CONSTRUCTION AND OPERATION OF A MILLION VOLT SURGE GENERATOR

Presented

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by

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FOREWORD

It was the intention in preparing this thesis to present the construction and specifications of the surge generator that has just been completed in the Southern California Edison Company High Voltage Laboratory at the California Institute of Technology.

Further, it was desired to present a determination of all the circuit constants and enough of the theory for the attainment of standard wave shapes for test purposes.

However, due to the inability to obtain, as yet, adequate oscillograms, all of the constants of the surge generator have not been determined.

GENERATION OF SURGES

There have been numerous circuits devised and used for the production of surges, all of which fundamentally perform the function of charging suitable condensers and then discharging them through the proper circuit constants to give the desired wave form. In some of these circuits, the condensers are charged with an A.C. potential, some with rectified A.C. and others with direct current from a D.C. generator.

The type in most common use today for the production of high voltage surges employs the Marx circuit for the parallel charging of banks of condensers and the series discharging of them. The most satisfactory means of charging is by the use of high voltage rectifying tubes connected in what is known as the voltage doubling circuit. The principles of these two features are shown in figure 1.

The condenser banks, consisting of as many condensers in series as the voltage rating of the charging circuit will permit, are charged in parallel through

SURGE - GENERATOR
CIRCUIT

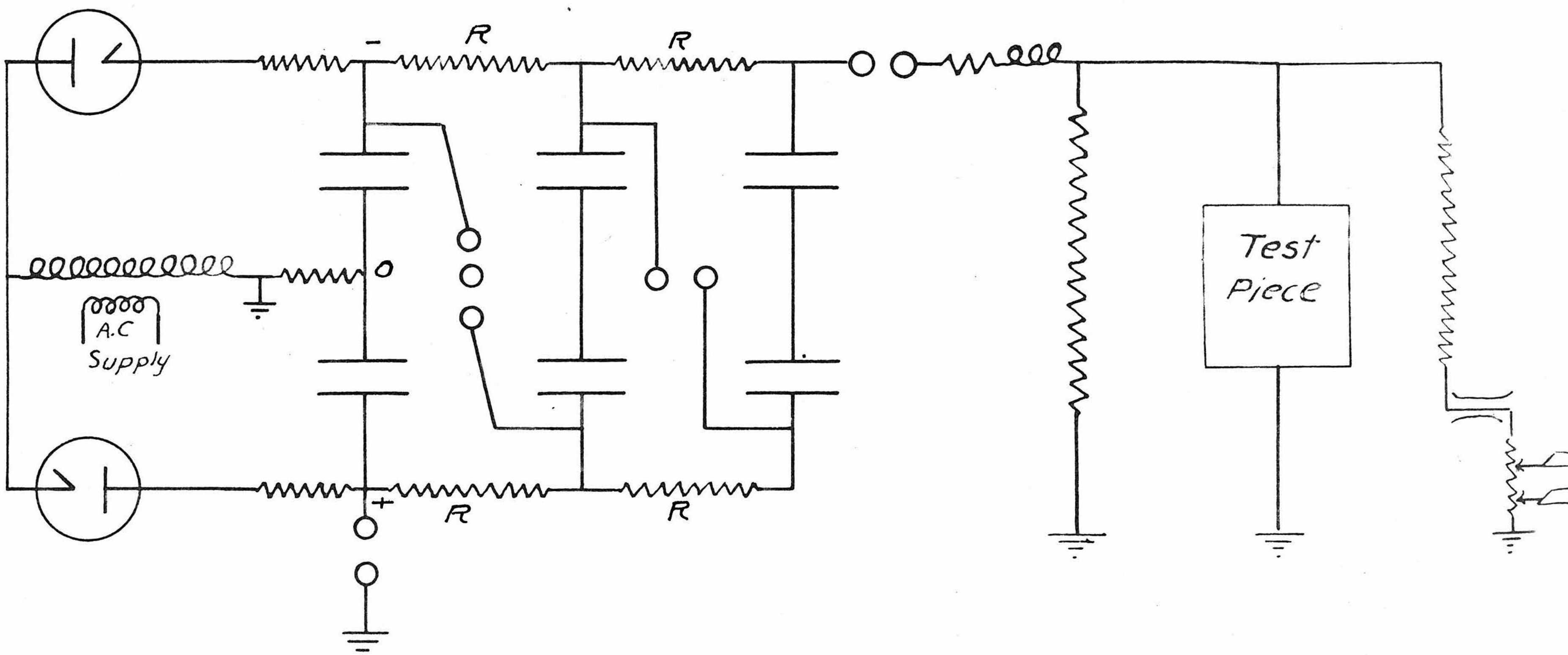


Fig. 1

the resistances labeled (R). After they have been charged, they are switched in series through the gaps shown. The triple gap connecting the first two banks is the control gap. It is either set so that it will flash over after the banks are charged up, or it can be initiated by applying a surge to the middle sphere. The second method enables synchronization of the surge. After the first gap has flashed over, each successive gap does likewise due to the increased potential applied to it after the breakdown of the one before it.

The charging resistances are of such a value that the points they connect are effectively open circuited for the transient condition. The time of discharge is so short that very little energy is lost in these resistances.

By the use of the Marx circuit, very high surge voltages can be obtained with a large number of banks. The only limits to the number that can be employed are the increased time necessary to charge up the last banks and the fact that the increased number of gaps reduces the voltage, since there is an appreciable drop across each of them.

The voltage doubler charging circuit, as shown in figure 1, has the mid-point of the bottom condenser bank and one end of the supply transformer tied to ground during charging. The other end of the transformer is connected to the two ends of the bank through the rectifying tubes, so that the ends are charged, one positively and one negatively, to the voltage of the supply transformer while the mid-point of the bank is at zero potential. One of the tubes is conducting during one half of the cycle and the other during the second half.

The bank, thus, is charged to twice the voltage of the transformer, permitting the use of one of a lower voltage rating. Also the initiating gap can be tripped by a surge of either polarity, since one sphere of the initiating gap is at a positive potential of a certain value and the other at a negative potential of the same value. In other types of charging circuits, one end of the bank is at ground potential, while the other is either positive or negative.

One precaution which must be taken in the design of such a charging circuit is the selection of rectifying tubes. The maximum voltage at any one time across the tubes is twice the voltage of the supply transformer. It is thus necessary to use tubes with an inverse voltage rating equal to the voltage of the condenser bank, or twice that of the supply transformer.

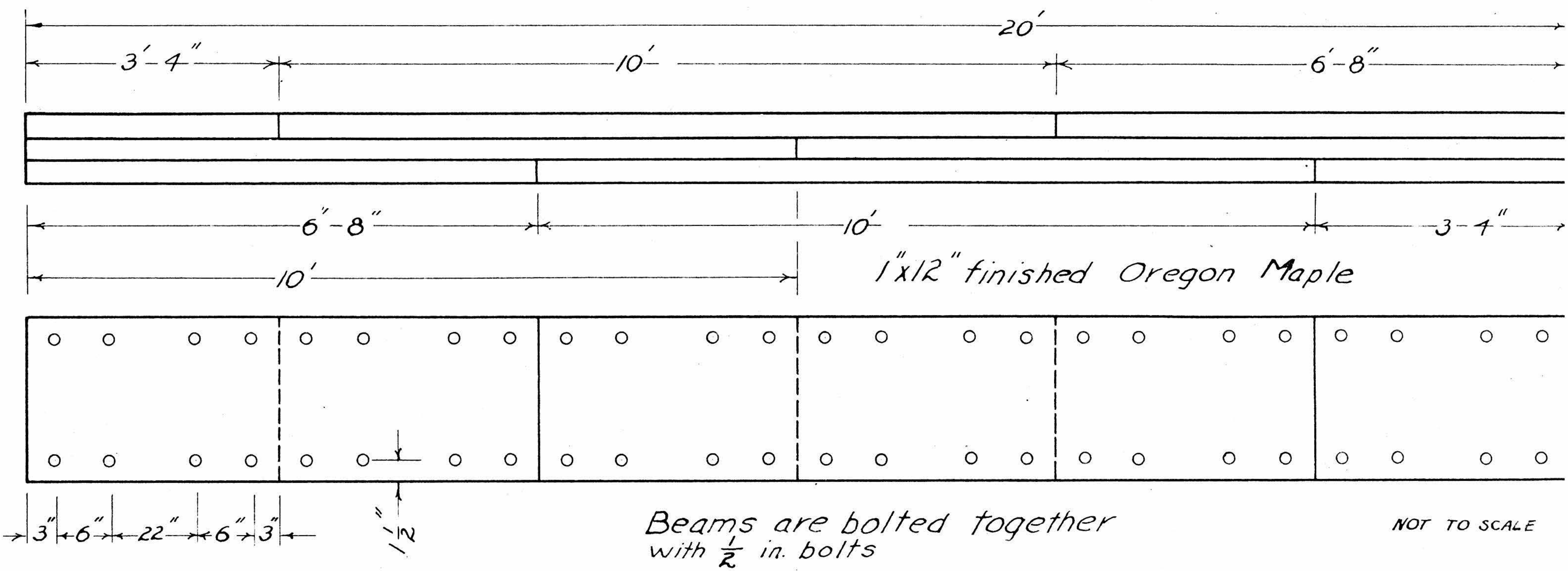
SPECIFICATIONS OF THE CALIFORNIA INSTITUTE OF TECHNOLOGY SURGE GENERATOR

The surge generator just completed in the high voltage laboratory of the California Institute of Technology is of the type that has been described.

Description and Plans of Structure

The frame work was designed so that if at any time it is desirable to do so its length can be increased to permit the addition of more banks of condensers and the attainment of higher voltage. It is so built and situated in the high voltage laboratory that at least four million volts can be attained. The width of the frame work is such that six of the General Electric 50,000 volt, 5 micro-farad Pyranol condensers may be placed on each bank with the minimum required spacing. The dimensions of these condensers are given in figures 3 and 4.

At the present time, the framework consists of five banks and four condensers are being used per bank, giving a rating of one million volts. It is made of Oregon maple



Plan of Side Beams.

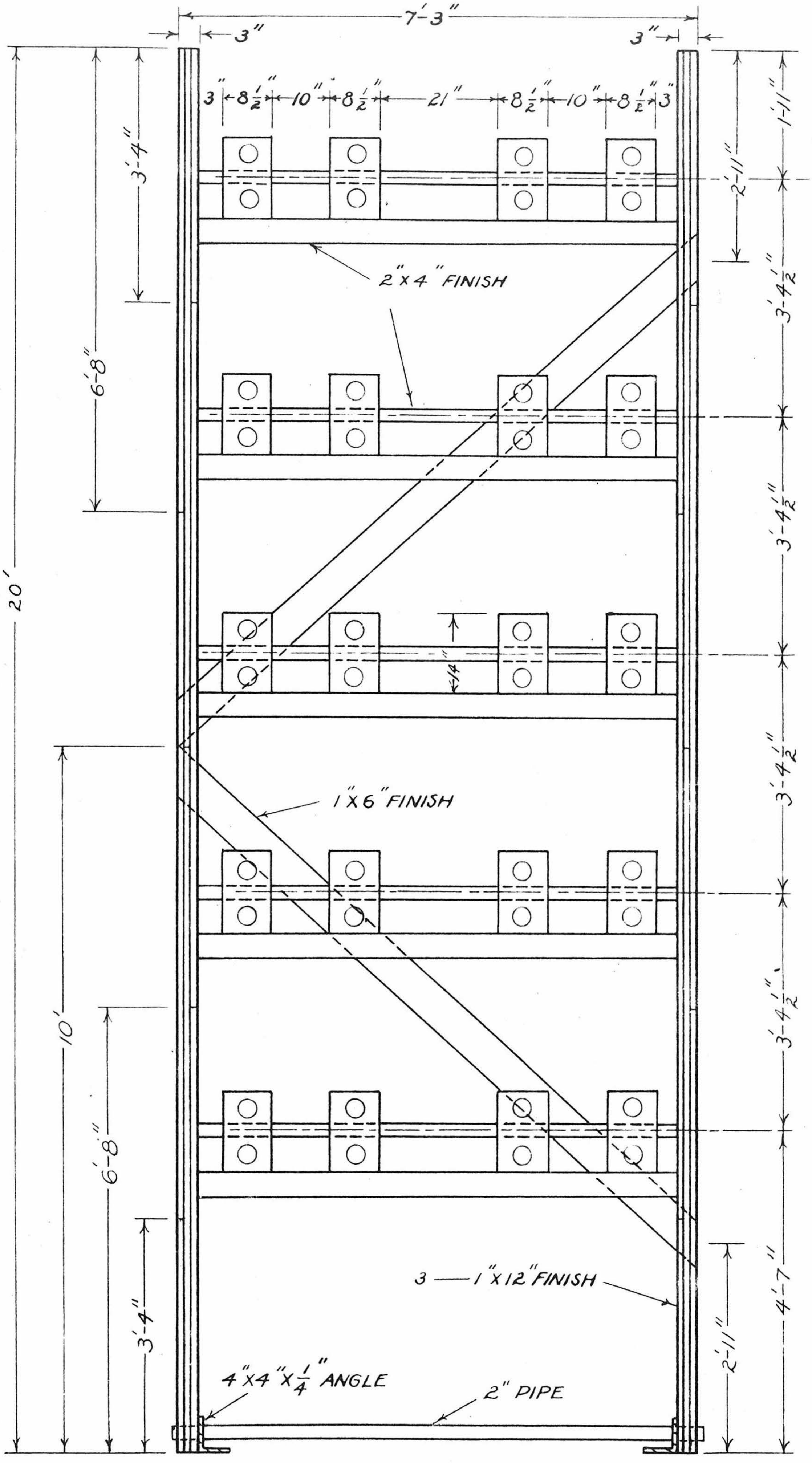
Fig. 2

all of which was parafin dipped. The structure is fastened together almost entirely with bolts.

The essential features of the framework are shown in figures 2, 3 and 4. As can be seen from these figures, its over-all dimensions are twenty feet by seven feet three inches, and it consists of two main beams twenty feet long and cross pieces forming the cradles for the condensers constructed of two by fours. The structure is further braced by two one inch by six inch braces.

The plan of the main beams is shown in figure 2. They are made of one inch by twelve inch finished maple bolted together in three layers with one-half inch bolts. The length of each board is such that all joints are evenly distributed throughout the length. The joints are all tightly fitted. As shown in figure 2, the bolts are arranged symetrically about each section with eight bolts per section.

Figure 3 shows the top view and figure 4 a side view of the assembled framework. The supports for each bank of condensers consist of three two inch by four inch



TOP VIEW.

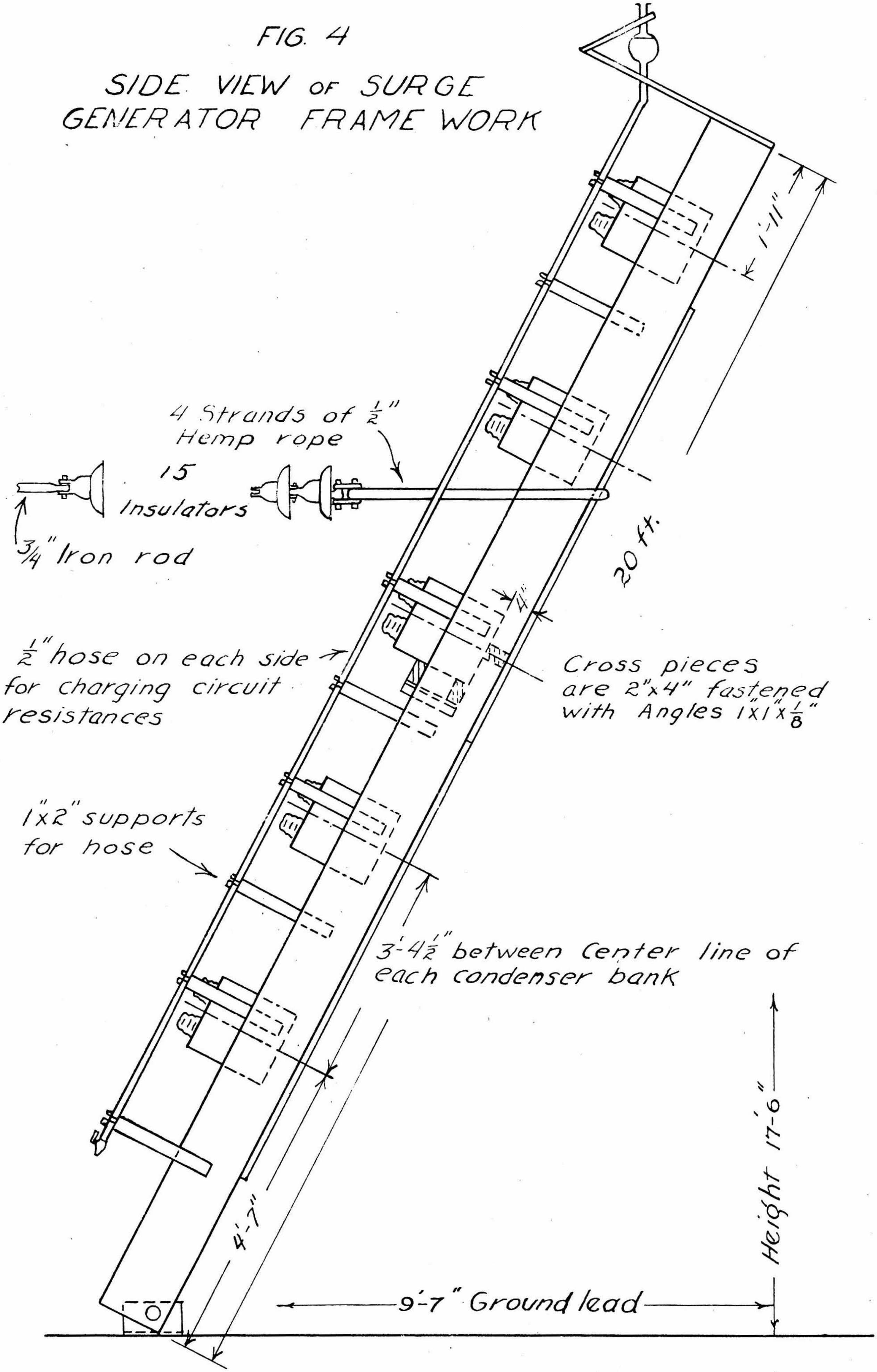
SURGE GENERATOR
FRAME WORK

SCALE 1/2" = 1 FOOT

Fig. 3

FIG. 4

SIDE VIEW OF SURGE GENERATOR FRAME WORK



finished beams fastened to the side beams with one inch by one inch by one-eighth inch angles and one-quarter inch bolts. The two cross braces constructed of one inch by six inch finished lumber are fastened to the bottoms of the side beams with wood screws.

Figure 3 shows the spacings of the condensers as they are arranged at present and the support for the gaps which runs the whole length of the framework. It consists of a runner carrying one sphere of each gap, except the triple gap, and guides upon which the other sphere of each gap is mounted. By this method, all of the gaps are adjustable simultaneously.

Figure 4 shows the method of supporting the framework which is set at an angle of about sixty degrees with the floor. Its base is connected with a two inch pipe to two four inch by four inch by one-quarter inch angles which are bolted to the concrete floor with one-half inch bolts. The two top supports are fastened to the floor of the first balcony with four inch by four inch by one-quarter inch angles, to which are fastened three-quarter inch iron rods. To each rod is fastened

Fig. 5

1. Standard Rod Gap
2. Kenotrons

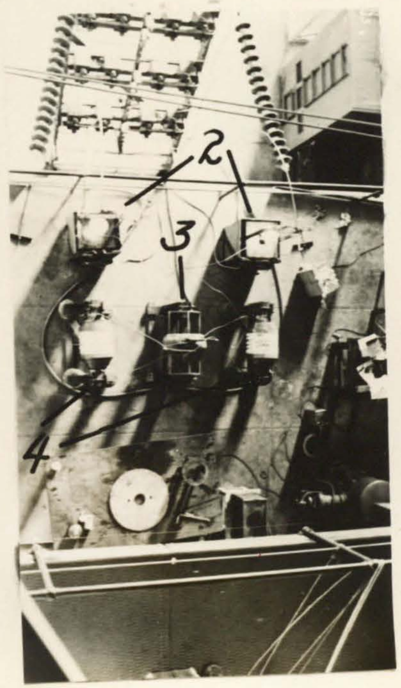


Fig 6

3. Insulation Transformer
4 Supply Transformers

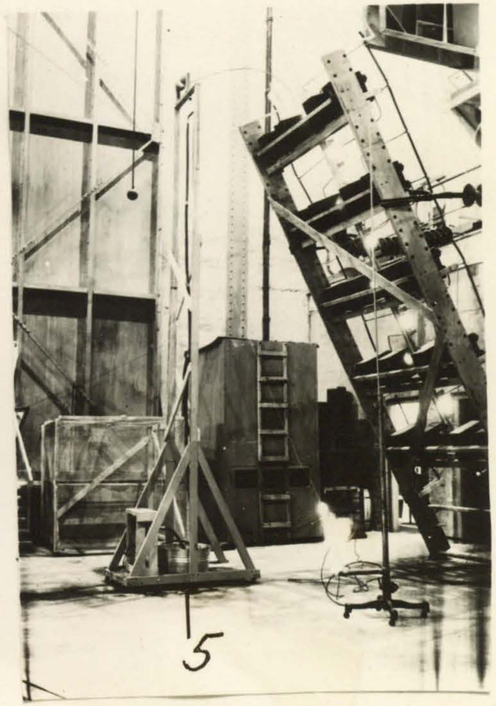


Fig. 7

5. Discharge Resistance

a string of 15 standard suspension insulators, which are in turn fastened to the surge generator framework with four strands of half inch hemp rope.

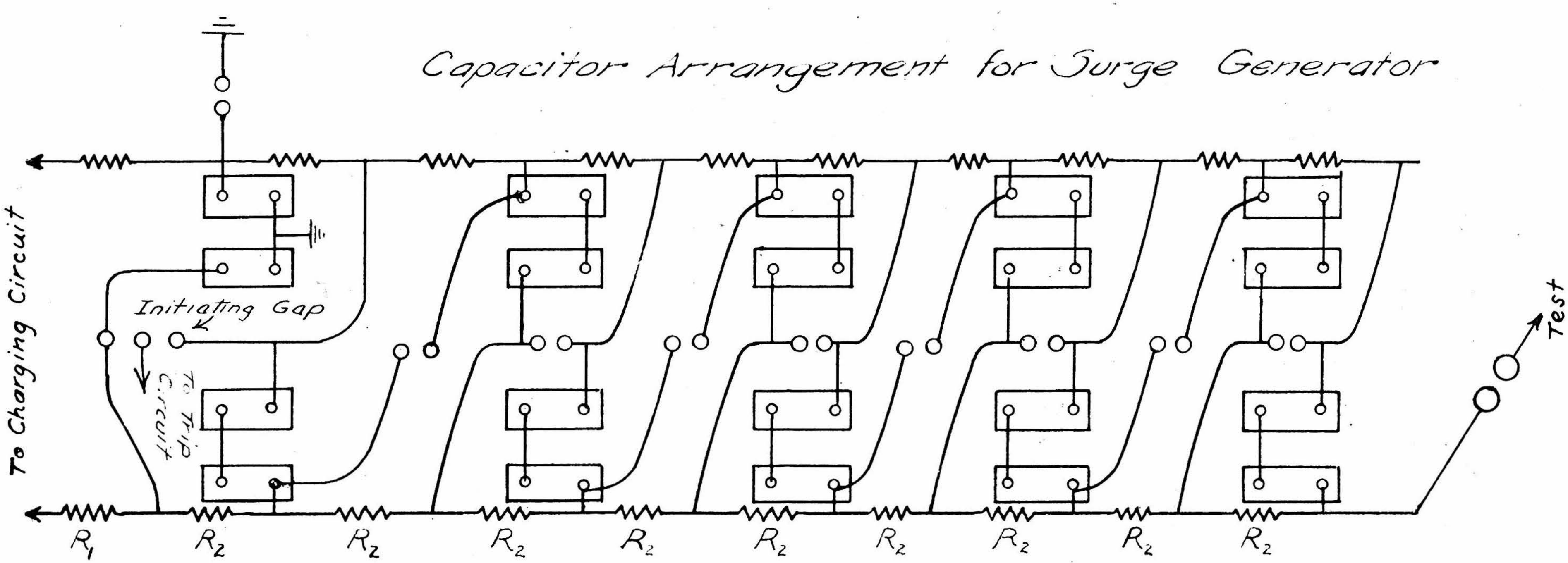
<u>The Condenser Circuit</u>

As shown in figure 8, although the condensers are arranged in five banks of four each, they are actually charged in ten sets of two each. This arrangement was necessary due to the voltage limitations of the Kenotrons which permit a maximum voltage across each set of 100 kilo-volts.

There are eleven discharge gaps, all but the top being made of three inch plumbers balls. The top gap, which is located as shown in figure 7 on top of the discharge circuit framework, is made of six inch plumbers balls. All of the balls are mounted on one-quarter inch brass shanks set in maple uprights.

The value of the charging resistors between each bank is 100,000 ohms, since this has been found empirically to be the least resistance that will protect against a surge voltage of 100 kilo-volts. They are formed by two water columns made of one-half inch

Capacitor Arrangement for Surge Generator



20 G.E. Pyronol Capacitors

50,000 V. 0.5 μF

$R_1 = 50,000\,\Omega$

$R_2 = 100,000\,\Omega$

Sphere Gaps: 2.5" spheres

Fig. 8

hose supported on the framework with one inch by two inch maple pieces, as shown in figure 4. The hose is cut in sections long enough to provide the proper resistance with tap water and is connected at the points where the circuit leads are fastened to it with one-half inch o.d. copper tubing.

It is, of course, necessary to adjust either the length of each section or the conductivity of the water to obtain the right resistance. In this case, ordinary tap water provides 100,000 ohms resistance for the 18 inch sections.

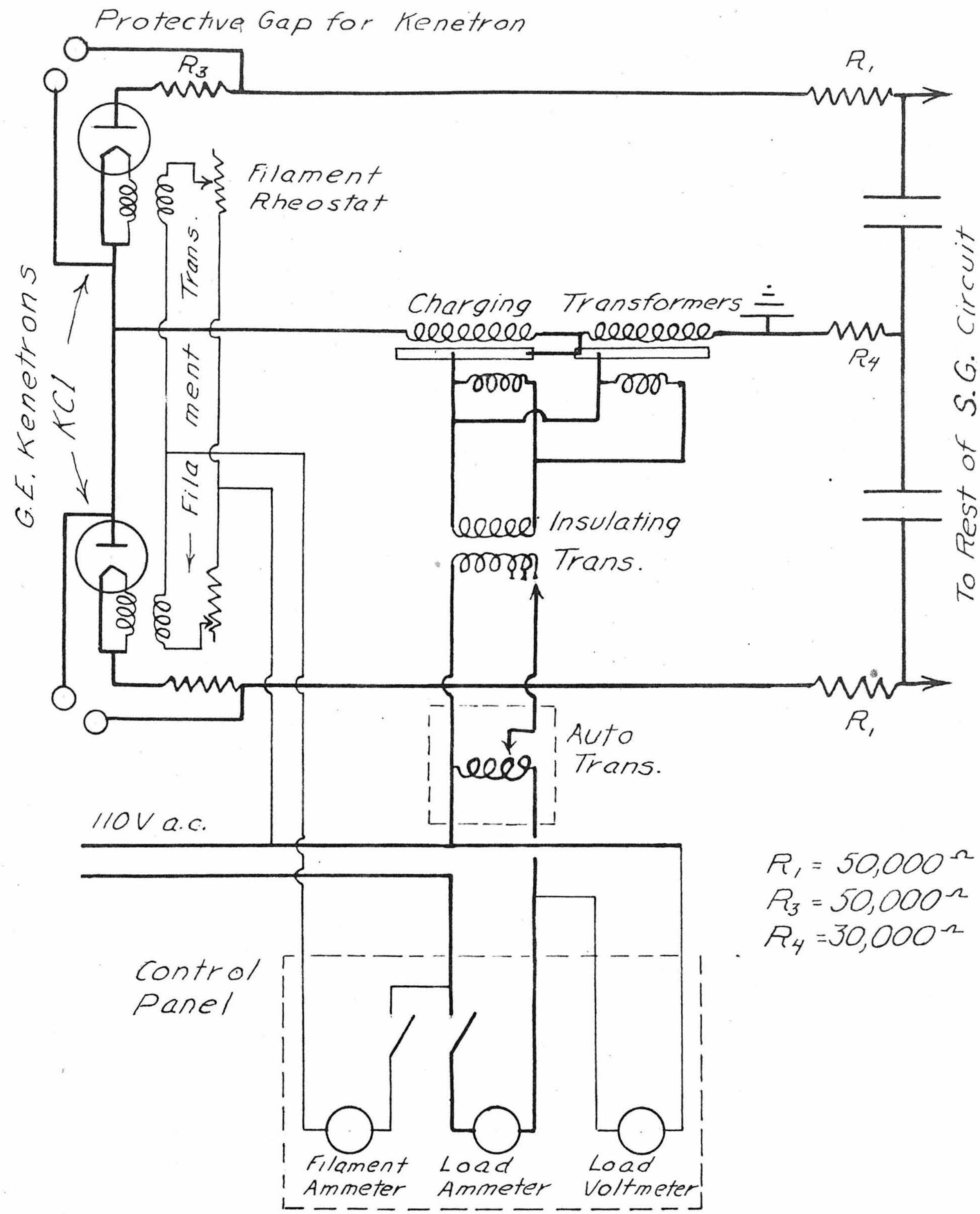
The leads in the discharge circuit are made of one-half inch o.d. copper tubing arranged so that the minimum spacing between each lead is ten inches. This is the minimum safe spacing for this type of configuration under surges with a difference of 100 kilo-volts between them.

The Charging Circuit

The charging circuit is shown in figure 9. The tubes used are General Electric Kenotrons (KC1) having

FIG 9

SURGE GENERATOR CHARGING CIRCUIT



an inverse voltage rating of 100 kilo-volts. The specifications of these tubes are given in table I. As shown in figure 6, the tubes are mounted on a metal container which has in it the filament transformer immersed in transformer oil. In this manner, the primaries and secondaries of the filament transformer are insulated against the high voltage of the secondaries.

There are two supply transformers used in series as shown in the circuit diagram, figure 9. These transformers are shown in figure 6 and their specifications are given in table II.

The insulating transformer is an air core transformer and is also shown in figure 6.

The auto-transformer for voltage regulation is designed to give regulation of from 50 to 110 volts in 10 volt steps. As shown in table V, this gives a charging voltage e_o* regulation of from 400 to 1000 kilo-volts.

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* e_o is the sum of the voltages across all of the condensers at the instant of discharge.

SPECIFICATIONS OF EQUIPMENT

TABLE I

Kenotrons

Filament	
Voltage	9.00
Current (Amp.)	32.00
Type	Tungsten
Maximum Peak Inverse Voltage	100,000
Maximum Peak Plate Current (Amp.)	1.00
Overall Dimensions	
Maximum Length	25-1/8"
Minimum Length	24-7/8"
Maximum Diameter	8-1/8"

Potential test-base of tube to edge of filament transformer container-flashed over at 130 KV

TABLE II

Supply Transformers

Core Type	
Mean Dimension of Window	33"x15"
Cross Section	4"x 6"

Rating 50,000/110 volts

Potential test-with 110 on primary-48 KV on secondary.
Regulation with 40 Amps. on primary about 60%.

TABLE III

Insulating Transformer

Core Type	
Window	34"x29"
Cross Section	4"x 5"
Primary	114 turns
Secondary	50 turns

Taps on Primary at 16, 31 and 47th turns

Potential test-primary to secondary windings flashed over 100 KV.

TABLE IV

Auto-Transformer

Shell Type	
Cross Section	4"x 4"
Windows	15"(legs)x12"

86 Turns
Primary Voltage 110 with 50, 60, 70, 80, 90, 100, and 110 volt taps for secondary

TABLE V

VOLTAGE CALIBRATION OF SURGE GENERATOR

110 volts applied to auto-transformer

Auto-trans. voltage taps	50	60	70	80	90	100	110
Voltage on auto-trans. secondary	45	59	71	84	90	95	110
Voltage across one condenser KV	20	28	34	39	41	45	50
e_o (KV peak)	400	560	680	780	820	900	1000

Voltage was measured across one condenser of the bottom bank of two with a 12.5 cm. sphere gap.

USE AND DEFINITION OF TEST WAVES

In the use of the surge generator, it is necessary to produce surges that are similar to those produced by natural lightning upon transmission lines and connected apparatus. Results of tests with the use of the Cathode Ray Oscillograph of such equipment under lightning strokes show that such surges may vary between wide limits from oscillatory waves of steep wave front to non-oscillatory waves of relatively sloping front; and that the surges are modified as they progress along a transmission line by the constants of the system, so that from the same stroke parts of the line and equipment at different places will have different surges impressed upon them.

In the earlier stages of surge testing, the different laboratories used a great variety of waves. It was in this stage that an attempt was made to define surges and many unsatisfactory definitions resulted. Waves were sometimes defined as to the portion used, whether whole or chopped; as to the steepness of the wave front, the crest value, or the shape of the tail. One very common method was to define the wave in terms of an equivalent frequency by considering the wave from zero to crest value as one-fourth of a cycle.

At the present time, however, it is the concensus of opinion that the majority of the surges caused by lightning and the ones which produce the most damage (cause insulation breakdown) are of short duration, have steep fronts and are non-oscillatory. Due to this and the great difficulty that has been encountered in obtaining consistant results throughout the country, the effort has been to have a few of the most representative waves standardized.

Out of this effort has grown a very satisfactory method of wave definition. Considering a non-oscillatory wave, which is the standard type adopted, it is defined by three terms; the crest value in kilo-volts, the time from zero to crest value (t_1) in micro-seconds, and the time from zero to one-half crest value (t_2). See figure 15.

It is obvious that specifying only two points of a curve, theoretically does not define it. But this definition carries with it the assumption that the wave is a smooth curve with the tail decreasing along an exponential curve. Due to the similarity of surge generators throughout the country, all waves produced by them and satisfying the above requirements are essentially the same.

There are today three waves which are somewhat standard and may be adopted as such by the American Institute of Electrical Engineers. They are the ($\frac{1}{2}$-5) micro-second wave, the (1-10) micro-second wave and the ($1\frac{1}{2}$-40) micro-second wave.

The ($\frac{1}{2}$-5) wave gives a crest flashover value of at least 150% of the 60 cycle flashover value where considerable time lag is involved. It is used primarily in testing insulators.

The (1-10) wave gives flashover values of about 125% of the 60 cycle crest flashover voltage where considerable time lag is involved.

The ($1\frac{1}{2}$-40) wave gives flashover values of about 110% of the 60 cycle values, and is more satisfactory for voltage time considerations.

Flashover with all of these surges usually occurs on the tail of the wave, but as the crest value of the surge is increased, it is brought nearer to the crest. Curves representative of the three waves as actually produced are shown in figure 15, where it can be seen (as is generally the case) that all three waves have fronts which rise at the same rate. The difference in the time to crest value occurs in the last 10% of the voltage rise.

At the present time, the (½-5) wave is less used because of the difficulty in obtaining it with the present high voltage generators and the longer discharge circuits. It has therefore been recommended* that a (1-5) wave be substituted instead.

The standardization of these three surges does not mean that they are the only ones used or specified for regular testing. There are other waves used for certain types of testing. For instance, the specifications for lightning arrestor testing require a wave which rises to crest in three micro-seconds.

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* "Recommendations for Impulse Voltage Testing", A.I.E.E., V 52, p 467.

ATTAINMENT OF TEST WAVES

The problem of actually applying these standard waves to test pieces is a difficult one. Before the perfection of the Cathode Ray Oscillograph, which gives a complete picture of the wave, the only means of determining wave shape was by means of a mathematical analysis of the circuit. Due to the difficulty in accurately determining the constants of the circuit under surge conditions and of analysing such a complex circuit, accurate results were seldom obtained. Simplified approximate equivalent circuits were used which did not represent true conditions. This difficulty has not yet been entirely overcome, and the Cathode Ray Oscillograph is the primary method of determining the wave shape. However, the development of the mathematics, the ability to more accurately determine circuit constants and their effect upon results have lead to much greater accuracy.

Even though the Cathode Ray Oscillograph has supplanted some of the former usefulness of the mathematical analysis in the determination of wave shape and magnitude of surges, it still plays an important part in surge testing.

In order to use the Cathode Ray Oscillograph effectively in obtaining the desired wave, it is necessary to have some starting point. At least an approximate idea must be known of the proper values of the circuit constants. Then too, the mathematical analysis affords the knowledge of how to correct the circuit to eliminate the deviations from the desired wave as shown by the Cathode Ray Oscillograph.

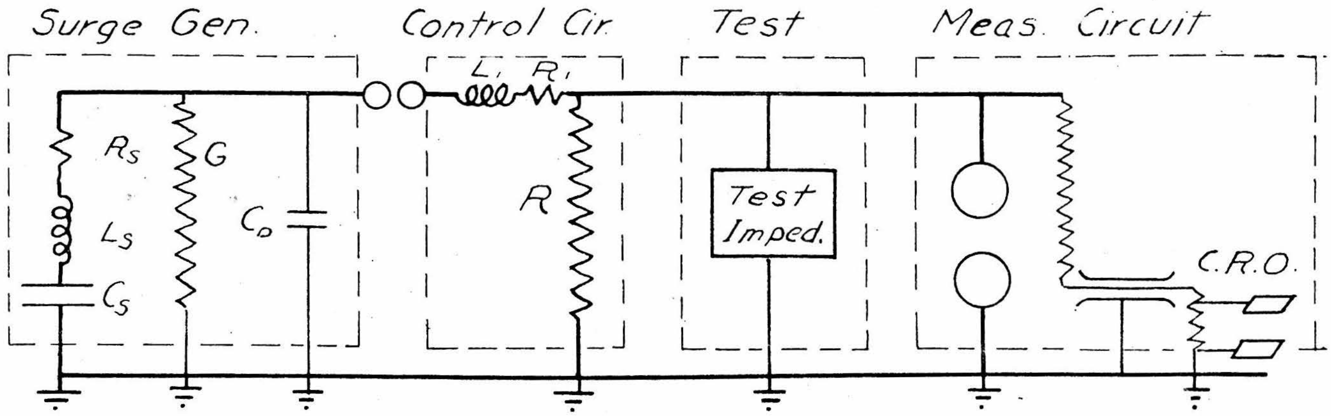
Mathematical Analysis

The complete circuit diagram, if all constants are considered to be lumped, is shown in figure 10a. The calculation of such a circuit is obviously too difficult, and some simplifications are needed before it can be analysed. The Cathode Ray Oscillograph circuit theoretically should be constructed so as to have no effect upon the wave as applied to the test piece and should accurately record it. Thus, for the purposes of this analysis it can be neglected.

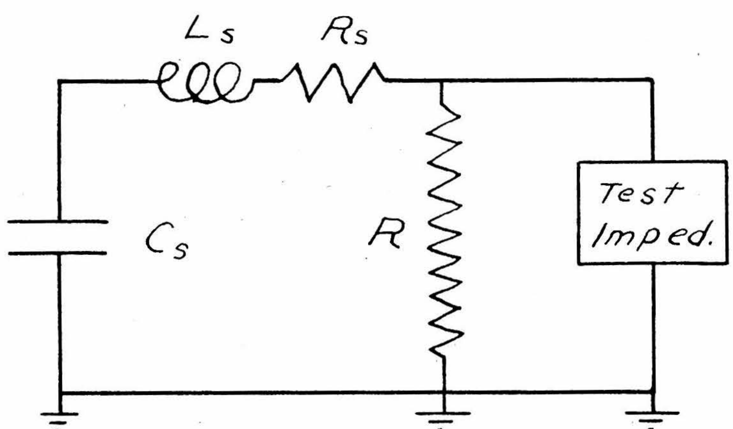
The values of the distributed capacitance to

FIG. 10

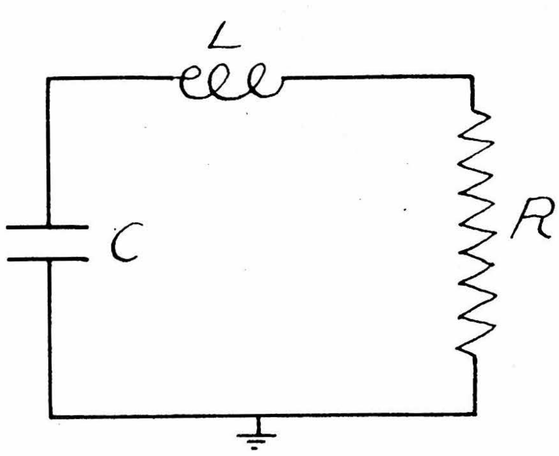
(A.)


Surge Gen.
Control Cir.
Test
Meas. Circuit
L_1 R_1
R_s
G
L_s
C_s
C_p
R
Test Imped.
C.R.O.

(B.)


L_s
R_s
C_s
R
Test Imped.

(C.)


L
C
R

ground (C_d) and the conductance to ground (G) of the surge generator proper are usually small enough to be neglected without serious error. In some of the large surge generators, however, they do become appreciable. Sometimes (C_d) is taken account of by lumping it with the capacitance of the test piece. Neglecting these quantities gives a circuit as shown in figure 10b. This circuit has been analysed for different types of loads and will be considered later.

The circuit having the most practical significance is the one shown in figure 10c where the load is entirely neglected. In many cases the impedance of the load is such that it can be neglected without appreciable error, as in insulator testing. Even if the load is appreciable, the use of this circuit through its simplicity is important to determine approximately the values of the circuit constants for a given wave under any loading. This, then, is the starting point in any test, and further refinements can be made to suit each particular one with the use of the Cathode Ray Oscillograph and a knowledge of the effect of the other factors upon the wave shape.

<u>Derivation of Equations for the Simplified Circuit</u>

Writing Ohm's law for any instant around the circuit shown in figure 10, the following differential equation is obtained:

(1) $$e = iR + L\frac{di}{dt} = q/C$$

where $e = \frac{q}{C}$ = instantaneous voltage across all condensers in series

q = instantaneous value of charge on condensers

i = instantaneous value of current

R, L and C are the three circuit constants

Differentiating with respect to time (t)

(2) $$\frac{de}{dt} = \frac{Ld^2i}{dt^2} + \frac{Rdi}{dt} = \frac{i}{C}$$

$\frac{dq}{dt} = -i$ since upon discharge of condensers, q is decreasing

Letting $\frac{d}{dt} = D$

$$\frac{de}{dt} = LD^2i + RDi = -\frac{i}{C}$$

(3) $$(LD^2 + RD + \frac{1}{C})i = 0$$

The solution for this equation is given by equation 4.

(4) $$i = A_1\varepsilon^{D_1 t} - A_2\varepsilon^{D_2 t}$$

where $D_1 = -\frac{R}{2L} + \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}$

$D_2 = -\frac{R}{2L} - \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}$

$D_1 = -\alpha + \beta \qquad D_2 = -\alpha - \beta$

$D_1 = -(\alpha - \beta) \qquad D_2 = -(\alpha + \beta)$

(5) $$i = A_1\varepsilon^{-(\alpha-\beta)t} + A_2\varepsilon^{-(\alpha+\beta)t}$$

Solution for A_1 and A_2:

At instant of discharge $t = 0$ and $i = 0$, since there is inductance in the circuit

Equation (5) at this time reduces to $0 = A_1 - A_2$

(6) $$A_1 = -A_2$$

Differentiating (5) and substituting in it the conditions when $t = 0$, equation (7) is obtained.

(7) $$\frac{di}{dt} = \left[-(\alpha-\beta)A_1 - (\alpha+\beta)A_2\right]$$

Substituting equation (7) and the value of i when $t = 0$ into equation (1):

(8) $$e_o = R(A_1 + A_2) - L\left[-(\alpha-\beta)A_1 - (\alpha+\beta)A_2\right]$$

Solving (6) and (8) simultaneously:

(9) $$A_1 = -A_2 = \frac{e_o}{2\beta L}$$

(10) $$i = \frac{e_o}{2\beta L}\left[\varepsilon^{-(\alpha-\beta)t} - \varepsilon^{-(\alpha+\beta)t}\right]$$

Since the test piece is connected across the discharge resistance, the voltage wave applied to the test is the voltage across the discharge resistance as given by the following equation:

$$e = \frac{e_0 R}{2\beta L}\left[\varepsilon^{-(\alpha-\beta)t} - \varepsilon^{-(\alpha+\beta)t}\right]$$

$$\text{since } \alpha = \frac{R}{2L}$$

$$(11) \qquad e = e_0 \frac{\alpha}{\beta}\left[\varepsilon^{-(\alpha-\beta)t} - \varepsilon^{-(\alpha+\beta)t}\right]$$

The equations by the proper adjustment of the circuit constants will satisfy the conditions for a non-oscillatory wave, a critically damped wave or an oscillatory one. As has been previously mentioned, the non-oscillatory, or aperiodic case, is the one of most practical interest. However, it is sometimes desirable to produce oscillatory surges for their analysis in determining the values of the circuit constants.

Determination of Circuit Constants to Produce a Given Wave

It is the general case in the use of the surge generator that its capacitance is fixed. The variables are, then, R and L.

The voltage has reached its crest value when $\frac{de}{dt} = 0$.

Thus differentiating (11) with respect to t and solving for t:

$$(12) \qquad t_1 = \frac{1}{2\beta} \log_\varepsilon \frac{\alpha+\beta}{\alpha-\beta}$$

This is the equation for time from zero to crest value of the surge.

$$(13) \qquad \text{Letting } b = \frac{\alpha+\beta}{\alpha-\beta} \text{ and } a = \log_\varepsilon \frac{\alpha+\beta}{\alpha-\beta}$$

$$(14) \qquad t_1 = \frac{1}{2\beta} \log_\varepsilon b = \frac{1}{2\beta} a$$

Solving for α and β in terms of a, b and t_1

$$(15) \qquad \alpha = \frac{a}{2t_1}\left[\frac{b+1}{b-1}\right] \text{ and } \beta = \frac{a}{2t_1}$$

The crest value e_1 of the voltage is obtained by substituting in (11) the value of t_1 of equation (14).

$$(16) \qquad e_1 = e_0 \left[\frac{b+1}{b-1}\right]\left[\varepsilon^{\frac{-a}{b-1}} - \varepsilon^{\frac{-ab}{b-1}}\right]$$

The value e_2 at the time t_2 to half crest value is the following:

$$(17) \qquad e_2 = \frac{e_1}{2} = e_0 \frac{\alpha}{\beta}\left[\varepsilon^{-(\alpha-\beta)t_2} - \varepsilon^{-(\alpha+\beta)t_2}\right]$$

Substituting in (17), the values of α and β as given by equation (15):

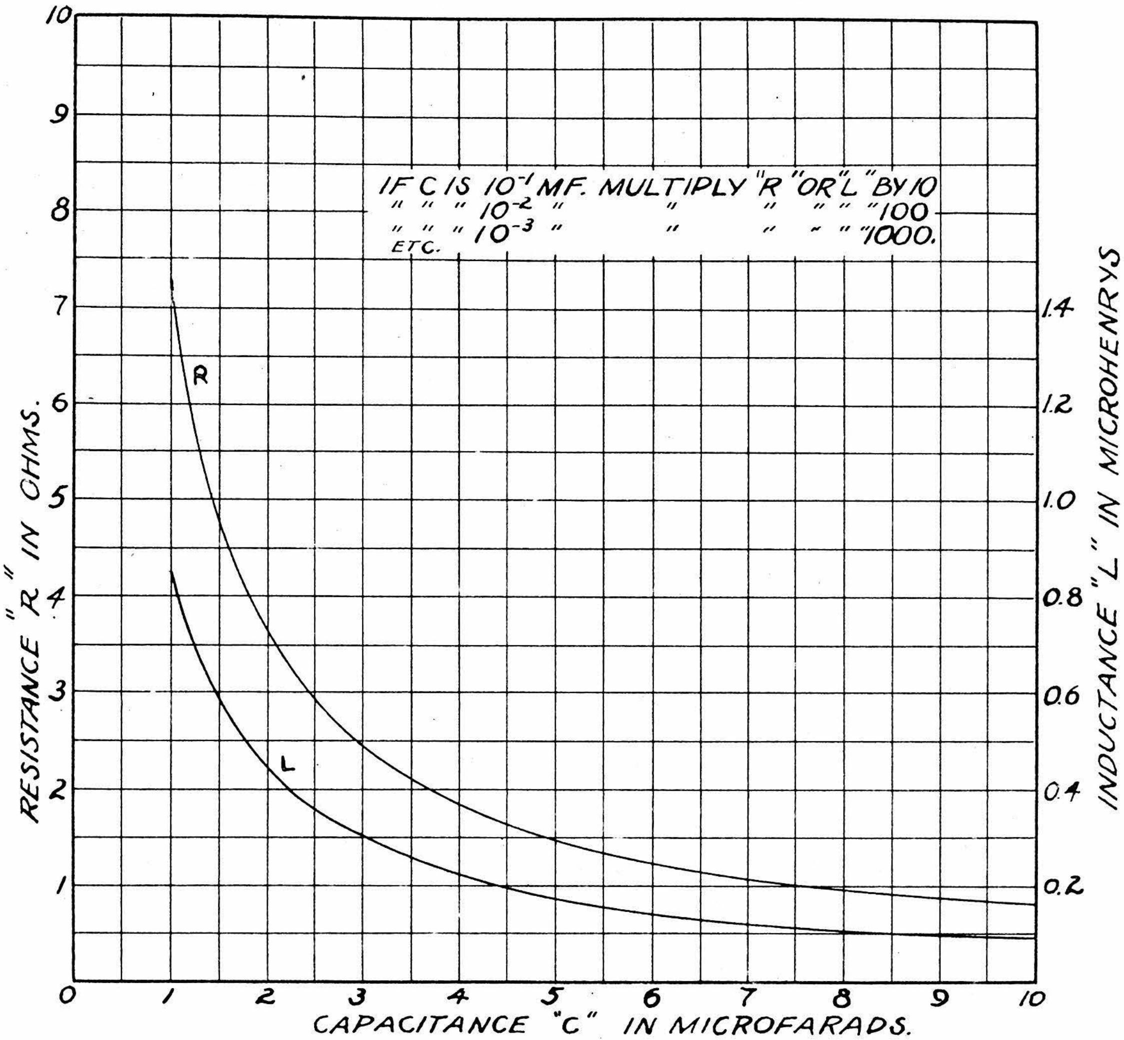
$$(18) \qquad e_2 = e_0 \frac{b+1}{b-1}\left[\varepsilon^{\left(\frac{-a}{b-1}\right)\frac{t_2}{t_1}} - \varepsilon^{\left(\frac{-ab}{b-1}\right)\frac{t_2}{t_1}}\right]$$

Curves can now be plotted of e_1 and $2e_2$, for any given ratio of t_2 over t_1 against <u>a</u>. The intersection of the two curves gives the proper value of <u>a</u> to give the desired wave defined by t_2 over t_1. From this and the equation for t_1, the values of α and β and hence of R and L can be obtained.

Curves showing the values of R and L as a function of C determined in this manner for the three standard waves are shown in figures 11, 12 and 13. From these curves the proper values of R and L can be found for a surge generator of any capacity. In table VI are shown the proper values for the California Institute of Technology surge generator as taken from these curves.

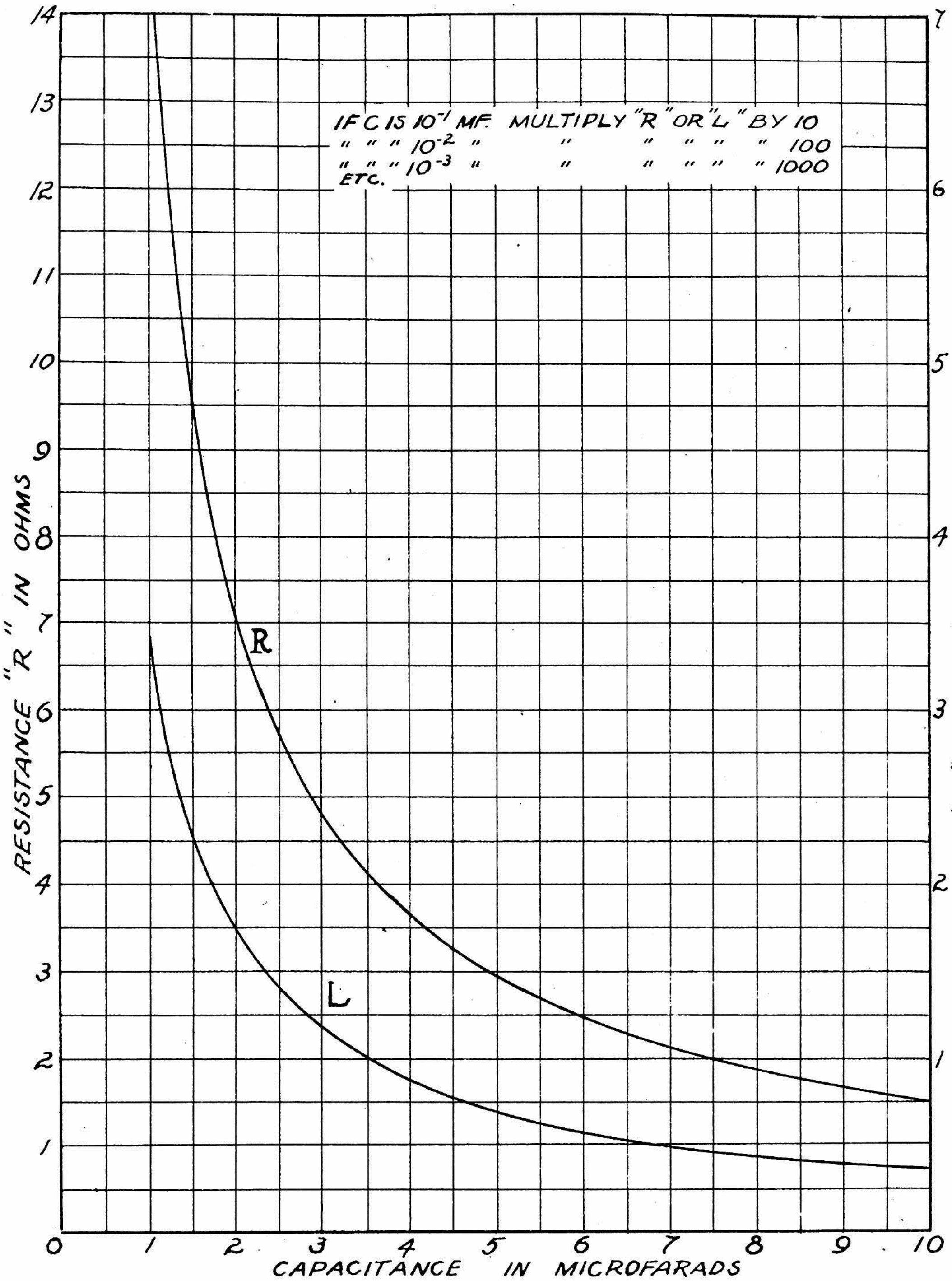
It might be noted here that in obtaining any specified wave, the crest value of the wave cannot be adjusted by changing the circuit constants. For any given wave shape it can be varied only by varying e_0, the voltage applied to the condensers in charging them.

In figures 14 and 15 are plotted the three standard calculated waves for a capacitance of .025 micro-farads. These, then, are theoretically the waves that should be obtained with the C. I. T. surge generator.



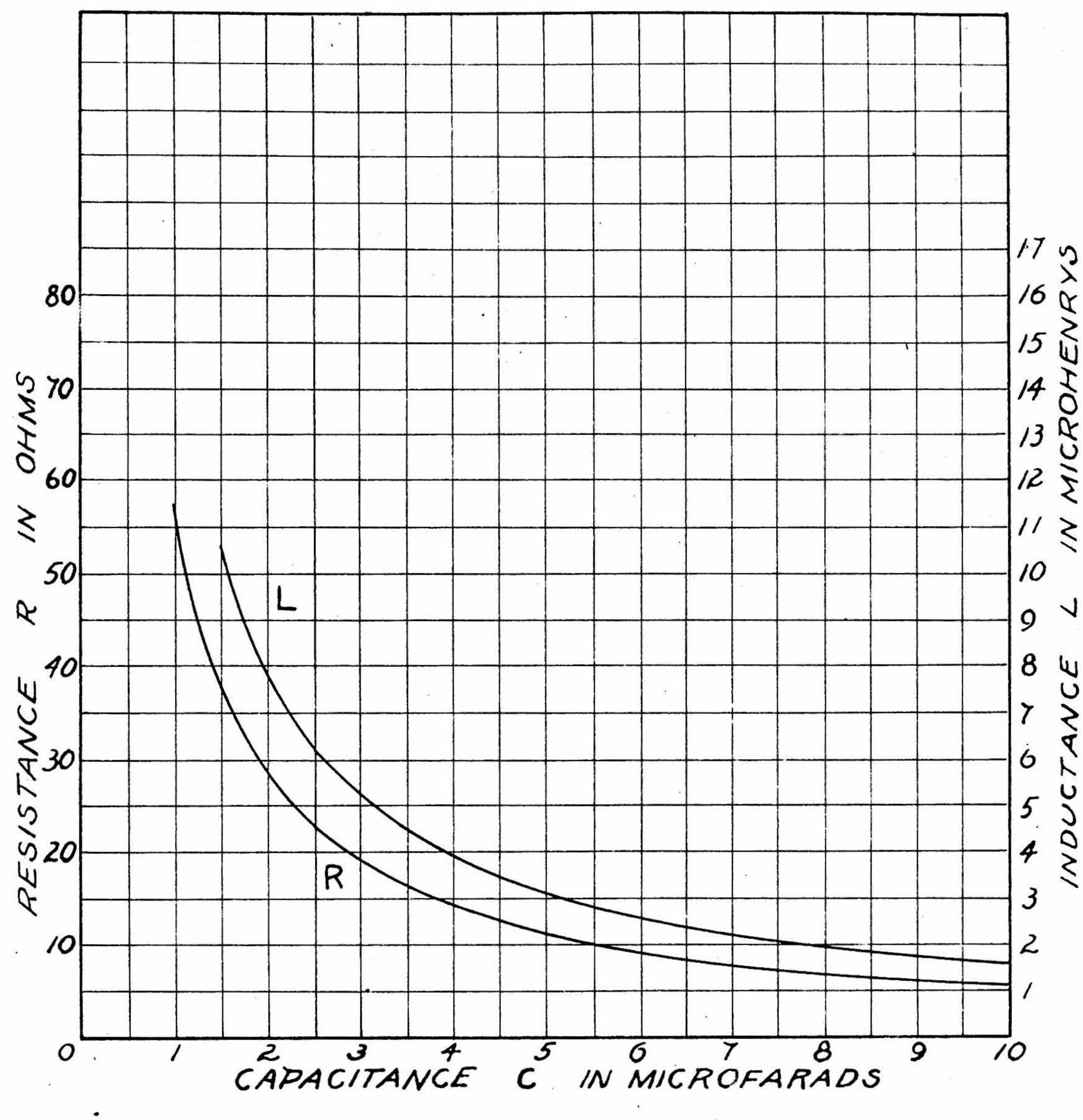
Circuit Constants for ½-5 Wave.

Fig. 11



Circuit Constants for 1-10 Wave.

Fig. 12



Circuit Constants for $1\frac{1}{2}$-40 Wave.

Fig. 13

THE CALIFORNIA INSTITUTE OF TECHNOLOGY SURGE GENERATOR

TABLE VI

Circuit Constants for Standard Waves

Wave	C micro-farads	L micro-Henries	R ohms
$\frac{1}{2}$-5	.025	36	290
1-10	.025	130	570
1$\frac{1}{2}$-40	.025	620	2300

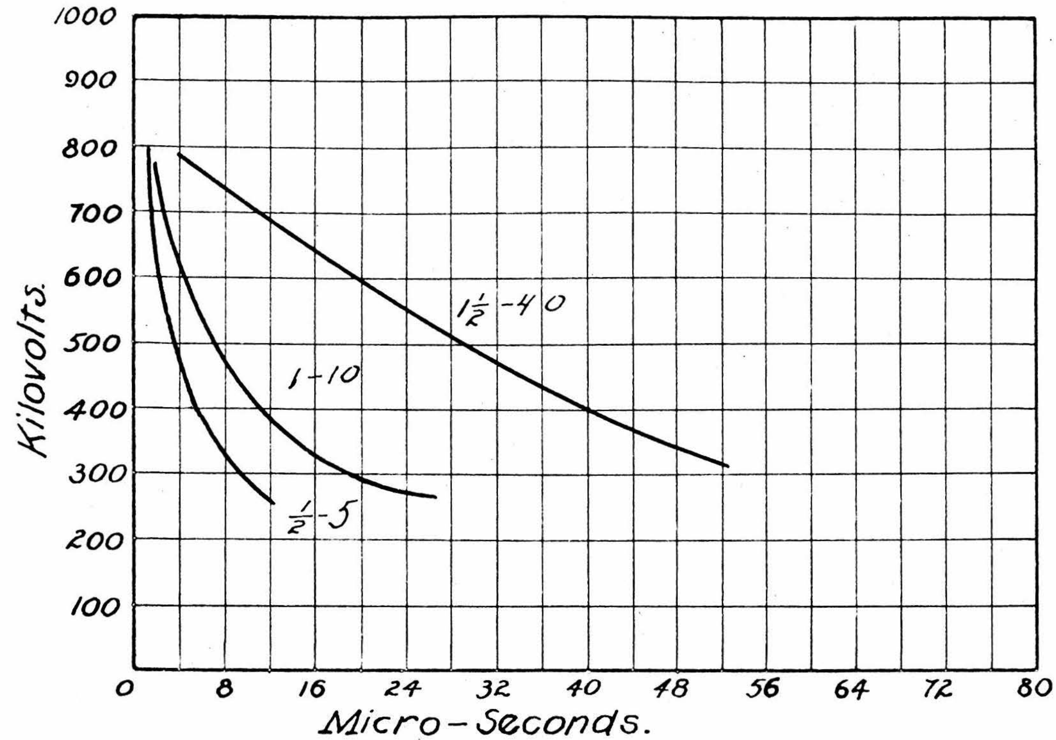


Fig. 14

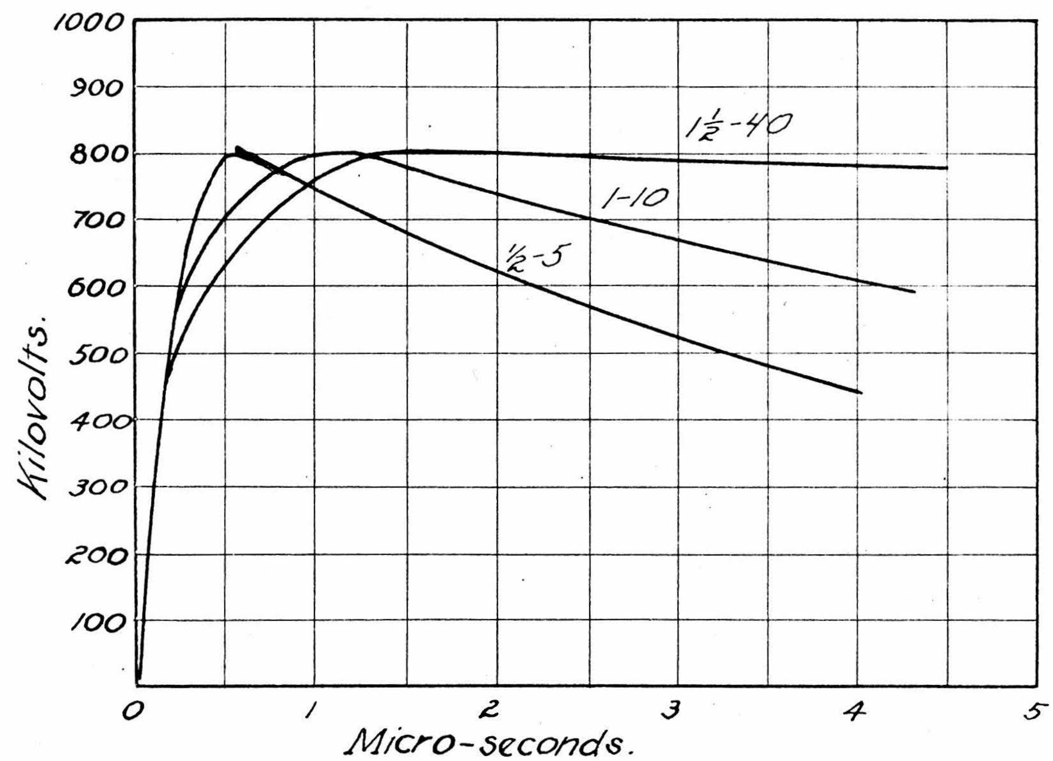


Fig 15

Calculated Standard Waves

DETERMINATION OF THE SURGE GENERATOR CONSTANTS

The inherent constants of the circuit which must be evaluated for the control of wave shapes are the following:

1. The series capacitance which consists primarily of the capacitors.

2. The inherent inductance of the surge generator which includes the discharge circuit and ground lead.

3. The surge resistance of the connections and gaps of the surge generator proper.

4. The distributed capacitance of the surge generator to space.

The last item is usually so small that it, along with the conductance to ground, can be neglected.

These constants, although distributed, must be treated as lumped and are determined by one or more of the following three methods:

1. The actual measurement with suitable equipment.
2. The calculation from physical considerations.
3. The calculation from analysis of oscillograms taken under the proper conditions.

None of these methods are exact. Actual measurements of constants are necessarily taken under steady state conditions which differ from surge conditions. The calculation from physical considerations requires simplifying assumptions which are not absolutely precise. The attainment of oscillograms under the exact conditions necessary is usually impossible, due to the values of the inherent constants themselves. Usually, however, this method gives the most accurate results. It is thus seen that it is very desirable to determine each constant in as many ways as possible.

Series Capacitance

The series capacitance is primarily that of the condensers themselves, the values of which are given on the name plates. However, it is more accurate and sometimes advisable to measure it directly with either a Schering or an Atkinson bridge. When a bridge is used, the gaps are shorted out and the charging resistors disconnected.

An approximation as to the value of the capacitance of the gaps can be made by the actual calculation for the capacitance of two spheres, or the gaps can be measured with a bridge. However, it varies with different gap settings, making it difficult to account for. This capacitance is so small in most cases that it can be neglected without much error in the mathematical analysis.

Calculation of the Surge Generator Inductance

Calculation from the Geometrical Configuration: The first part that will be considered is that part of the discharge circuit joining together the condensers as shown in figure 16a. If it is assumed that all conductors are in the same plane (which is very nearly true), little error is introduced by assuming the section (d-e), figure 16a, to be a single straight conductor (k-l), figure 16b. If the portion represented by (k-l-m), figure 16b, is further considered to be a rectangle (w-x-y-z) as in figure 16c, whose sides are $\underline{a} = \frac{1}{2}$k-m and $\underline{a_1}$ = k-l, the configuration thus arrived at can be calculated. The equivalent circuit, then, consists of four rectangular turns and two sides of a rectangle at the top.

FIG. 16

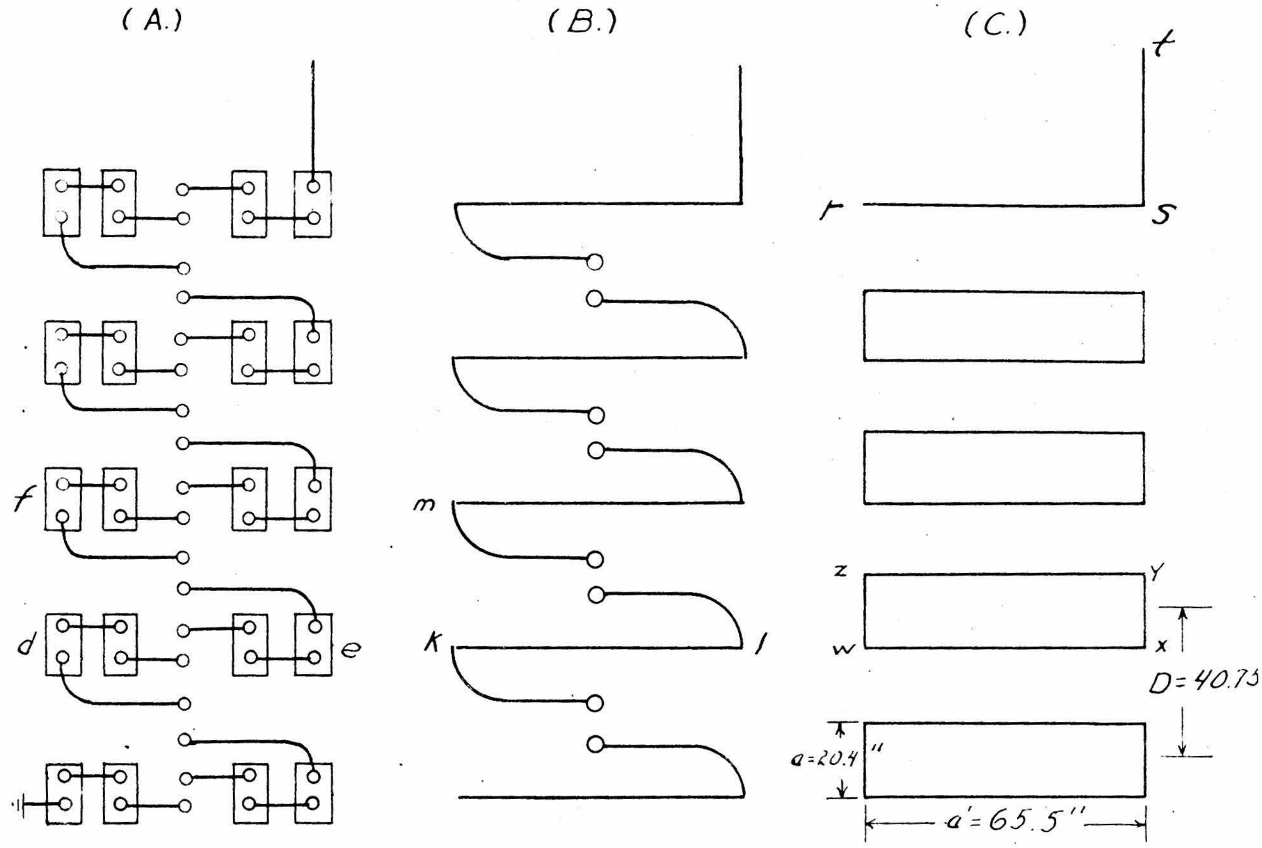
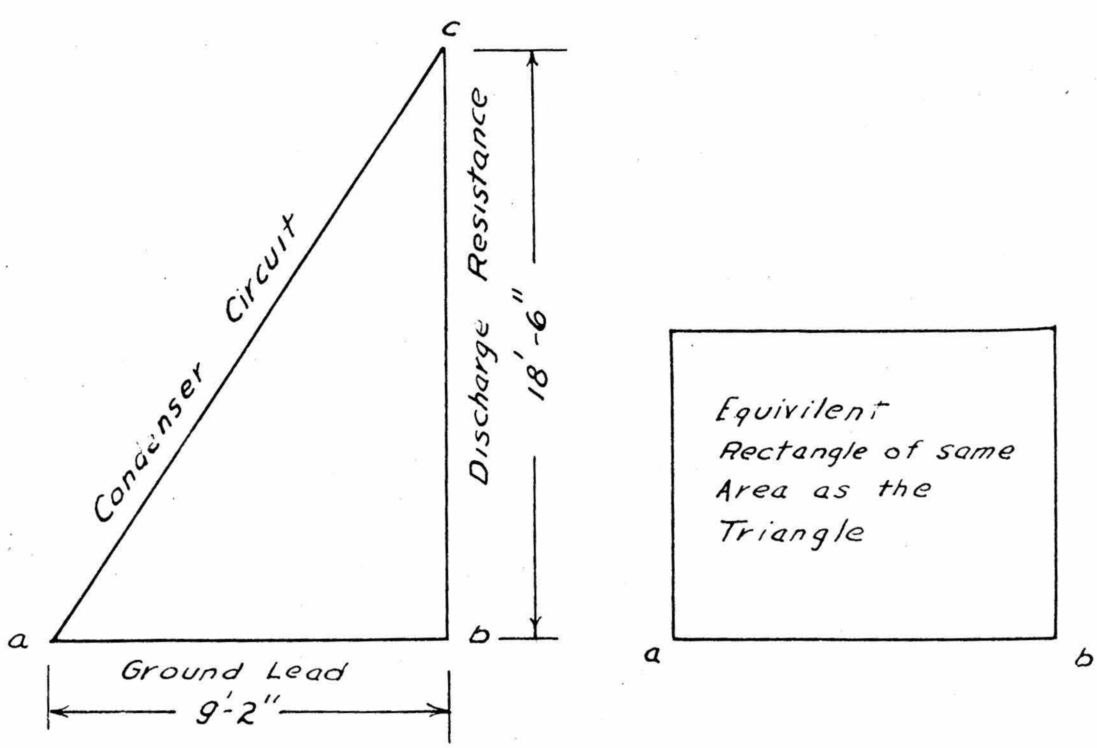

(A.)
(B.)
(C.)
f
d
e
m
K
l
t
r
s
z
Y
w
x
D = 40.75
a = 20.4"
a' = 65.5"

FIG. 17


c
Condenser Circuit
Discharge Resistance
18'-6"
a
b
Ground Lead
9'-2"
Equivilent
Rectangle of same
Area as the
Triangle
a
b

The precise effective diameter of the conductors under surge conditions is unknown. In this case, it was assumed equal to the physical diameter, since it is hollow tubing.

All of the formulas given in the following are taken from the Scientific Bulletin of the Bureau of Standards, Volume 8 for the year 1912.

Self Inductance: The self inductance of a rectangle in micro-Henries is given by the following formula:

$$(19) \qquad L_R = .00921\left[(a+a_1)\log_{10}\frac{4aa_1}{d} - a\log_{10}(a+g) - a_1\log_{10}(a_1+g)\right] + .004\left[\mu\delta\ (a+a_1) + 2\left(g+\frac{d}{2}\right) - 2(a+a_1)\right]$$

where a is short side of rectangle

a_1 " long " " "

$g = \sqrt{a_1^2+a^2}$

d = diameter of conductor

All dimensions of length and diameter are given in centimeters.

The self inductance of one straight conductor of finite length is given by the following formula:

$$(20) \qquad L = .002\times l\left(2.303\log_{10}\frac{4l}{d} - .75\right) \text{ micro-Henries}$$

The total self inductance of the portion represented by figure 16c is $4L_R + L_{rs} + L_{st}$.

<u>Mutual Inductance</u>: The mutual inductance of two flat rectangular turns is given by the following equation:

$$(21)\qquad M_{12} = .00921\left[a\log_{10}\frac{a+\sqrt{a^2+D^2}}{a+\sqrt{a^2+a_1^2+D^2}} \times \frac{\sqrt{a_1^2+D^2}}{D} + a_1\log_{10}\frac{a_1+\sqrt{a_1^2+D^2}}{a_1+\sqrt{a^2+a_1^2+D^2}} \times \frac{\sqrt{a^2+D^2}}{D}\right] + .008\left[\sqrt{a^2+a_1^2+D^2} - \sqrt{a^2+D^2} - \sqrt{a_1^2+D^2} + D\right.$$

where D is the distance between centers of the rectangles considered.

The mutual inductance of two parallel sections of finite length is given by the following formula:

$$(22)\qquad M = .002\left[l \times 2.303\log_{10}\frac{l+\sqrt{l^2+d^2}}{d} - \sqrt{l^2+d^2} + d\right]$$

where l is the length of conductors.

The total mutual inductance is $6M_{12} + 4M_{13} + 2M_{14}$ as calculated by equation 21, plus the mutual inductance of the length r-s with the long sides of all the rectangles. The mutual inductance of conductors with the length s-t is so small that it may be neglected.

Discharge Circuit: There is next to be considered the inductance of the discharge circuit, including the discharge resistance and its ground lead, in conjunction with the circuit just computed. This is shown in figure 17a.

The self inductance of a-b and b-c can be calculated from equation 20.

The mutual inductance of the set-up can be obtained by calculating the mutual inductance of an equivalent rectangle, figure 17b, whose base a-b is the same as that for the triangle and whose altitude is one-half that of the triangle. Equation 22 is used for this.

Determination of Inductance from Oscillograms

If the resistance of the simple series discharge circuit is close enough to zero, it can be calculated from the equation for the frequency of the wave produced under these conditions.

When $\frac{R^2}{4L^2}$ is less than $\frac{1}{LC}$, β may be written as $j\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$ or $\beta = j$

Equation 11 then reduces to equation 23.

(23) $$e = \frac{e_0 R}{j2\gamma L} \varepsilon^{-\alpha t} (\varepsilon^{j\gamma t} - \varepsilon^{-j\gamma t})$$

(24) $$e = \frac{e_0 R}{L\gamma} \varepsilon^{-\alpha t} \sin\gamma t$$

The period (T) of the wave given by this equation is equal to $2 \frac{1}{\gamma}$. If R is equal to zero, T is given by the following equation:

(25) $$T_1 = 2\pi\sqrt{LC}$$

If the discharge resistance is shorted out and all series resistance removed, the inductance can be found easily with the use of this formula. The oscillogram thus obtained will be somewhat damped due to the inherent resistance. The frequency, however, will not be appreciably affected. L and C are in the order of 10^{-6}, while the inherent resistance is never over 200 ohms. Substitution of these values in the equation for γ will show how little R affects the frequency.

Inherent Resistance

The inherent resistance may be determined from the damping of the oscillations in the oscillogram taken for the inductance calculation.

Considering equation 24: At a time t_1 at which an oscillation has reached a crest value $\sin\gamma t_1 = 1$ and the equation becomes the following:

(26) $$e_1 = \frac{e_o R}{L\gamma} \epsilon^{-\alpha t_1}$$

At the peak of the next wave:

(27) $$e_2 = \frac{e_o R}{L\gamma} \epsilon^{-\alpha(t_1+T)}$$

Where T is the period of oscillations.

$$\frac{e_1}{e_2} = r = \text{the ratio of successive amplitudes}$$

$$r = \frac{\epsilon^{-\alpha t_1}}{\epsilon^{-\alpha(t_1+T)}} = \epsilon^{-\alpha T}$$

$$\alpha = \frac{R}{2L}$$

(28) $$\log_e r = \frac{R}{2L} T$$

By obtaining the period and ratio of successive amplitudes, the inherent resistance can be found.

Distributed Capacitance to Space

When the value of the discharge resistance is such that the wave is essentially non-oscillatory, any oscillations appearing on the crest of the wave will be due to the distributed capacitance of the surge generator as long as there is no test load connected.

This capacitance can be determined by recording the oscillation on the crest of a full wave with all inserted series resistance removed. If T_2 equals the period of the secondary oscillation, L is the inherent inductance, and C_L the distributed capacitance, the equation for the determination of this is given by the following:

(29) $$T_2 = 2\pi\sqrt{LC_L}$$

The theory for this is the same as that for equation 25.

An approximation of this capacitance can be made by finding the capacitance of the connecting leads of the surge generator to space. In some laboratories, this has been done by stringing up a suitable length of No. 25 guage wire a distance equal to half the generator height from ground. The capacitance of this is then measured.*

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* "Calculating Surge Generator Waves", McAuley and Benedict, Electric Journal, V 30, p 326

CALCULATION OF THE INDUCTANCE
of
THE CALIFORNIA INSTITUTE OF TECHNOLOGY SURGE GENERATOR

Part shown in figure 16c

$a = 51.7$ cm., $g = 171.8$ cm.
$a_1 = 166.1$ cm., $d = 1.27$ cm.

$L_R = 5.96$ micro-Henries

$D_{12} = 103.5$ cm.

$M_{12} = .0646$ micro-Henries

$D_{13} = 207$ cm.

$M_{13} = .0135$ micro-Henries

$D_{14} = 311$ cm.

$M_{14} = .0061$ micro-Henries

$\text{Total} = 4L_R + 6M_{12} + 4M_{13} + 2M_{14}$

$= 24.25$ micro Henries

Part shown in figure 17b

$l_{ab} = 279$ cm.
$d = 1.27$ cm.

$L_{ab} = 3.38$ micro-Henries

$l_{bc} = 559$ cm.

$L_{bc} = 7.50$ micro-Henries

$l = 279$ cm.
$d = 279$ cm.

$M = 1.043$ micro-Henries

$\text{Total} = L_{ab} + L_{bc} + M$

$= 11.92$ micro-Henries

Inductance of Surge Generator $= 11.92 + 24.25 = 36.2$ micro-Henries

EFFECTS OF THE LOAD IMPEDANCE

The determination of the circuit constants necessary to obtain the standard waves with no test apparatus in the circuit was given in the preceding section on the Attainment of Test Waves. There also are shown the wave shapes as calculated for our surge generator.

However, when the apparatus to be tested is inserted in the circuit, the wave shape may be distorted somewhat by both the test impedance and the impedance of the connecting lead. In consideration of this last point, it is always best to have the connecting lead as short as possible.

In some cases a complete picture of the effects is obtainable only through analysis of the particular circuit, which is laborious even with the use of operational Calculus. This has been treated rather thoroughly and most of the needed circuit analyses are available.*

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* "Impulse Generator Circuit Formulas", J. L. Thomason, A.I.E.E., V 53 p 169.

In most cases, however, the only element of the test piece causing any appreciable effect is capacitance, which is so small in relation to the surge generator capacitance and discharge resistance that the only important distortion of the wave is in the form of secondary oscillations appearing on the wave front and crest. This is due to the series inductance of the circuit acting with this capacitance. Figure 19 shows this effect.

Indeed, in many cases these oscillations are of such small magnitude and short duration that, due to the relatively long time lag of the apparatus being tested, they are not considered objectionable by some engineers.* They can, however, be damped by the insertion of the proper series resistance.

Determination of Damping Resistance

When the capacitance of the test is considered, the equivalent circuit is as shown in figure 18. By the use of Heaviside's Operational Calculus, the equa-

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* "Technique of Surge Testing", F. D. Fielder, Electric Journal, V 30, n 2, p 73

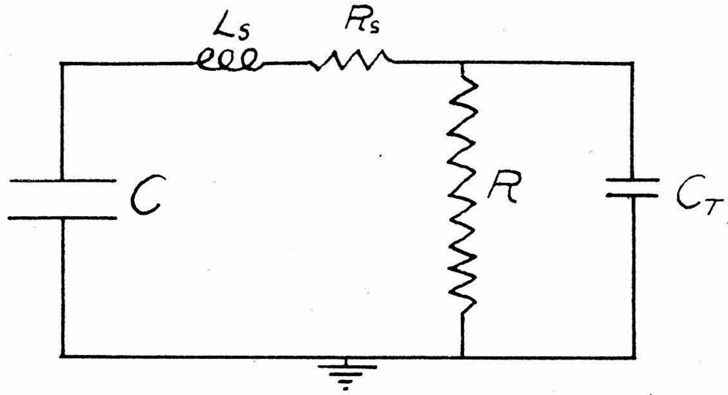
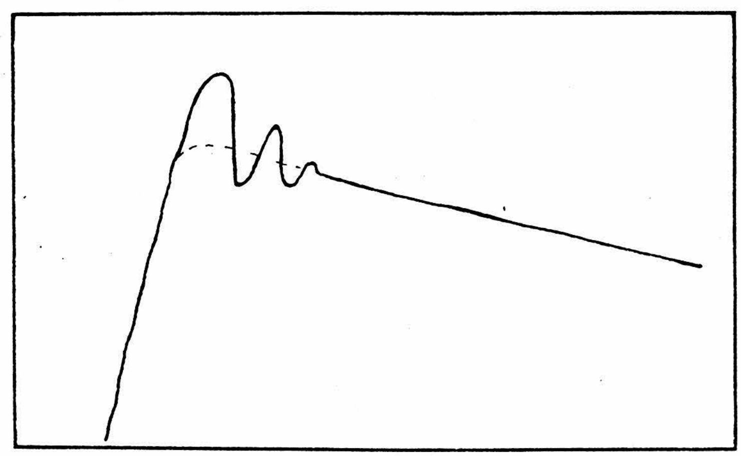


Fig. 18



Effect of Load Capacitance C_T

Fig. 19

tion for voltage can be set up as follows:

$$(30) \qquad e = e_o \frac{\dfrac{R}{RC_t\rho + 1}}{\dfrac{1}{C\rho} + L_s\rho + R_s + \dfrac{R}{RC_t\rho + 1}}$$

This can be expanded to the following form:

$$(31) \qquad e = \frac{e_o A}{(\lambda-\alpha)^2+\omega^2}\left[\mathcal{E}^{-\alpha t} - \mathcal{E}^{-\lambda t}\left(\frac{\lambda-\alpha}{\omega}\sin\omega t + \cos\omega t\right)\right]$$

Analysis of equation 31 shows that an oscillation is superimposed on the unidirectional component $\dfrac{e_o A}{(\lambda-\alpha)^2+\omega^2}\mathcal{E}^{-\alpha t}$

The oscillation can be eliminated by making $\omega^2 = 0$. The value of R necessary to do this can be obtained by consideration of the equivalent simple series circuit with the discharge resistance neglected due to its relatively high value.

$$(32) \qquad C_o = \frac{C\ C_t}{C-C_t} \cong C_t$$

For such a simple circuit critical damping is attained when the perameter $\beta = \sqrt{\dfrac{R_s^2}{4L_s^2} - \dfrac{1}{L_sC_o}} = 0$

$$(33) \qquad \frac{R_s^2}{4L_s^2} = \frac{1}{L_sC_o}$$

$$(34) \qquad R_s = 2\sqrt{\frac{L_s}{C_t}}$$

Equation 34 determines the value of the damping resistance. This is usually inserted at the terminal of the surge generator. However, it has been found in some cases better to distribute it along the surge generator circuit. When the resistance is located only at the terminal, the charging current of the condensers does not flow through it and the important damping effect is lost.

The actual discrepancy is not as great as might be imagined due to the inherent resistance. This is effective in damping to a certain extent the oscillations caused by both the load capacitance and the distributed capacitance of the surge generator.

When the circuit is being adjusted, there are other modifications of the wave that must be considered. Before going into this, however, it might be best to consider the effects of each constant.

Effect of Circuit Constants upon Wave Shape

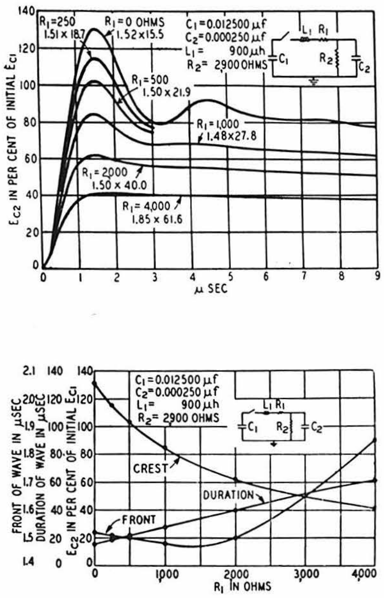
Curves showing the effect of each constant as determined from an analysis of the circuit of figure 18 are given in figure 20.

Discharge Resistance: The most notable effect is shown to be upon the crest value of the voltage obtainable. Since the voltage across the test piece is the voltage across this resistance, its crest value is decreased by decreasing the resistance. As shown, the duration of the wave is almost directly proportional to the discharge resistance, while for the usual range of this resistance (0-3000) ohms, little effect is noticed upon the wave front.

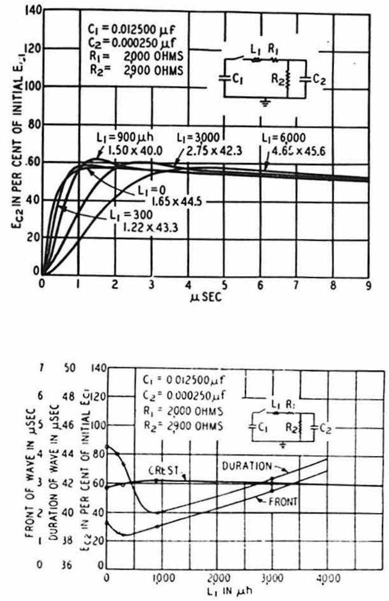
It can thus be said that, practically, the discharge resistance affects the tail and crest value, but not the front.

Series Inductance: Almost the reverse is true of the inductance. It has little effect upon the crest value and an appreciable effect upon the wave front. The time to crest value is almost proportional to the inductance. Its effect upon the tail of the wave, though slight, is not appreciable.

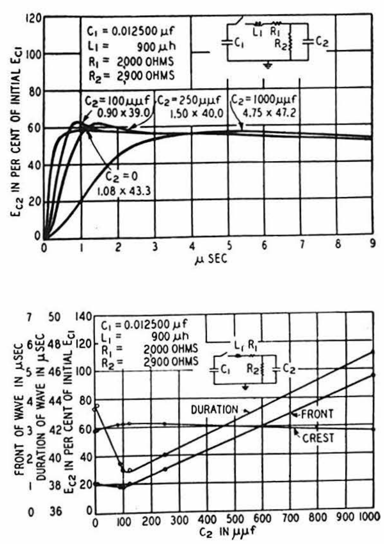
Load Capacitance: In the range of the capacitance of most test pieces, the effect is slight except for



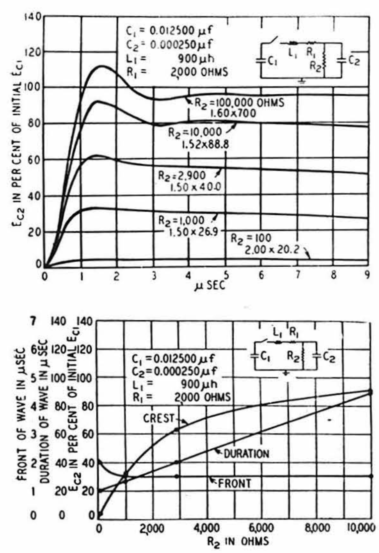
Damping Resistance



Series Inductance



Load Capacitance



Discharge Resistance

Curves showing effect of constants upon wave form

Figure 20

the formation of crest oscillations. However, if the capacitance is large, it increases the front of the wave considerably.

Damping Resistance: As in the case of the discharge resistance, it has little effect upon the wave front and a proportional effect upon the duration. However, increasing this resistance cuts down the crest value of the wave considerably.

Adjustment of Constants

It is of importance to note that in the case of the simple series circuit, the effects of L and R are practically the same as shown in these curves.

It can now be seen that in correcting for crest oscillations two major difficulties arise; one in the effect upon the duration of the wave and the other upon the crest value. The introduction of damping resistance may so increase the duration of the wave that it will be difficult to obtain some of the shorter duration waves, such as the ($\frac{1}{2}$-5) or the (1-5).

In this connection it should be noted also that the load capacitance itself, the inherent inductance and the distributed capacitance of the surge generator are also factors which increase the wave front. The comparatively large values of inherent inductance and distributed capacitance of some of the larger generators form the basis for the present proposals to have the (1-5) wave standardized to replace the ($\frac{1}{2}$-5).

The effect of the damping resistance upon the crest value of the wave is very important in determining the voltage class of testing that can be performed. It is necessary in order to obtain the least distortion in varying R_s to vary the discharge resistance also, so that their sum shall be approximately the same. Thus, the increasing of R_s causes a decreasing of R, which further cuts down the crest value.

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