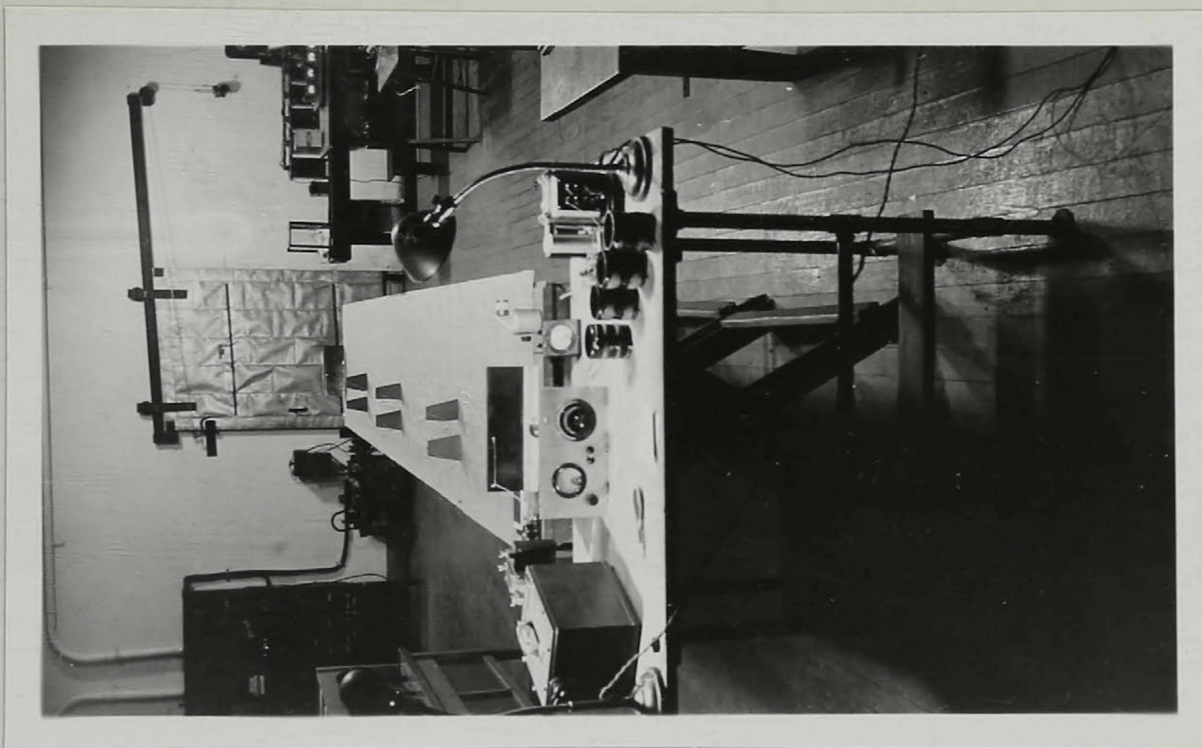
$$f_m = p f_a$$ (Fundamental Natural Period)

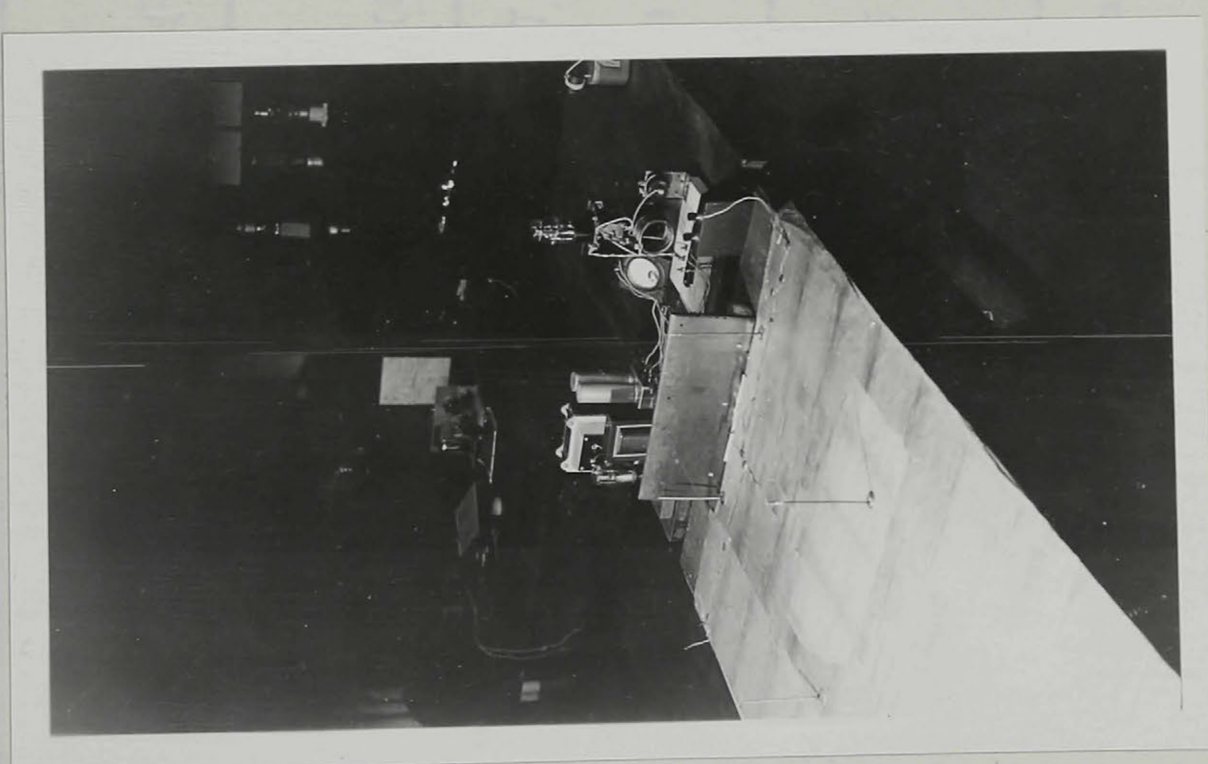
Accordingly a model of the trolley system was constructed for p = 50 and a 900 foot section (the distance between feeder taps) represented. It is shown in Figures 19, 21 and has the following dimensional values:

Length	18.17 ft.	=	555. cm.
Height of trolley	4.32 in.	=	10.97 cm.
Trolley to feeder	4.80 in.	=	12.20 cm.
Diameter trolley 4/o	.010 in.	=	.025 cm.
Diameter trolley 2/o	.007 in.	=	.018 cm.
Diameter feeder	.0162 in.	=	.0412 cm.

The ground plane was of tin foil three feet wide. This, in the case of Figure 21, was extended four feet further on each side by copper gauze. By use of specially arranged oscillators the characteristics of this model were measured at its fundamental, third and fifth harmonics, which, for the model, are 11, 33 and 55 megacycles, fifty times the values of the actual system. The details of such apparata and measurements are contained in Appendices A and B so the results only need be tabulated here. They form a complete check upon the calculations and upon the method of model investigation in general.

FIG. 19





Model Constants, excited with fundamental frequency, C.W.

Quantity	Single 2/o Trolley no feeder wood poles	Single 4/0 trolley no feeder wood poles	Single 4/o trolley with feeder wood poles	Double 4/o trolley with feeder wood poles	Double 4/o trolley with feeder steel poles
C eff uuf	35	37	70	90	99
C static uuf	64 (41)	64 (42)	92 (84)	113 (103)	119 (110)
L eff uh	53	51	26	22	22
L static uh	72 (89)	72 (80)	48 (45)	44	44
fo (incl. ammeter) mc.	11.67	11.64	11.69	11.29	10.85
fo (no ammeter) mc.	11.94	11.80	12.22	11.90	11.45
R total (incl. Sm and ammeter)	4.15	3.25	1.25	0.90	0.98
Res. ammeter = .3					

N.B. Bracketed values are calculated checks. All others are measurements.

The above table chiefly corroborates the calculations made in the previous chapter of Inductance, Frequency and capacity. When reduced to the same units for the same system, the variation between calculations and model measurements is of the order of 5%.

The measurements of resistance require further analysis. The value of resistance measured on the model includes the radiation resistance, the coupled impedance of objects in the induction field, the dielectric losses in addition to the ohmic resistance. For the case of the single 4/o trolley with feeder and wood poles the resistance measured at the following frequencies is

11.7 megacycles, 0.95 ohms

34.5 megacycles, 2.95 ohms

58.4 megacycles, 1.05 ohms.

To properly interpret this result one would have to divide the resistances into their component parts for each frequency. This was not considered of sufficient value to warrant the time and trouble of analysis because one knows the resistance, even in its greatest value, is too low to give any attenuation worthy of close analysis and the radiation component varies with the height and frequency as in any other antenna.

Two factors, however, did require experimental verification in the opinion of the writer. They are firstly, an investigation of the seriousness of the cumulative effect caused by a travelling wave suffering reflections and refractions as noticed in Chapter III, Figure 3 , and secondly, an investigation of the effect of foreign objects and circuits in the field of radiation and induction.

The two following chapters will consider these problems in turn.

CHAPTER VIII

Artificial System

The model as constructed only represented 900 ft. of trolley system. To study the wave propagation, the whole system, complete with its discontinuities of type and configuration, is necessary. At a scale of p = 50 this would mean tremendous space for even the model. So one had the alternative of reducing the scale or constructing a lumpy equivalent. As will be shown later (Chapter X) the former would be the best alternative, but at that time the writer chose the latter.

It is well known that a transmission line may be completely and accurately represented in its behavior at one frequency by properly chosen lumped circuit elements. That it might be extended to cover the range of frequencies required in this problem with sufficient accuracy was the writer's desire and qualified accomplishment.

The construction was chiefly empirical, the usual equivalent π formulae proved powerless at 12 megacycles. Rather than make the artificial system equivalent to the actual system, it was made equivalent to the model in order that the model could be inserted at any place in the lumpy system to give greater detail or to make radiation measurements which, of course, cannot be made with a lumped system. To simplify the process, the five types of line were grouped to three types as shown in the following table. This table shows the average values from the model measurement and the corresponding values from the measurement of a single π section in its final form.

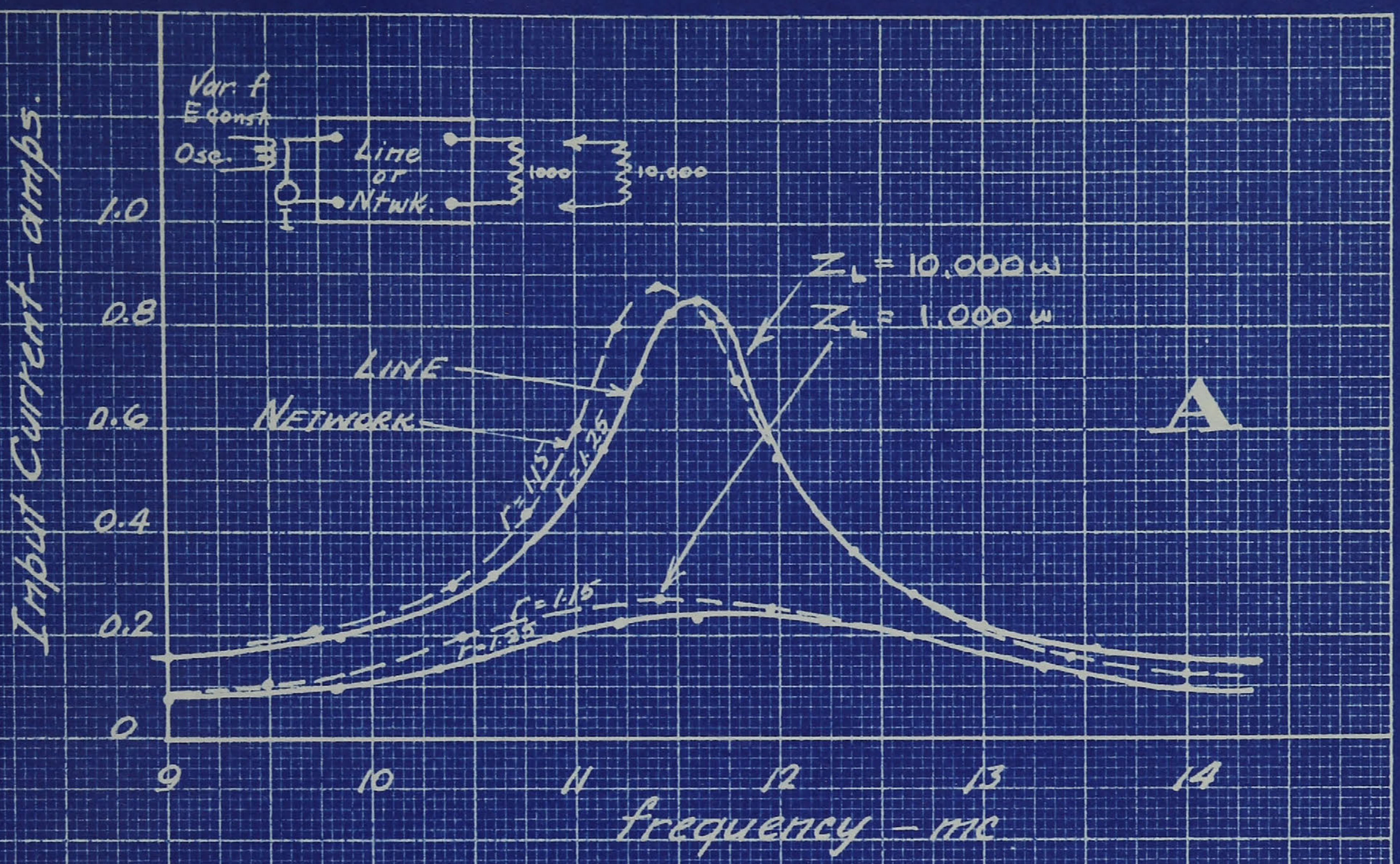
TABLE VIII

	Double 4/o Trolley with feeder wood or steel poles		Single 2/o or 4/o trolley on wood poles		Single 4/o trolley with feeder on wood poles	
	Model	Lumps	Model	Lumps	Model	Lumps
C eff.	95		35		70	68
C static	115	125	65	55	92	95
L eff.	2.2		5.2		2.6	
L static	3	3.7	8	8.5	4	4.5
fo	11.0	11.2	11.6	11.7	11.7	11.5
R total	1.0	0.98	3.7	4.0	1.25	1.25

The series coil in the case of the single 4/o trolley with feeder was composed of 13 turns of #29 wire d.s.c. wound on a stiff paper form 1-1/8 inches in diameter and spaced to occupy a length of 1-3/8 inches. The other types were similar. The schematic layout is shown in Figure 14 and the physical arrangement in Figure 15 . The length of the leads proved to be a critical matter in so far as resistance was concerned. The first section tested for complete equivalence had a resistance of 1.15 ohms rather than 1.25 as was required. The effect is demonstrated in the following curves. The matter was corrected in the final construction by lengthening the leads by 1-1/2 inches!

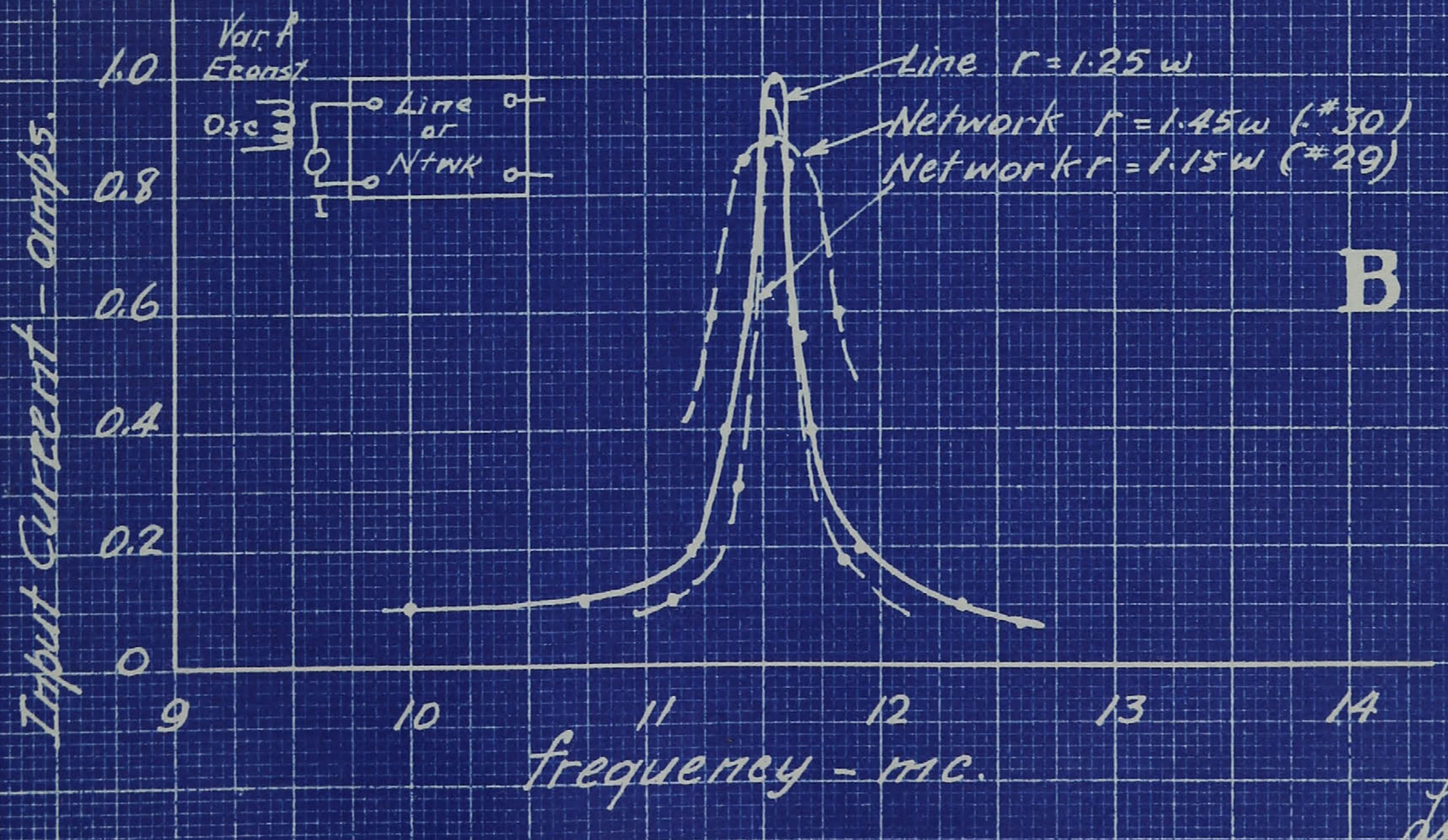
Exhaustive tests to prove or disprove the equivalence of the model and the lumped section were then made. The reactions of the line and network were observed at the output for given imput conditions and the reactions of each at the input were observed for given output conditions all over a wide frequency range. The results are plotted in Figures 12 and 13 . These curves demonstrate the near approach of the network to the model line. When the resistance of the network was raised to its proper value as mentioned above, the discrepancy between the line and network curves was lessened. In any case this demonstrates that a lumped system can be made to simulate a distributed one over a very wide band of frequencies. The limit is reached however, when the distributed system approaches its third harmonic resonance at which point the network fails to follow.

FIG. 12



COMPARISON OF LINE and NETWORK INPUT CONDITIONS

See P.



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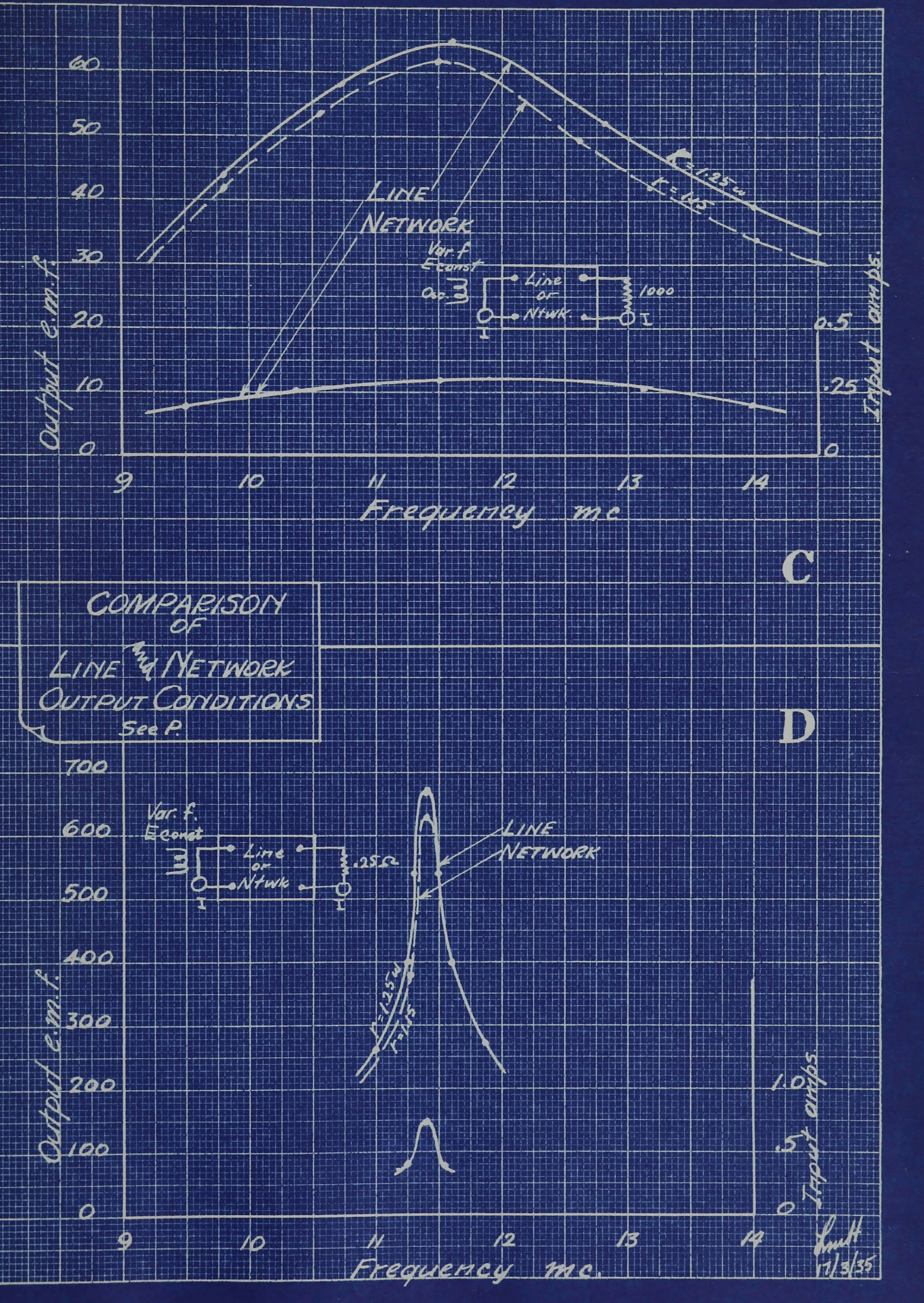
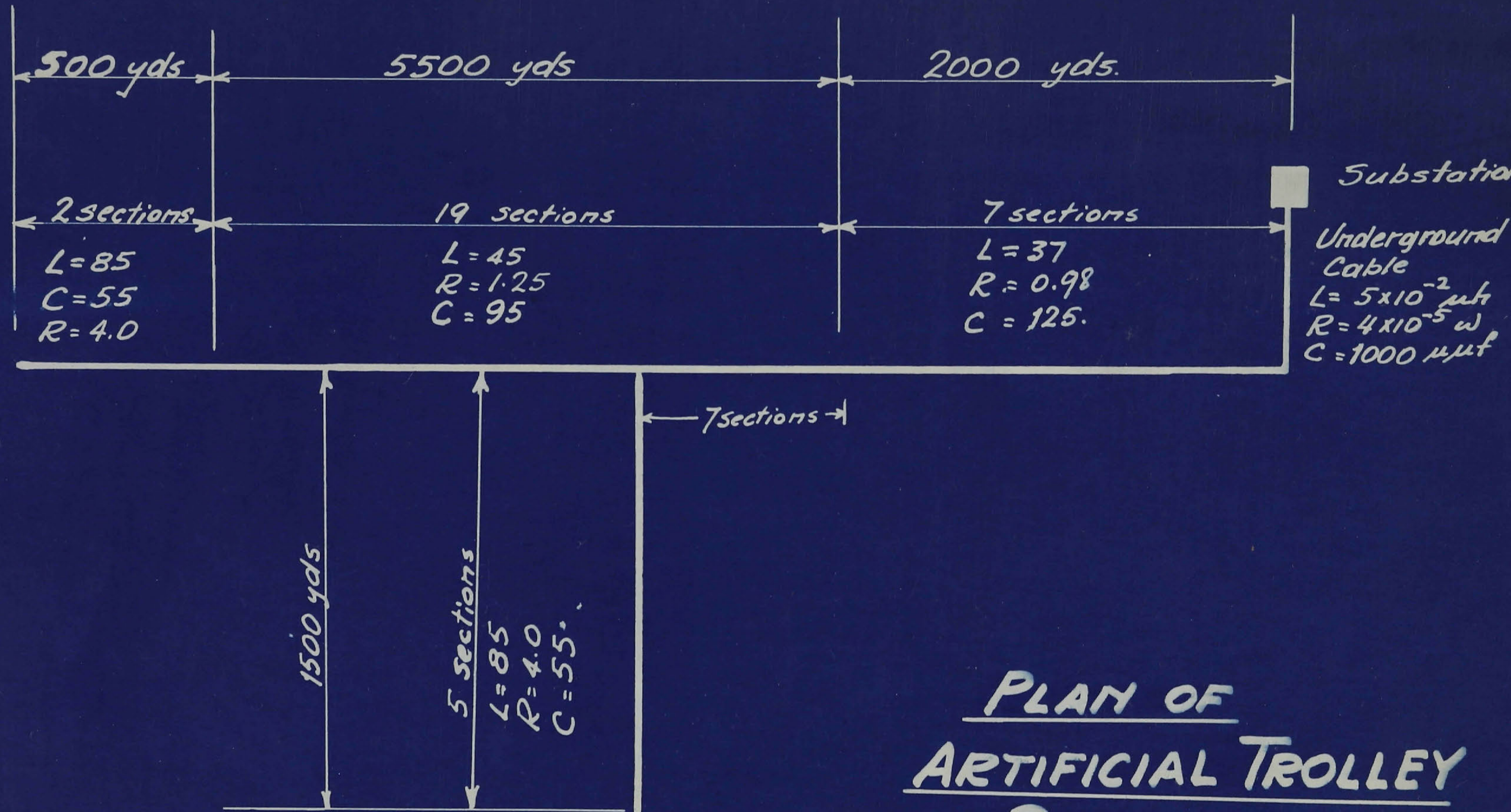
13/3/35

FIG. 13



LINE
NETWORK
Var. f
E const
Osc.
Line or Ntwk.
1000
I
r=1.25 ω
r=1.15
Output e.m.f.
Input amps.
Frequency mc
C
COMPARISON OF LINE and NETWORK OUTPUT CONDITIONS
See P.
D
Var. f.
E const
Line or Ntwk
.25Ω
LINE
NETWORK
r=1.25 ω
r=1.15
Output e.m.f.
Input amps
Frequency mc.
17/3/35



PLAN OF ARTIFICIAL TROLLEY SYSTEM.

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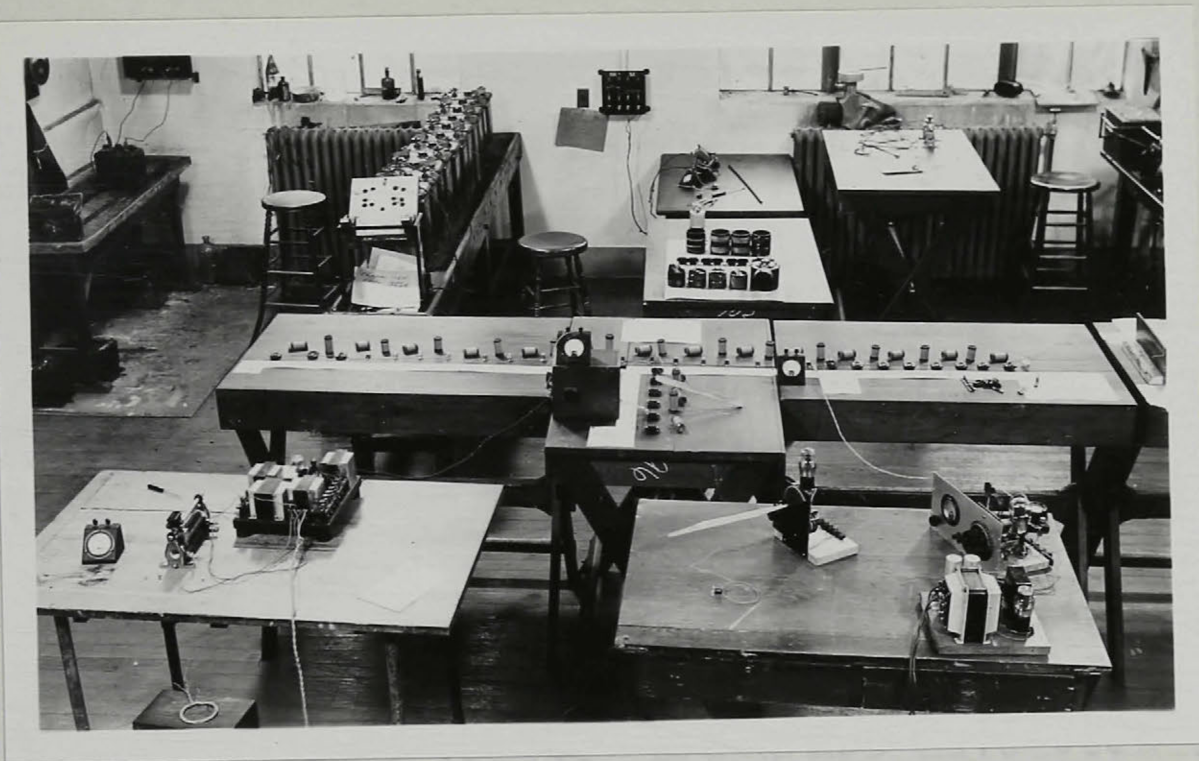
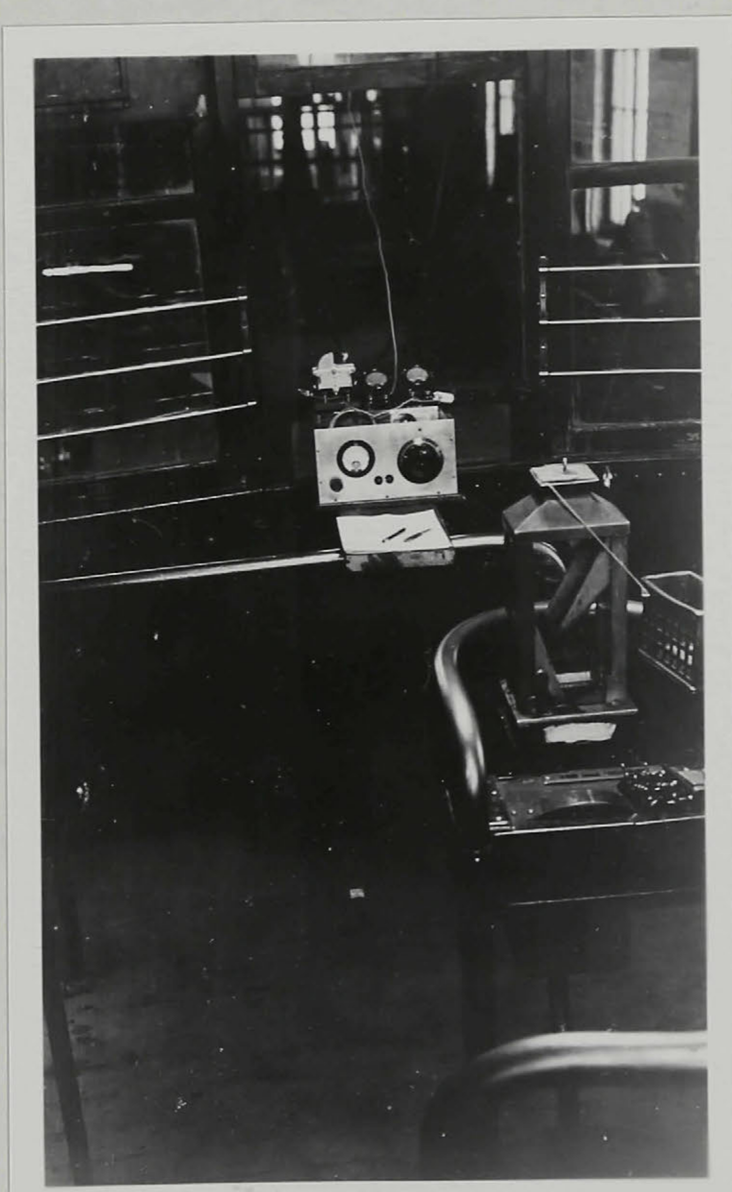
FIG. 14

FIG. 15



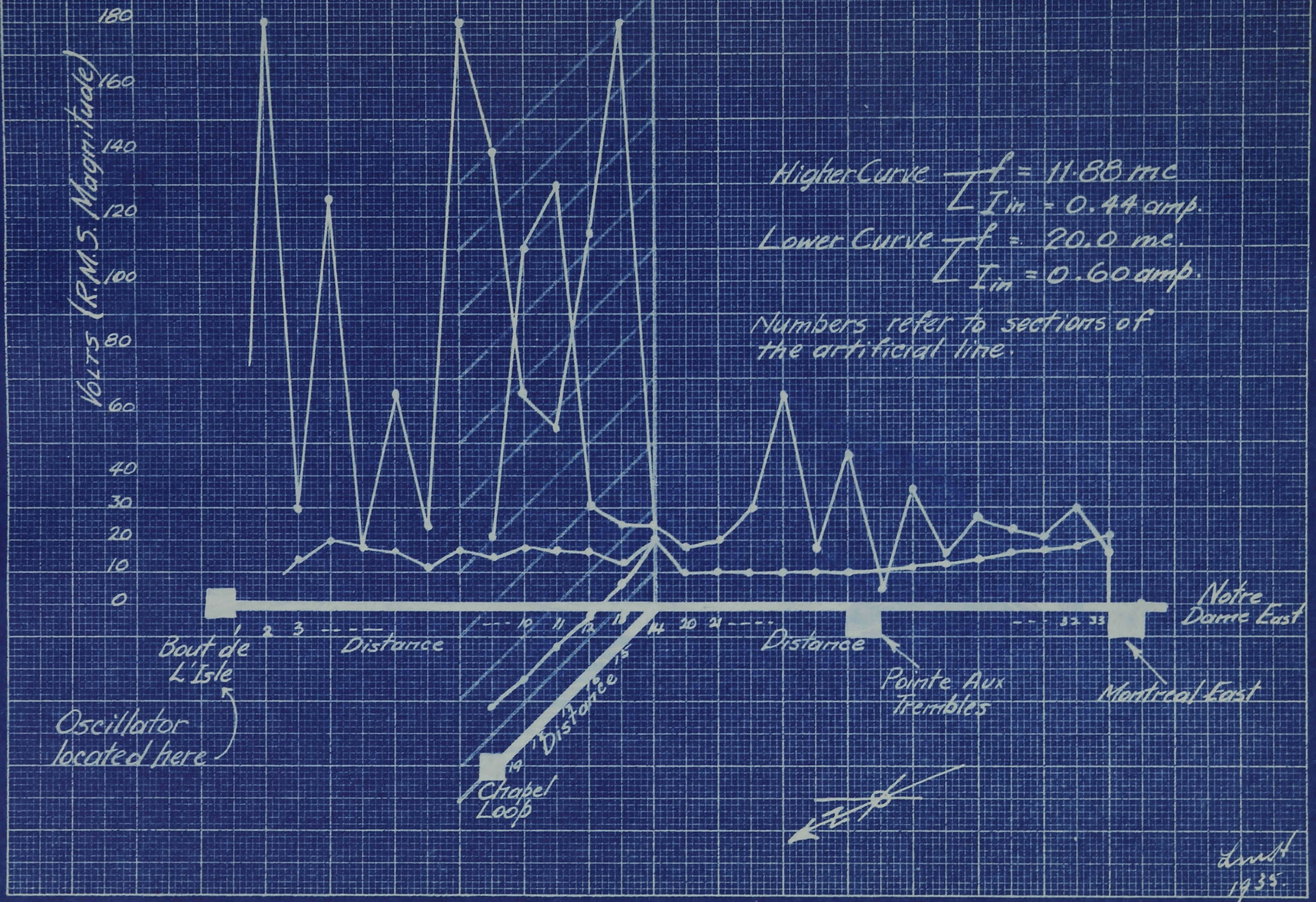


Having constructed the artificial system and determined its capabilities and limitations, it is now possible to verify the effect of discontinuities upon the wave travel. To investigate the travel of a twelve magacycle impulse wave is a formidable, though quite possible, task. It is much easier, however, to excite the line with Continuous voltage and observe at leisure the wave pattern. This yields sufficient information to satisfy the purpose.

Figure 16 shows the voltages at various points along the line in response to voltage at the Bout de L'Ile end of the line. The oscillator voltage could not have been over 30 when delivering such a current into that impedance. The bizarre nature of the voltage distribution together with the actual magnitudes reached are astounding. To obtain a smooth curve between the points plotted, one would have to insert the model between each section in turn and measure voltages along it by small intervals. This, together with many more determinations similar to this curve and those following were performed by the writer. Similar results to those of Figure 16 were obtained for various positions of the oscillator.

Figures 17 and 18 represent the same phenomenon occurring under frequency variation. The sawtooth nature of the input impedance may be due to irregularities of the lumps or to the variation of the standing wave pattern, or both. The weird nature of the voltage pattern at distant points is also very evident.

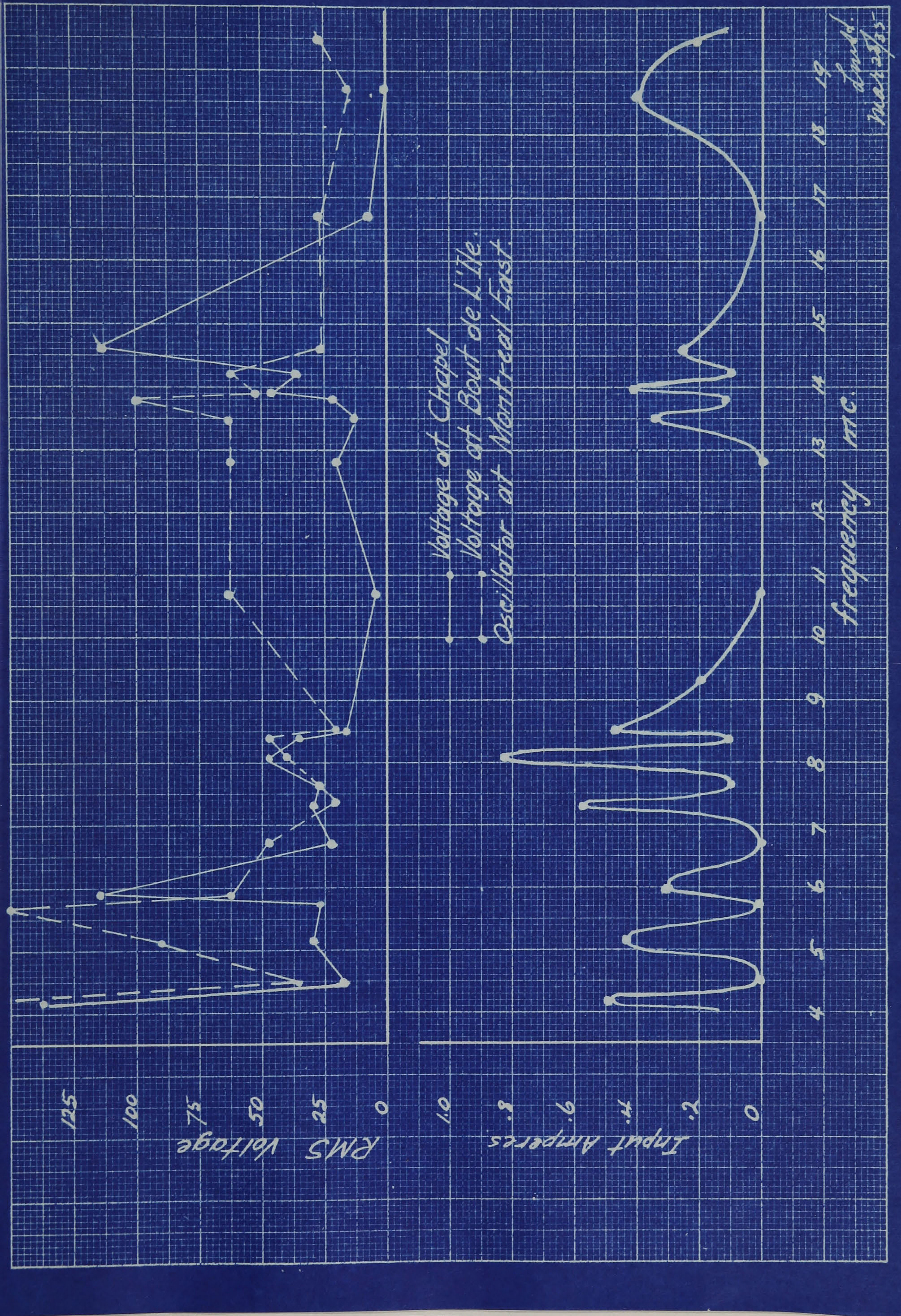
At any rate it leaves no doubt in one's mind concerning the possibility of reflections and refractions producing enormous voltages of a virtually indeterminant nature quite beyond the scope of any directive antenna to analyse.



Volts (R.M.S. Magnitude)
180
160
140
120
100
80
60
40
30
20
10
0
Higher Curve $f = 11.88$ mc
$I_{in} = 0.44$ amp.
Lower Curve $f = 20.0$ mc.
$I_{in} = 0.60$ amp.
Numbers refer to sections of the artificial line.
1 2 3
Distance
10 11 12 13 14 20 21
Distance
32 33
15 16
Distance
19
Bout de L'Isle
Oscillator located here
Chapel Loop
Pointe Aux Trembles
Notre Dame East
Montreal East
1935.

FIG. 16

FIG. 17



Voltage at Chapel
Voltage at Bout de L'Ile.
Oscillator at Montreal East.
RMS Voltage
125
100
75
50
25
0
Input Amperes
1.0
.8
.6
.4
.2
0
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
frequency mc.

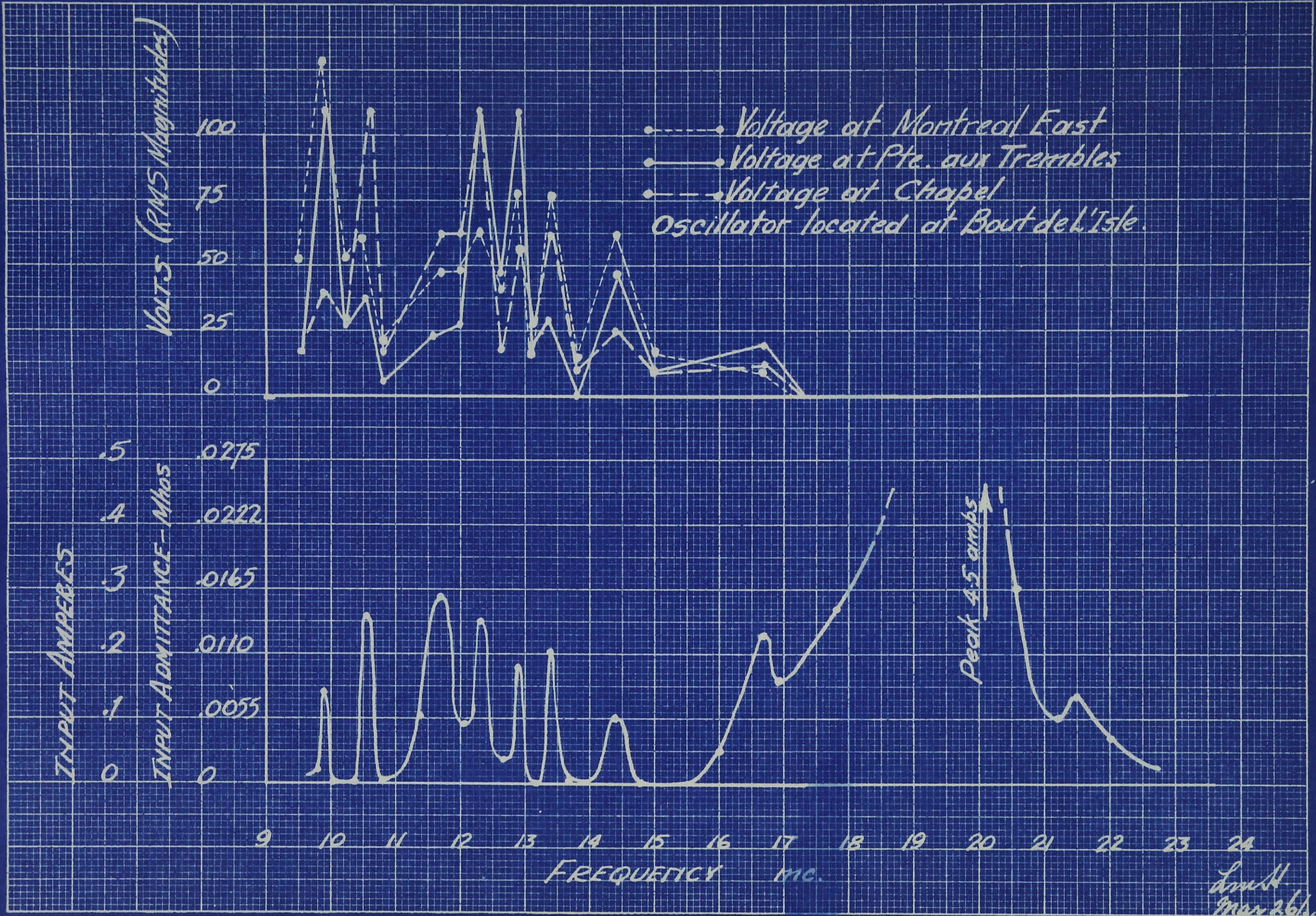

Voltage at Montreal East
Voltage at Pte. aux Trembles
Voltage at Chapel
Oscillator located at Bout de L'Isle.
VOLTS (RMS Magnitudes)
100
75
50
25
0
INPUT AMPERES
INPUT ADMITTANCE-Mhos
.5
.4
.3
.2
.1
0
.0275
.0222
.0165
.0110
.0055
0
Peak 4.5 amps
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
FREQUENCY mc.
Mar 26/35

FIG. 18

CHAPTER IX

Radiation Investigation

In the investigation of radiation and induction fields about the trolley system, the model demonstrated its real power. The tests fell into two classifications depending upon the method of excitation. General Radiation Characteristics were obtained with continuous excitation and shock excitation was then employed to simulate actual conditions.

PART A

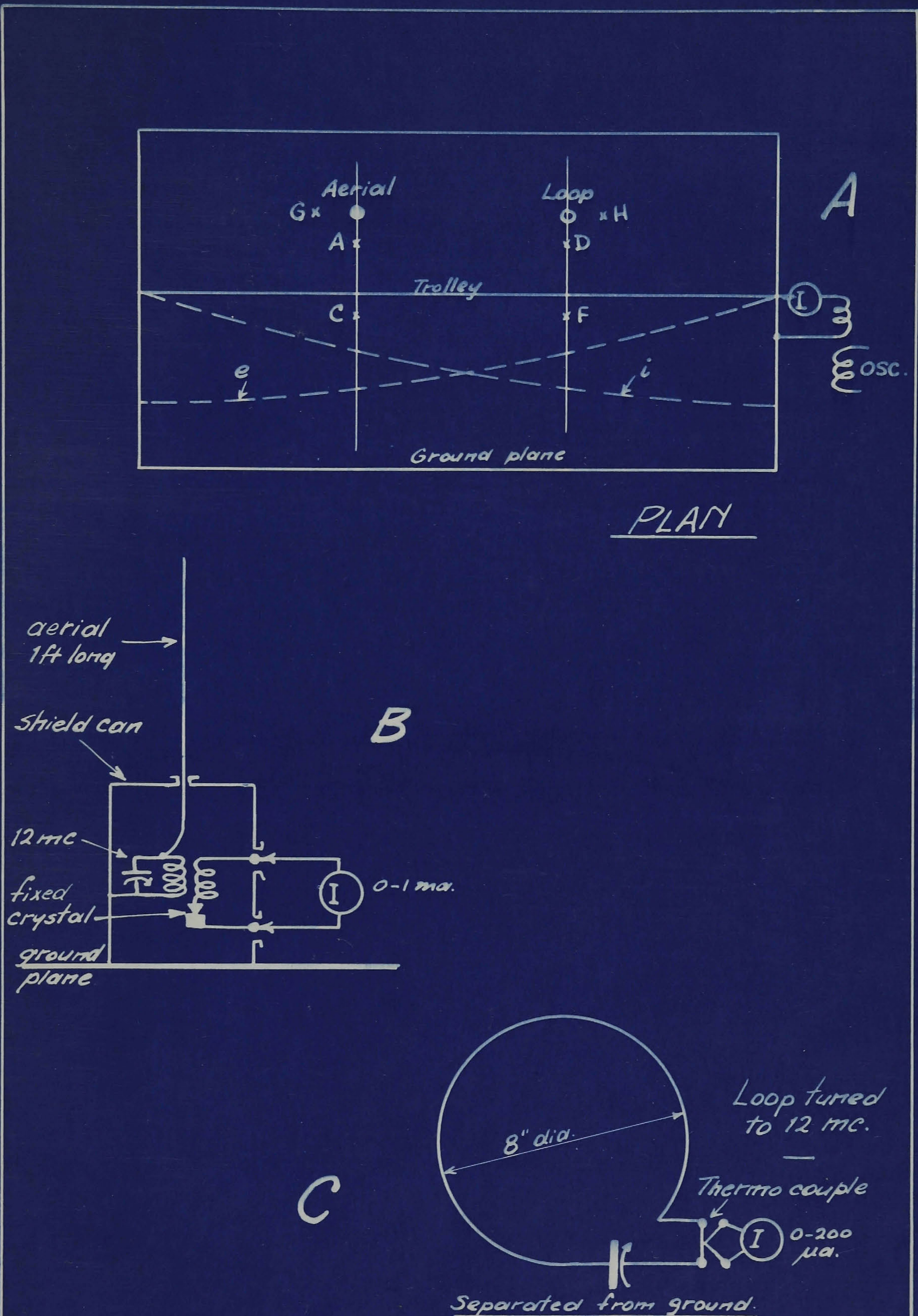
Continuous Excitation

The model with extended ground plane as shown in Figure 21 was excited by an oscillator located at the near end. Radiation and Induction was then measured by two methods; a detector using electrostatic pickup, ie, a straight aerial and secondly a detector using electromagnetic pickup, ie, an ungrounded loop. These two devices were located as shown in Figure 20A at similar positions relative to the voltage and current loops in the antenna. That is, the aerial is located 60 degrees from the voltage node in the antenna and the loop is located 60 degrees from the current node and both are equidistant from the trolley or antenna wire. In this discussion it is convenient to refer to the transmitting trolley system as the antenna and the receiving systems as the aerial and loop.

Circuit details of the two detectors are shown in Figures 20B and 20C and their physical aspects appear in Figures 21A and 21B. Both are tuned circuits and employ different detection systems.

Tests were made with different system types, different objects in the field, different foreign circuits present.

FIG. 20



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1935

FIG. 21

A

B

In all cases the input radio frequency current was kept at 0.7 amperes and the necessary voltage was essentially constant. Resonance conditions existed in the trolley antenna and in the two receiving circuits. The values given are only relative. The bases of reference are the outputs of the detectors for the single 4/o trolley with feeder on wood poles and a field clear of objects ar foreign circuits. This value is assigned 100 and all others may be compared thereto. The letters in the table refer to positions shown in Figure 20A.

TABLE IX

Effect of Objects in Field

Field Condition	Loop Output	Aerial Output
Copper box 9" cubed at A	100	60
Iron box 9" cubed at A	100	60
Dry Wood 6" cubed at A	100	100
Wet Wood 6" cubed at A	95	90
Copper box at G	100	70
Iron box at G	100	75
Dry Wood at G	100	100
Copper box at D	60	100
Iron box at D	70	100
Dry wood block at D	100	100
Wet wood block at D	90	85
Copper box at H	115	100
Iron box at H	115	100
Dry wood at H	100	100
Copper box at C	60	50
Iron box at C	40	25
Wet wood at C	80	80
Dry wood at C	100	100
Copper box at F	75	80
Iron box at F	80	85
Wet wood block at F	85	85
Dry wood block at F	100	100

TABLE X

Effect of Foreign Circuits

Field Condition	Loop Output	Aerial Output
Grounded wire (sheathed telephone cable) on feeder side of the street (P)		
A. Grounded at both ends	42	35
B. Grounded at near end	15	13
C. Grounded at far end	0	30
Same grounded wire on opposite side of the street to feeder but on same side as detectors (Q)		
A. Grounded at both ends	80	90
B. Grounded at near end	50	60
C. Grounded at far end	200	25

TABLE XI

Effect of Types of System

Field Condition	Loop Output	Aerial Output
Single 4/0 trolley, feeder, wood poles	100	100
Single 4/0 trolley ohly	130	140
Double 4/0 trolley, feeder, wood poles	85	100
Double 4/0 trolley, feeder, steel poles	90	85

TABLE XII

<u>Effect of Frequency</u>

Field Condition	Loop Output	Aerial Output
Fundamental Frequency	100	100
Third Harmonic	500	450

To summarize these data, one may say that the introduction of conducting masses into the field has, in general a shielding effect but the reduction rarely exceeds 25%. In the case of the electrostatic aerial, the permeability of the conducting mass is unimportant.

The effect of foreign circuits is very great, particularly the position of their grounding point. This requires more exhaustive investigation.

The type of system is not important but the particular frequency under consideration is an important factor in the induced voltages.

PART B

Shock Excitation

The question naturally comes into one's mind concerning the legitimacy of applying the results of tests taken under continuous voltage to conditions where the voltage is a train of impulses. Consequently an attempt was made to exactly duplicate the conditions of shock voltage input and aural output measurement, which is the ultimate standard of judgement.

Figure 22 sketches the general arrangement. An aerial composed of an uplead and a flat top portion is located midway along the line and close to it (2 feet). A potentiometer attenuator, receiver and speaker are located "underground". The trolley line is energized with direct voltage E1 and a load resistor R2 placed at the output end. Various "car" circuits Zc can then be placed arbitrarily along the system and interrupted by the investigator at will. The results of varying different situations are tabulated below. The values termed

'Audibility' are very roughly the microvoltages of the disturbances above a zero value corresponding to the threshhold of audibility. Enough results in sufficiently accurate form were not available to justify conversion to Loudness or Sensation levels or Noise Units.

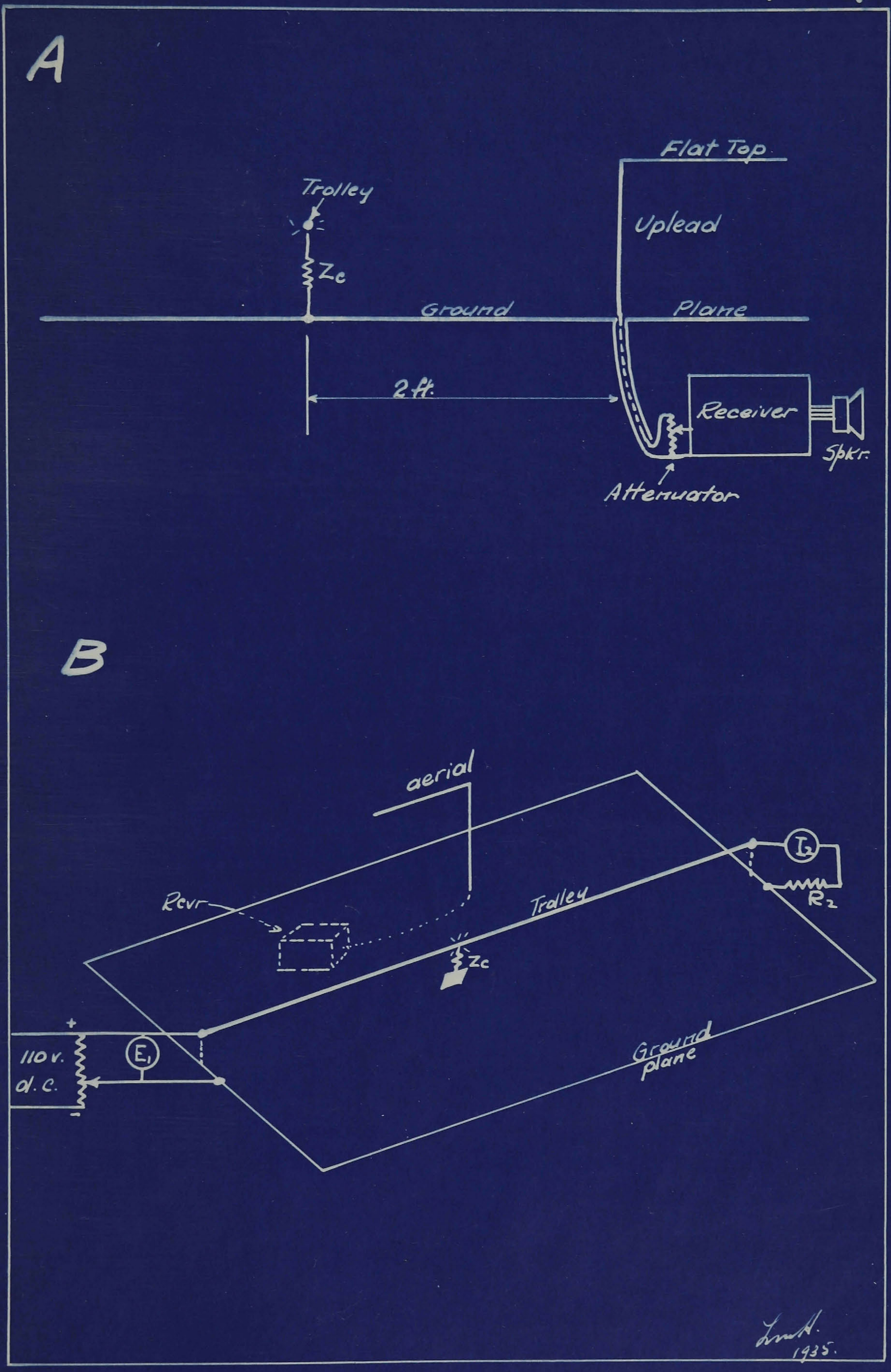

A
Flat Top
Trolley
Uplead
Zc
Ground
Plane
2 ft.
Receiver
Spkr.
Attenuator
B
aerial
Rcvr
Trolley
Zc
110 v.
d. c.
+
-
Ground
plane
1935.

FIG. 22

TABLE XIII

	E1	I2	Zc=Rc	Audibility
Varying Car Load	90	0.8	10,000	20
	90	.8	1,000	45
	90	.8	710	110
	90	.8	320	125
Varying Load on System	90	0	1,000	100
	90	.4	1,000	45
	90	.8	1,000	35
	90	1.3	1,000	25
Varying d.c. voltage	30	.3	1,000	20
	60	.3	1,000	35
	90	.3	1,000	60
	112	.3	1,000	65
Varying Objects in Field				
Metal box behind aerial			1,000	35
Metal box under aerial			1,000	40
Metal box in front of aerial			1,000	100
Varying Car Circuit				
Pure Resistance 1000 ohms				45
Pure Capacitance 500 uuf				0
Inductance and 1000 ohms resistance				45
Resonant Circuit and 1000 ohms resistance				45
Varying Aerial Configuration				
1 ft. uplead, 1 ft. flat top, parallel to trolley				45
1 ft. uplead, 1 ft. flat top, perpendicular to trolley				40
1 ft. uplead, 6 in. flat top, parallel to trolley				35
6 in. uplead, 1 ft. flat top, parallel to trolley				40
3 in. uplead, 1 ft. flat top, parallel to trolley				25
1 ft. uplead, no flat top				30

Varying Car Position

This had no effect upon the interference. The Audibility of 45 was obtained whether the car was at either end or in the centre of the model.

Varying Trolley System

Changing from one type of System to another or adding a ground wire appeared to have no effect on the magnitude of the interference.

....

In concluding this chapter the writer regrets to admit that lack of time has left many questions unanswered and many facts not rigorously determined. It is evident that the results of Part A conform to one's ideas of radiation and induction whereas those of Part B do not wholly. The fact that the severity of the interference depends upon the magnitude of the current broken corroborates ideas presented earlier in the paper. But the fact that the external load upon the system is also a factor influencing the interference, is a new idea that requires additional verification Also the independence of the nature of the car circuit to interference originating at the trolley wheel is verified for certain conditions if not universally. The effect of external objects and additional foreign circuits in the neighborhood together with possibilities of remedial measures for the whole situation, all remain indefinite.

The results of this chapter are quite superficial. To make any definite statement with authority one would need to conduct a much more exhaustive study than this outline represents.

CHAPTER X

Conclusion

The considerations outlined in this thesis have led the writer to the following definite conclusions.

1. The magnitude of the interference depends upon two factors

(a) The time rate of change of current during the break. (This includes the rise and decay as well as any oscillatory motion that may exist)

(b) The nature of the system at a point under consideration, with respect to reflection cumulative effect.

2. The propagation to distant parts depends upon two factors

(a) The nature of the system with regard to transmission through discontinuities.

(b) The attenuation factor, largely a resistance function.

3. No economical method exists for keeping the contact between the trolley wheel and wire unbroken.

4. Finally, no imaginable circuit within the car can materially affect the interference resulting from current ruptures at the trolley wheel.

....

Also, there are certain opinions held by the writer which, in the light of fuller knowledge may not be correct. They are

1. A properly designed coil-condenser combination placed upon the car roof in the main lead would eliminate all interference resulting from circuit breaks within the

car. By "properly designed" is meant a low pass filter built after well known principles and rigorously tested in the laboratory before testing on a street car. 'Cut and try' methods are useful only when other more useful tools have failed.

2. The effect of finite conductivity of the ground is largely obviated by the presence of the rails embedded in the surface of the ground. The rails must have no high resistance joints for electrolytic considerations and many regions of Montreal have welded joints. Even considering the rails absent, calculation by Carson's formulae gives the ground resistance a value of 40 to 60 ohms per mile, still a low figure considering attenuation.[26,27]

....

Two questions remain wholly unanswered in the writer's opinion.

1. Do foreign circuits act as electrostatic shields, reducing the interference or do they act as propagators, aggravating the interference condition? Do they act as both and under what circumstances?

2. Is it possible, electrically and economically, to devise a surge absorber to be placed periodically along the system to keep the trouble localized and prevent reflections? It must be remembered that a by-pass condenser is by no means such a device - travelling waves reflect from short circuits even more perfectly than from a discontinuity. The only solution is an impedance between the trolley and ground equal to the characteristic impedance. Can it be constructed and installed economically? Will it work in both directions? Maintenance?

....

Suggestion

1. In the writer's opinion there is but one way to answer all these questions. That is to conduct an investigation by means of a complete model. Select a representative portion of the system, somewhat isolated, if possible, such as that selected in this thesis. Construct the whole thing as a model, reducing the scale as required for the space and measuring equipment available. Simulate the ground conductivity, if possible, by the use of a mixture of powdered gypsum and lampblack, for instance, on a tray. Duplicate the rails by iron wire and use available information on resistivity from water main electrolysis investigations. Duplicate to scale the streetcar circuits in a form that can be incorporated in the model. Measure interference upon an aural basis only. Apply possible corrective measures to the system and test at will. The system is a true replica of the real one and it is at the complete disposal of the investigator to treat as he wishes, when he wishes.

2. Investigate the possibility of improvement in the situation by more selective receivers, superior antenna systems. As a starting point there is a comprehensive paper by Carson upon this topic.[28]

....

Only after these questions are answered by exhaustive investigation is one in a position to say 'Yes' or 'No' and why for the problem of Suppression of Radio Interference from Street Railway Systems.

APPENDIX A

Apparatus

1. Low Frequency Circuit Driver

For the audible range of frequencies, the portable solution of bridge power source was the device shown in Figure 27A . The bypass condenser eliminated the most spurious harmonics of the 1000 cycle note. The device was capable of maintaining up to 20 volts across a pair of headphones with a 6 volt storage battery energizing the primary.

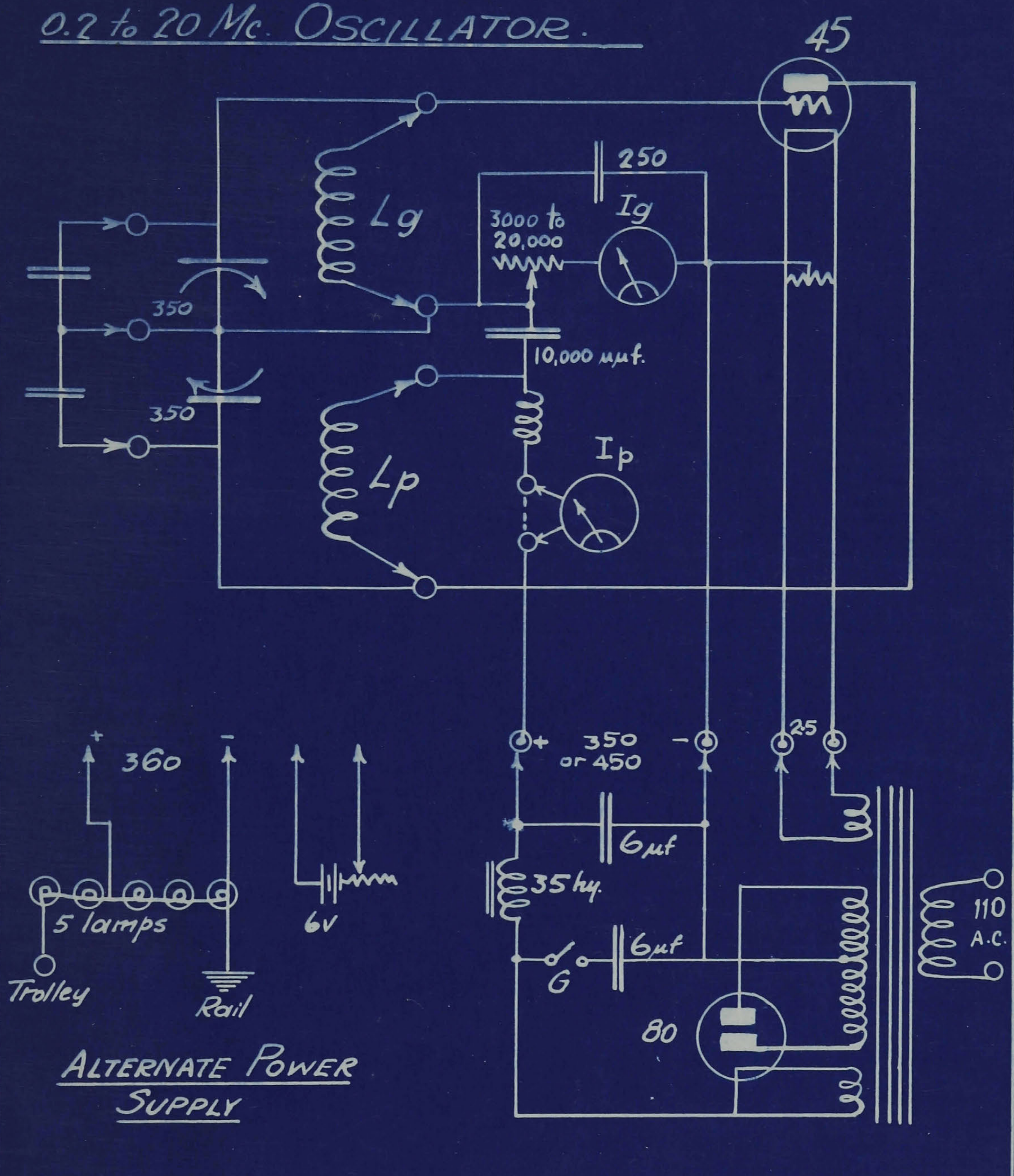
2. Medium High Frequency Circuit Driver.

The following four points were borne in mind in the design of this type oscillator.

(a) Output. A more stable situation, fewer extraneous frequencies and more uniformity can be obtained in radio frequency measurements if the oscillator has sufficient power that close coupling of the pickup coil and overloading of the oscillator are unnecessary. It was found that a single type 45 in the circuit of Figure 23 was sufficient for all but the occasional test. In the latter case, closing switch G raised the plate voltage from 350 to 450 and provided extra output. This device was capable of maintaining an output of 10 to 15 watts over a wide frequency range.

(b) Frequency Range. Five plug-in coils give a continuous variation of frequency from 450 to 21,000

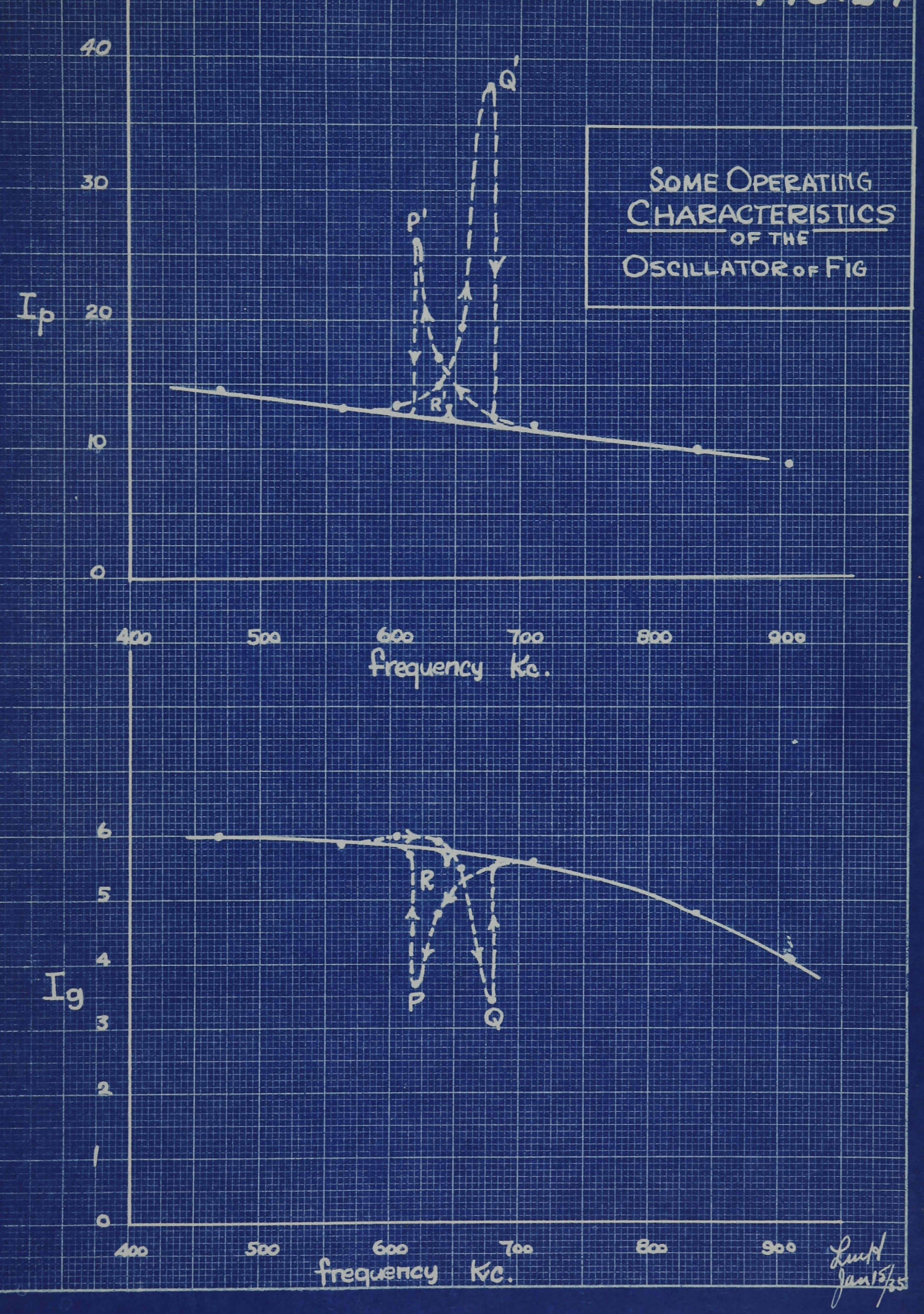
FIG. 23

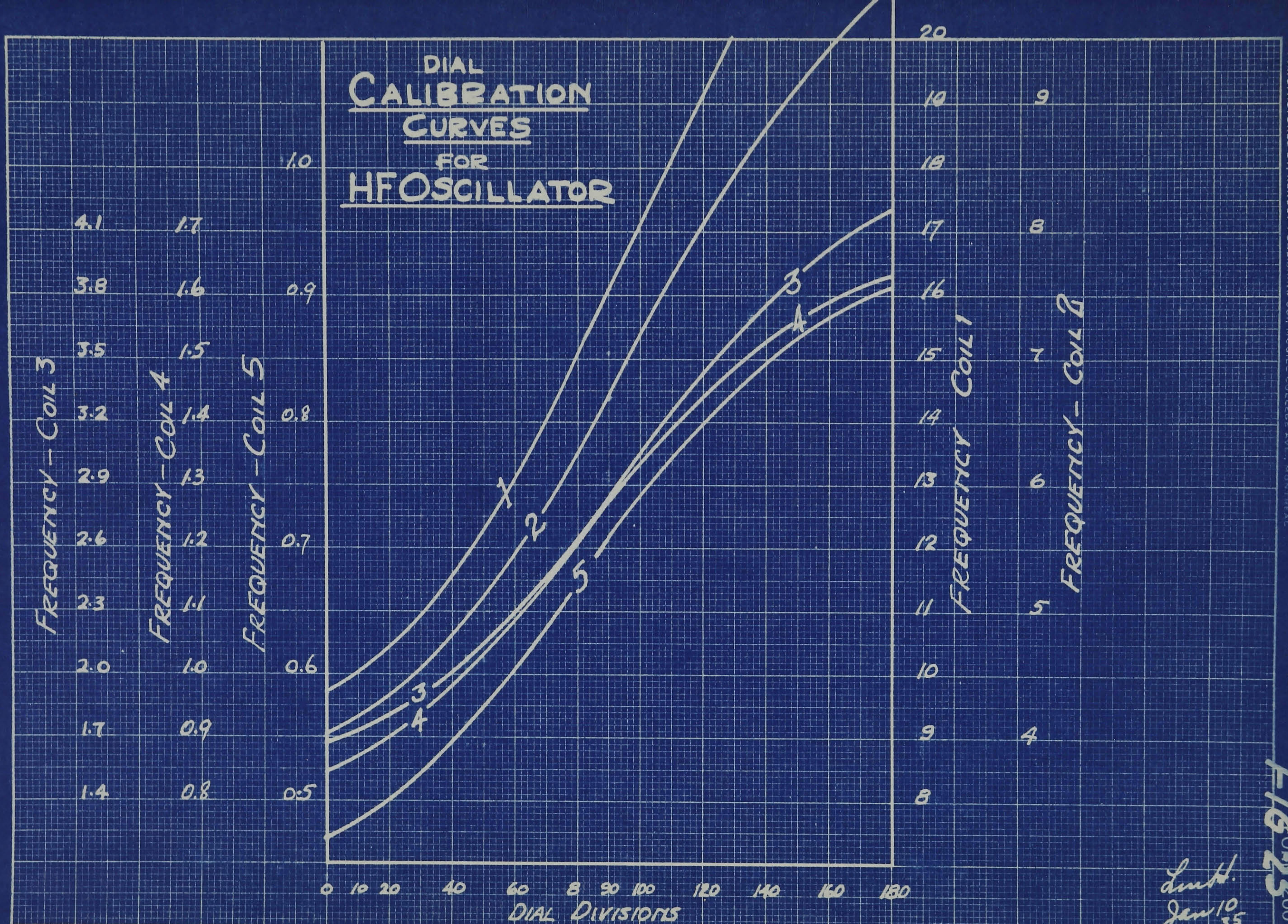


COIL	TURNS	WIRE	DIAM.
1	2	14 bare	2½ in.
2	5	14 dcc	3⅛
3	14	14 dcc	3⅛
4	26	18 dcc	3⅛
5	47	22 dsc	3⅛

LmH
1935

FIG. 24


SOME OPERATING CHARACTERISTICS OF THE OSCILLATOR OF FIG
Ip
0
10
20
30
40
P'
Q'
R
400
500
600
700
800
900
frequency Kc.
Ig
0
1
2
3
4
5
6
R
P
Q
400
500
600
700
800
900
frequency Kc.
Luck
Jan 15/35



DIAL
CALIBRATION
CURVES
FOR
HF OSCILLATOR
FREQUENCY - COIL 3
FREQUENCY - COIL 4
FREQUENCY - COIL 5
FREQUENCY COIL 1
FREQUENCY - COIL 2
DIAL DIVISIONS
1
2
3
4
5

FIG 25

kilocycles per second. If lower frequency is required plug-in condensers extend the range down to 200 kilocycles.

(c) Constant Plate and Grid Currents. In order that sudden loads coming on the oscillator, such as a resonant condition in the driven circuit, may be detected by the reaction on the plate and grid currents, these quantities must remain steady under all other conditions including varying frequency. The circuit chosen to satisfy this duty is the tuned plate, tuned grid arrangement. The grid and plate coils were made identical and their tuning condensers are similar and gauged and the net result is demonstrated by the flatness of the solid curves of Figure 24

(d) Circuit Details. The photograph in Figure 26A indicates the arrangement of parts. Grid current was metered continuously though terminals were provided for the external insertion of a plate currnet meter in the circuit. The grid leak is a variable compression disc resistor to give proper operating conditions and convenient reading on the grid meter. The R.F. choke is obviously unnecessary in such a circuit and final construction would eliminate it. The power supply is the conventional arrangement where a.c. service is available. In Tramways Shops the tube filament was supplied by a storage battery and the plate voltage was from a voltage divider formed by a bank of six 110 volt lamps hung across the 600 volt trolley system.

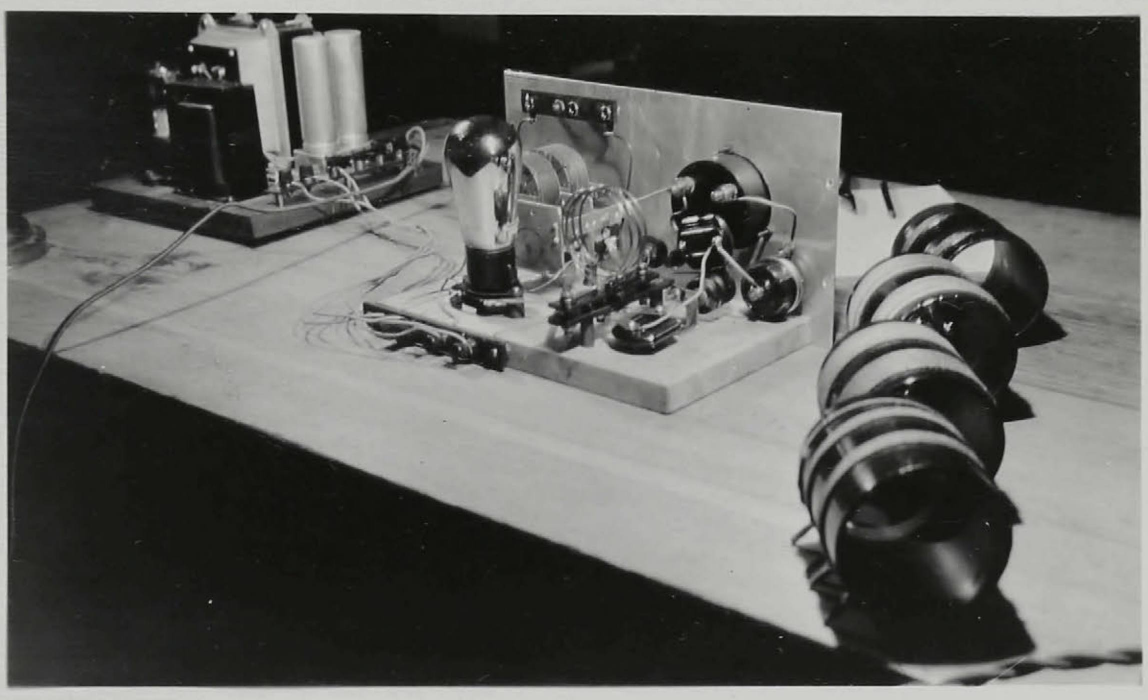
....

In the operation of this oscillator the dial calibration can only be accepted if the coupled load is small. Suppose, for instance, the resonant frequency of a circuit is required. Resonance will be indicated (in this circuit) by a peak in the plate current and a hollow in the grid current. Considering Figure 24 , if the pickup is too great the resonant frequency will appear at P,P' or Q,Q' depending upon whether the resonance is approached from the low side or the high side. Neither value is correct. By loosening the coupling the two peaks diminish in amplitude and approach each other. The coincident peak (or dip) at R,R' indicated the correct frequency.

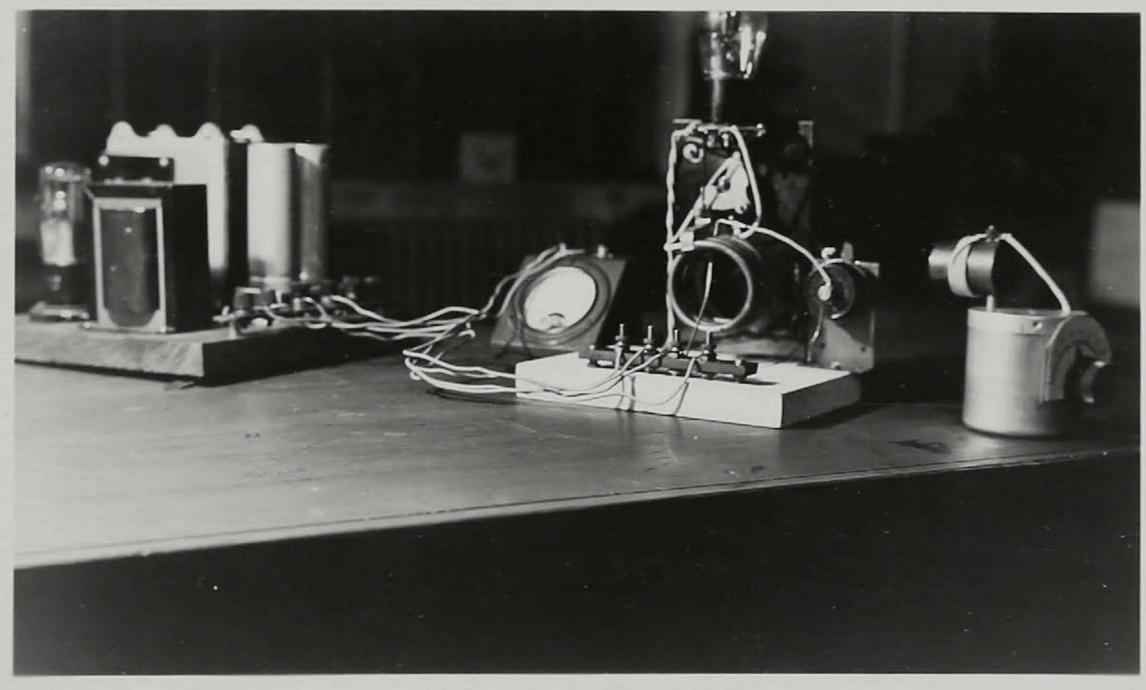
3. High Frequency Circuit Drivers. The two oscillators in Figures 26 B C cover frequency ranges from 15 to 40 and from 40 to 75 megacycles respectively, They are essentially the same circuit with minor alterations and different arrangements physically. It is the Unity coupled, push-pull circuit employing the duplex triode and is capable of nice output at that frequency. The circuit is shown in Figure 27B.

4. Cathode Ray Oscillograph. The type used was a 6 inch Von Ardenne 2000 volt tube. A sweep circuit using a variable condenser charged through a saturated diode and discharged through a small thyratron (W.E. 269 A) was capable of sweep frequencies anywhere up to 12,000 per second.

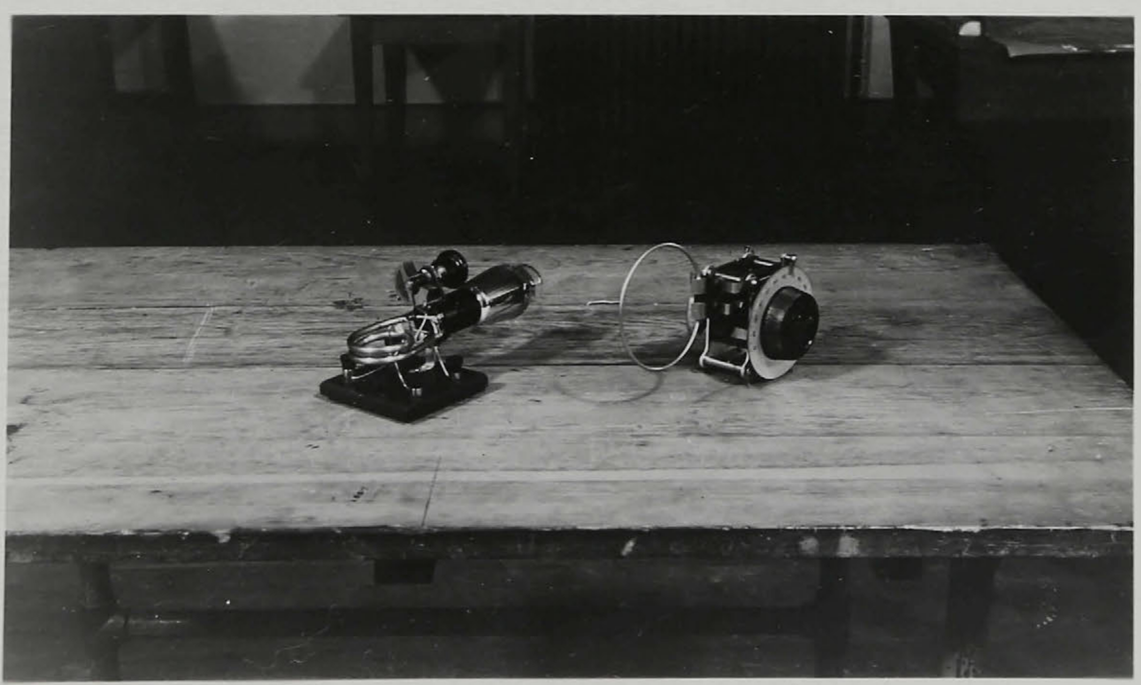
FIG. 26



A

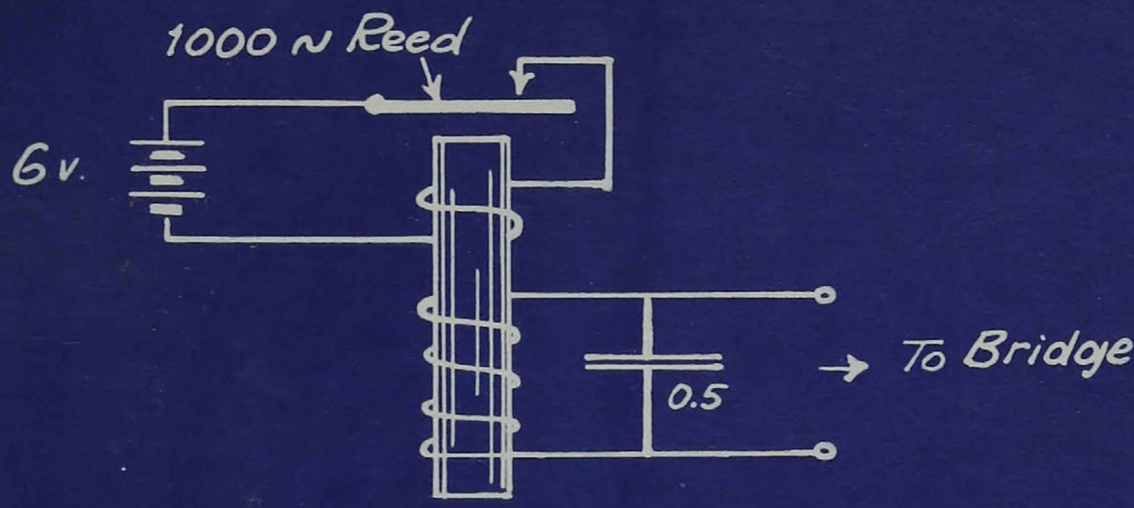


B



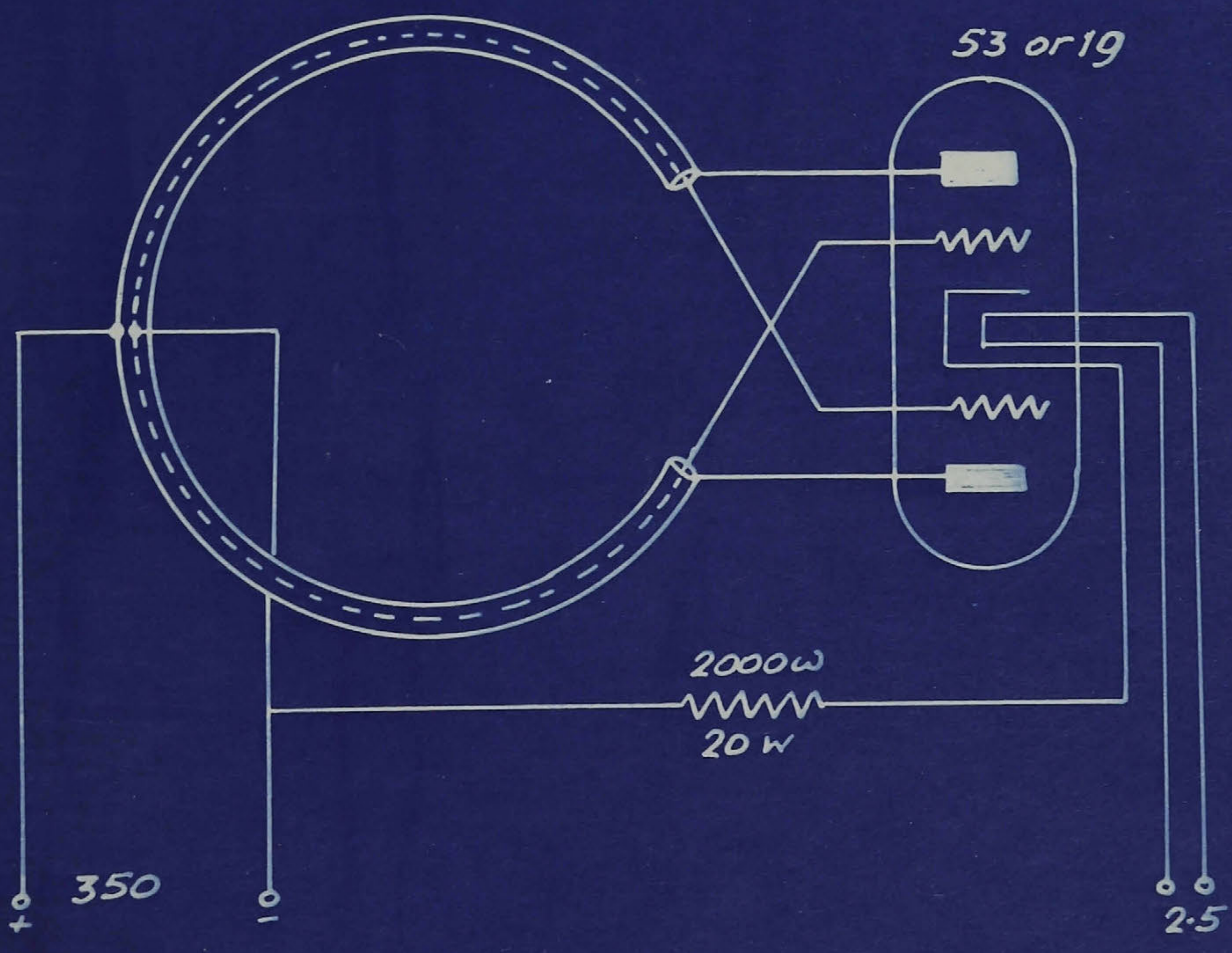
C

FIG. 27



A

1000 cycle OSCILLATOR.



B

20-75 Mc. OSCILLATOR

1935

5. Portable Radio Receiver. For such observation as was required by the writer, the simple, self-contained circuit of Figure 28 was found adequate. It is a linear detector with two stages of audio amplification. The output can be observed with a speaker, oscillograph or meter. The device is provided with switches and terminals to facilitate such observation. The output meter is mounted directly on the front panel and serves as a filament voltmeter. Plug-in coils allow the tuning range to be extended.

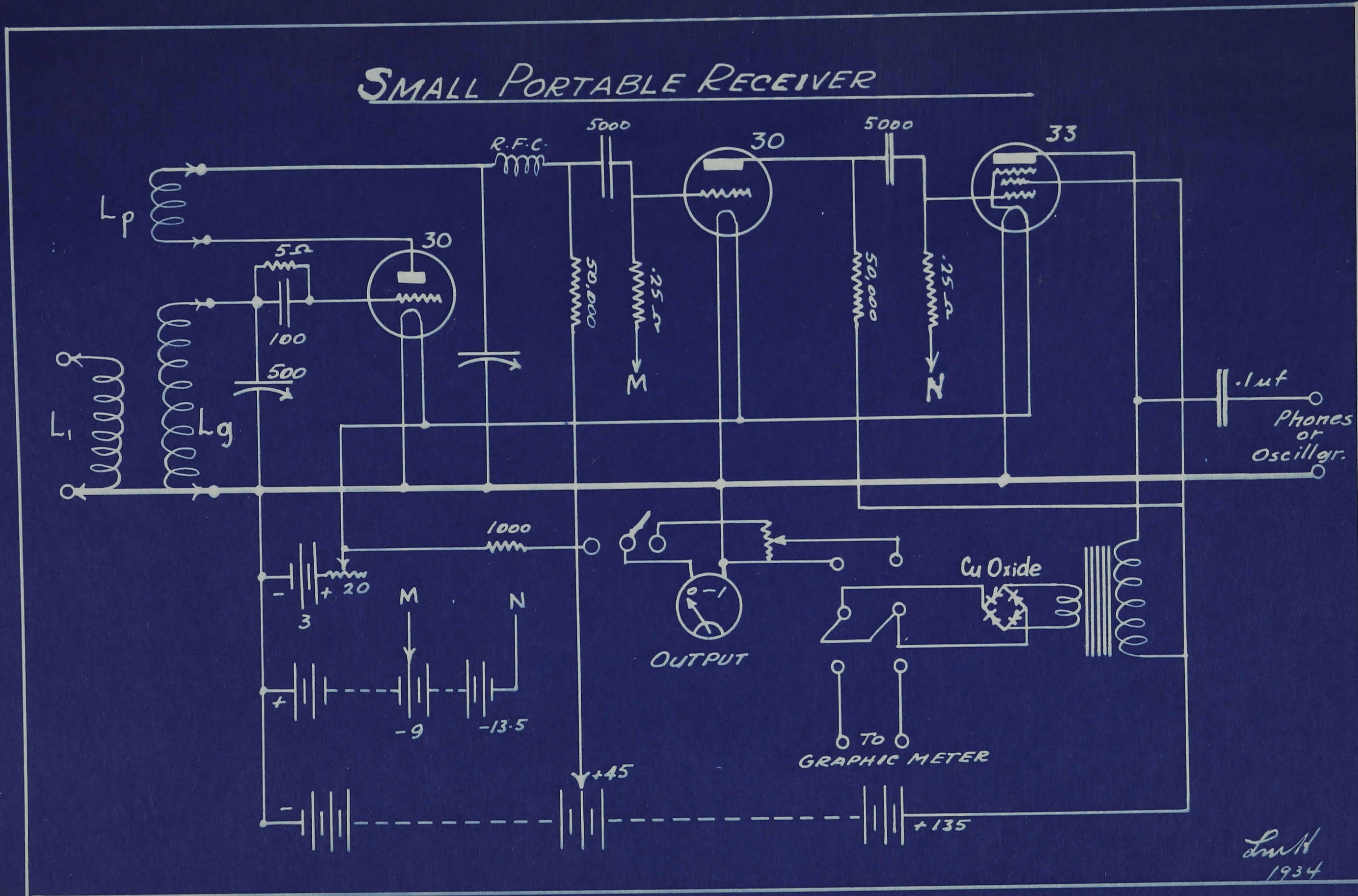

SMALL PORTABLE RECEIVER
Lp
Lg
L1
5Ω
100
500
30
R.F.C.
5000
50,000
.25Ω
M
30
5000
50,000
.25Ω
N
33
.1uf
Phones or Oscillgr.
1000
- + 20
3
M
N
+
-9
-13.5
0-1
OUTPUT
Cu Oxide
To GRAPHIC METER
+45
-
+135
1934

FIG. 28

APPENDIX B

Methods of Measurement

In general, the writer was satisfied with an accuracy of 10%. In a chain of factors, one of which is the earth, one cannot expect precise results and precise results are of no value as such. To claim an improvement of 10% in a condition of radio interference due to any manipulation is certainly over-optimism. The writer came across a report of an investigation wherein "a considerable improvement" was indicated by the comparison of two graphic millivoltmeter charts, one of which was said (and also "looked") to have greater interference voltages than the other. A planimeter analysis, however, showed the difference in the mean ordinates of the two records to be less than a hundredth of an inch!

Every "field" problem is beset by its own typical difficulties. In this case, the lack of a source of alternating current about the street railway shops necessitated complete use of batteries for all oscillators, circuit drivers, receiver and measuring instruments.

1. Measurement of Current

   a. Thermocouple - milliammeter instrument

   b. Hot wire instrument

   c. E.M.F. across a resistance.

The first two methods were used exclusively. The third method is capable of precise results when used with a vacuum tube voltmeter and does not alter existing circuit conditions by the insertion of the measuring instrument.

The wide variety of thermocouples on the market enables one to select almost any sensitivity and heater resistance required. They are more accurate and stable than the Hot-wire types but the latter possess several advantages. A hot wire instrument gives an instantaneous, dead heat reading which is not true of thermojunction types. Hence a resonance peak is indicated at once with the former. The hot wire instrument is simple, only two short leads and a short, inductanceless element. For this reason it is preferrable where there is induction or radiation fields. Under such conditions the induced current may completely mask the conductive current required, when a thermocouple meter is used. Examples of such instruments are shown in Figure 29B.

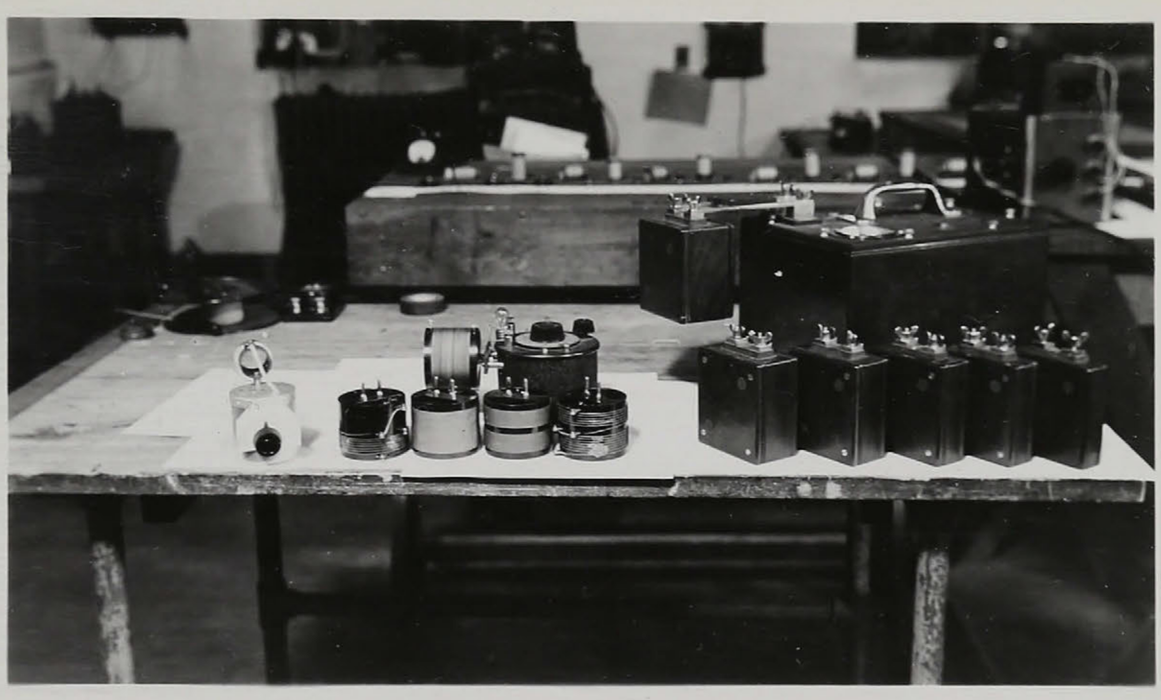
2. Measurement of Electromotive Force

The following methods were used as occasion demanded and are listed in probable ascending order of refinement and accuracy.

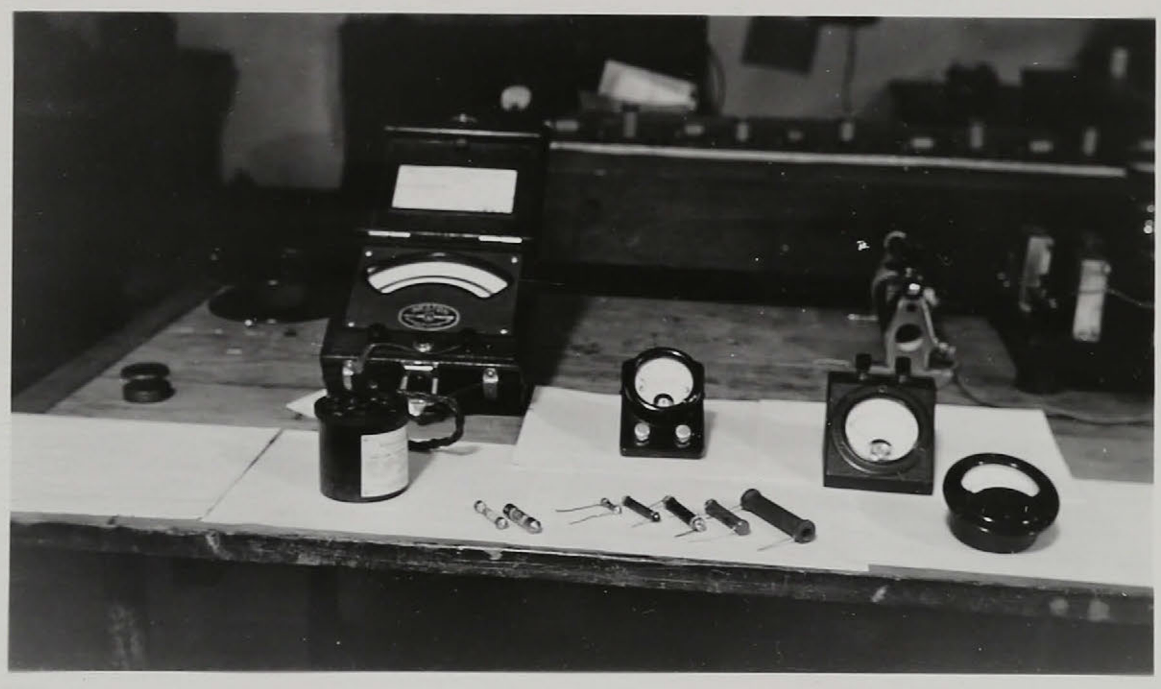
1. Neon Glow lamp
2. Metal Rectifier meter
3. Resistance and Thermoammeter.
4. Hotwire Ammeter and pickup loop
5. Vacuum Tube Voltmeter.

An ordinary commercial glow lamp held in the fingers by its glass bulb will emit a glow in rough proportion to the magnitude of the R.F. potential of a conductor into contact with which one lamp terminal is brought. Otherwise it may be connected directly across the source of voltage as in the wavemeter in Figure 29A. Obviously it is a

FIG. 29



A



B

C

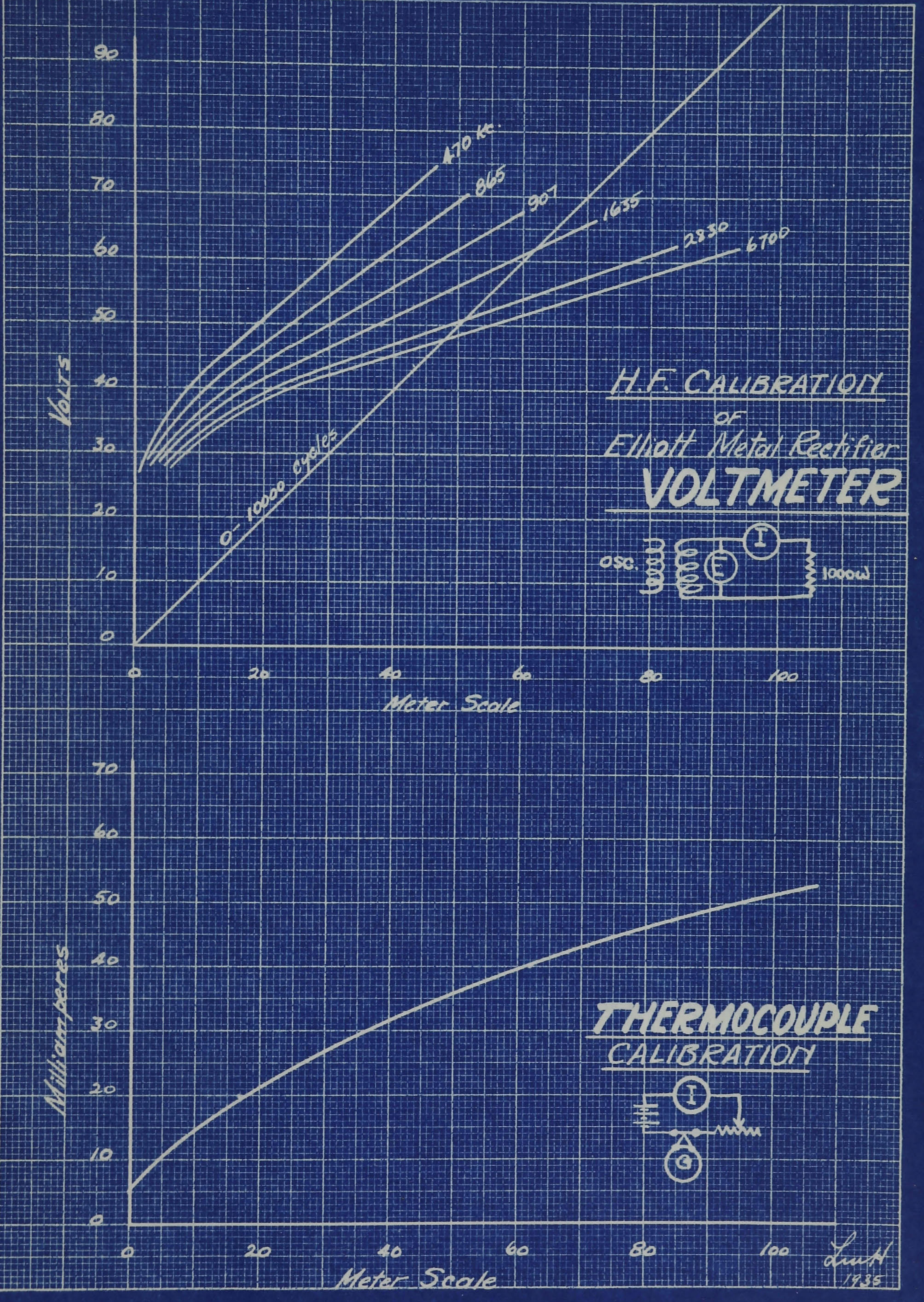
rough method, draws current, alters circuit conditions and is of use chiefly for preliminary exploring.

The Elliott metal rectifier instrument shown in Figure 29C was found usable for even high freqpency potentials if its Calibration Curves (Figure 30) were used. The rectifier has considerable capacity, however, and is the deciding factor in its use.

A Resistance-thermocouple-microammeter combination was effective where the inductive pickup of the leads was not prohibitive. This involves a shielding problem which introduces unwanted capacity where the instrument is connected.

For cases where the e.m.f. in a pickup coil was to be kept constant, the following method was applied by the writer. Entwined about the pickup coil is a 'potential' coil-a single loop of insulated wire, the leads from which are brought, transposed, to a 0-250 range miliammeter. An auxiliary non-inductive, non-capacitive resistor is placed in the circuit to give a suitable deflection on the meter. Due to the intimate position of the pickup coil and potential loop, essentailly the same flux will link each. So when a constant deflection is kept on the meter by varying the driver coupling one may be assured that the driving potential in the pickup loop is substantially constant. This is made so by viture of the fact that the impedance of the single loop of the potential coil is never, at any frequency used, appreciable compared with the resistance of the meter and auxiliary resistance (90 ohms). Hence the dial of the meter may be calibrated directly in

FIG 30


H.F. CALIBRATION
OF
Elliott Metal Rectifier
VOLTMETER
VOLTS
90
80
70
60
50
40
30
20
10
0
470 kc.
865
907
1635
2830
6700
0–10000 cycles
OSC.
E
I
1000ω
0
20
40
60
80
100
Meter Scale
THERMOCOUPLE
CALIBRATION
Milliamperes
70
60
50
40
30
20
10
0
I
G
0
20
40
60
80
100
Meter Scale
1935

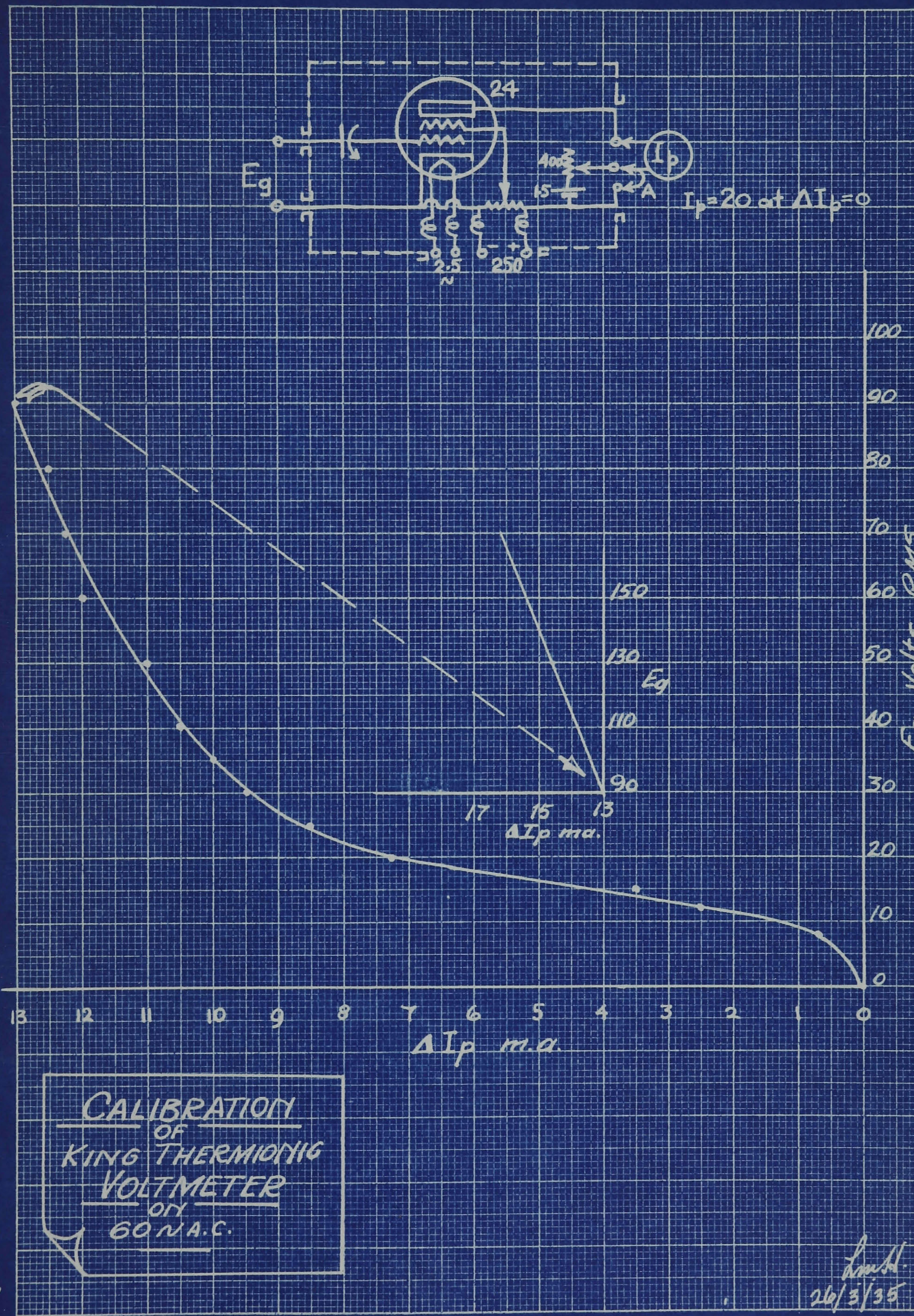
volts by using a 60 cycle e.m.f. to give required deflections. Then the potential effective in the pickup loop is, to a first approximation, the turns ratio of the pickup coil to the potential loop times the indicated voltage.

For accurate measurement of high frequency potentials the Vacuum tube voltmeter is unequalled. The particular circuit use is that described by King[17] and consists of a type 24 tube in the circuit shown with its calibration in Figure 31 . By varying the value of the blocking capacity in the control grid lead the operation of the instrument can be extended to great sensitivity or great range as required. The shield box must not be connected to the circuit. Three terminals are brought out for connection of a plate current meter or a delicate galvanometer, from the circuit of which the direct component of the plate current has been neutralized. A feature of the circuit is a high input impedance represented by 5.3 uuf., the lowest available in standard tube types.

3. Measurement of Frequency

Figure 29A shows the type of frequency measuring apparatus used. All are absorption type, other methods were found unnecessary. The larger instrument on the right (by General Radio Co.) was used as a standard up to 20 megacycles. Other more portable instruments shown were calibrated from the larger instrument. For frequencies from 20 to 100 megacycles the wavemeter (also by G.R.) shown with the 50 megacycle oscillator in Figure 26C was used. Its range was extended downward by suitable shunt condensers.

FIG. 31

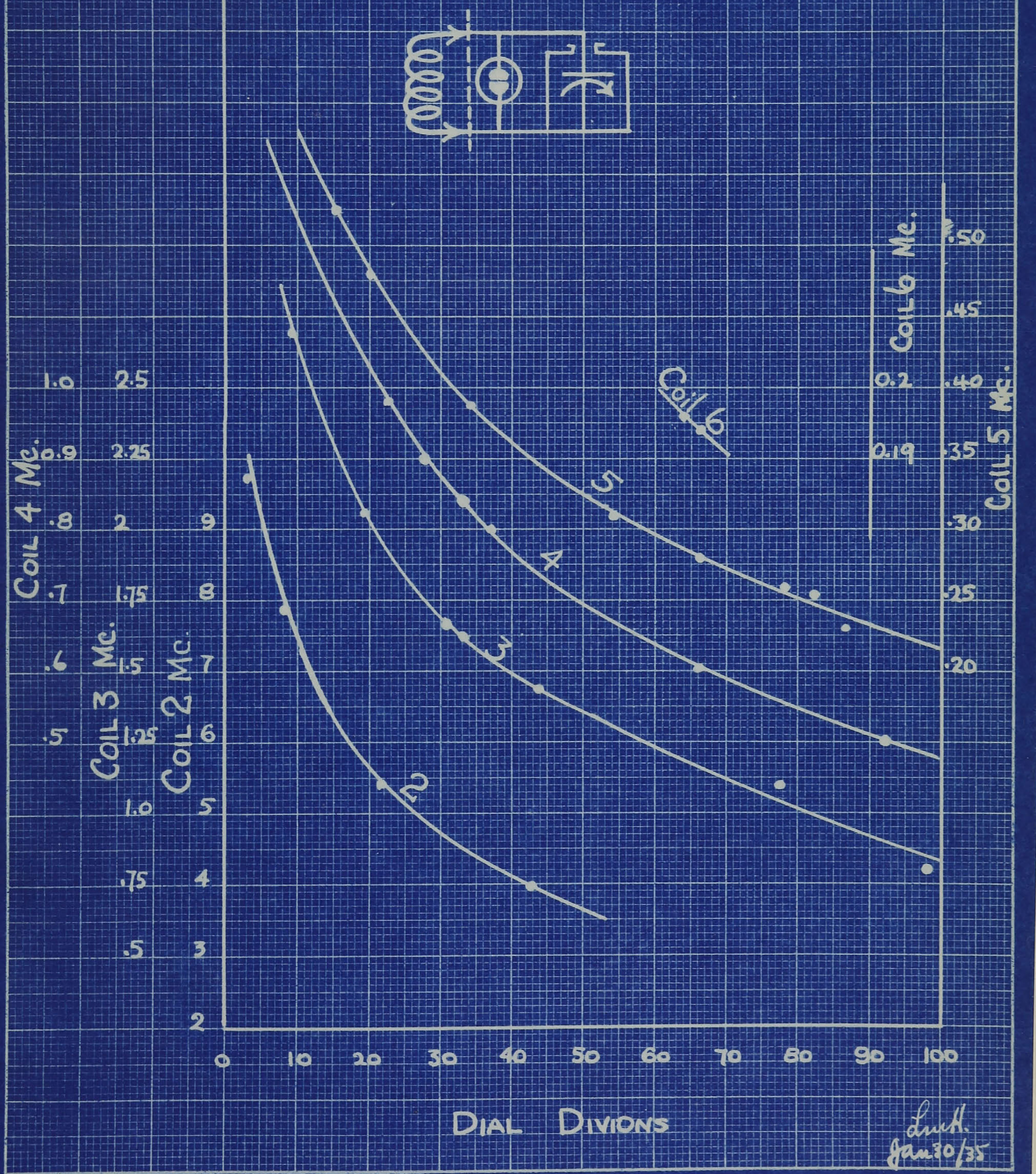

24
Eg
Ip
400Ω
15
A
2.5
250
Ip=20 at ΔIp=0
Eg Volts RMS
ΔIp ma.
Eg
ΔIp m.a.
CALIBRATION OF KING THERMIONIC VOLTMETER ON 60 ~ A.C.

26/3/35

FORM 200

FIG. 32

WAVE METER
CALIBRATION



4. Measurement of Resistance

The only method relied upon was the Substitution Method. Values thus obtained were checked where possible by voltage - current quotient where such quantities were available at resonant conditions.

Considerable care is necessary when selecting resistances for substitution. Wire wound types are questionably non-inductive in use above five megacycles. Compression disc types, though convenient and versatile, are also inadvisable by virtue of the capacitance between faces of the contact plates. The resistor found suitable in present case was a single straight wire having a resistance of about an ohm per inch. No terminals were used but drops of solder were placed along the wire at distances of one ohm. Calibration was made by d.c. and a correction factor applied for high frequency skin-effect.

Other precautions mentioned by Brown[18,19] were found quite necessary and duly taken.

5. Measurement of Inductance and Capacity.

True or static values are most easily obtainable by the use of an impedance bridge, if such an instrument capable of determining the small values encountered in radio work, is available. When using such a bridge for low values of unknowns it is advisable to check the accuracy of the measurement by determining an unknown first by varying the standard with a fixed bridge ratio, then by varying the bridge ratios with a fixed standard. If discrepancy results one must adhere exclusively to one method or the other as good judgement dictates. Again, one can often obtain a balanced bridge with the unknown terminals open. In the instrument used by the writer this was 12 uuf. Since, in this case at least, this value was cumulative with any unknown added, it was deducted from all measurements made.

Effective values of Inductance or Capacity result from two conditions. In elongated circuits as antennas and transmission lines, the current is not uniform throughout the length of the circuit and the Apparent or Effective values of Capacity and Inductance are not the same as the true values. In the case of coils the Apparent Inductance is less than the true value due to inter-turn capacity. These factors must be considered and measurement be made by Capacity Substitution as indicated by Brown is quite a standard procedure.

APPENDIX C

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