DEVELOPMENT OF A FLASHOVER DETECTOR AND ANALYZER FOR TRANSMISSION STRUCTURES

by

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FIGURES

PREFACE

In lightning regions, many undesired outages are caused by lightning striking the lines and arcing across insulators to ground through the steel towers. In cases where the damage to the insulators is not permanent and power is restored soon after the outage, it is necessary to inspect the lines to determine where the failure took place. If the lightning current, that flows through the tower leg, is sufficiently large there are a number of indicators that may be used for indicating the tower or towers carrying current. With the following indicators, the amount of current in the lightning stroke may be measured:

1. General Electric Indicator and Surge-Crest Ammeter
2. Westinghouse Magnetic Surge- Front Recorder.

But it has been found in the field that when the lightning stroke is small or the stroke flashed over more than one tower, these devices would not indicate the amount of current. For this reason the Bonneville Power Administration did some experimenting to develop some means of indicating which tower was struck. While working at Oregon State College, to do some of their testing, a method was developed that would detect these lower values of lightning current. It is the further development and theory of operation that is used for the writing of this thesis. The work was carried out under the supervision of Professors

F. O. McMillan, E. C. Starr, and A. L. Albert. The author wishes to express his thanks for the guidance that was given to him and for the privilege of working in cooperation with them.

The author is also indebted to the other members of the Electrical Engineering Department who offered encouragement when the going was difficult, especially to W. H. Huggins, who aided in the mathematical solutions of the indicator.

Alan K. Johnson's name should appear on the title page of this thesis but the Army Air Corps called him to active duty before it could be completed. The work was then carried out on a cooperative basis by correspondence. The material on skin effect was completely worked out by Mr. Johnson.

B. L. Giffin

June 1946

DEVELOPMENT OF A FLASHOVER DETECTOR AND ANALYZER FOR TRANSMISSION STRUCTURE

INTRODUCTION

In order to render continuous service to its customers, it is necessary for power companies to keep their transmission lines in good repair. If lightning strikes a line but is not of sufficient size to destroy the insulators, it is necessary for a patrolman to inspect the insulators. If only slight damage results it may not be visible from the ground, even with the aid of field-glasses. In such cases it is desirable to have a detector located at the base of all towers that may be easily read by the patrolman. The detector should be of such a design that the cost for installation on each tower of a two or three mile transmission line is not prohibitive.

The detector uses a laminated, soft-iron slug[1] to indicate when current has passed through the tower leg. The soft-iron slug, or link, as it hereafter will be referred to, has to be completely demagnetized when it is placed in the detector. Therefore, when current flows through the tower leg the link is magnetized and the amount of residual magnetism remaining in the link is an indication that current has flowed through the detector. This residual magnetism will cause a compass needle to deflect from its

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1 This link is the one used in the General Electric Indicator.

normal position, thus telling the patrolman which tower has been struck. If the compass indicates residual magnetism, the link may be placed in a retainer and sent to the laboratory where the surge-crest ammeter is used to record the reading of the link. From this reading the amount of tower current may be determined. The actual amount of current in the stroke will be four times the amount indicated by the detector since there are four paths to ground.

REQUIREMENTS FOR THE IDEAL DETECTOR

Although the primary consideration in the design of the detector will be to record lightning strokes and their magnitude, there are other factors that should be considered and incorporated into the design of the detector.

If the detector will register, when current flows due to the lowest value of lightning voltage necessary to spark-over a string of insulators, then it fulfills its primary purpose. Appendix H shows that the flashover voltages of a span of 16 units varies with the rate of rise of the front of the wave. The amount of current that will flow through the tower, when the voltage applied is a 1 1/2-40 microsecond wave, will be 4,750 amperes. One fourth of this current will flow through each leg, therefore the detector will have to indicate when a current of 1,188 amperes flows in the tower leg.

A second condition that must be met by the lightning detector is that of a flashover of the insulators due to some foreign object forming a path across the insulators and allowing the energy, stored in the line, to be discharged to ground. In a flashover of this type the voltage acting would be the line to neutral voltage. The impedance to such a discharge would be one-half of the line surge impedance plus the ground resistance. The calculations for the current flowing are shown in Appendix H. For a 230 Kv. line, the current would be 627 amperes or 1565 amperes per leg.

In the cases mentioned above, it is possible for the path across the insulators to become ionized. If ionization takes place and the line voltage is increasing then it is quite possible that a power-arc may follow. If a power-arc follows, the current will be alternating in form and will tend to demagnetize any detector using a magnetic link as a recorder. For this reason it is necessary that the detector be designed for minimum indication of an alternating current. It has been found that fault currents, for 230 Kv. line with steel towers, rarely exceed 4,800 amperes or a current per leg of 1,200 amperes.

THE FLASH-OVER DETECTOR

A photograph of the flashover detector mounted in place on a tower leg section is shown in figure 1. The detector is a closed loop of heavy wire which has in one corner a coil in which the link is placed. The coil, containing the link, is situated on the inside vertex of the angle iron where it is shielded from the strong field which surrounds the tower leg during flash-over. The loop is located in a position as to include a large number of flux linkage for a given area. The magnetic link which resides in the coil will give an indication of the peak

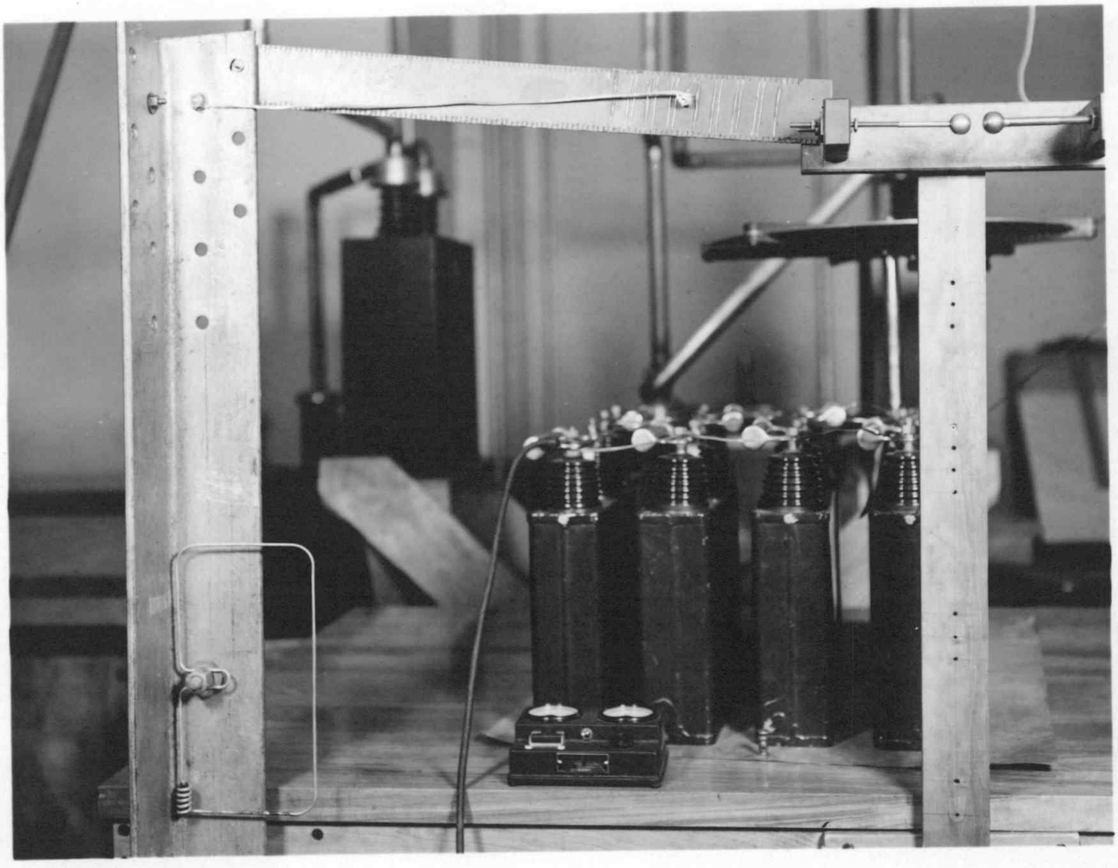


Figure I. THE DETECTOR IN PLACE ON A SECTION OF TOWER LEG current flowing in the loop. Current flowing down the tower leg induces a current in the loop making the link reading an indication that current was flowing to ground through the transmission tower.

THEORETICAL DISCUSSION

Two general types of current will be expected to flow in the tower when a lightning flashover occurs: First, the impulse current of relatively short time duration and having a fast rate of rise; second, an a-c current of the power frequency flowing in the path ironized by the impulse.

There are three specific types of impulse currents to be considered in studying a lightning flashover.

1. The most common lightning current is the type known as over-damped, having a rapidly rising front and a relatively slow rate of decay.

2. This wave has a rapidly rising front and a relatively fast rate of decay. The origin of such a current could be from one such as type 1, where the current in the tower has built up to crest at the same time an adjacent tower flashes over. A parallel path has then been offered for the current and it decays rapidly. A current of this type could be represented by a critically damped impulse.

3. This type considers the current which has some oscillation coupled with fast rates of rise and decay. Current of an oscillatory nature is expected to comprise only a very small percent of the total lightning currents.

A mathematical analysis requires two assumptions: that the parameters of the loop are lumped; and that these parameters do not vary for a given type of current. When the line is originally flashed over, whether by lightning or by some other means, there will be a current wave of an impulsive nature flowing down the tower. Once the arc has been established across the insulator string an a-c current is apt to flow to ground. With this type of flashover detector the a-c follow-up will have a demagnetizing effect on the link and in some cases could completely wipe out the surge indication. Therefore the loop must be designed to keep this a-c current to a minimum.

The equation for each of the currents discussed above is as follows:

Overdamped:

$$i = \frac{E}{(P_2 - P_1)L}\left(\varepsilon^{P_2 t} - \varepsilon^{P_1 t}\right) \qquad (1)$$

Where

$$P_1 = -\alpha + \Omega'$$

$$P_2 = -\alpha - \Omega'$$

Critically damped:

$$i = \frac{E}{L} \quad t \, \varepsilon^{-\alpha t} \tag{2}$$

Where

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

Oscillatory:

$$i = \frac{E}{L\Omega} \left(\varepsilon^{-\alpha t} \quad \sin \Omega t \right) \tag{3}$$

Where

$$\Omega = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$$

60 cycle a-c:

$$i = I \; \varepsilon^{j377t} \tag{4}$$

Where:

E = Voltage applied to surge circuit, volts

L = Inductance of surge circuit, henrys

R = Resistance of surge circuit, ohms

C = Capacitance of surge circuit, farads

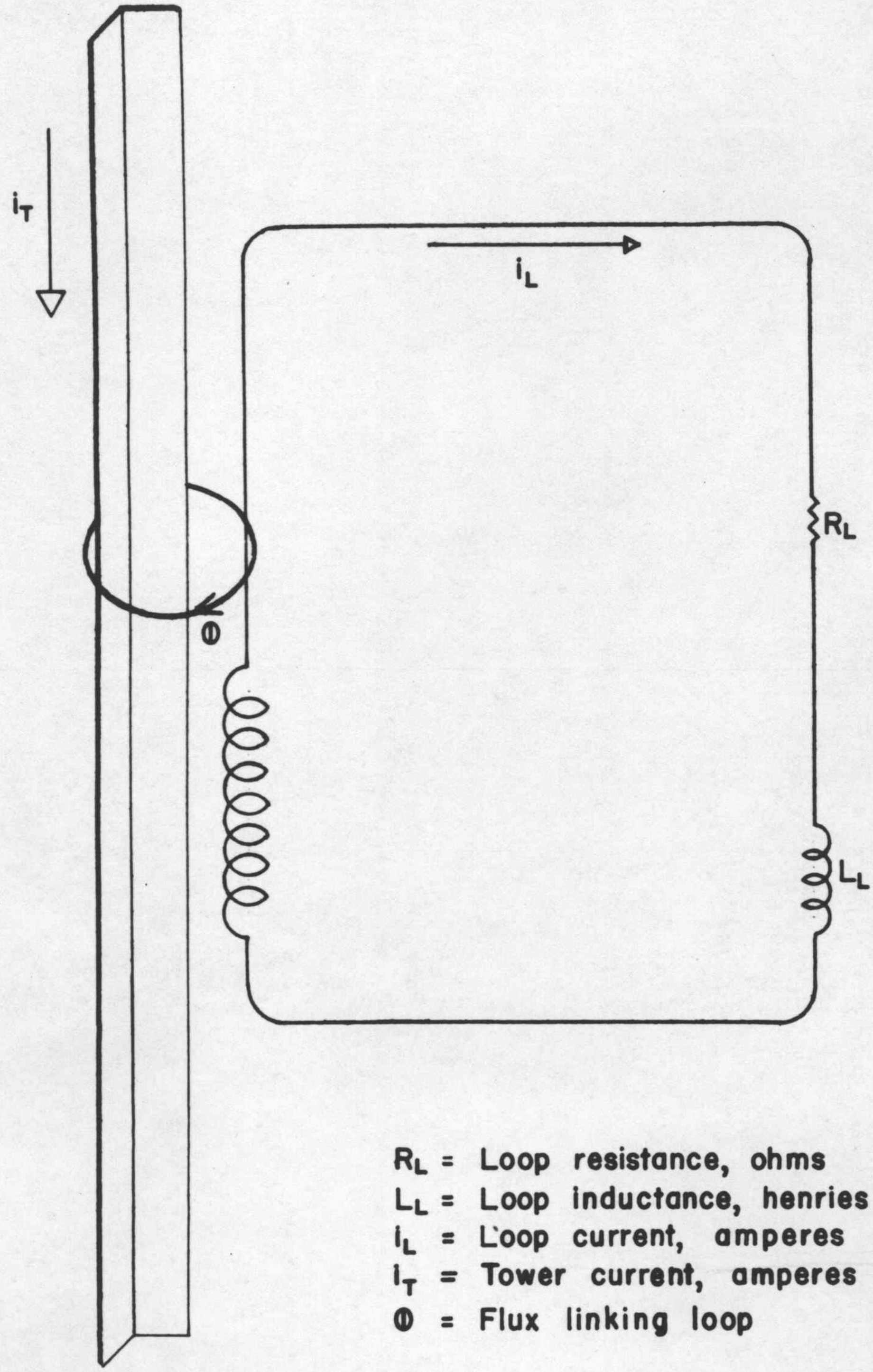
I = Maximum value of a-c wave, amperes

i = Tower current, amperes

Figure II shows the loop and tower and the respective parameters of the loop and tower. The voltage induced in the loop will depend upon the rate of change of the tower current.

$$e_L = M \frac{di}{dt} \tag{5}$$

where M = mutual inductance, henrys.



R_L = Loop resistance, ohms
L_L = Loop inductance, henries
i_L = Loop current, amperes
i_T = Tower current, amperes
Φ = Flux linking loop

Figure 2. EQUIVALENT TOWER AND LOOP CIRCUITS

Using the operator $p = \frac{d}{dt}$ the above equation may be written:

$$e_L = M\,p\,i \tag{6}$$

Since there is no voltage source in the loop the induced voltage must equal the voltage developed by the loop current.

$$0 = (R_L + p\,L_L)\,i_L + M\,p\,i \tag{7}$$

then, solving for the loop current:

$$i_L = \frac{-M\,P\,i}{R_L + p\,L_L} + i_t \tag{8}$$

From equation (8) and the four tower current equations, the expressions for the loop current are derived in Appendix C.

Overdamped:

$$i_L = \frac{M\,E}{L\,L_L\,(P_2 - P_1)} \left[\frac{P_1}{P_1 + \partial} \varepsilon^{P_1 t} - \frac{P_2}{P_2 + \partial} \varepsilon^{P_2 t} + \frac{\partial\,(P_2 - P_1)}{(\partial + P_1)\,(\partial + P_2)} \varepsilon^{-\partial t} \right] \tag{9}$$

where $\partial = R_L / L_L$

Critically damped:

$$i_L = \frac{M\,E}{L\,L_L\,(\alpha\partial)^2} \left[-\partial \varepsilon^{-\partial t} + (\partial - \alpha\partial t + \alpha^2 t)\varepsilon^{-\alpha t} \right] \tag{10}$$

Oscillatory:

$$i_L = \frac{M E}{L L_L}\left[-\frac{\partial \, \varepsilon^{-\partial t}}{(\partial^2 - 2\alpha\partial + \alpha^2 + \Omega^2)} + \frac{\varepsilon^{-\alpha t}}{(\partial^2 - 2\alpha\partial + \alpha^2 + \Omega^2)} \right.$$

$$\left. - \frac{\alpha \partial + \alpha^2 + \Omega^2}{\Omega} \sin \Omega t + \partial \cos \Omega t \right] \quad (11)$$

60 cycle a-c:

$$i_L = \frac{j\,377\,M\,I}{L_L\,(\partial + j\,377)}\,\varepsilon^{j\,377\,t} \quad (12)$$

Equation (8) shows that when R_L is equal to zero the loop current will be proportional to the tower current. For any other resistance the loop current will have a negative rate of change of the tower current. The negative loop current is definitely undesirable because it will tend to reduce the link magnetism left by the positive crest of loop current.

The three surge currents and their corresponding loop currents have been plotted as functions of time and are shown in figures 5, 6, and 7. The slow rate of decay of overdamped tower current, shown in figure 5, will induce a small negative current in the loop . This characteristic lends itself well to magnetic link recording. In the critically damped case the rate of decay of the tower current is fast; this induces a large negative current in the loop. This negative current will remove more of the magnetism of the link than the overdamped surge making it more difficult to record. The diagram, figure 5, of the oscillatory loop current shows that there is a possibility of the negative current being large enough to completely demagnetize the link. It has been previously stated that very few oscillatory lightning strokes occur. Therefore the critically-damped tower current has been chosen as the criterion of loop design.

In order to calculate the loop currents, it is necessary to determine the mutual inductance between the tower leg and the indicating loop. The shape of the tower leg and the type of current flowing in the tower leg make it impossible to calculate or measure the mutual inductance between the tower leg and the loop.

This makes it necessary to determine the mutual inductance by experimental means. This experimental determination was done by using a tower current that had a slow rate of decay. The linear part of the 1 1/2 by 40 data was used for obtaining this data. Therefore it is necessary to solve the equation for the maximum value of the loop current in terms of the mutual inductance. This was done by plotting a curve of the loop current as a function of time. It was found that the loop current reaches a maximum at 0.7 microseconds. Substituting this value into the equation for the 1 1/2 - 40 loop current and solving for M is given below:

$$i_L = \frac{M E}{LL_L(P_2 - P_1)} \left[\frac{P_1}{P_1 + \partial} \varepsilon^{P_1 t} - \frac{P_2}{P_2 + \partial} \varepsilon^{P_2 t} + \right.$$

$$\left. + \frac{(P_1 - P_2)}{(P_1 + \partial)\ (P_2 + \partial)} \varepsilon^{-\partial t} \right] \qquad (13)$$

The following are the constants for the 1 1/2 - 40 current:

$P_1 = -0.02 \times 10^6$
$P_2 = -3.6 \times 10^6$
$L = 13.88 \times 10^{-6}$ henries.

For the original iron loop (No. 1)

$\partial = 0.2968 \times 10^6$
$L_L = 1.28 \times 10^{-6}$ henries
$R = 0.38$ ohms

By substitution the above equation reduces to:

$$i_L = \frac{M E}{79.76 \times 10^{-6}} \qquad (14)$$

Solving for M gives:

$$M = \frac{i_t\ (79.76) \times 10^{-6}}{E} \qquad (15)$$

From the above equation it is seen that the mutual inductance is a function of the loop current and the voltage (E) applied to the section of the tower leg.

To obtain the value of loop current it is necessary to refer to curves of Surge-Crest Ammeter reading as a function of the applied voltage (Fig. 3, page 17). From this curve a measure of the amountof residual magnetism is obtained for a given voltage. To obtain the loop current it is necessary to refer to the curve of the Surge-Crest Ammeter reading plotted as a function of the loop current. This current was obtained for both a-c crest value and for d-c current and the two curves coincide. Then substituting this value of loop current and its corresponding voltage in equation (15) gives the value of mutual inductance. The following table gives the values obtained by this method:

Tower voltage in Kv.	20	40
Surge Crest Ammeter Reading	9.2	18.2
Loop Current in Amperes	23.2	45.2
Mutual Inductance in microhenries	0.09	0.09

Using this value of mutual inductance, the loop currents were calculated and plotted as a function of time. These curves were plotted with their corresponding tower currents. A maximum tower current of 1000 amperes was chosen in each case to give a comparison for the respective loop currents. Both of these curves for each tower current are shown in figures 5, 6, and 7.

1 1/2—40
VOLTAGE CHARACTERISTICS

FOR DETERMINATION OF MUTUAL INDUCTANCE
USING
IRON WIRE LOOP 0.144" DIAMETER

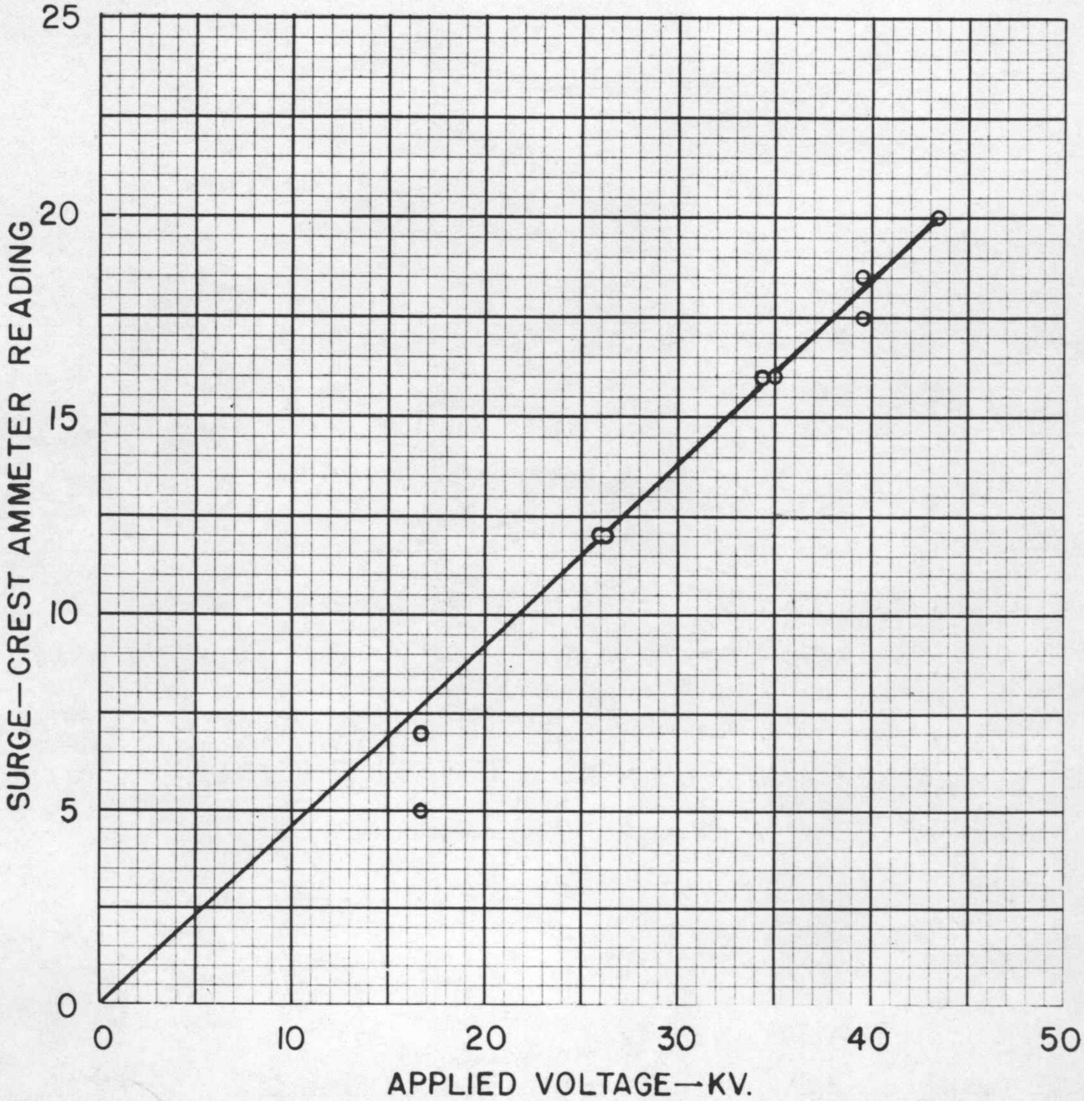


FIGURE 3

MAGNETIZING CHARACTERISTICS OF
THE G.E. SURGE-CREST AMMETER LINK

NOTE: ALL DATA WERE TAKEN WITH LINK IN SEVEN-TURN COIL OF DETECTOR LOOP. A-C POINTS WERE TAKEN BY BREAKING CURRENTS ON THE CREST OF THE WAVE. THE A-C CREST AND D-C POINTS ARE COINCIDENT.

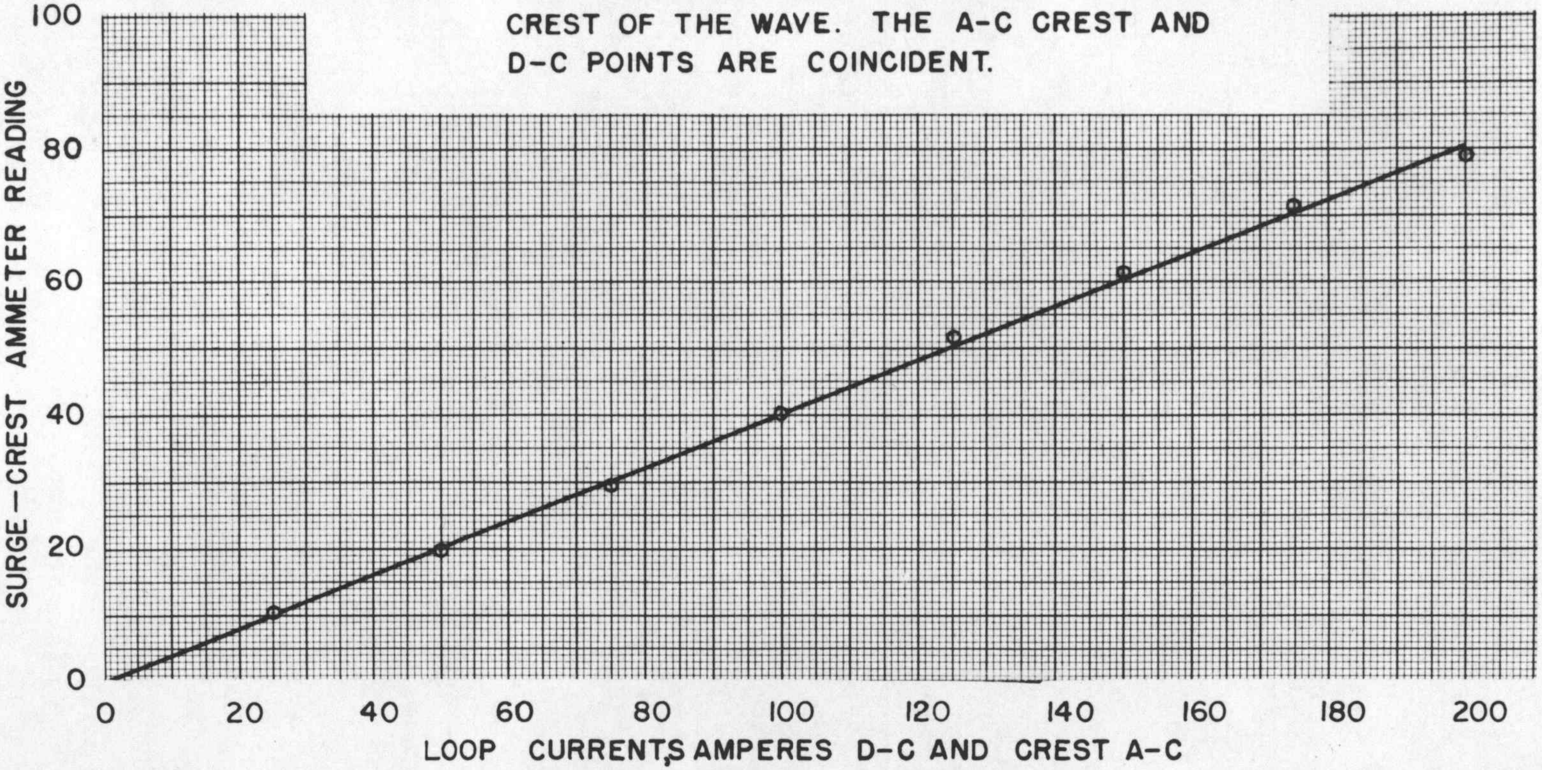


FIGURE 4

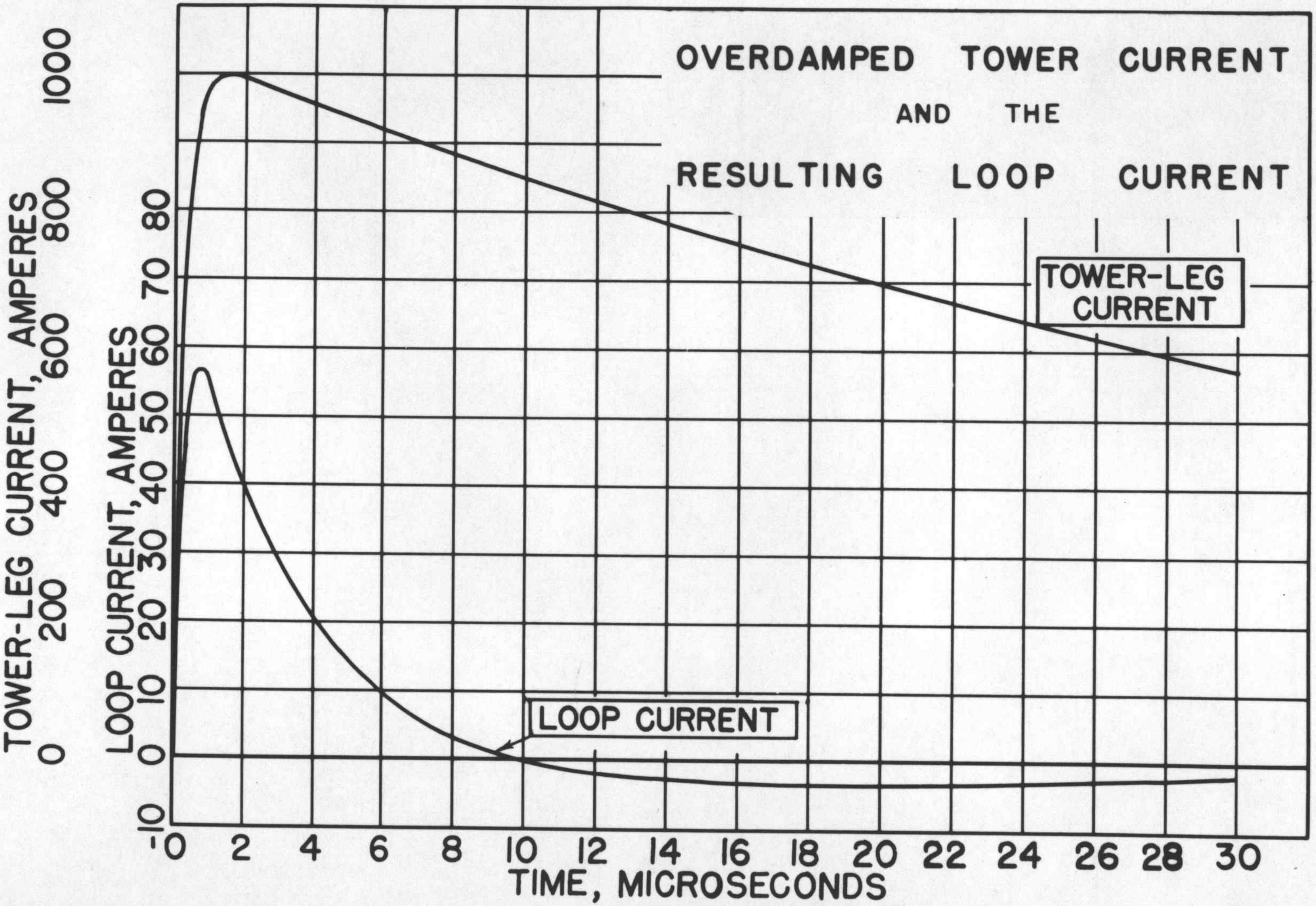

OVERDAMPED TOWER CURRENT
AND THE
RESULTING LOOP CURRENT
TOWER-LEG CURRENT
LOOP CURRENT
TOWER-LEG CURRENT, AMPERES
0 200 400 600 800 1000
LOOP CURRENT, AMPERES
-10 0 10 20 30 40 50 60 70 80
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
TIME, MICROSECONDS

FIGURE 5

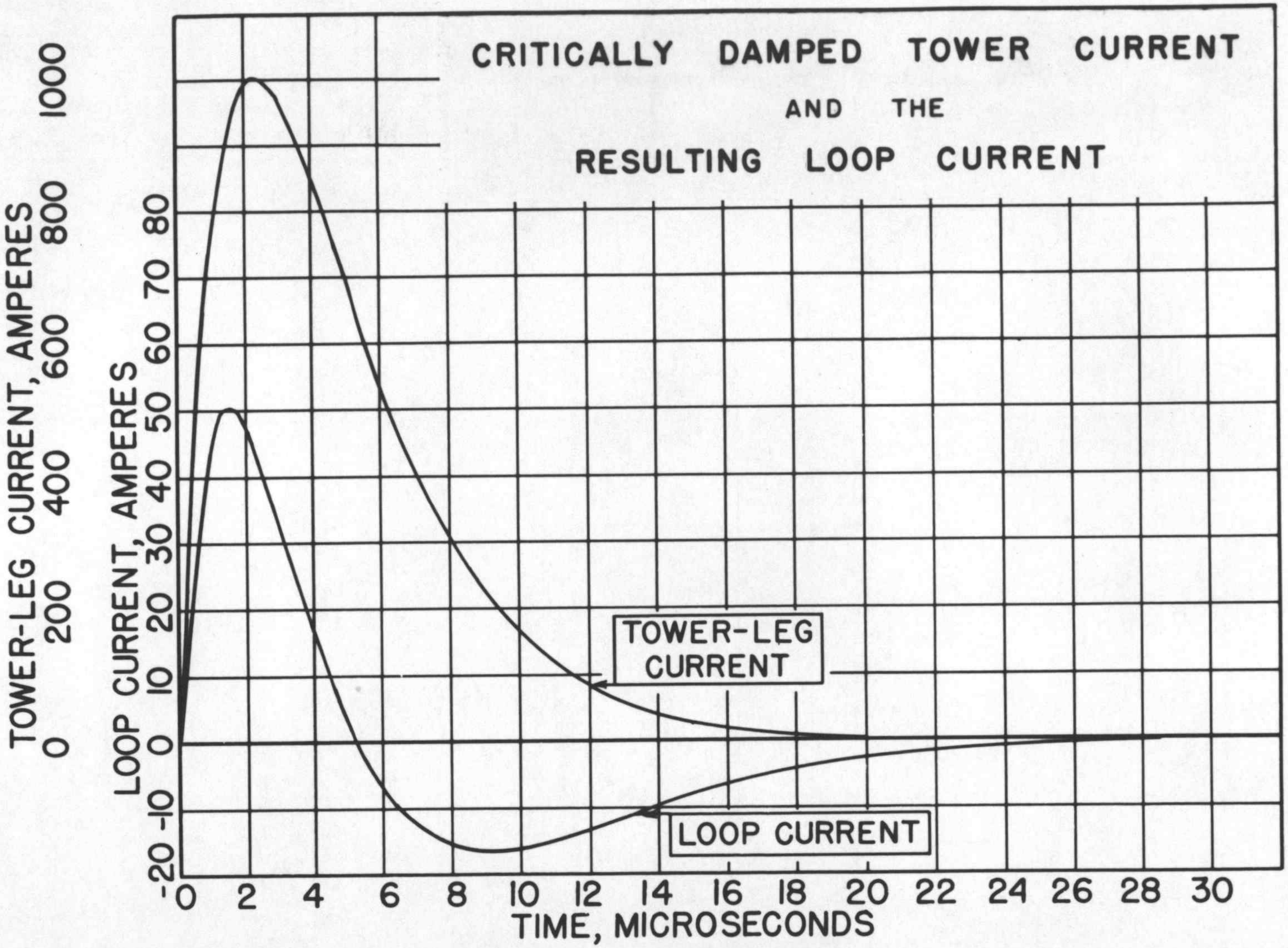

CRITICALLY DAMPED TOWER CURRENT
AND THE
RESULTING LOOP CURRENT
TOWER-LEG CURRENT, AMPERES
0
200
400
600
800
1000
LOOP CURRENT, AMPERES
-20
-10
0
10
20
30
40
50
60
70
80
TOWER-LEG
CURRENT
LOOP CURRENT
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
TIME, MICROSECONDS

FIGURE 6

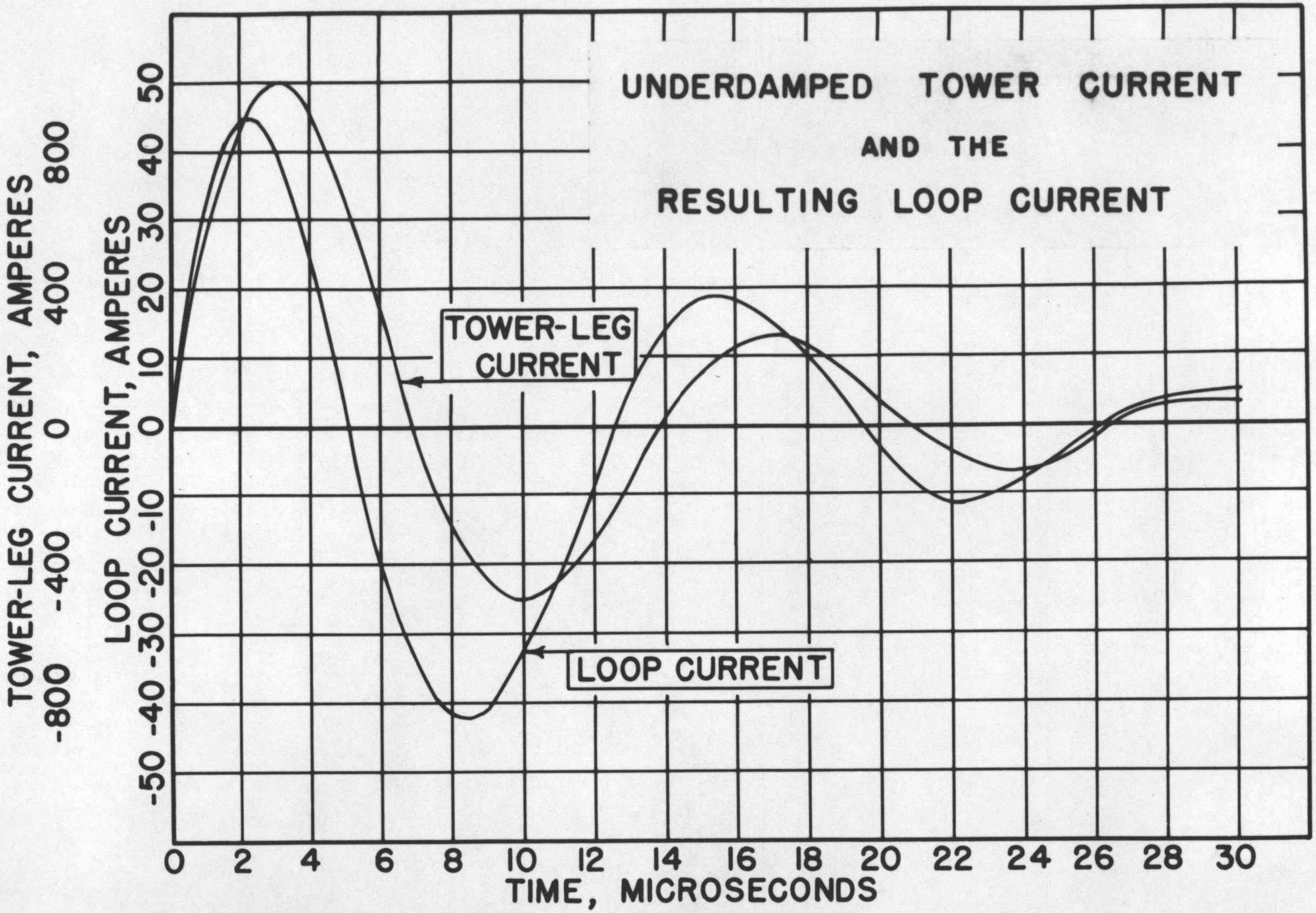

UNDERDAMPED TOWER CURRENT
AND THE
RESULTING LOOP CURRENT
TOWER-LEG CURRENT
LOOP CURRENT
TOWER-LEG CURRENT, AMPERES
-800 -400 0 400 800
LOOP CURRENT, AMPERES
-50 -40 -30 -20 -10 0 10 20 30 40 50
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
TIME, MICROSECONDS

FIGURE 7

Examination of these curves shows that the maximum current will flow in the loop when the tower current is overdamped. This is natural since the rate of rise of the front of the wave is greatest for the overdamped case and decreases as the tower current approachesthe pure oscillatory case. The overdamped tower current has another characteristic that makes it easier to record. This is due to the slow rate of decay of the tail of the wave which induces less current into the loop. With a small current induced into the loop there will be less magnetism removed.

The critically-damped tower current wave has both a rapid rate of rise and a rapid rate of decay. Therefore, the first negative maximum current will remove part of the magnetism placed in the link by the positive flow of current.

In the case of the oscillatory tower current, the rate of rise of the front of the wave and the rate of decay of the tail of the wave approach the same value as the current approaches the pure oscillatory condition. If the tower current were to be oscillatory in nature, then all of the magnetism could be removed from the link if the tower current is interrupted at the correct point of the cycle.

LINK CHARACTERISTICS

In order to better understand the operation of the loop, the magnetizing characteristics of the link will be discussed. If an alternating current flows through the tower then an alternating current will be induced in the loop. If the link is initially demagnetized, then the magnetizing curve will be followed up to respective peak value of current. As the current decreases, the flux will decrease along the hysteresis curve and complete the hysteresis cycle as the current goes through one complete cycle.

In case a surge current flows through the tower, the flux in the link will increase to the maximum value and drop back on a hysteresis curve as the tower current goes from zero to maximum. If the detector recorded only the front of the wave, then a measure of the flux in the link would be an indication of the rate of rise of the tower current. Figure 8 shows this phenomena by increasing on the magnetizing curve from O to A and decreasing on the hysteresis curve to point B. The value O B would be the measure of the rate of rise of the tower current, but the loop current reverses its direction as the tower current starts to decay. This causes the above curve to extend down to point C due to the maximum value of the negative loop current. As the rate of change of the tower current approaches zero, the loop current also approaches zero and

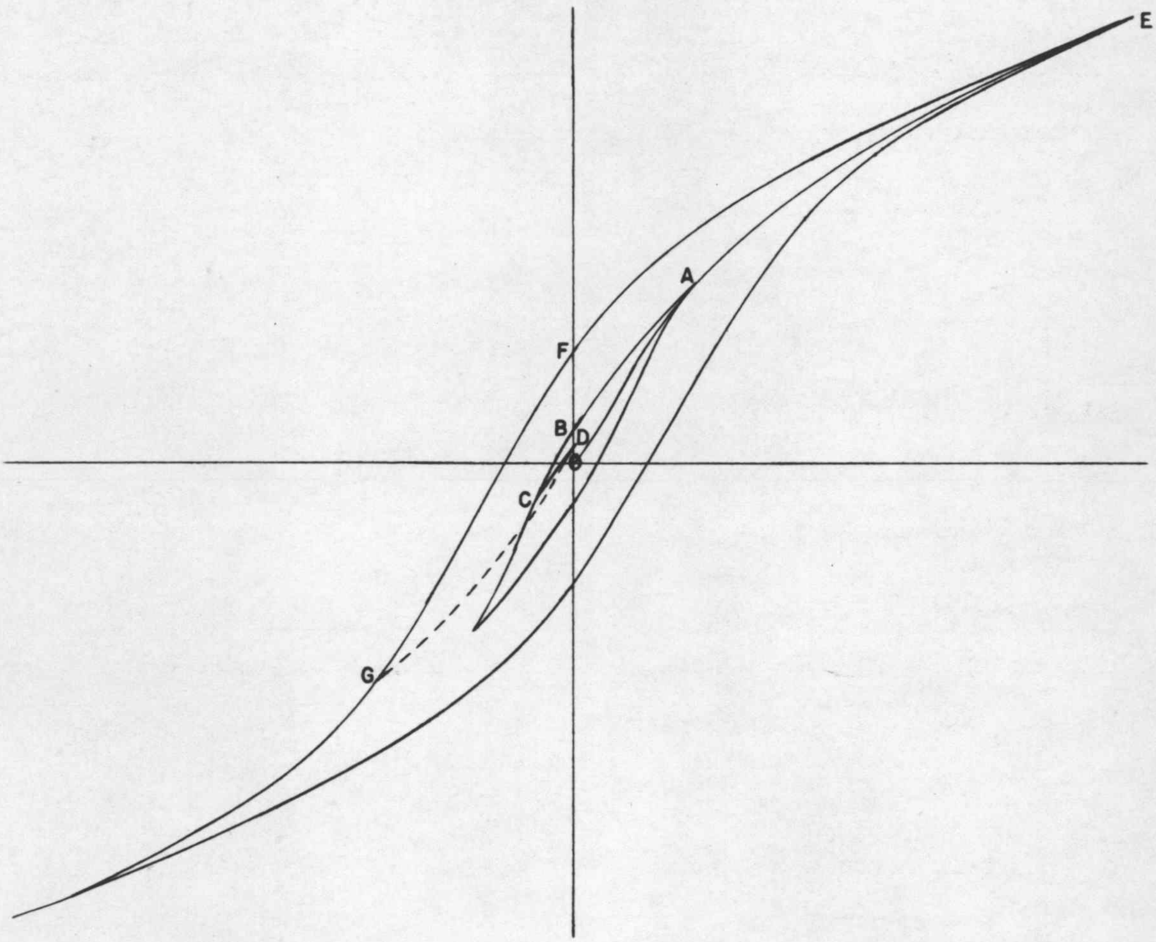


Figure 8. HYSTERESIS LOOP FOR G.E. LINK

the flux will increase to point D on a new hysteresis cycle. This leaves a value O D which cannot be used for a calibration curve since it can be obtained by a number of different values of magnetizing force. (i.e. curve OEFGD).

OPERATION OF THE ORIGINAL LOOP

Using the above values, the operation of the theoretical loop will be discussed. The factors that will influence the operation of the loop are:

1. The resistance and inductance of the loop.
2. The amount of current induced in the loop by the front of the wave (the first positive peak current).
3. The amount of current induced in the loop by the tail of the wave, (the first negative peak current).
4. The use of rectifiers to allow the current to flow in only one direction.

In order to show the effect of varying the ratio $\partial = \frac{R_L}{L_L}$, a number of calculations for the maximum currents in the loop have been made. The maximum currents, both for the first positive and the negative maximums, have been plotted as a function of ∂. The curve of the first positive maximum currents, as a function of ∂, is shown in figure 9, page 26. The curve of the first negative maximum currents as a function of ∂, is shown in

FIRST POSITIVE MAXIMUM LOOP CURRENT

FOR CRITICALLY DAMPED TOWER CURRENT

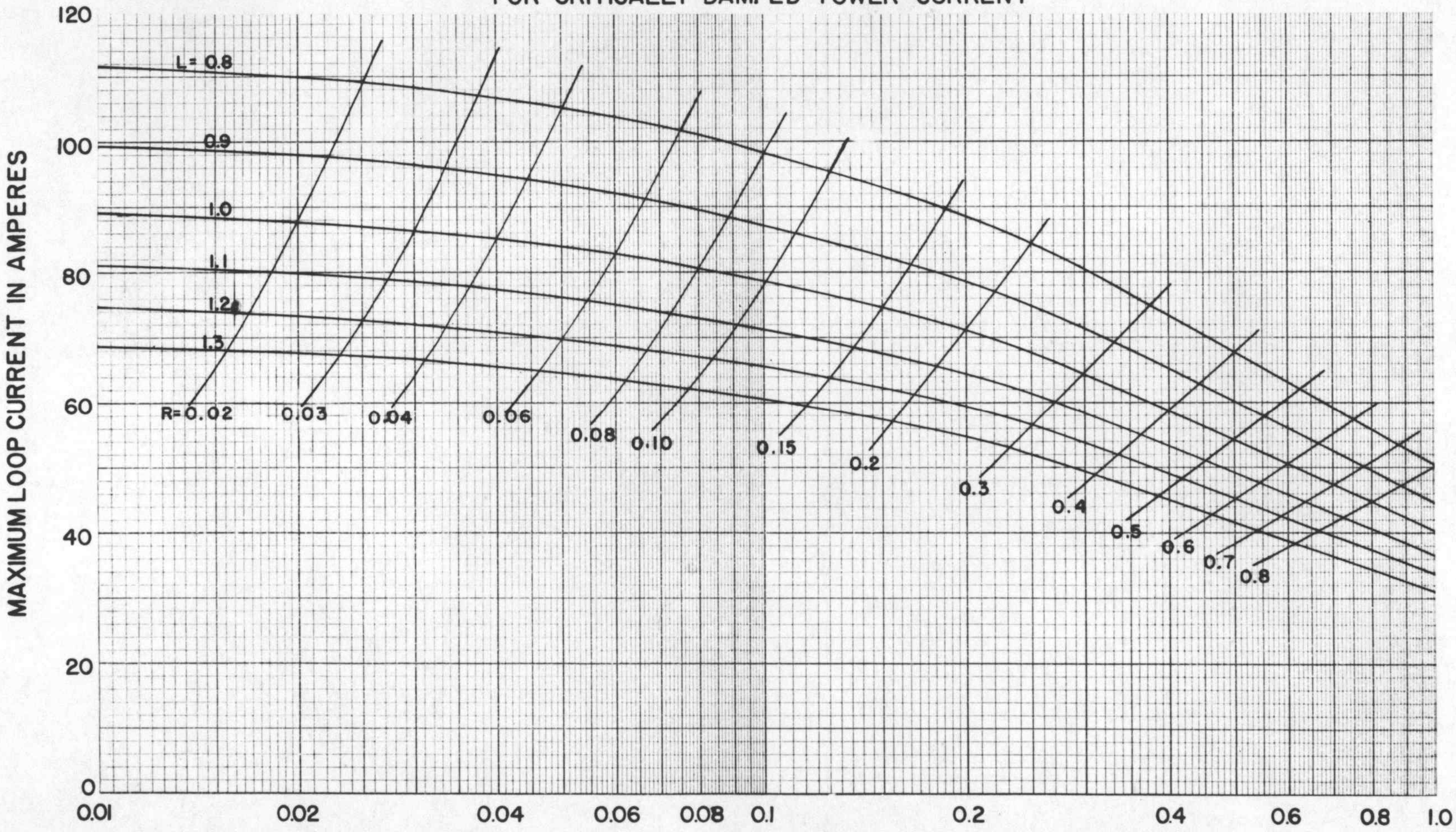


FIGURE 9

$\delta \times 10^{-6}$

figure 10, page 28. In order to show the value of ∂ , which will give the best theoretical operation, a curve of the ratio of the first negative maximum to the first positive maximum has been plotted in figure 11, page 29. This curve is called the per unit oscillation of the loop current. The equations used and sample calculation for these curves are given in Appendix D.

Using the per unit oscillation curve, the values of for the best loop operation, may be selected. The ratio is a maximum for a value of $\partial = 4.5 \times 10^6$. Thus any loop operating in this region will have large negative current flowing which will remove part of the reading left by the positive flow of current. If the value of ∂ is decreased, the resistance of the loop becomes so low that the follow-up a-c current will remove a considerable amount of the residual.

A number of loops were tested in order to find a value of ∂ that would allow the least value of negative maximum current to flow and not be effected by the a-c follow up. The characteristic curves of these loops are shown in Appendix E along with their corresponding data.

Taking all factors into consideration, the tests have shown the loop giving the best results is made of 17-st. duralumin, 0.125 inches in diameter with a coil of three turns for holding the link. This loop has a reading of

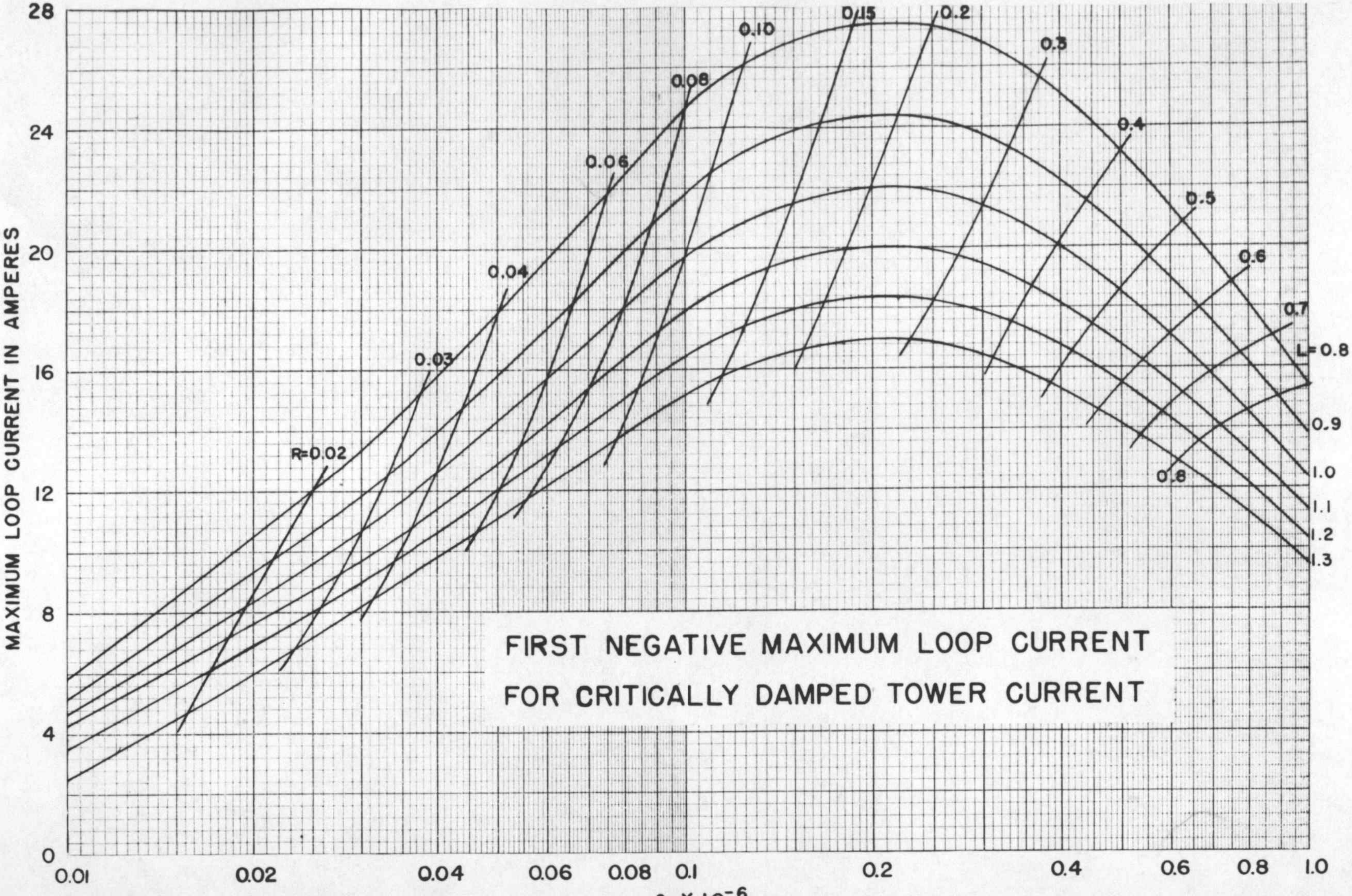

FIRST NEGATIVE MAXIMUM LOOP CURRENT
FOR CRITICALLY DAMPED TOWER CURRENT
MAXIMUM LOOP CURRENT IN AMPERES
δ X 10⁻⁶
0
4
8
12
16
20
24
28
0.01
0.02
0.04
0.06
0.08
0.1
0.2
0.4
0.6
0.8
1.0
R=0.02
0.03
0.04
0.06
0.08
0.10
0.15
0.2
0.3
0.4
0.5
0.6
0.7
0.8
L=0.8
0.9
1.0
1.1
1.2
1.3

FIGURE 10

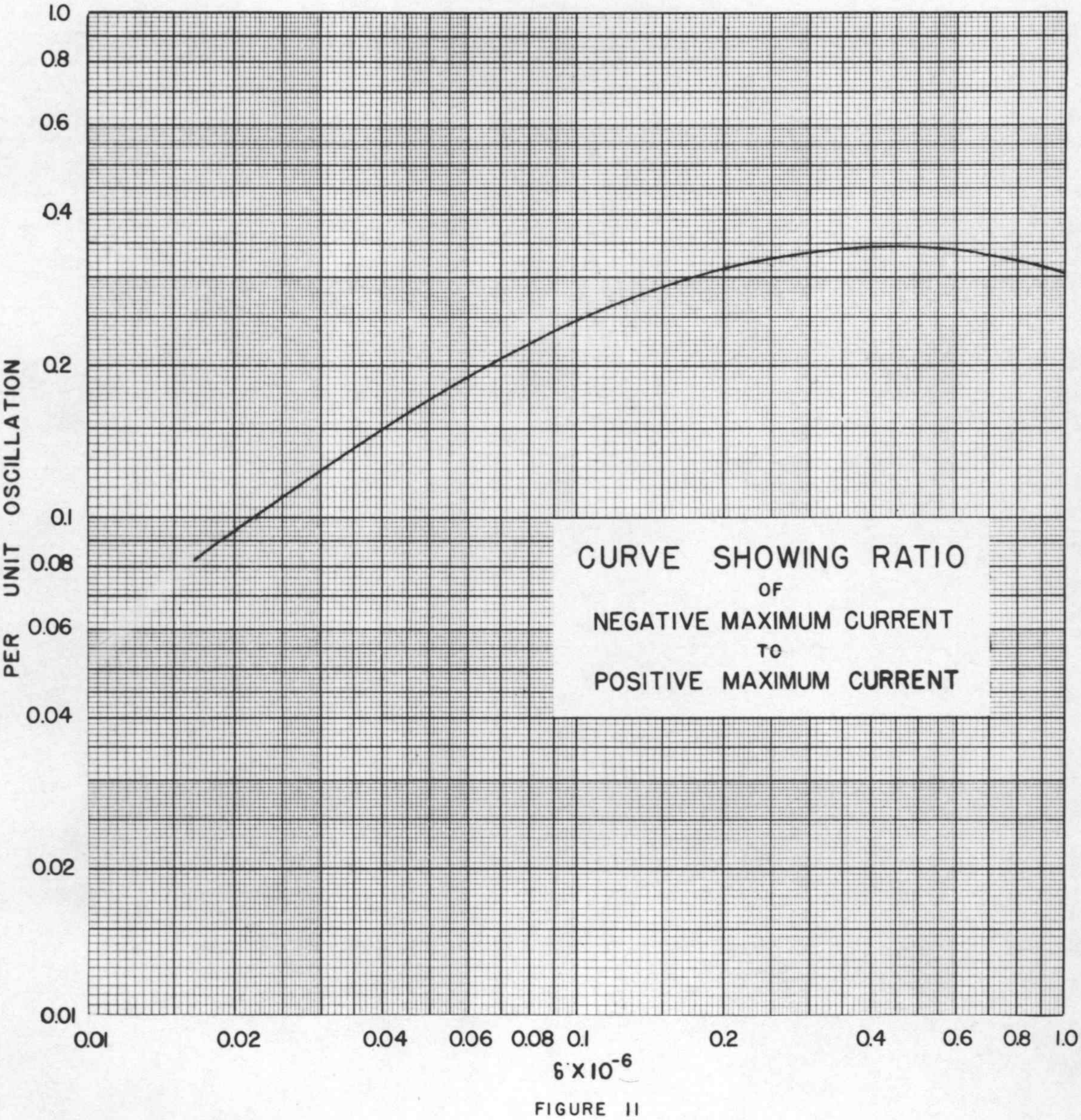

CURVE SHOWING RATIO
OF
NEGATIVE MAXIMUM CURRENT
TO
POSITIVE MAXIMUM CURRENT
PER UNIT OSCILLATION
1.0
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
0.01
0.02
0.04
0.06
0.08
0.1
0.2
0.4
0.6
0.8
1.0
δ X 10⁻⁶

FIGURE 11

68.5 S.C.A. units at 6,000 amperes before the a-c follow-up current is applied. After 1,200 amperes is applied to the tower leg, the reading drops to 61.5 S.C.A. units. As a comparison, to illustrate how a loop of a low value of ∂ ($\partial = 0.0789$) would respond, the No. 7 size copper loop, of seven turns, gives a reading of 73 S.C.A. units but drops to approximately 31 when an a-c current of 1,200 amperes follows the surge.

All of the characteristic curves show the effect of the negative loop current. At low tower currents, the loops have a linear response and as the tower current increases the negative portion of the loop currents becomes large enough to remove part of the residual magnetism.

The effect of the negative portion of the loop current can be decreased by changing the number of turns in the loop. This is shown in figure 12, page 31. The duralumin wire, 17-st, 0.125 inches in diameter, was used and the number of turns varied from nine to two. Nine turns was the maximum number of turns that could be used and not extend the coil beyond the ends of the link. The effect of changing the amount of the link, covered by the coil, is shown in figure 14, Page 33. These curves, for both the five and six turn coils, show that when the coil is compressed and does not cover the entire link, the amount

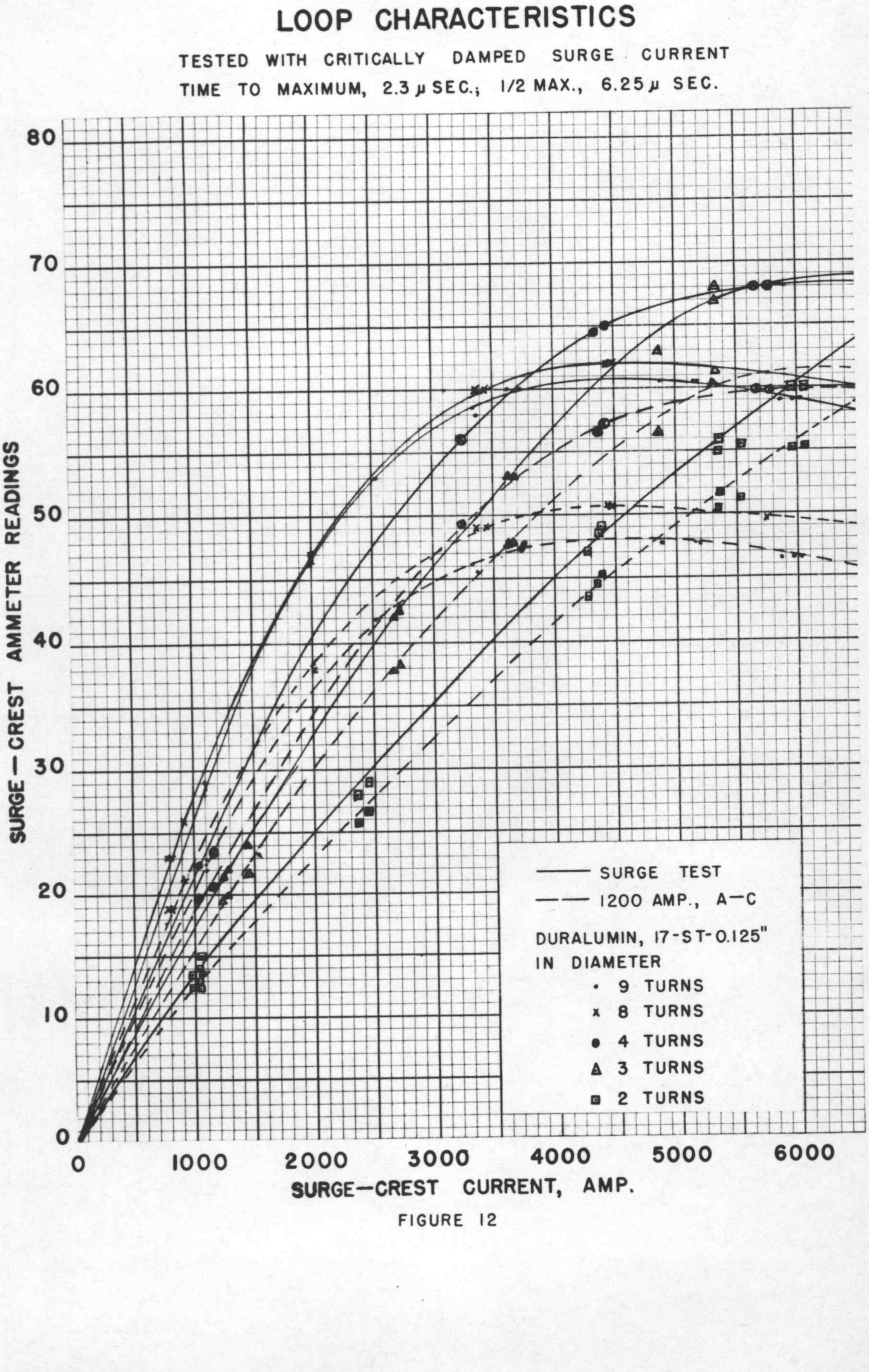

LOOP CHARACTERISTICS
TESTED WITH CRITICALLY DAMPED SURGE CURRENT
TIME TO MAXIMUM, 2.3 μ SEC.; 1/2 MAX., 6.25 μ SEC.
SURGE — CREST AMMETER READINGS
0
10
20
30
40
50
60
70
80
0
1000
2000
3000
4000
5000
6000
SURGE—CREST CURRENT, AMP.
SURGE TEST
1200 AMP., A—C
DURALUMIN, 17-ST-0.125" IN DIAMETER
• 9 TURNS
x 8 TURNS
● 4 TURNS
Δ 3 TURNS
⊡ 2 TURNS

FIGURE 12

LOOP CHARACTERISTICS

TESTED WITH CRITICALLY DAMPED SURGE CURRENT

TIME TO MAXIMUM, 2.3 μ SEC.; 1/2 MAX., 6.25 μ SEC.

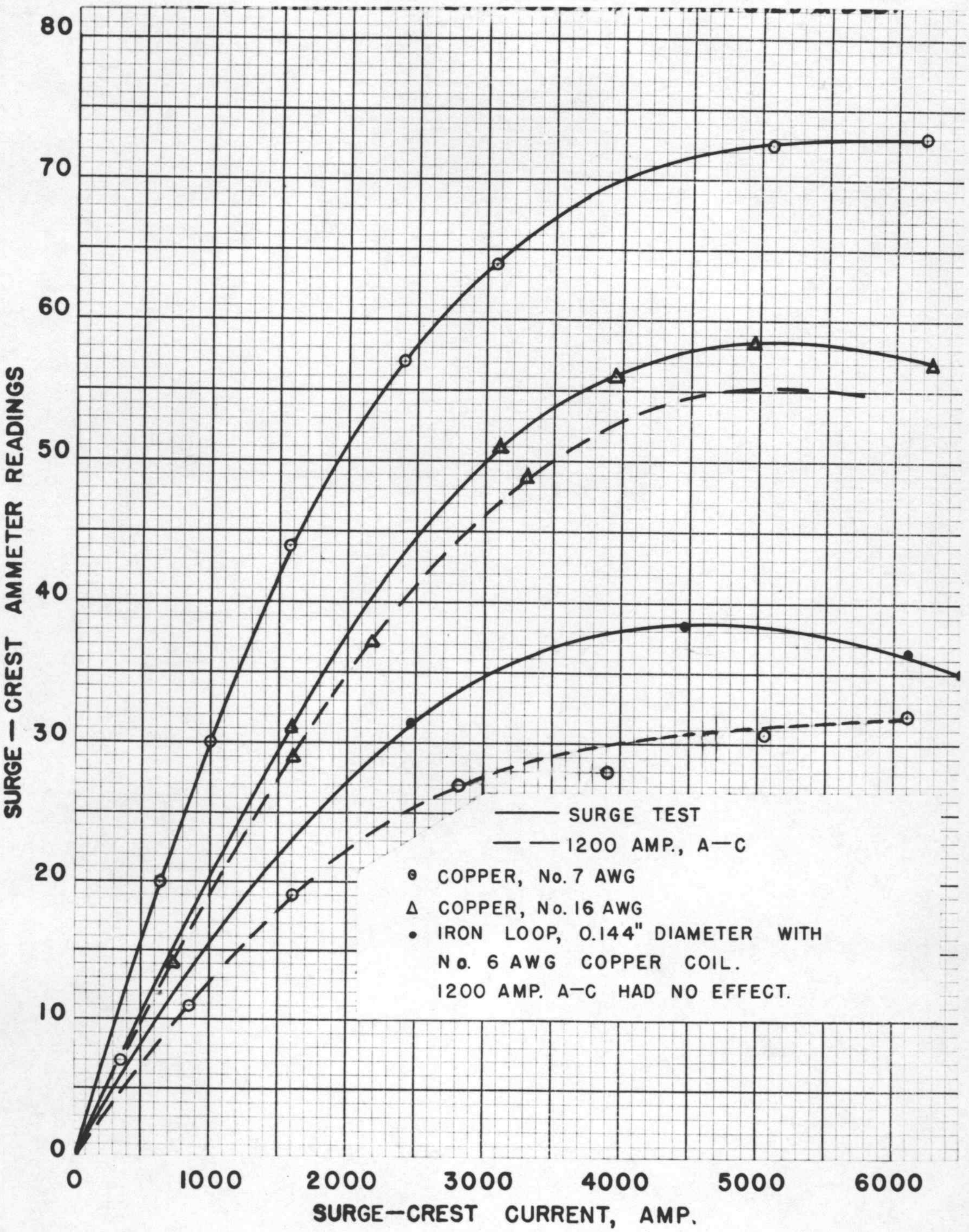


FIGURE 13

LOOP CHARACTERISTICS

TESTED WITH CRITICALLY DAMPED SURGE CURRENT

TIME TO MAXIMUM, 2.3 μ SEC.; 1/2 MAX., 6.25 μ SEC.

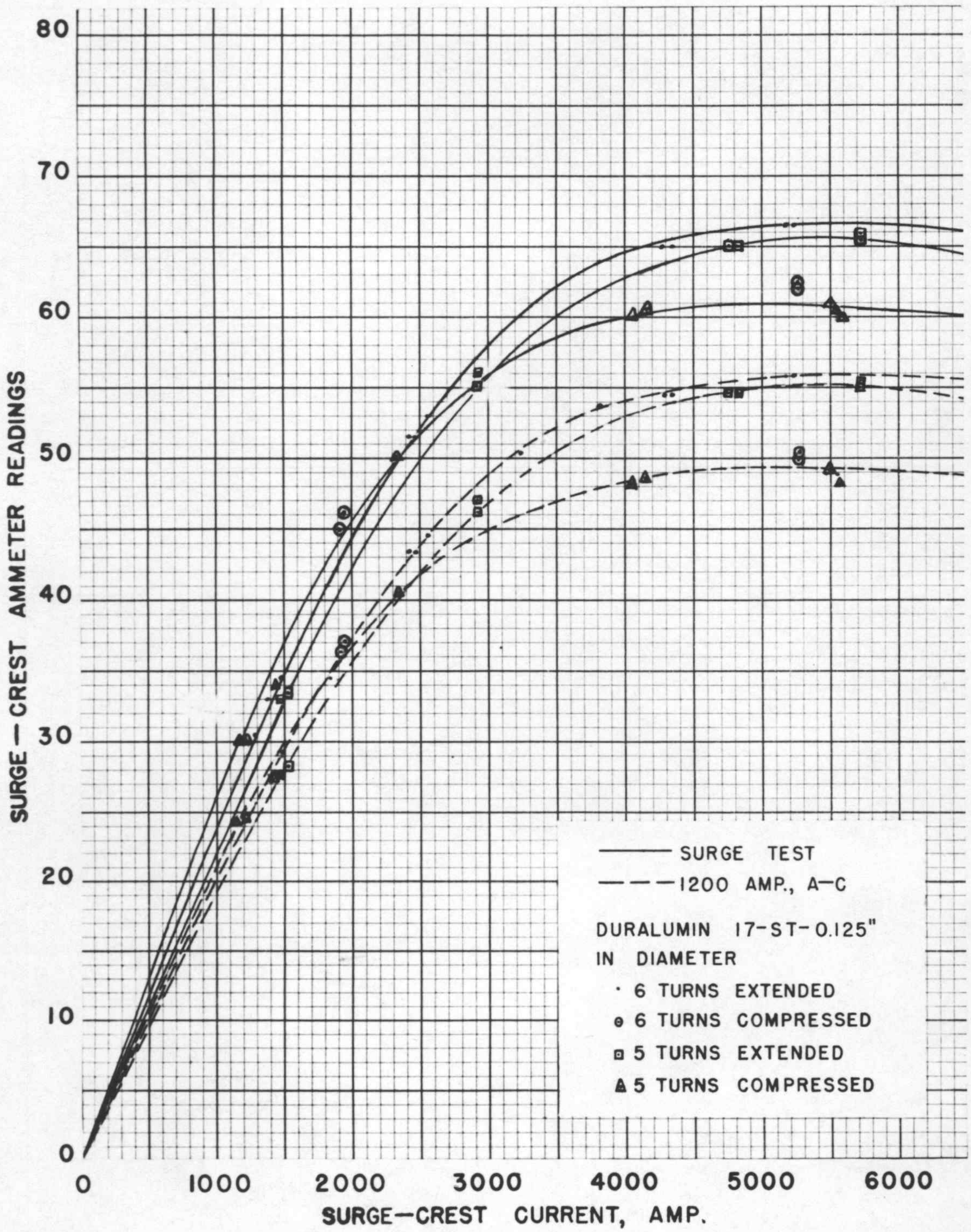


FIGURE 14

of residual magnetism left is less than if the coil covers the entire link.

The characteristic curve of the original iron loop, designed and put into operation by the Bonneville Power Administration, is shown in figure 15, page 35. The original loop had no galvanizing on its surface, therefore, to prevent rusting of the loops, they were galvanized. In so doing they placed on the surface of the loop a conducting medium that allowed the negative current to remove a larger portion of the magnetism. This effect is also shown in the copper-weld wires that were tested.

The iron wire loops have one advantage over the other loops in that there is no residual magnetism removed when an alternating current flows through the tower leg. This is due to the high resistance which gives a high value of δ .

The characteristic curves taken, using the 1 1/2 - 40 surge current, show the linear response over the range tested. It was not possible to test with higher currents because of the limitations of the surge equipment.

Two types of underdamped surge currents were used. One was slightly underdamped and the other was the 50% oscillatory current for which the tower and loop currents were plotted. For the first case, figure 32, page 75g

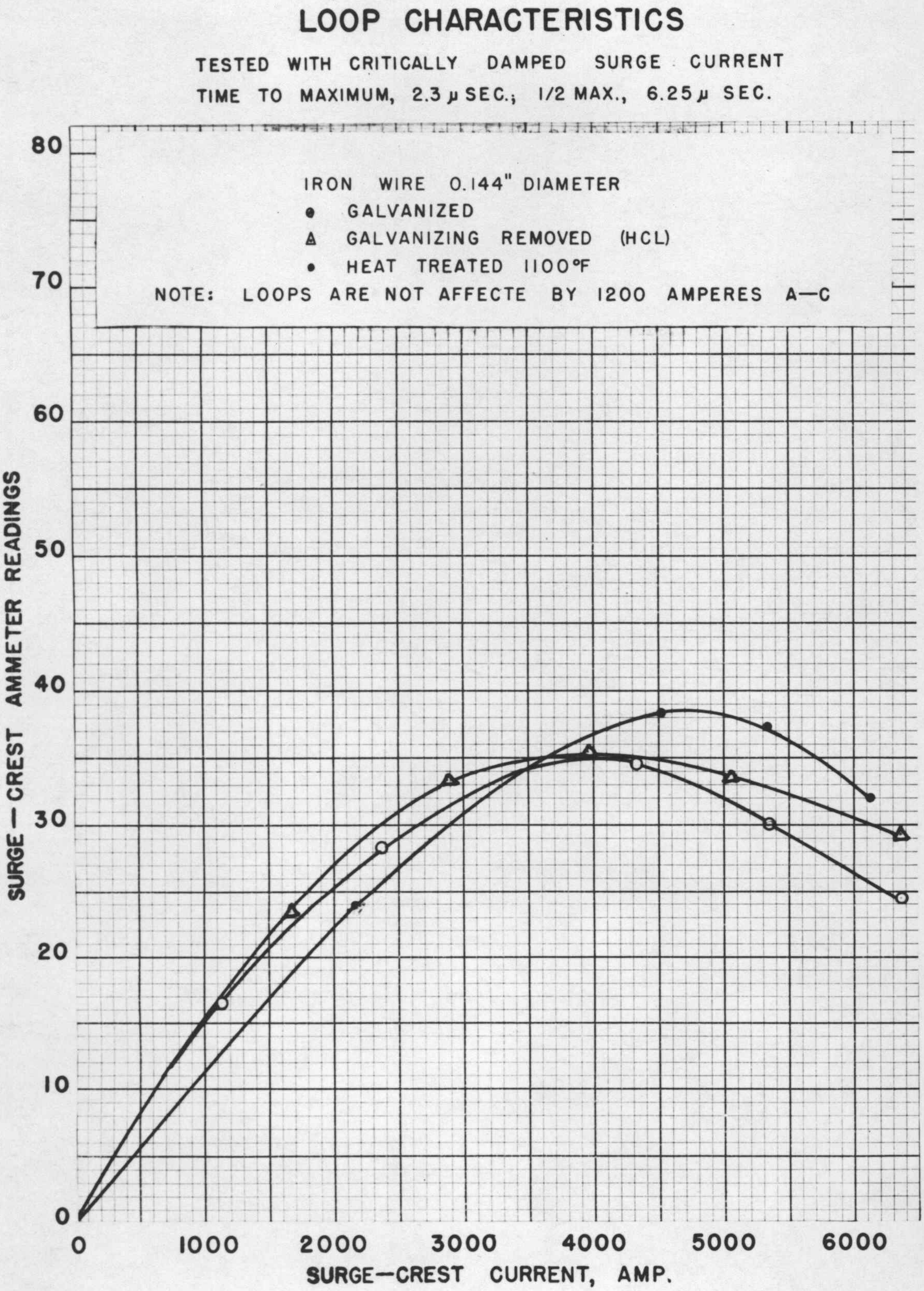

LOOP CHARACTERISTICS
TESTED WITH CRITICALLY DAMPED SURGE CURRENT
TIME TO MAXIMUM, 2.3 μ SEC.; 1/2 MAX., 6.25 μ SEC.
IRON WIRE 0.144" DIAMETER
● GALVANIZED
Δ GALVANIZING REMOVED (HCL)
• HEAT TREATED 1100°F
NOTE: LOOPS ARE NOT AFFECTE BY 1200 AMPERES A—C
SURGE — CREST AMMETER READINGS
0
10
20
30
40
50
60
70
80
0
1000
2000
3000
4000
5000
6000
SURGE—CREST CURRENT, AMP.

FIGURE 15

shows that the negative loop current becomes large enough to reverse the residual magnetism after the tower current becomes greater than 5,500 amperes. For the 50% oscillatory case, the negative loop controls the residual magnetism causing it to be negative for all values.

SKIN EFFECT

Another factor that will effect the operation of the loop is the change of the resistance and inductance of the loop due to skin effect. The lightning flashover-detector loop conducts very high speed impulse currents induced in it by the adjacent tower leg. It is known that any conductor which carries rapidly changing current is subject to a condition called "skin effects." Therefore, to enable a more complete analysis of loop problems a brief study of these skin effects must be made. Ordinarily skin effect studies are made for conductors carrying high-frequency alternating current. But it will be shown that the steep wave fronts of impulse currents also present an important problem. Currents of power frequencies alternate so slowly that compared to induced lightning impulses they are almost the same as direct current. Therefore, this study is directed mainly at the impulse current.

Previous equations show how the induced loop current depends upon the resistance and inductance of the loop. Then by having an understanding of how these parameters vary with changing current, a better overall understanding at loop performance may be had.

Theoretical discussion of skin effects

A wire of homogenious cross section carrying direct current will have the same current density throughout its entire cross section. A unit length of wire may be assumed to be made up of small filaments all connected in parallel. Therefore, the voltage drop across all of the filaments will be the same. Since the current density is uniform, each will carry the same current and the total will be the summation of all of these small currents. The d-c resistance of such a wire will be given by the following:

$$R = \frac{\rho l}{A} \text{ ohms} \tag{16}$$

where: R = resistance in ohms

ρ = resistivity

l = length

A = Area of cross section

Now consider the case of an alternating current in the wire. In accordance with Lenz's law, the changing magnetic field, produced by the alternating current, will induce a voltage of such a direction as to oppose the current flow in the wire. There must still be the same voltage drop across each filament of conductor because they were assumed to be connected in parallel

But a filament in the center of the wire will be surrounded by a greater number of flux linkages than a filament at the surface. This means a greater induced voltage at the center of the wire, which will in turn require a smaller ohmic drop to make the total voltage drop in this filament equal to that on the surface. Since an ohmic drop depends upon the magnitude of the current, it follows that the greatest amount of current must be flowing on the surface of the wire because the ohmic drop is greatest there.

It is now apparent that the resistance of a wire carrying a-c must increase with frequency. This must be true because when frequency increases, more of the current crowds toward the surface at the wire. This utilizes a smaller cross section area of the wire and as in equation (1) the resistance will be higher.

Some very accurate formulas have been derived for the a-c resistance and inductance of round wires. The formulas for a sinusoidal current were relatively easy to derive because they involve simple functions. But other types of current will present skin effect problems as well. The exponential current induced in the lightning flashover-detector loop is a very rapidly changing current and as such must be considered for skin effects. It will not be attempted to derive any formulas for these currents because of their extremely complex equations. Since these conditions must be studied in order to explain the operation of the loops, an empirical method will be used. The graph of figure 16 shows how sine waves have been assumed so that a definite frequency can be calculated for a given time to maximum. It has been assumed that the time to maximum of the exponential wave is the same as 1/4 of a sine wave. Therefore, four times this time would be a full cycle and the reciprocal of 4 t would be the frequency. A similar assumption is used when considering the decaying wave for a given time, t_1, to half maximum. In the later case a full cycle is 8 t_1 and the frequency is the reciprocal of 8 t_1.

$$f = \frac{1 \text{ cycle}}{4\,t} \qquad (17)$$

t = time to max-micro second

$$f_1 = \frac{1 \text{ cycle}}{8\,t_1} \qquad (18)$$

t_1 = time to half decay micro second

Although figure 16 is only an approximation, it may be used to translate impulse wave data to appropriate frequencies of sine waves for use with a-c resistance and inductance curves and formulas. Some formulas, which may be used to calculate a-c resistance and inductance of homogenious round wires, are as follows:

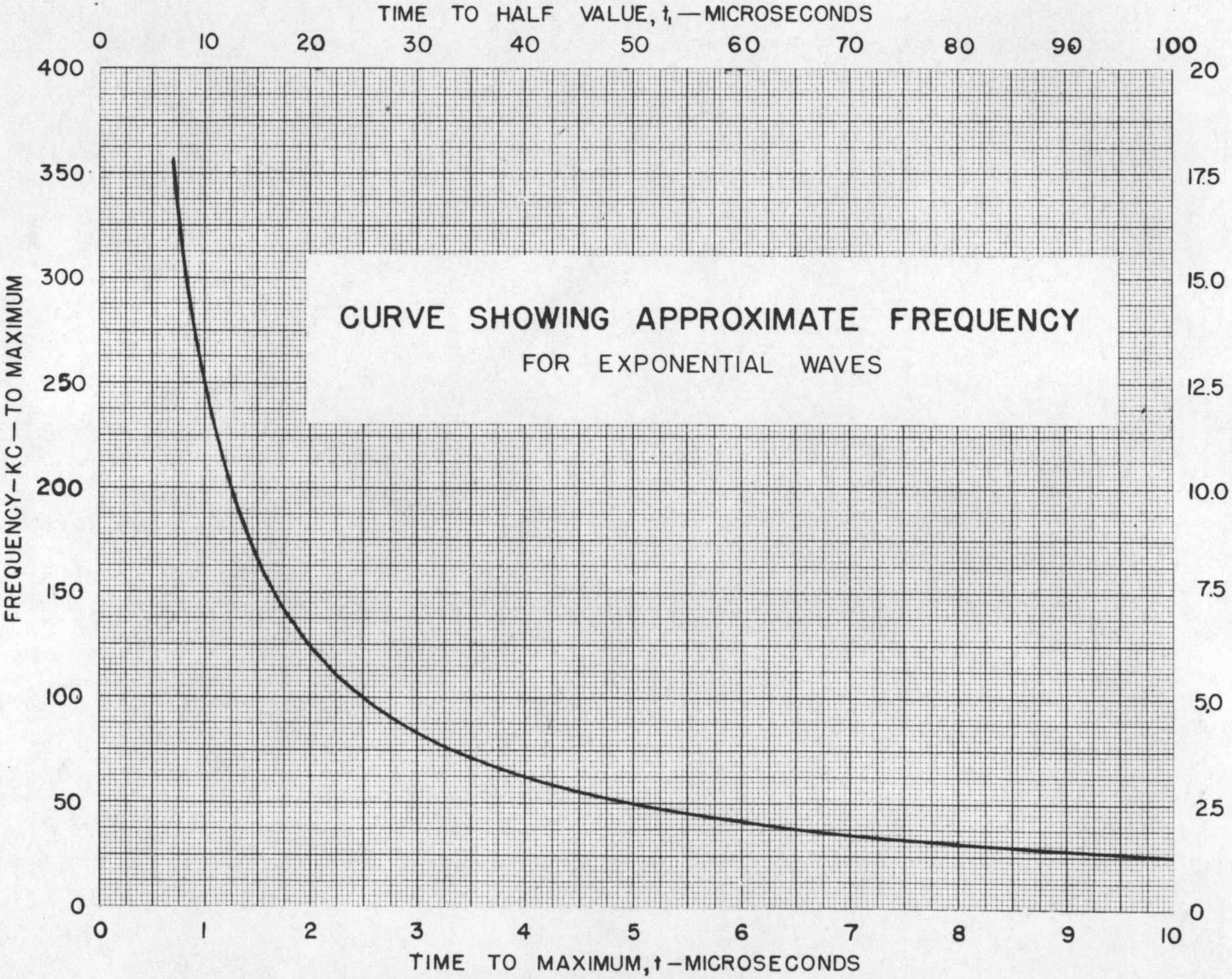

TIME TO HALF VALUE, t_1 — MICROSECONDS
0 10 20 30 40 50 60 70 80 90 100
CURVE SHOWING APPROXIMATE FREQUENCY
FOR EXPONENTIAL WAVES
FREQUENCY-KC-TO MAXIMUM
400 350 300 250 200 150 100 50 0
FREQUENCY-KC-TO HALF VALUE
20 17.5 15.0 12.5 10.0 7.5 5.0 2.5 0
0 1 2 3 4 5 6 7 8 9 10
TIME TO MAXIMUM, t — MICROSECONDS

FIGURE 16

$$R = \frac{\rho n}{2\pi r}\left[\frac{\text{bei}'(nr)\,\text{ber}(nr) - \text{ber}'(nr)\,\text{bei}(nr)}{[\text{ber}'(nr)]^2 + [\text{bei}'(nr)]^2}\right] \quad (19)$$

$$L = \frac{\rho n}{2\pi \omega r}\left[\frac{\text{ber}(nr)\,\text{ber}(r) + \text{ber}'(nr)\,\text{bei}'(nr)}{[\text{ber}'(nr)]^2 + [\text{bei}'(nr)]^2}\right] \quad (20)$$

where:

ρ = Resistivity of wire in ohm-meters

r = radius of wire in meters

$\omega = 2\pi f$ = angular velocity in radians/sec.

ber and bei are bessel functions, real and imaginary

ber' and bei' are first darivatives of real and imaginary bessel functions.

$$nr = r\sqrt{\frac{\omega\mu}{\rho}} \quad (21)$$

where:

μ = permeability of wire

The use of these formulas is very laborious so the curve of figure 2 has been included. When using figure 17 all that is necessary is to know the values of nr for the desired frequencies and the ratio. R_{ac}/R_{dc} can be determined. Equation (6) is used to calculate nr.

Skin effects applied to the loops

Figure 3 is a curve showing the calcuh ted a-c resistance of several of the test loops. These curves were calculated as outlined above and were based upon the wire

SKIN EFFECT INDUCTANCE AND RESISTANCE RATIOS

FOR SOLID ROUND WIRES

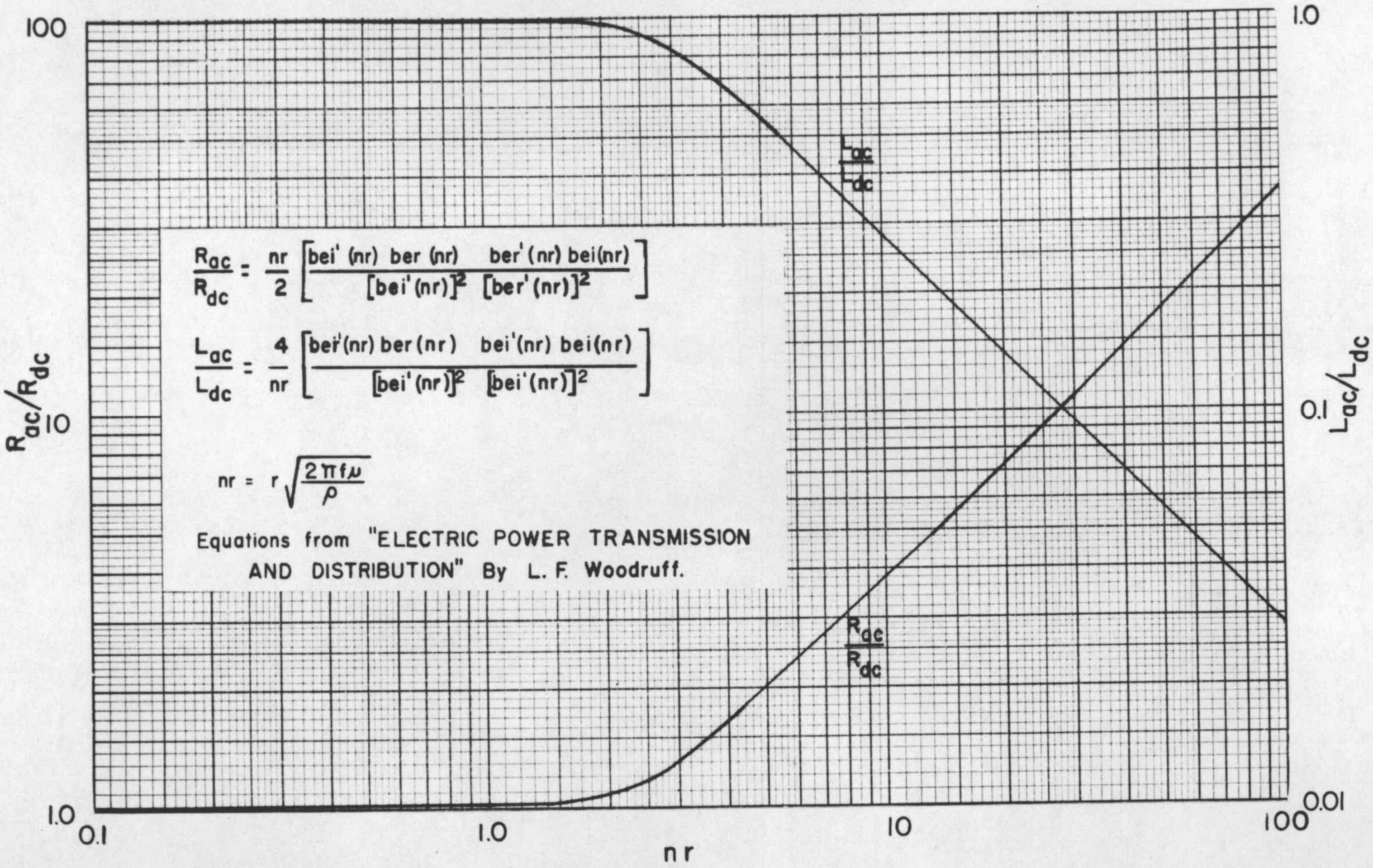


FIGURE 17

diameter, resistivity, and loop resistance. Appendix B gives the resistance data for all loops tested. The calculations assume a wire in free space not affected by surroundings. But in the case of the loop the tower leg may have some proximity effect. Figure 18 does show how much resistance of the loop may change with frequency, or with change in the slope of the test wave. Consider the case of loop number 28 with the 1.5-40 second test wave. From figure 16

$T = 1.5$ sec. $f = 166$ kc

$T_1 = 50$ sec. $f_1 = 3.12$ kc

From figure 18 the resistances are:

when $f = 166$ kc $R = 0.024$ ohms

when $f_1 = 3.12$ kc $R = 0.0071$ ohms

Table II

Calculated resistance of round wires

Data used for curve figure 18

All loops have 7-turn coils

Loop No.1	Loop Material	Loop Resistance Ohms	Resistivity Ohm-meter x10-8	Wire Radius Meters x10-7	Permeability x10-7	AWG Wire Size
1	iron	0.0185	12.2	1.83	≈6290	7
12	copper	0.0281	1.77	0.510	≈12.56	18
10	copper	0.01093	1.77	0.815	12.56	14
9	copper	0.00720	1.77	1.025	12.56	12
14	Weld 30%	0.01199	See Note	1.45	See Note	9
18	Aluminum	0.004496	2.78	1.625	12.56	8
20	Aluminum 17-St	0.007741	3.31	1.30	12.56	10
23	Duralumin 24-St	0.003843	4.84	2.37	12.56	0.187 in.
24	Duralumin 17-St	0.009514	5.79	1.59	12.56	0.125 in.
28	Duralumin	0.007135	4.40	1.59	12.56	0.125 in.

Note: Data for Loop No. 14 curve was taken from the paper " Copper Covered Steel Wire at RF" By B. R. Teare and E. R. Schatz, July 1944 IRE.

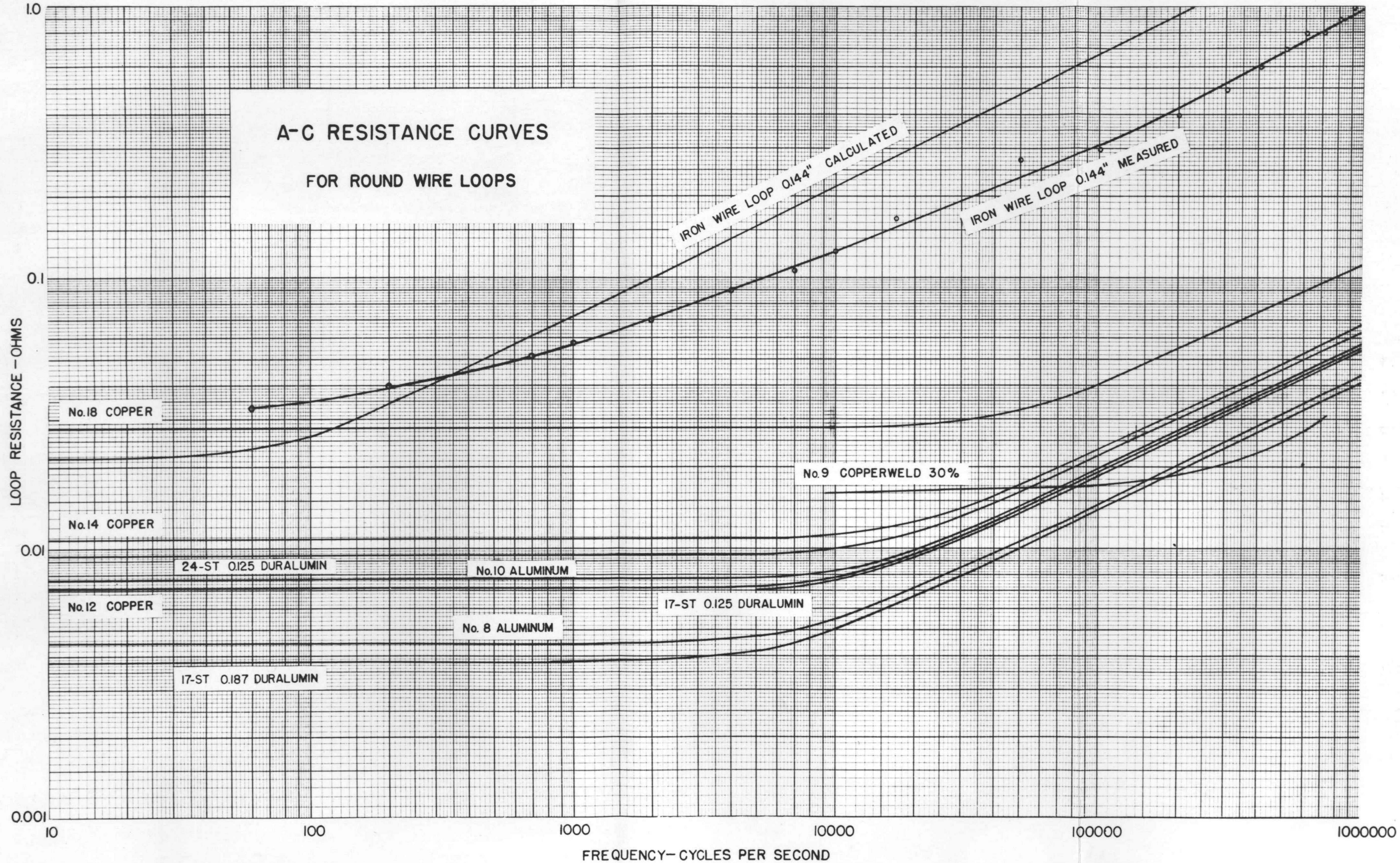

A-C RESISTANCE CURVES
FOR ROUND WIRE LOOPS
IRON WIRE LOOP 0.144" CALCULATED
IRON WIRE LOOP 0.144" MEASURED
No.18 COPPER
No.9 COPPERWELD 30%
No.14 COPPER
24-ST 0.125 DURALUMIN
No.10 ALUMINUM
No.12 COPPER
17-ST 0.125 DURALUMIN
No. 8 ALUMINUM
17-ST 0.187 DURALUMIN
LOOP RESISTANCE - OHMS
1.0
0.1
0.01
0.001
10
100
1000
10000
100000
1000000
FREQUENCY- CYCLES PER SECOND

FIGURE 18

This shows that the resistance of the loop, after the wave crest has passed, is only 34% of what it was before the crest. This is merely an approximation but it does show how much the skin effect can alter the resistance of the loop as the tower current wave passes from a steep front to a slowly decaying tail.

The curve of figure 2 shows that inductance varies in a manner opposite to resistance, increasing with a decrease in frequency. Thus it appears that the loop design factor $\delta = \frac{R}{L}$ is not linear with time. Therefore, δ decreases as the tower current wave passes from wave front to tail. Equation (2), of the section "Mathematical Analysis of the Loop," shows that loop current will be increased at a given time when δ is decreased. This increase of loop current will occur on the tail of the wave where loop current is negative. The result of skin effects is to decrease at the time when the loop current has reversed, giving more demagnetizing effect to the link. This means a smaller link reading than would be obtained if δ remained constant.

The curve of figure 19 has been calculated from figure 17. It shows how δ will vary with frequency for a given size and type of wire. Since R_{dc}, L_{ac}, r, ρ and μ are all constants, the ratio R_{ac}/L_{ac} will vary as a function of the square root of frequency. This bears out what has been said previously about the variation of δ with frequency.

CURVE OF δk AS A FUNCTION OF nr

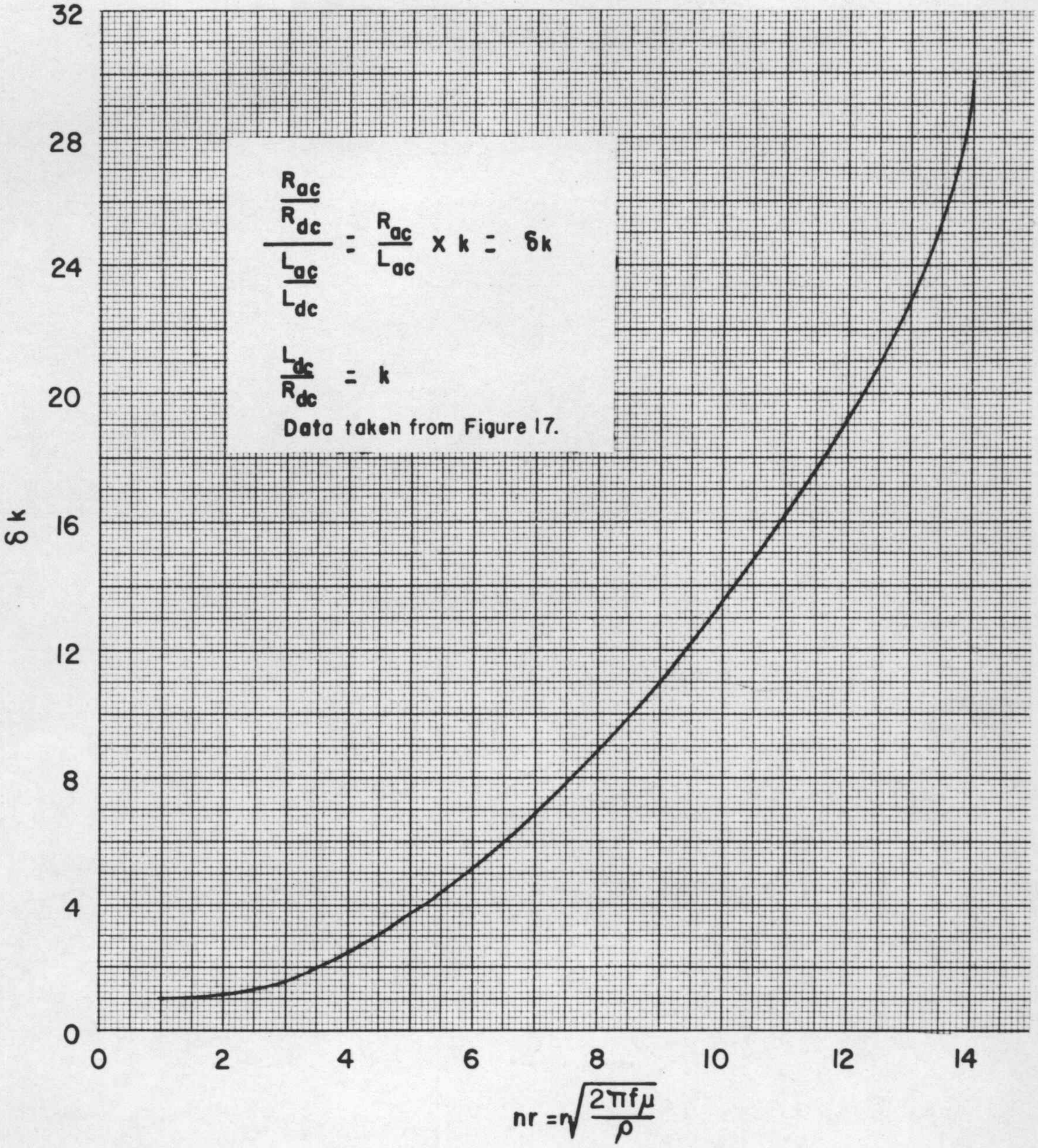


FIGURE 19

Some data on the effect of frequency upon bi-metallic conductors has been obtained from the paper "Copper Covered Steel Wire at Radio Frequency" by B. R. Teare and E. R. Schatz, July 1944 IRE. From this paper the curve of loop No. 14, figure 18, (#9 copperweld 30% wire) has been plotted. It is interesting to note that the change in resistance, with frequency, is not as great for the medium range as with the solid conductors. This is true because copperweld wire, with its copper skin, is going to carry the majority of the current on the surface regardless of frequency. The fact that copperweld wire maintains a high resistance at low frequency is its most important feature here. This means that induced sixty cycle currents will be low, while operation at impulse frequency is not impaired.

A galvanized wire is actually similar to the copperweld wire because it is a bi-metallic conductor. The zinc coating, though not nearly as conducting as copper, will have a material effect upon the operation of the iron wire loop. But it happens that the combination of zinc on iron actually impairs the efficiency of the loop (see loop characteristics curves). This combination causes the loop to have a ∂ ratio which permits the ratio of negative to positive loop current to be large. As has been previously discussed, this condition will cause severe downward bending of the loop characteristic curve.

THE USE OF RECTIFIERS TO REMOVE THE EFFECT OF THE NEGATIVE LOOP CURRENT

The primary purpose of this work is to develop this type of lightning detector for use as a measuring device. The basic reason why this could not be accomplished up to this point is the removal of part of residual magnetism by the negative portion of the loop current. In an effort to remove this effect a metallic rectifier was inserted in series with recording loop. By doing this the current was allowed to flow in only one direction. This type of unit was tested using the critically damped tower current and the characteristic curve is shown on page 51. This unit would be very useful in determining either the rate of rise or the rate of decay of a surge current. It would measure the rate of rise when the front of the loop that would be permitted to flow in the loop. In a similar manner it could be used to measure the rate of decay of the surge current. The main objection to using it in this manner is that lightning current can flow from the earth to a cloud or in the opposite direction. If the loop was designed to measure the front of a wave flowing from earth to cloud, it would block satisfactorily the back voltage, due to the tail of the wave. On the other hand, if the current wave was flowing from a cloud to earth, the voltage induced by the front of the wave would be quite large compared to the voltage induced by the tail of the wave flowing in the opposite direction. If the rectifier is designed to withstand all back voltages, then it would involve a large rectifier or a series of rectifiers.

In order to prevent the destruction of small rectifiers or the use of large rectifiers, another type of loop was designed. A picture of this loop is shown in figure 23, page 57a. Rather than using the rectifiers for blocking the voltage, they are used to shunt the current through one of two paths. In this loop there are two coils and two rectifiers; one rectifier is set to allow the current due to the front of the wave to flow. The coil connected to this rectifier will give the rate of rise of the wave. The other is set to allow the current, due to the tail of the wave to pass, giving a measure of the rate of decay of the wave.

The value of residual magnetism remaining in the link was shown to be a direct function of the maximum current that flows in the loop. The current that flows in the loop is acting as a result of the voltage impressed on the loop. This voltage is induced in the loop according to the following equation:

$$e = M \frac{di}{dt} \qquad (22)$$

LOOP CHARACTERISTICS

TESTED WITH CRITICALLY DAMPED SURGE CURRENT

TIME TO MAXIMUM, 2.3 μ SEC.; 1/2 MAX., 6.25 μ SEC.

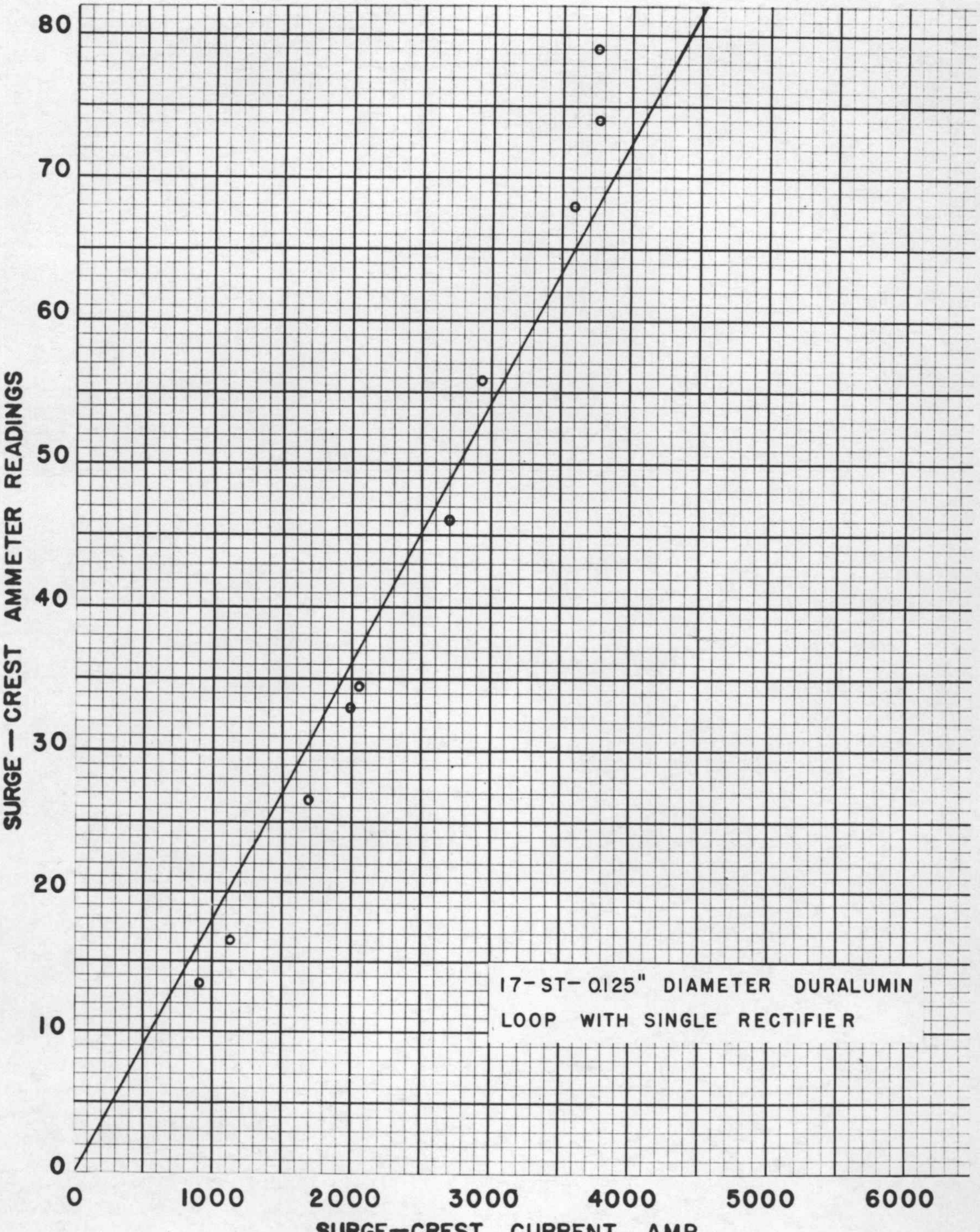


FIGURE 20

where: i is the current in the tower,

M is the mutual inductance between the tower and the loop

If the rate of change of the tower current is maximum, then the voltage induced in the loop will be maximum in value. If the loop is composed of pure resistance, the current flowing in the loop will be maximum when the induced voltage is maximum. The loop cannot be designed with zero inductance. Therefore, the maximum current that flows in the loop will lag behind the maximum voltage. The same factors will influence both the maximum current induced in the loop by the rate of rise of the wave and the rate of decay of the wave.

It has been shown that there is a direct relationship between the maximum rate of change of the tower current and the amount of residual magnetism remaining in the link. This factor is the reason why the loop using two rectifiers and two loops can be used to measure the type of wave that has passed through the tower and the magnitude of the current.

The type of wave flowing through the tower may be determined by the ratio of maximum rate of rise of the wave to the maximum rate of decay of the wave. This ratio η should be equal to the ratio of larger surge crest ammeter reading to the smaller reading expressed in equation form.

$$\eta = \frac{\frac{di}{dt}\text{ (front)}}{\frac{di}{dt}\text{ (tail)}} = \frac{\text{larger S.C.A. Reading}}{\text{smaller S.C.A. Reading}}$$

The curve, figure 21, page 54, gives this ratio (η) as a function of the ratio of the time to half value (t_2) to the time to maximum (t_1). In order to determine the value of t_1 and t_2 it is necessary to obtain the maximum rate of change of the front of the wave. This value is obtained from figure 23, page 57b, using the larger link reading and the ratio of t_2 to t_1 obtained from figure 21. Knowing the maximum rate of change of the front of the front of the wave, the maximum current flowing is found from figure 24. This curve gives the maximum rate of change of the front of the wave as a function of the maximum current. This is a family of curves for different values of the ratio of t_2 to t_1. After the actual rate of change of the front of the wave is found, it is necessary to determine the rate of change of the front of the wave for a maximum tower current of 1000 amperes holding the ratio of t_2 to t_1 constant. With this value of the rate of change of the front of the wave, the values of t_1 and t_2 can be determined from figure 25, page 57e. These values are obtained at the point where the maximum rate of change of the front of the wave coincides with the value of the ratio t_2 to t_1 obtained from figure 21.

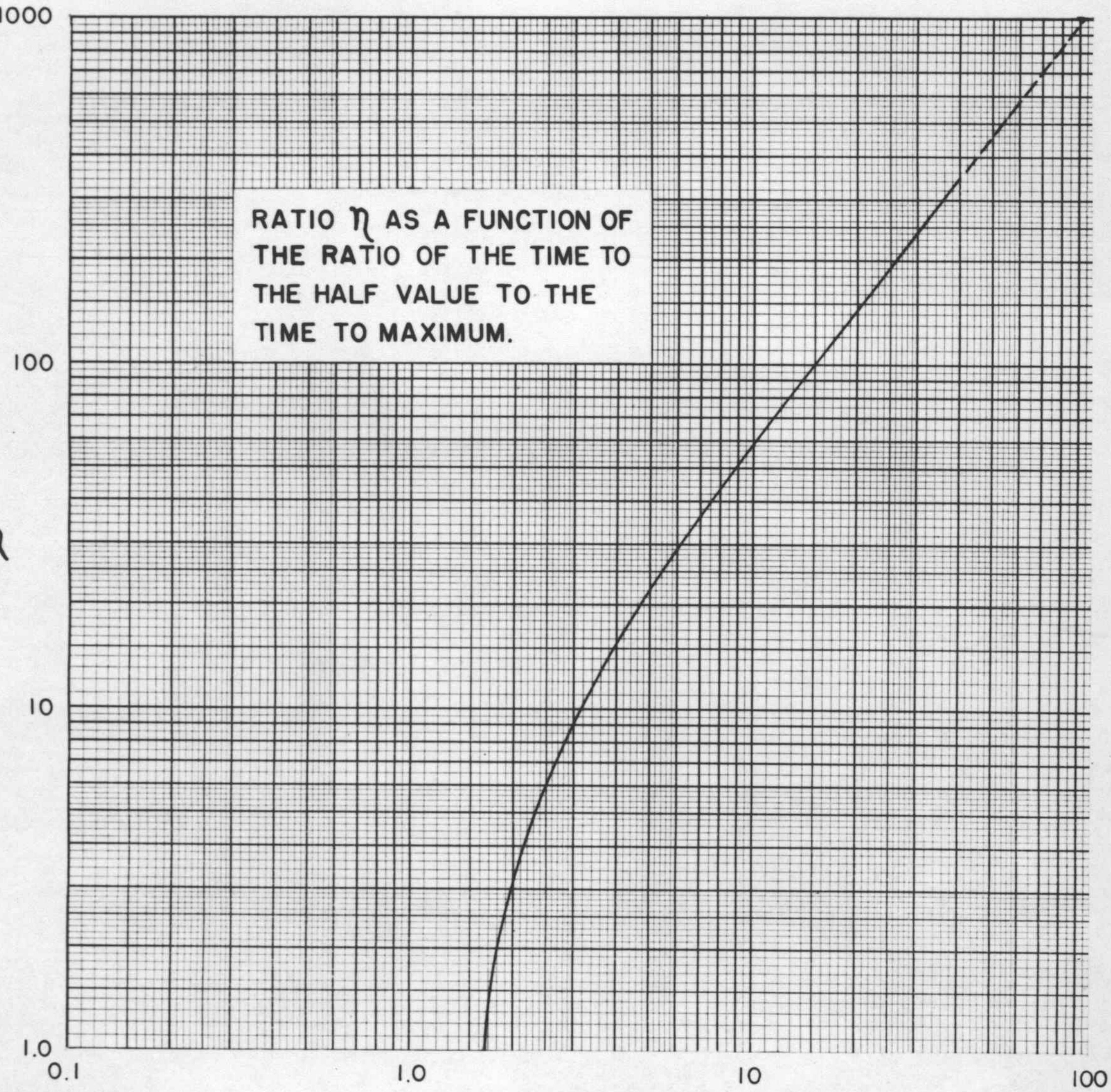

RATIO η AS A FUNCTION OF THE RATIO OF THE TIME TO THE HALF VALUE TO THE TIME TO MAXIMUM.
1000
100
10
1.0
η
0.1
1.0
10
100
t2 / t1

FIGURE 21

Example:

A tower is struck by lightning and the links are magnetized to the following values.

1. 73.0 S.C.A. units

2. 10 S.C.A. units

For these values:

$\eta = 7.3$

From figure 21:

$t_2/t_1 = 2.717$

From figure 23:

$$\left(\frac{di}{dt}\right)_{max} = 5.1 \times 10^9 \quad \frac{\text{amperes}}{\text{second}}$$

From figure 24:

The maximum loop current is 4,700 amperes.

At 1000 amperes teh value of $\left(\frac{di}{dt}\right)_{max}$ on the $\frac{t_2}{t_1} = 2.717$ curve is:

$$1.09 \times 10^9 \quad \frac{\text{amperes}}{\text{second}}$$

Using this value and the value of $t_2/t_1 = 2.717$ on figure 25, the values of t_1 and t_2 are found to be:

$t_1 = 2.5$

$t_2 = 6.8$

The above results show all the information necessary to identify the type of wave and the maximum value of current that has passed through the conductor on which the indicator is mounted.

There is one factor that prohibits the use of this analyzer for all types of current waves. It is the range of the surge crest ammeter. In order to measure wave shapes that are overdamped it is necessary to have a large ratio of η . This is shown by the 1 1/2 - 40 wave which has a value of η equal to 205. This means that the larger reading would have to have a magnitude of 205 and the smaller a reading of one. This cannot be obtained on the present instrument because the working range of the instrument is from 10 to 80. In order to extend the range of the surge crest ammeter it would need two scales one of low sensitivity for use in reading large values and one of high sensitivity for reading the smaller of the two values.

LOOP CHARACTERISTICS

TESTED WITH CRITICALLY DAMPED SURGE CURRENT

TIME TO MAXIMUM, 2.3 μ SEC.; 1/2 MAX., 6.25 μ SEC.

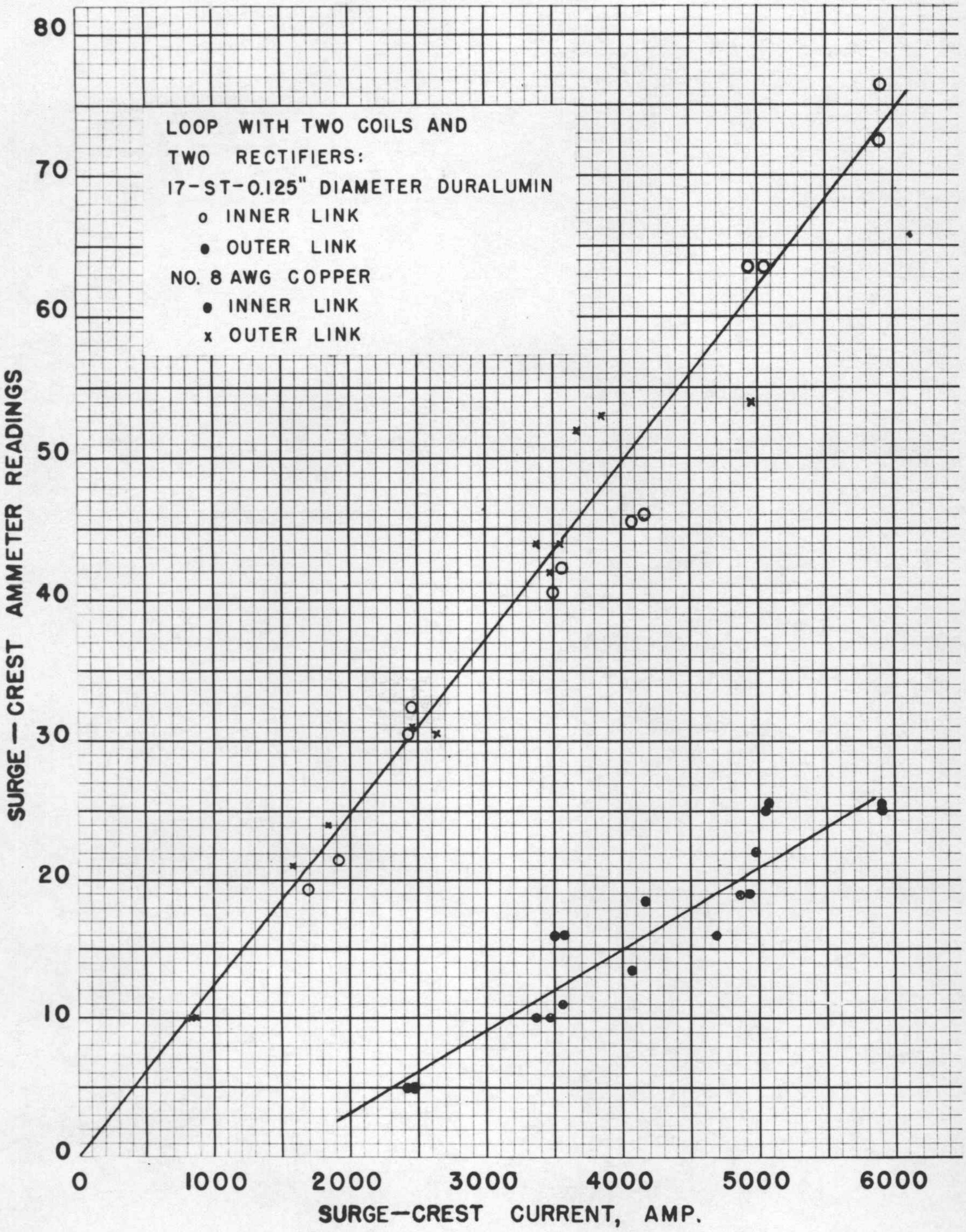


FIGURE 22

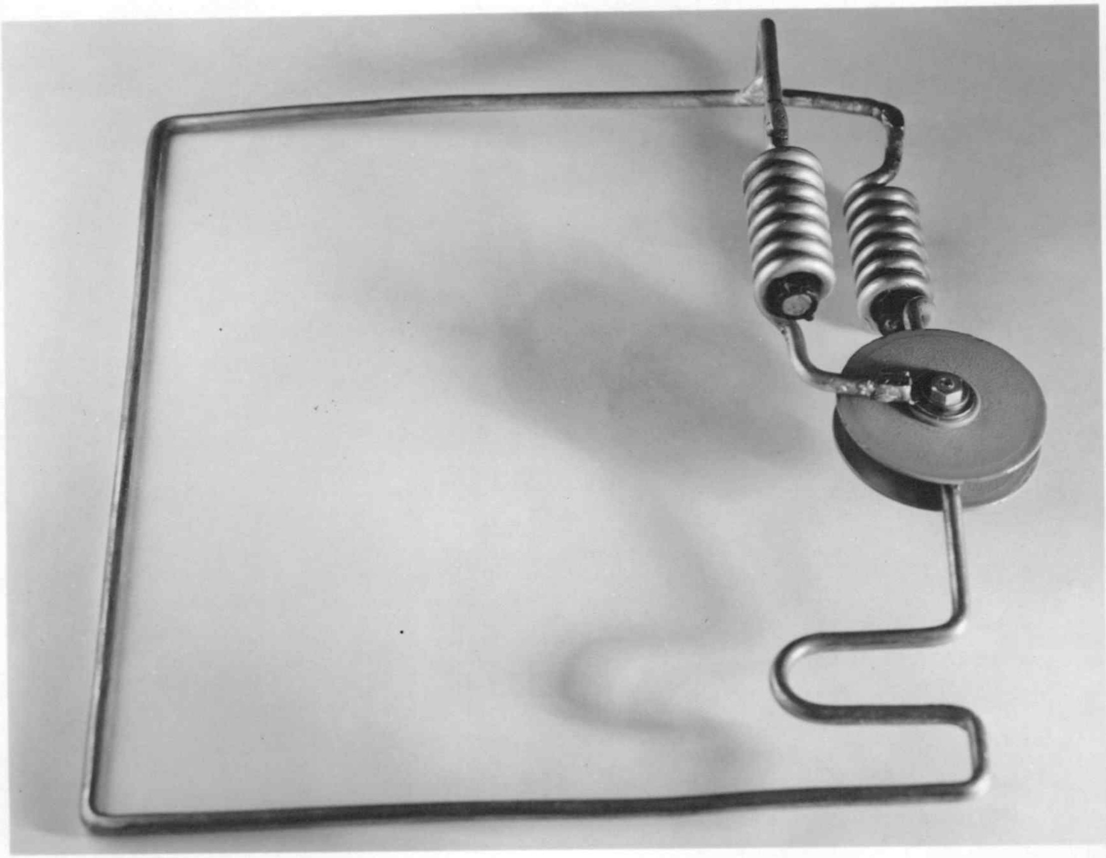


Figure 22a. THE DOUBLE RECTIFIER LOOP

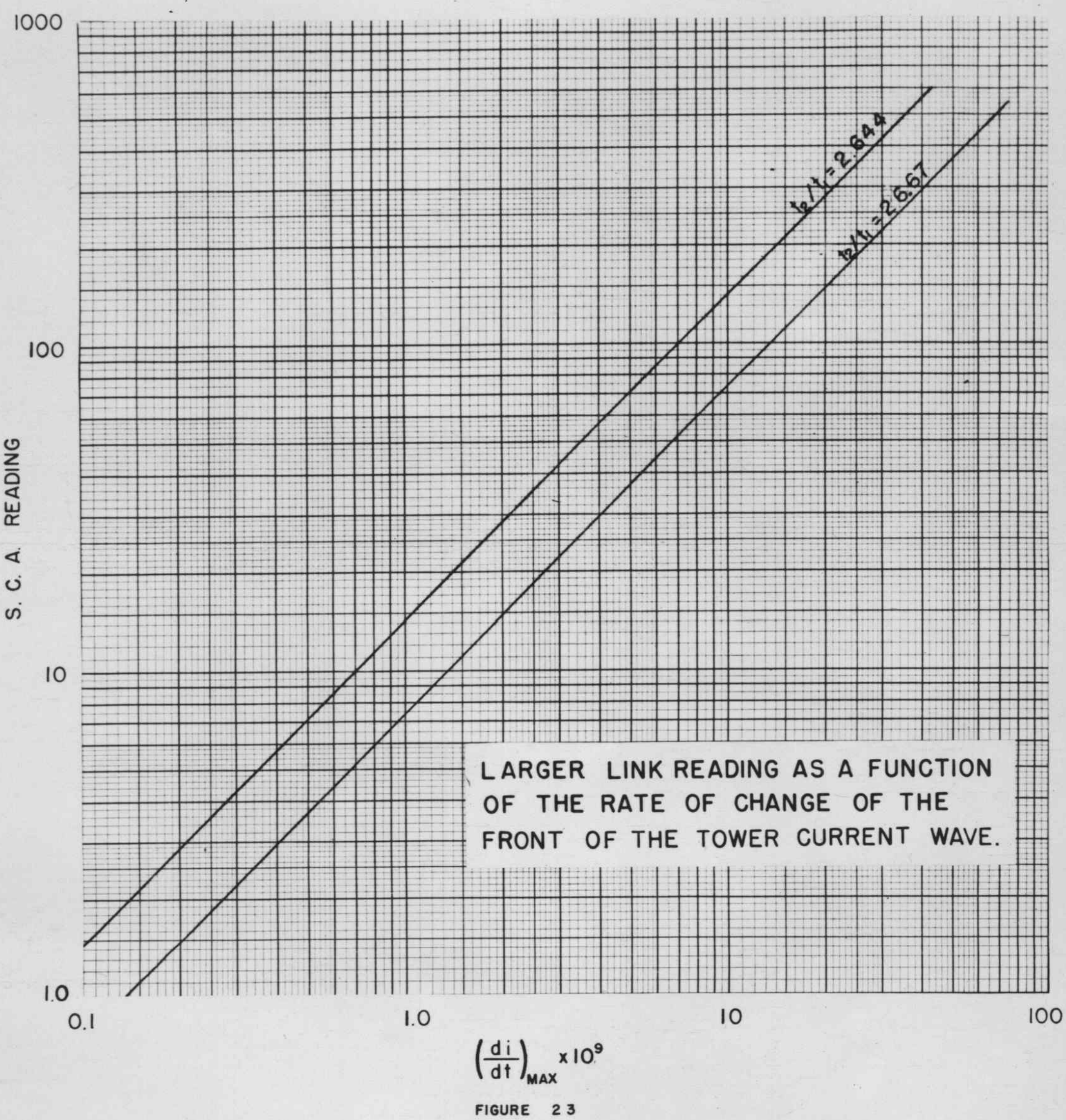

1000
100
10
1.0
S. C. A. READING
$t_2/t_1 = 2.644$
$t_2/t_1 = 26.67$
LARGER LINK READING AS A FUNCTION OF THE RATE OF CHANGE OF THE FRONT OF THE TOWER CURRENT WAVE.
0.1
1.0
10
100
$\left(\frac{di}{dt}\right)_{MAX} \times 10^9$

FIGURE 23

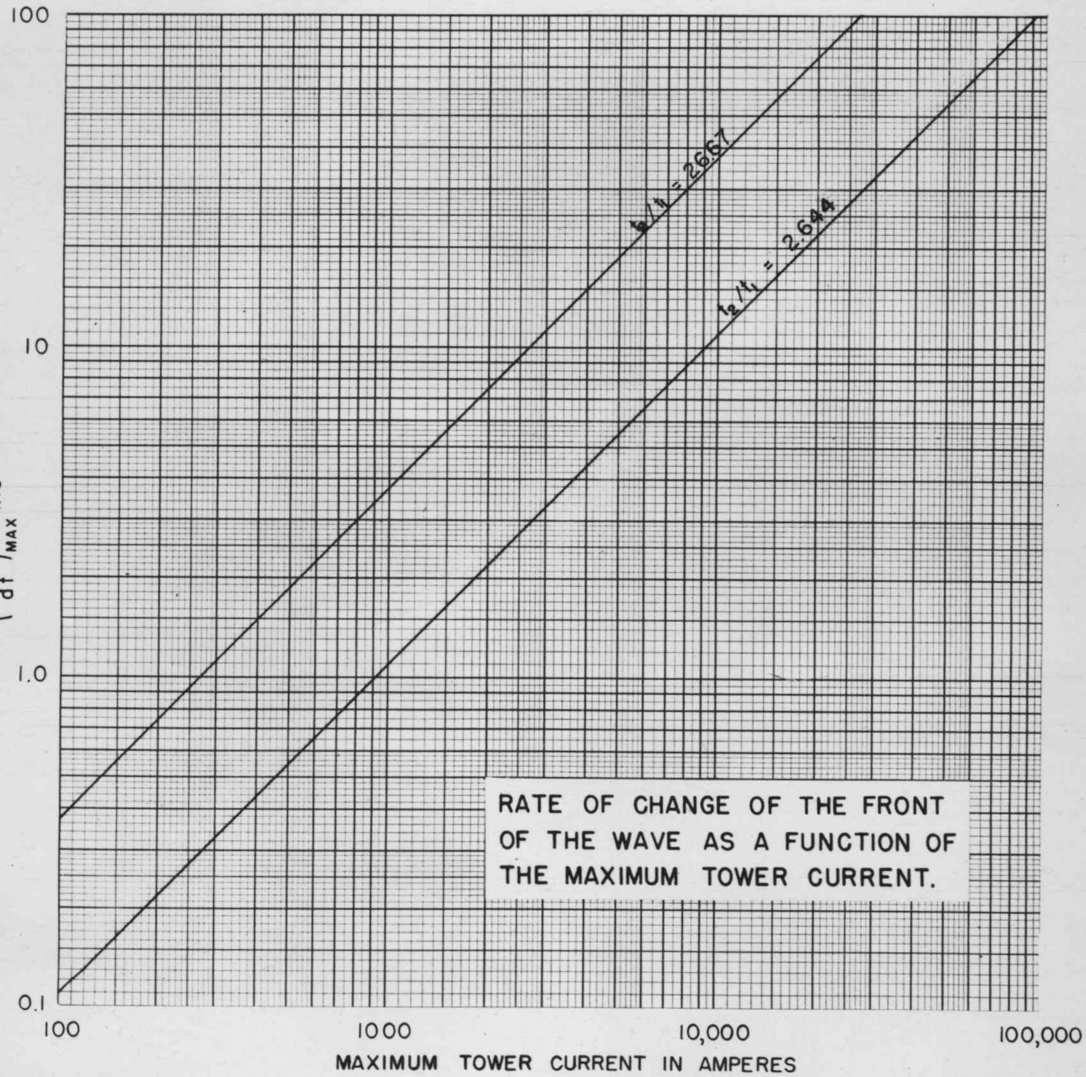

100
10
1.0
0.1
$\left(\frac{di_T}{dt}\right)_{MAX} \times 10^9$
$t_2/t_1 = 2.667$
$t_2/t_1 = 2.644$
RATE OF CHANGE OF THE FRONT OF THE WAVE AS A FUNCTION OF THE MAXIMUM TOWER CURRENT.
100
1000
10,000
100,000
MAXIMUM TOWER CURRENT IN AMPERES

FIGURE 24

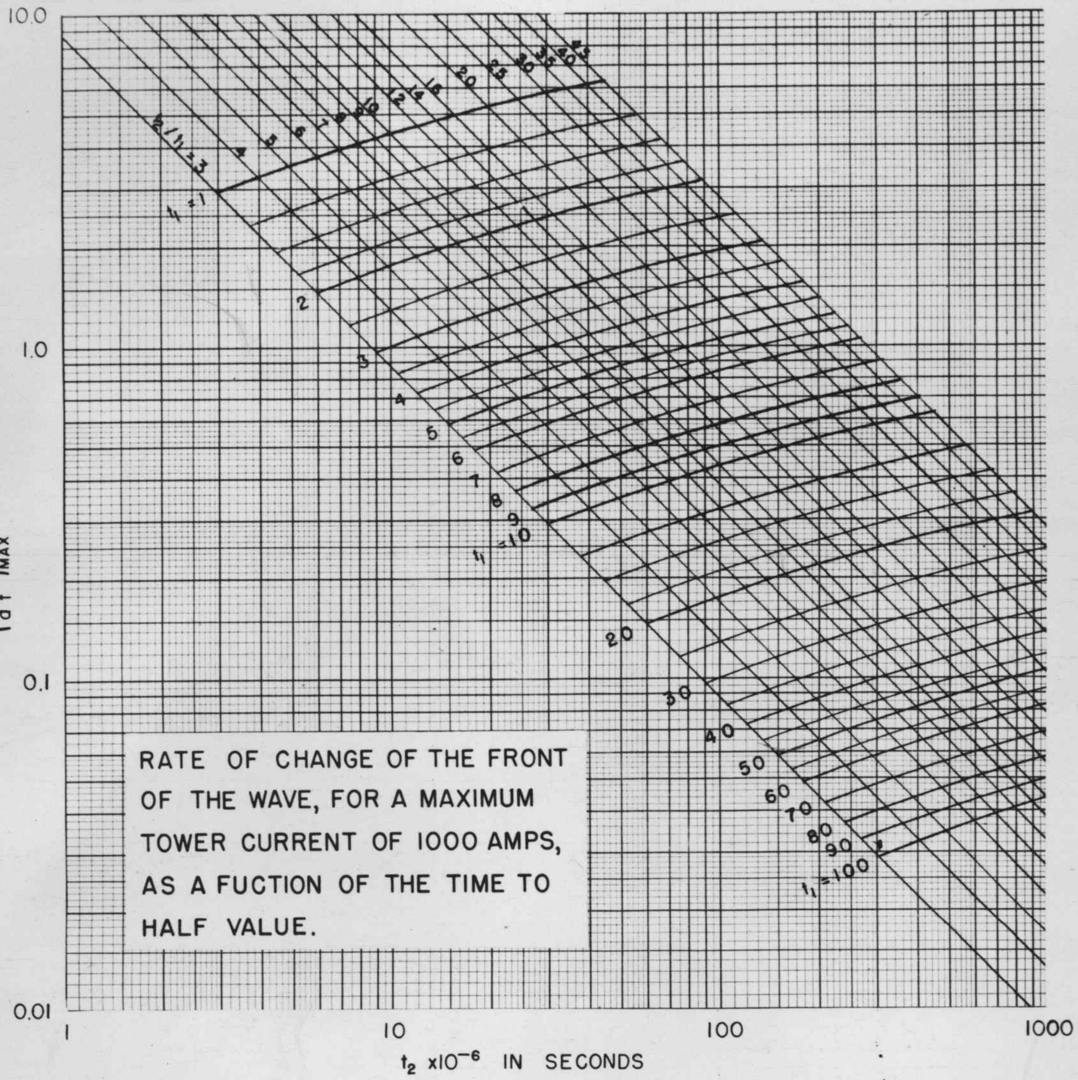

10.0
1.0
0.1
0.01
1
10
100
1000
$\left(\frac{d\,i_T}{d\,t}\right)_{MAX} \times 10^9$
$t_2 \times 10^{-6}$ IN SECONDS
$t_2/t_1 = 3$
4
5
6
7
8
9
10
12
14
16
20
25
30
40
$t_1 = 1$
2
3
4
5
6
7
8
9
$t_1 = 10$
20
30
40
50
60
70
80
90
$t_1 = 100$
RATE OF CHANGE OF THE FRONT OF THE WAVE, FOR A MAXIMUM TOWER CURRENT OF 1000 AMPS, AS A FUCTION OF THE TIME TO HALF VALUE.

FIGURE 25

CONCLUSIONS

The detector developed is a versatile instrument in that it can be used to measure a large range of currents. To measure low values of current, it is necessary to increase the area of the loop, permitting a greater flux linkage. To measure large values of current, the size of the loop is decreased in area, reducing the flux linkage.

The detector may be used either as an indicator or as an alalyzer. To use it as an indicator, the following loops are recommended:

> For values of currents between 400 and 1000 amperes, the loop size should be approximately seven by thirteen inches, with a coil of eight or nine turns.
>
> For values of currents of 6000 amperes or greater, the loop should be seven by thirteen inches, having only two or three turns in the coil.
>
> The material that gives the best results when an alternating current follows the flashover, is 17-St duralumin, one eighth of an inch in diameter.

To use the detector as an analyzer, it is necessary to use two coils and two rectifiers. One for measuring the rate of rise of the current wave; the other for meas-uring measuring the rate of decay of the current wave. The ratio of the two readings will be equal to the ratio of the maximum rate of rise of the wave to the maximum rate of decay of the wave. Since this ratio defines the type of current wave, the magnitude of the tower current can be determined from a set of calibration curves.

For use as an analyzer, the size should be seven by eight inches with both coils having seven turns. A loop of this size will measure currents from 800 to 8000 amperes.

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INDEX TO THE APPENDIX

APPENDIX A

INDEX TO LOOPS TESTED

Loop No.	A.W.G. No. or inches in diameter	No. of turns	Loop Description
1	0.144	7	Original iron loop
2	0.144	7	No. I Galvanized Iron Loop
3	0.144	7	No. I Iron Loop after galvanizing removed
4	0.144	7	No. II Galvanized iron loop
5	0.144	7	No. II Iron loop with coppercoil (No. 6)
6	0.144	7	No. II Iron loop and copper (half and half)
7	7	7	Copper loop (No.7) with iron coil
8	7	7	Copper loop
9	12	7	Copper loop
10	14	7	Copper loop
11	16	7	Copper loop
12	18	7	Copper loop
13	8	7	Copper-weld loop
14	9	7	Copper-weld loop 30%
15	0.128	7	Plain iron tubing
16	0.128	7	Iron tubing with copper core

Loop No.	A.W.G. No. or inches in diameter	No. of turns	Loop Description
17	5	7	Aluminum str. 795 MCM
18	8	7	Aluminum (Str. 262960 cm. Spec. Longview crossing, B.P.S.)
19	6	7	Aluminum (Special alloy tie wire (soft), B.P.A.
20	10	7	Aluminum str. #2 Sparate
21	16	8	Copper
22	18	7	Copper
23	0.187	7	17-St. Duralumin
25	0.156	7	43-St. Duralumin
26	0.125	9	17-St. Duralumin
27	0.125	8	17-St. Duralumin
28	0.125	7	17-St. Duralumin
29	0.125	6	17-St. Duralumin
30	0.125	5	17-St. Duralumin
31	0.125	4	17-St. Duralumin
32	0.125	3	17-St. Duralumin
33	0.125	2	17-St. Duralumin
33 a	0.125	7	24-St. Duralumin
34	0.125	6	24-St. Duralumin
35	0.125	5	24-St. Duralumin

Loop No.	A.W.G. No. or inches in diameter	No. of turns	Loop Description
36	0.125	4	24-St. Duralumin
37	0.125	3	24-St. Duralumin
38	0.144	7	Iron wire loop No. III
39	0.144	7	Galvanizing removed
40	0.144	7	Annealed 1100° F
41	0.125	7	17-St. Duralumin with single rectifier
42	0.125	2 coils of 7 turns	17-St. Duralumin with two rectifiers
43	8	2 coils of 7 turns	Copper with two rec-tifiers

APPENDIX B

D-C RESISTANCE OF LOOPS

Loop No.	Resistivity in ohms per foot	Loop Resistance in ohms
1	0.00435	
2	0.00327	
3	0.00347	0.0185
4		0.014756
5	0.00322	0.01367
6	0.00167	0.00711
7	0.00161	0.006822
8	0.000498	
9	0.00159	0.007204
10	0.0025	0.010928
11	0.00402	0.017624
12	0.00638	0.028105
13	0.0016	0.006998
14	0.00269	0.001199
15	0.00864	0.03670
16	0.00166	0.00708
17	0.00054	0.002497
18	0.00102	0.004496
19	0.00102	0.004959
20	0.0019	0.007741
21	0.00402	0.01756
22	0.00638	0.02793
23	0.000836	0.003843
24	0.002213	0.009514
25	0.000777	0.003390
26	0.001692	0.007819
27	0.001692	0.007293
28	0.001692	0.007135
29	0.001692	0.006955
30	0.001692	0.006710
31	0.001692	0.006433
32	0.001692	0.006238
33	0.001692	0.006140
34	0.002213	0.008782
35	0.002213	0.008715
36	0.002213	0.008277
37	0.002213	0.007858

APPENDIX C

DERIVATION OF THE EQUATIONS FOR LOOP CURRENT

The general equation for loop current (equation 8, page 12) is stated as follows:

$$i_L = -\left[\frac{M P}{(P + \partial)L_L}\right] i + i_t \qquad \text{c-1}$$

1. The derivation of the loop current equation for an overdamped tower current:

$$\text{Let } i = \frac{E}{L} \frac{(\varepsilon^{P_1 t} - \varepsilon^{P_2 t})}{P_2 - P_1} \qquad \text{c-2}$$

Where: P_1 and P_2 are the exponents which determine the wave shape

E = voltage of exciting circuit

L = inductance of tower circuit

substituting equation (2) in equation (1) gives:

$$i_L = -\frac{M P E}{(P + \partial) L_L L} \frac{(\varepsilon^{P_1 t} - \varepsilon^{P_2 t})}{P_2 - P_1} + i_T \qquad \text{c-3}$$

The loop is a simple RL circuit so the transient will be of the form:

$$i_t = A\varepsilon^{-\partial t} \qquad \text{c-4}$$

Where: A is a constant

$$\partial = \frac{R}{L}$$

Then equation (3) may be written:

$$i_L = -\frac{M P E}{(P + \partial) L_L L} \frac{(\varepsilon^{P_1 t} - \varepsilon^{P_2 t})}{P_2 - P_1} + A\varepsilon^{-\partial t} \qquad \text{c-5}$$

Where: $P_2 - P_1 = 2\Omega'$

This may now be expanded for the values of P_1 and P_2.

$$i_L = -\frac{M\,E}{2\Omega' L_L L}\left[\frac{P_1}{P_1+\partial}\,\varepsilon^{P_1 t} - \frac{P_2}{P_2+\partial}\,\varepsilon^{P_2 t}\right] + A\,\varepsilon^{-\partial t} \qquad \text{c-6}$$

At the instant just after time equals zero:

$$0 = -\frac{M\,E}{2\Omega' L_L L}\left[\frac{P_1}{P_1+\partial} - \frac{P_2}{P_2+\partial}\right] + A \qquad \text{c-7}$$

$$A = \frac{M\,E}{2\Omega' L_L L}\left[\frac{P_1}{P_1+\partial} - \frac{P_2}{P_2+\partial}\right] \qquad \text{c-8}$$

$$= \frac{M\,E}{2\ ' L_L L}\left[\frac{\partial\ \ (P_1 - P_2)}{(\partial + P_2)(\partial + P_1)}\right] \qquad \text{c-9}$$

Now the equation for the loop current will be obtained by substituting equation (9) into equation (6).

$$i_L = \frac{M\,E}{2\Omega' L_L L}\left[\frac{-P_1}{P_1+\partial}\varepsilon^{P_1 t} + \frac{P_2}{P_2+\partial}\varepsilon^{P_2 t} - \frac{\partial\ \ (P_1 - P_2)}{(\partial + P_1)(\partial + P_2)}\varepsilon^{-\partial t}\right] \qquad \text{c-10}$$

2. The derivation of the loop current equation for a critically damped tower current:

Let

$$i = \frac{E}{L}\,t\,\varepsilon^{-\alpha t} \qquad \text{c-11}$$

Substituting equation (11) in equation (1) gives:

$$i_L = \frac{MEP\ t}{(P + \partial)L_L L}\ \varepsilon^{-\alpha t} + A\ \varepsilon^{-\partial t} \qquad \text{c-12}$$

Where: $\alpha = \frac{R}{2L}$ (tower circuit quantities)

The coefficient of the transient term can not be solved from the initial conditions because of the variable, t, appearing in the coefficient of the first term. Equation (12) may be solved by the use of a Laplacian transform, which transforms the time function to a function of P, and gives a solution which includes the transient term.

$$t \; \varepsilon^{-\alpha t} \supset \frac{1}{(P + \alpha)^2} \qquad \text{c-13}$$

Then the $\mathcal{L}$ transform of equation (12) becomes:

$$\tilde{i}_L = \frac{M \; P}{L_L \; (P + \partial\;)} \; \frac{E}{L} \; \frac{1}{(P + \alpha\;)^2}$$

$$= \frac{E\,M}{L_L L} \; \frac{P}{(P + \partial)(P + \alpha)^2} \qquad \text{c-14}$$

Now using the formula for the inverse transform

$$\mathcal{L}^{-1} \; \frac{A\;(P)}{B\;(P)} = \sum_{K=1}^{M} \; \frac{A\;(P_K)}{B_K\;(P_K)} \; \varepsilon^{P_K t} \qquad \text{c-15}$$

From equation (14)

$$A\;(P) = \frac{E\,M}{L L_L} \; P$$

$$B\;(P) = (P + \partial)\;(P + \alpha)\;(P + \alpha)$$

Since B(P) contains repeated roots, equation (15) can be used to solve only the $(P + \partial)$ factor. The following equation must be used to solve for the repeated roots:

$$\lim_{P \to P_s} \left\{ \frac{d}{d\,P} \left[\frac{(P-P_s)^2 \quad A(P)}{B(P)} \varepsilon^{Pt} \right] \right\} \qquad \text{c-16}$$

Then the complete solution for equation (14) will be:

$$i_L = \frac{E\,M}{LL_L} \left\{ \left[\frac{-\,\partial}{(-\,\partial + \alpha)^2} \varepsilon^{-\partial t} \right] + \lim_{P \to P_K} \left[\frac{d}{dP} \frac{(P+\alpha)^2 \quad P}{(P+\partial)(P+\alpha^2)} \varepsilon^{Pt} \right] \right\}$$

$$= \frac{E\,M}{LL_L} \left[\frac{-\,\partial}{(-\,\partial + \alpha)^2} \varepsilon^{-\partial t} + \frac{(\alpha^2 t - \alpha\,\partial t + \partial\,)\varepsilon^{-\,\alpha t}}{(-\,\alpha + \partial)^2} \right]$$

$$= \frac{E\,M}{LL_L\,(-\,\partial + \alpha)^2} \left[-\partial\varepsilon^{-\,\partial t} \quad (\alpha^2 t - \alpha\partial t + \partial) \quad \varepsilon^{-\,\alpha t} \right] \qquad \text{c-17}$$

3. The derivation of the loop current equation for an oscillatory tower current.

$$\text{Let } i = \frac{E}{L\Omega} \left[\varepsilon^{-\,\alpha t} \quad \sin \Omega t \right] \qquad \text{c-18}$$

Where:

$$\Omega = \left(\frac{1}{Lc} - \frac{R^2}{4\,L^2}\right)^{1/2} \quad \text{(tower circuit quantities)}$$

Substituting equation (18) in equation (1) gives:

$$i_L = \frac{M\,E\,P}{LL_L\Omega\,(P + \partial)} \left[\varepsilon^{-\,\alpha t} \quad \sin \Omega t \right] + A\,\varepsilon^{-\,\partial t} \qquad \text{c-19}$$

Now, as in part 2, the Laplacion transform must be used to obtain a solution of equation (19), using the $\mathcal{L}$-transform:

$$\frac{1}{\Omega}\,\varepsilon^{-\,\alpha t} \quad \sin \Omega t \quad \supset \quad \frac{1}{(P + \alpha)^2 + \Omega^2} \qquad \text{c-20}$$

equation (19) becomes:

$$\tilde{i}_L = \frac{ME}{LL_L} \frac{P}{(P + \partial)(P + \alpha)^2 + \Omega^2} \qquad \text{c-21}$$

and when factored equals:

$$\tilde{i}_L = \frac{ME}{LL_L} \frac{P}{(P + \partial) \; P - (-\alpha + j\Omega) \; P - (-\alpha - j\Omega)} \qquad \text{c-22}$$

Now by the use of equation (15) the inverse transform may be written:

$$\tilde{i}_L = \frac{ME}{LL_L} \left[C_1 \varepsilon^{-\partial t} + C_2 \varepsilon^{(-\alpha + j\Omega)t} + C_3 \varepsilon^{(-\alpha - j\Omega)t} \right] \qquad \text{c-23}$$

Where:

$$C_1 = \frac{-\partial}{(-\partial + \alpha - j\Omega)(-\partial + \alpha + j\Omega)}$$

$$= \frac{-\partial}{\partial^2 + \alpha^2 + \Omega^2 - 2\alpha\partial} \qquad \text{c-24}$$

$$C_2 = \frac{-\alpha + j\Omega}{(-\alpha + j\Omega + \partial)(-\alpha + j\Omega + \alpha + j\Omega)}$$

$$= \frac{-\alpha + j\Omega}{-2\Omega(\Omega + j\alpha - j\partial)} \qquad \text{c-25}$$

$$C_3 = \frac{-\alpha - j\Omega}{(-\alpha - j\Omega + \partial)(-\alpha - j\Omega + \alpha - j\Omega)}$$

$$= \frac{-\alpha - j\Omega}{-2\Omega(\Omega - j\alpha + j\partial)} \qquad \text{c-26}$$

The complex menbers in the exponents of equation (23) must be eliminated so the first step is to obtain the common denominator of the last two terms.

$$\frac{-\varepsilon^{-\alpha t}}{-2\Omega} \frac{(-j\Omega^2 + j\alpha^2 - j\alpha\partial - \partial\Omega)\varepsilon^{j\Omega t} + (-j\Omega^2 - j\alpha^2 + j\alpha\partial - \partial\Omega)\varepsilon^{-j\Omega t}}{(\partial^2 + \alpha^2 + \Omega^2 - 2\alpha\,\partial)} \qquad \text{c-27}$$

The denominator can be factored out since it appears in C_1. Let C_4 be this constant.

$$C_4 = (\partial^2 + \alpha^2 + \Omega^2 - 2\alpha\,\partial) \qquad \text{c-28}$$

But equation (27) can be further simplified by multiplying out the terms of the numerator and factoring. Then the following relationships are useful for simplification.

$$\sin\Omega t = -1/2\, j\,(\varepsilon^{j\Omega t} - \varepsilon^{-j\Omega t}) \qquad \text{c-29}$$

$$\cos\Omega t = 1/2\,(\varepsilon^{j\Omega t} + \varepsilon^{-j\Omega t}) \qquad \text{c-30}$$

Then the simplified form of equation (27) is the following:

$$\frac{\varepsilon^{-\alpha t}}{C_4} \frac{(-\alpha\partial + \Omega^2 + \alpha^2)\sin\Omega t}{\Omega} - \partial\cos\Omega t \qquad \text{c-31}$$

The final equation for current in the loop is:

$$i_L = \frac{ME}{LL_LC_4}\left\{-\partial\varepsilon^{-\partial t} + \varepsilon^{-\alpha t}\left[\left(\frac{-\alpha\partial + \Omega 2 + \alpha 2}{\Omega}\right)\sin\Omega t + (\partial\cos\Omega t)\right]\right\} \qquad \text{c-32}$$

APPENDIX D

CALCULATION FOR OSCILLATION USING THE CRITICALLY-DAMPED TOWER CURRENT WAVE

When the current in the tower leg is critically-damped the equation for the current is:

$$i_T = \frac{E}{L_T} t \, \varepsilon^{-\alpha t} \qquad \text{d-1}$$

The resulting current in the loop will be

$$i_L = \frac{M E}{L_T L_L (\alpha - \partial)^2} \left[-\partial \varepsilon^{-\partial t} + \varepsilon^{-\alpha t} (\partial - \alpha \partial t + \alpha^2 t) \right] \qquad \text{d-2}$$

It was shown on page 20 the loop current will oscillate when a critically damped tower current flows. Examining the part of the equation within the brackets shows that the time to maximums depends upon the ratio $\partial = \frac{R_L}{L_L}$. Using values of ∂ within the range of the loops, the maximum value can be calculated by assuming values of time and plotting the current as a function of time.

The important points are the first positive maximum, the first negative maximum and the ratio of the negative maximum to the positive maximum.

The following data were used in making the calculations:

$$\alpha = \frac{R_T}{2L_T} = 0.43 \times 10^6$$

$$L_T = 5.93 \times 10^{-6} \text{ henries}$$

R_T = 5.1 ohms

E = 7,000 volts

M = 0.09×10^{-6}

TABULATION OF THE TIME TO POSITIVE

AND NEGATIVE MAXIMUM

	Time to Maximum in Microseconds	
$\partial \times 10^6$	Positive	Negative
0.01	2.3	23
0.03	2.2	18
0.0961	2.0	15
0.18		10.8
0.22		10
0.2968	1.5	9
0.6	1.2	7
0.961	0.9	6

Tabulation of the positive maximum currents as a function of ∂ and L_L. L in microhenries; $\partial \times 10^6$.

L / ∂	0.8	0.9	1.0	1.1	1.2	1.3
	Loop Current in Amperes					
0.010	111.72	99.31	89.37	81.25	74.48	68.75
0.030	108.20	96.20	86.60	78.70	72.10	66.60
0.0961	98.80	87.82	79.04	71.85	65.87	60.78
0.297	81.01	72.01	64.81	58.91	54.01	49.84
0.600	63.30	56.20	50.60	46.00	42.20	38.90
0.961	51.26	45.56	41.01	37.28	34.16	31.54

Tabulation of the negative maximum currents as a function of ∂ and L_L. L in microhenries; $\partial \times 10^6$.

L / ∂	0.8	0.9	1.0	1.1	1.2	1.3
	Loop Current in Amperes					
0.010	5.82	5.17	4.65	4.23	3.88	3.58
0.030	13.38	11.89	10.70	9.73	8.92	8.23
0.0961	24.28	21.58	19.43	17.66	16.19	14.94
0.180	27.34	24.31	21.87	19.88	18.22	16.82
0.220	27.52	24.46	22.02	20.01	18.34	16.93
0.297	26.93	23.94	21.54	19.58	17.95	16.57
0.600	21.33	18.96	17.06	15.51	14.21	13.12
0.961	15.99	14.21	12.79	11.63	10.66	9.84

In equation c-2 it can be seen that the ratio of the negative maximum to the positive maximum, called the per unit oscillation, is dependent only upon the terms inside of the bracket.

Tabulation of the per unit oscillation as a function of ∂ :

$\partial \times 10^6$	Oscillation Per unit
0.01	0.0521
0.02	0.0950
0.03	0.1235
0.06	0.1900
0.1	0.2460
0.2	0.310
0.3	0.336
0.4	0.345
0.5	0.345
0.7	0.331
0.8	0.323
0.961	0.312

LOOP CHARACTERISTICS

TESTED WITH CRITICALLY DAMPED SURGE CURRENT
TIME TO MAXIMUM, 2.3 μ SEC.; 1/2 MAX., 6.25 μ SEC.

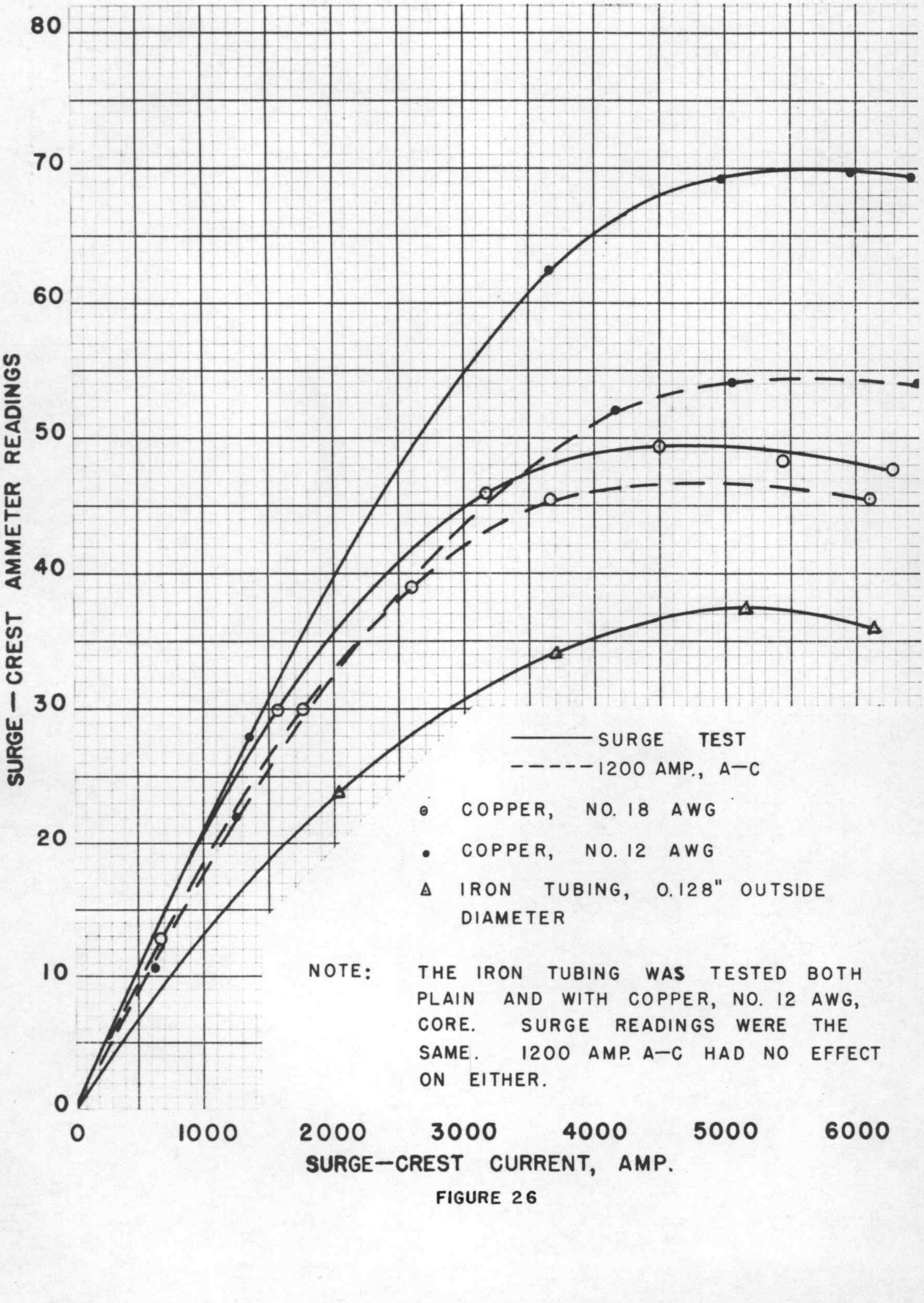

FIGURE 26

LOOP CHARACTERISTICS

TESTED WITH CRITICALLY DAMPED SURGE CURRENT

TIME TO MAXIMUM, 2.3 μ SEC.; 1/2 MAX., 6.25 μ SEC.

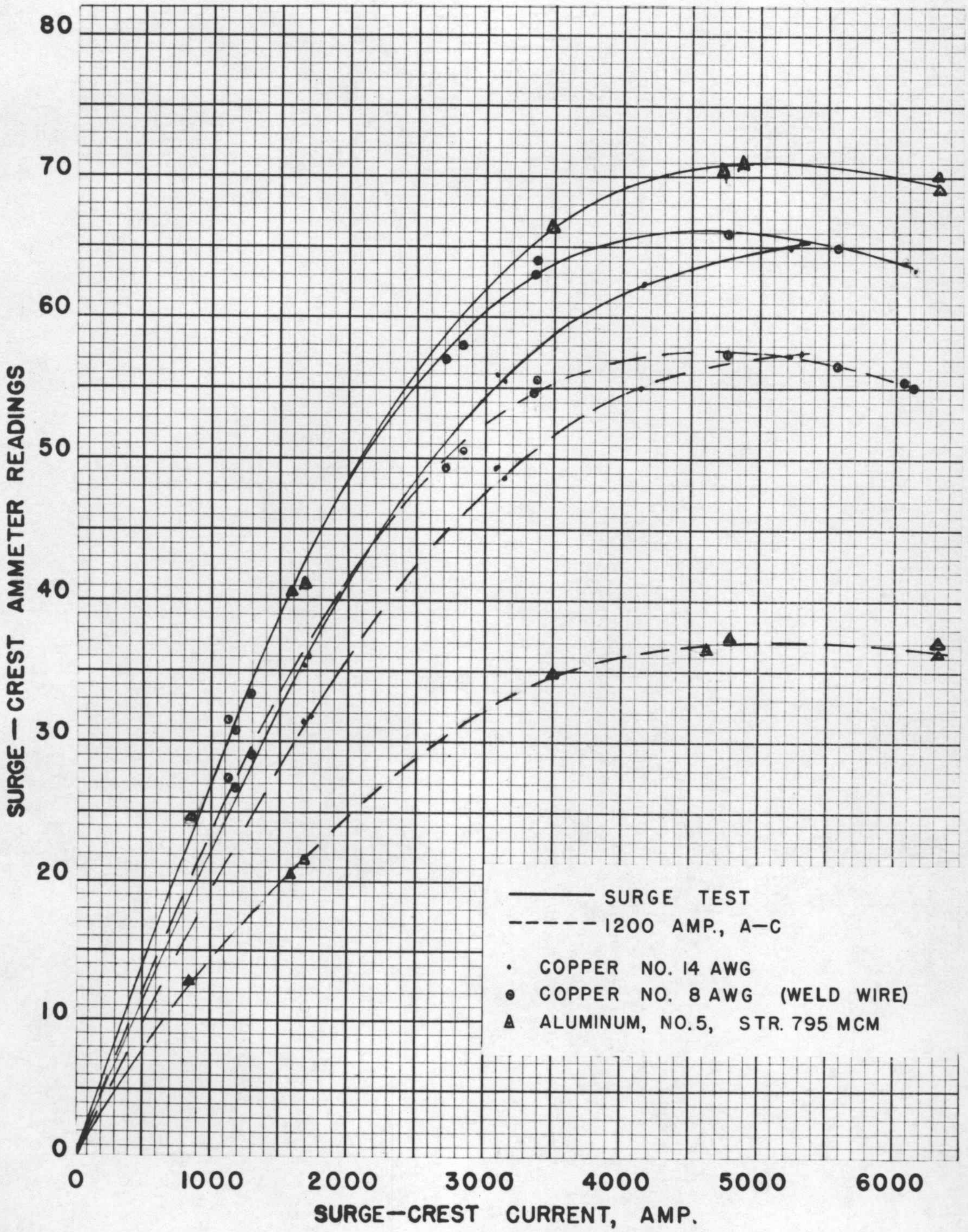

FIGURE 27

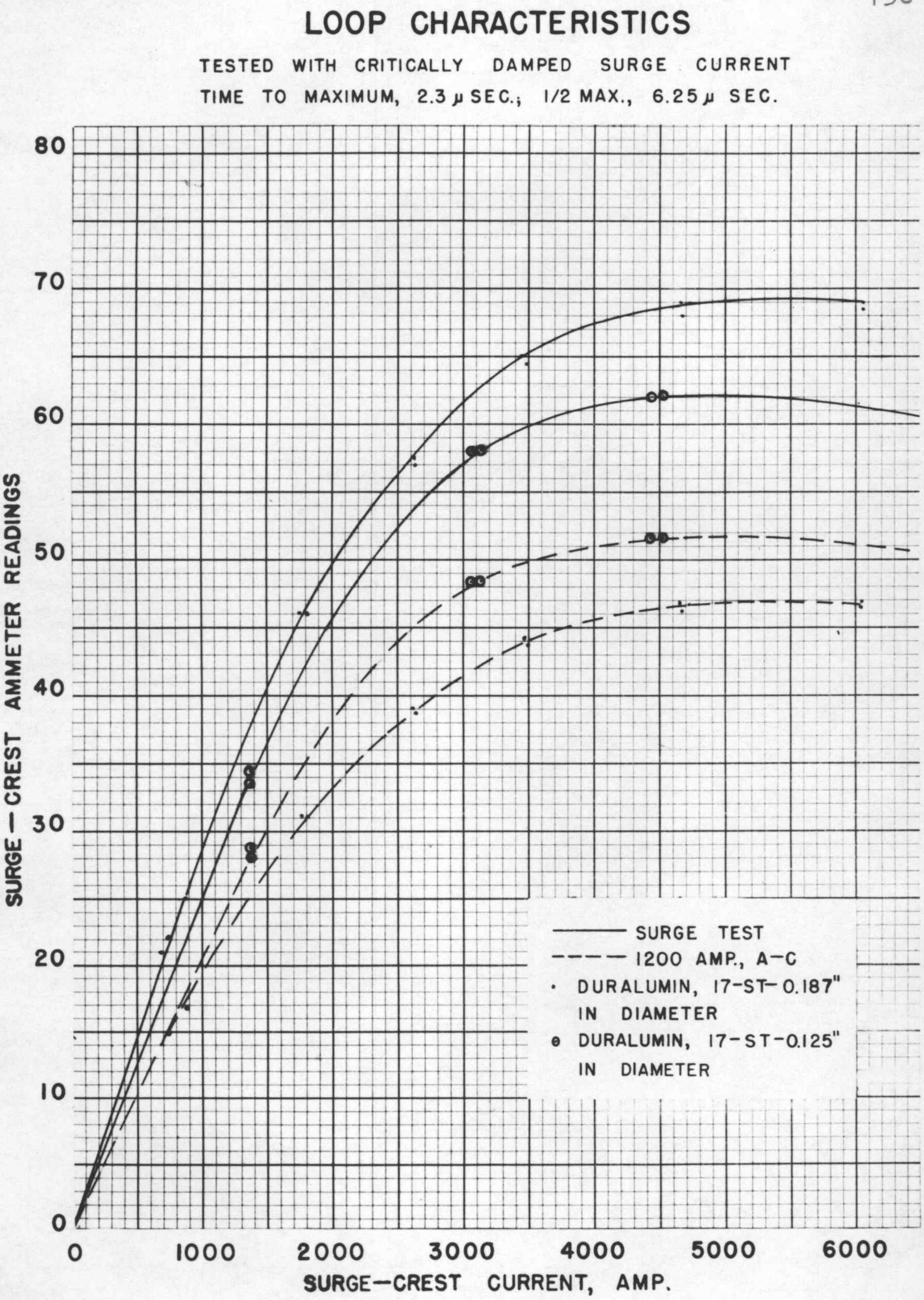
LOOP CHARACTERISTICS
TESTED WITH CRITICALLY DAMPED SURGE CURRENT
TIME TO MAXIMUM, 2.3 μ SEC.; 1/2 MAX., 6.25 μ SEC.
80
70
60
50
40
30
20
10
0
0
1000
2000
3000
4000
5000
6000
SURGE — CREST AMMETER READINGS
SURGE—CREST CURRENT, AMP.
SURGE TEST
1200 AMP., A-C
DURALUMIN, 17-ST-0.187" IN DIAMETER
DURALUMIN, 17-ST-0.125" IN DIAMETER

FIGURE 28

LOOP CHARACTERISTICS

TESTED WITH 1 1/2-40 CURRENT WAVE

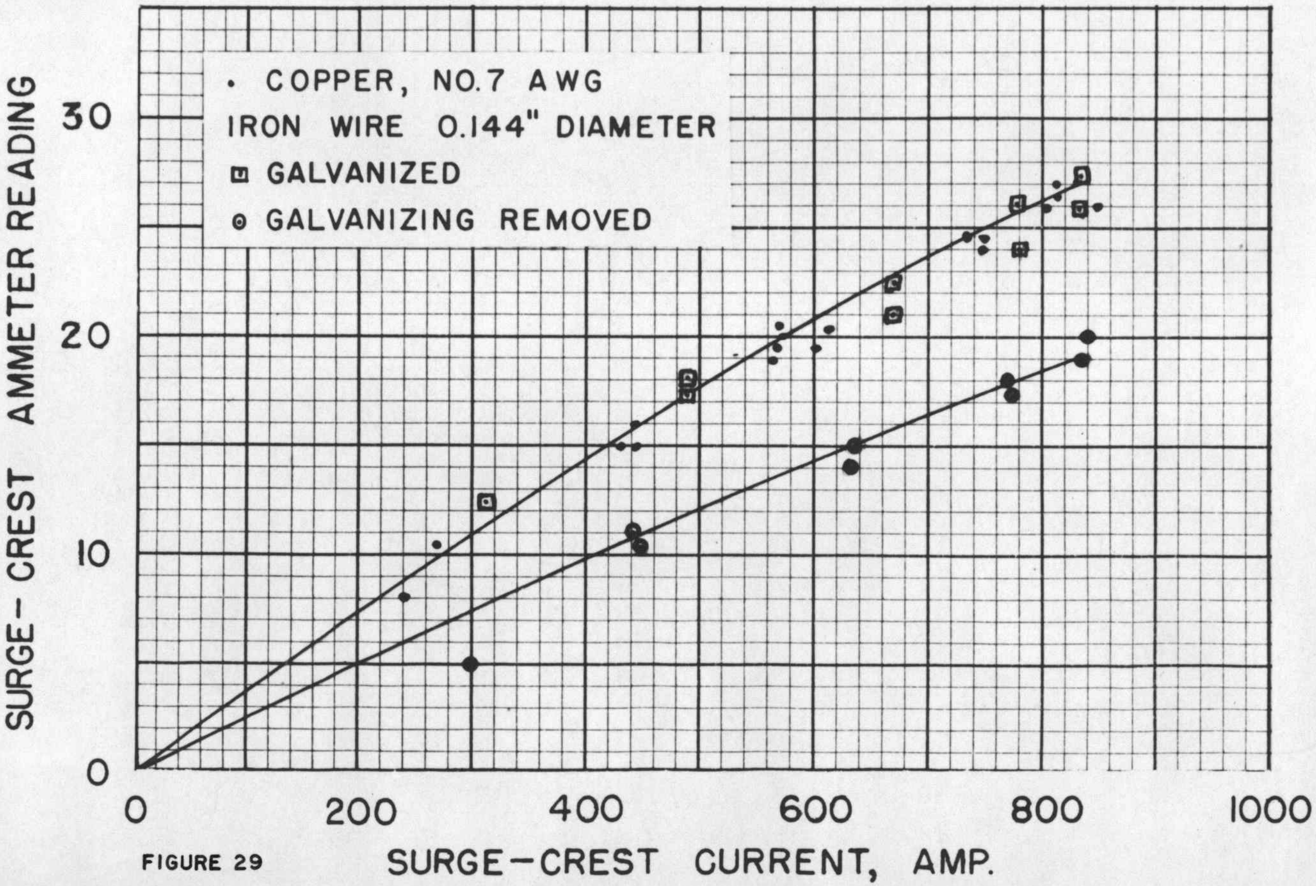

FIGURE 29

LOOP CHARACTERISTICS

TESTED WITH OVERDAMPED CURRENT

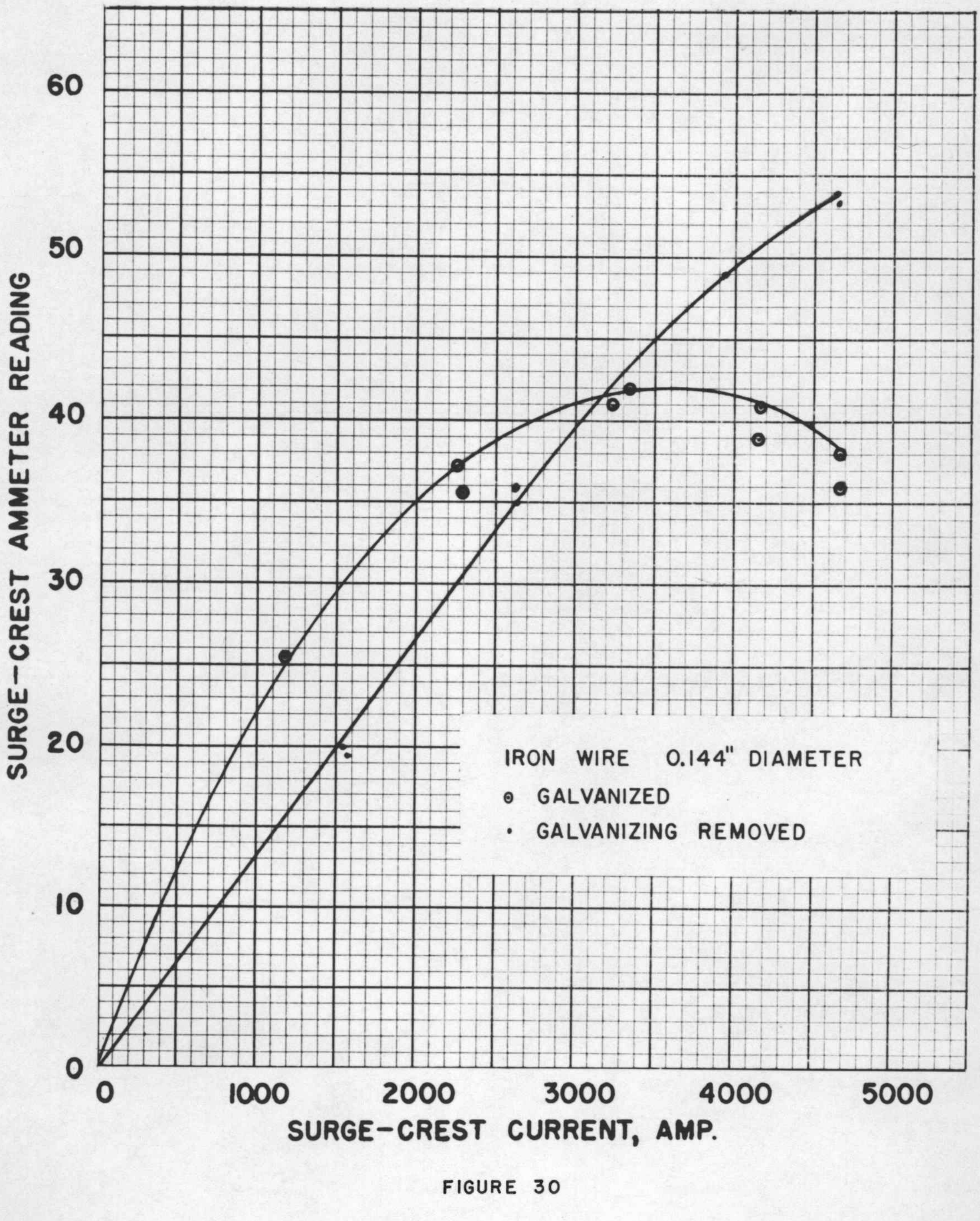

FIGURE 30

LOOP CHARACTERISTICS

TESTED WITH UNDERDAMPED CURRENT WAVE

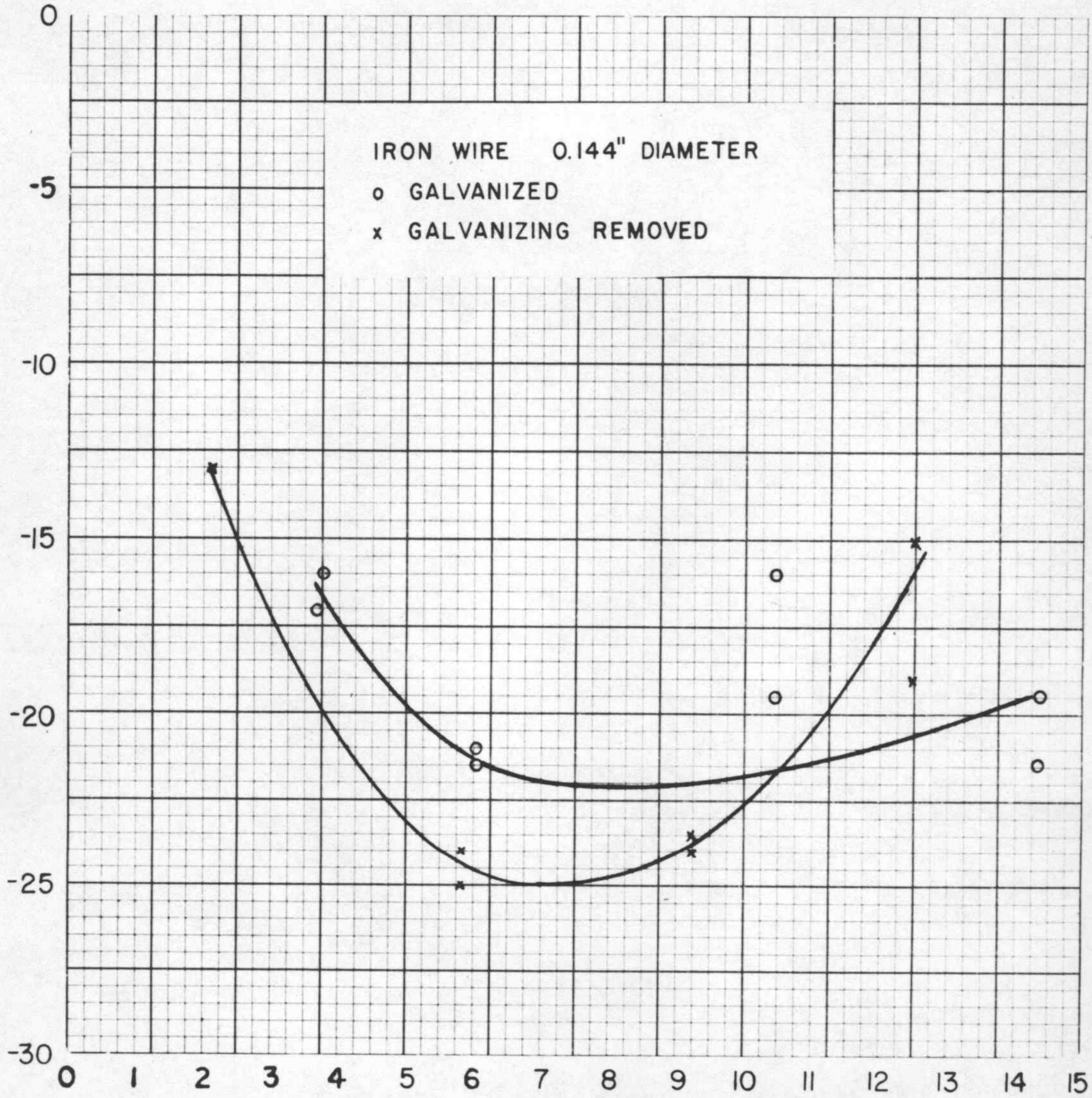

FIGURE 31

LOOP CHARACTERISTICS

TESTED WITH UNDERDAMPED CURRENT WAVE

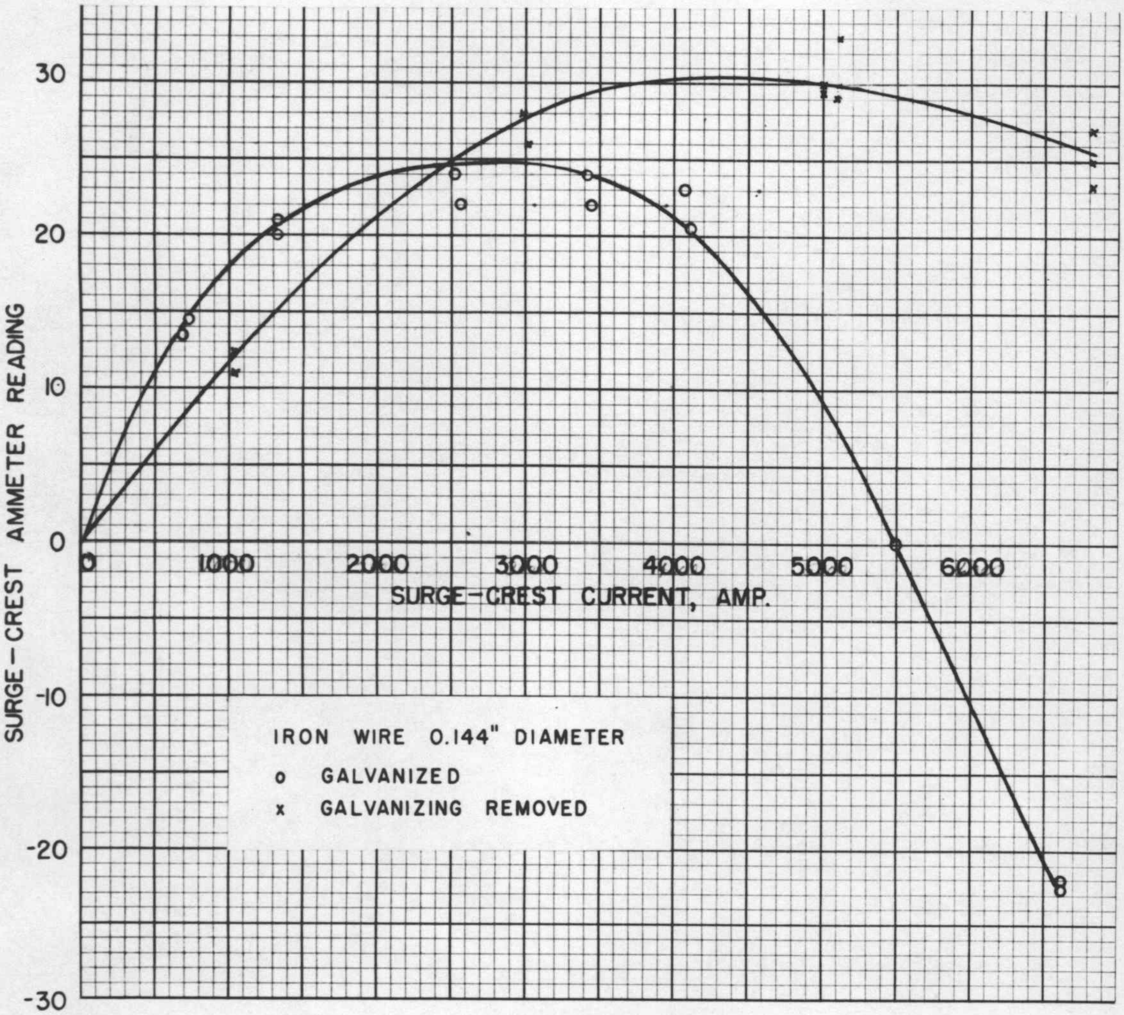

FIGURE 32

APPENDIX E

DATA FOR LOOP CHARACTERISTICS
TESTED WITH A CRITICALLY DAMPED TOWER CURRENT

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading	Surge Crest Ammeter Reading After 1200 Amps a-c
ORIGINAL IRON LOOP				
15	14.5	2.088	23	22.2
15.2	14.7	2.116	22.5	21.5
24.5	23.4	3.369	31.5	30.5
24.6	23.5	3.384	33	32
28.9	27.9	4.017	35.5	34.4
34	32.7	4.708	38	37
34.1	32.8	4.723	39	38
38.2	36.5	5.256	38	37
38.4	36.9	5.313	40	38.8
42.8	41	5.904	39	38
42.8	41	5.904	39	38
46.2	44.2	6.364	39	38
46.2	44.2	6.364	40.5	39.4
GALVANIZED IRON LOOP				
4.4	4.3	.619	13	12
4.9	4.8	.691	14.5	13.5
7.5	7.2	1.036	19	18
7.8	7.5	1.080	19.5	18.5
12.2	11.7	1.684	24.5	23.5
12.3	11.8	1.699	26	25
16.1	15.5	2.232	30	29
16.2	15.5	2.232	30	29
16.3	15.6	2.246	28	27
16.6	16	2.304	29	28
19.2	18.5	2.664	31	30
19.3	18.6	2.678	32	31
26.3	25.2	3.628	30.5	29.5
26.3	25.2	3.628	30.5	29.5
30.2	29.1	4.190	29	28
30.3	29.2	4.204	28.5	27.5
33.9	32.5	4.680	30	29
34.2	32.8	4.723	26.5	25.5

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading	Surge Crest Ammeter Reading After 1200 Amps a-c
GALVANIZED IRON LOOP (cont.)				
34.2	32.8	4.723	27	26
34.2	32.8	4.723	26	25
34.5	33.1	4.766	27	26
39.2	37.5	5.400	23	22
39.2	37.5	5.400	24	23
46.2	44.2	6.364	18	17
46.2	44.2	6.364	18	17
GALVANIZING REMOVED				
10.0	9.6	1.382	17	16
10.7	10.1	1.454	19	18
26.3	25.1	3.614	35	34
26.5	25.3	3.643	43	41.9
27	25.9	3.729	36	35
37.7	35.8	5.155	43	41.9
37.7	35.8	5.155	40	38.9
38	36.1	5.198	40	38.9
45.9	44	6.336	38	37
45.9	44	6.336	38.5	37.5
HOME-MADE LOOP (Stress Removed				
8.7	8.4	1.209	13.1	No Data
8.9	8.5	1.224	14	
12.7	12.2	1.756	20	
12.8	12.3	1.771	20.5	
15.4	14.9	2.145	24	
15.5	15	2.160	28.5	
15.5	15	2.160	24	
28.2	28.1	4.046	42.5	
28.3	27.2	3.916	35.5	
28.3	27.2	3.916	35	
32.6	31.1	4.478	49	
32.6	31.1	4.478	39	
32.7	31.2	4.482	38	
38.4	36.8	5.299	37.5	
38.8	37.1	5.342	37	
39.4	37.6	5.414	35	

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading	Surge Crest Ammeter Reading After 1200 Amps a-c
HOME-MADE LOOP (Stress Removed) (cont.)				
39.3	37.5	5.400	35.5	No Data
44.4	42.5	6.120	34	
45.5	42.6	6.134	35	
OLD IRON LOOP (COPPER COIL)				
8.2	8	1.152	15.5	14.5
8.2	8	1.152	16	15
22.1	20.1	2.894	31	30
22.5	20.7	2.980	26	25
22.5	20.7	2.980	32	31
32	30.6	4.406	39	38
33	31.5	4.536	38	37
42.3	40.3	5.803	36	35
42.4	40.4	5.817	39.5	38.5
42.1	40.2	5.788	36.5	35.5
47.3	45.2	6.508	35	34
47.6	45.5	6.552	35	34
COPPER LOOP No. 7				
2.46	2.4	.345	12	5.25
2.55	2.4	.345	12.5	5.5
4.4	4.3	.619	20	8.7
4.4	4.3	.619	20	8.7
7.2	7	1.008	30	12.9
7.3	7.1	1.022	29.5	12.75
11.7	11.2	1.612	44	19
11.9	11.6	1.670	43.5	18.7
12.6	12.4	1.785	43	18.5
17.1	16.6	2.390	57	24.5
17.3	16.8	2.419	57	24.5
22.1	21.3	3.067	64	17.4
22.3	21.5	3.096	64	17.4
26.2	25.2	3.628	66	18.3
29.3	28.1	4.046	65	17.8
29.4	28.2	4.060	66	18.3
29.4	28.2	4.060	67	28.7

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading	Surge Crest Ammeter Reading After 1200 Amps a-c
COPPER LOOP No. 7 (cont.)				
33.3	32.2	4.636	67	28.7
33.4	32.3	4.651	70	30
36.2	34.8	5.011	44.5	19.2
36.9	35.4	5.097	75	32.2
37	35.5	5.112	68	29.2
37	35.5	5.112	71	30.4
37	35.5	5.112	75	32.2
41.8	40	5.760	71	30.4
45	43.1	6.206	74	31.7
45.2	43.3	6.235	70	30
45.2	43.3	6.235	75	32.2
COPPER LOOP No. 12				
8.3	8.1	1.166	27	22.5
9.3	9	1.296	29	24.3
26.3	25.2	3.628	65	54.6
26.7	25.6	3.686	63	52.8
26.7	25.6	3.686	62	52.1
36.3	34.8	5.011	69.5	58.4
36.7	34.4	4.953	69	57.9
43	41.2	5.932	69.5	58.4
43.2	41.4	5.961	70	68.8
46.4	44.4	6.393	70	68.8
46.5	44.5	6.408	69	58.4
COPPER LOOP No. 14				
12.1	11.8	1.699	35.5	31.3
12.2	11.9	1.713	36	31.8
22.4	21.5	3.096	56	49.3
22.8	21.9	3.153	55.5	48.8
30	28.8	4.147	62.5	55
30.2	29	4.176	62.5	55
38.2	36.2	5.212	65	57.25
38.2	36.2	5.212	65	57.25
45.6	43.7	6.292	65	57.25
45.7	43.8	6.307	65.5	57.7

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading	Surge Crest Ammeter Reading 1200 Amps a-c
COPPER LOOP No. 16				
11.6	11	1.584	31	29.1
11.9	11.3	1.627	31	29.1
12.9	12.3	1.771	23	21.6
22.5	21.6	3.110	51	48
22.7	21.8	3.139	51	48
28.4	27.2	3.916	56	52.2
28.7	27.5	3.960	56.5	53.2
36	34.3	4.939	59	55.5
36.3	34.6	4.982	59	55.5
36.3	34.6	4.982	58	54.5
45.5	43.6	6.278	57	53.6
45.6	43.7	6.292	57	53.6
COPPER LOOP No. 18				
8.5	8.3	1.195	25	24.7
7.4	7.1	1.022	23	22.7
22.7	20.9	3.009	46	45.4
23	21.2	3.052	48	47.4
33.5	32	4.608	51	50.3
35	33.4	4.809	50	49.3
35.2	33.6	4.838	51	50.3
42.3	40.3	5.803	48	47.4
42.4	40.4	5.817	49.5	48.8
46.6	44.6	6.422	46	45.4
46.7	44.7	6.436	49	48.4
COPPER WELD LOOP No. 8				
8.5	8	1.152	31.5	27.4
8.7	8.2	1.180	31	26.9
9.4	9	1.296	33.5	29.1
19.7	18.8	2.707	57	49.5
19.7	18.8	2.707	57	49.5
20.4	19.6	2.822	58	50.4
24.6	23.5	3.384	63	54.8
24.7	23.6	3.398	64	55.6
34.7	33.2	4.780	66	57.4
34.8	33.2	4.780	66	57.4
40.5	38.8	5.587	65	56.5

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading	Surge Crest Ammeter Reading 1200 Amps a-c
COPPER WELD LOOP No. 8 (cont.)				
40.5	38.8	5.587	65	56.5
40.5	38.8	5.587	65	56.5
44.1	42.2	6.076	64	55.6
44.5	42.6	6.134	63.5	55.2
PLAIN IRON TUBING				
14	13.4	1.929	21	No effect
14.5	14	2.016	23.5	
14.5	14	2.016	23	
26.7	25.7	3.700	33	
26.8	25.8	3.715	31	
26.9	25.9	3.729	36	
37.1	35.4	5.097	40.5	
37.1	35.4	5.097	38	
37.2	35.5	5.112	37	
44.5	42.4	6.105	36	
44.6	42.5	6.120	36	
IRON TUBING WITH COPPER CORE				
13	12.7	1.828	21.5	No effect
13.7	13	1.872	24	
13.9	13.2	1.900	21.5	
28.7	27.2	3.916	40	
28.8	27.6	3.974	34	
28.9	27.7	3.988	36	
29	27.8	4.003	35	
39.8	38	5.472	37	
40	38.2	5.500	40	
40.1	38.3	5.515	37.5	
40.7	42.9	6.177	36	
44.8	43	6.192	34.5	
44.8	43	6.192	34.5	
ALUMINUM STR. 795 MCM				
6	5.8	.835	24.5	12.8
6.2	6	.864	24.5	12.8

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading	Surge Crest Ammeter Reading 1200 Amps a-c
ALUMINUM STR. 795 MCM (cont.)				
11.7	11.1	1.598	40.5	20.3
11.7	11.1	1.598	41	21.5
12.2	11.8	1.699	41.1	21.6
25	24	3.456	66.5	34.9
25.1	24.1	3.470	66	34.6
25.3	24.3	3.499	66.5	34.9
34.1	32.7	4.708	70.5	36.9
45.7	43.8	6.307	70	36.7
17-St. DURALUMIN 0.187 (7 turns)				
5.0	4.8	.691	21	14.1
5	4.8	.691	21	14.1
5.3	5	.720	22	14.9
6.2	6	.864	25	16.9
13.3	12.2	1.756	46	31.2
13.4	12.3	1.771	46	31.2
13.6	12.5	1.800	46	31.2
19.1	18.2	2.620	57.5	39
19.2	18.3	2.635	57	38.7
19.2	18.3	2.635	57	38.7
25	24	3.456	65	44.2
25.3	24.3	3.499	64.5	43.8
25.3	24.3	3.499	64.5	43.8
33.8	32.3	4.651	69	46.8
34.	32.5	4.680	68	46.2
34.2	32.7	4.708	69	46.8
34.2	32.7	4.708	69	46.8
44	42.1	6.062	68.5	46.5
44	42.1	6.062	68.5	46.5
44	42.1	6.062	69	46.8
17-St. DURALUMIN 0.125 (9 turns)				
7.4	7.1	1.022	28	22.1
7.5	7.2	1.036	28.5	22.5
7.9	7.7	1.108	29	22.9
18.2	17.6	2.534	53	41.8
18.2	17.6	2.534	53	41.8

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading	Surge Crest Ammeter Reading 1200 Amps a-c
17 St. DURALUMIN 0.125 (9 turns) (cont.)				
24	23	3.312	58.5	46.1
24.4	23.5	3.384	58	45.7
30	28.7	4.132	60	47.3
30.5	29.4	4.233	60	47.3
35.4	34	4.896	60.5	47.7
37.5	35.9	5.169	60.5	47.7
37.6	36	5.184	60.5	47.7
42.5	40.7	5.860	59	46.5
43.2	41.5	5.976	59	46.5
43.5	41.8	6.019	59	46.5
47.5	45.5	6.552	58	45.7
47.5	45.5	6.552	58	45.7
8 TURNS				
5.7	5.5	.792	23	18.8
5.8	5.6	.806	23	18.8
6.5	6.3	.907	26	21.2
14.5	13.9	2.001	47	38.4
14.5	13.9	2.001	46.5	38
24.5	23.5	3.384	60	49
24.9	23.9	3.441	60	49
32	30.8	4.435	62	50.7
32.3	31.1	4.478	62	50.7
41.9	40	5.760	61	49.7
41.9	40	5.760	61	49.7
47.6	45.6	6.566	60	49
47.6	45.6	6.566	60	49
7 TURNS				
9.9	9.5	1.368	33.5	28
10	9.6	1.382	34.5	28.8
22.2	21.2	3.052	58	48.3
22.6	21.6	3.110	58	48.3
22.7	21.7	3.124	58	48.3
32.4	31	4.464	62	51.7
32.7	31.3	4.507	62	51.7
48.3	46.3	6.667	60	50.1

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading	Surge Crest Ammeter Reading 1200 Amps a-c
7 TURNS (cont.)				
48.3	46.3	6.667	60.5	50.4
6 TURNS				
8.9	8.5	1.224	29	24.5
8.9	8.5	1.224	29	24.5
9.3	9	1.296	30.5	25.7
10	9.6	1.382	33	27.8
10.7	10.3	1.483	34.5	29.2
13.2	12.7	1.828	41	34.5
13.6	13	1.872	42	35.3
17.6	17	2.448	51.5	43.3
17.8	17.2	2.476	51.5	43.3
18.5	17.8	2.563	53	44.5
23.5	22.5	3.240	60	50.4
23.6	22.5	3.240	60	50.4
27.8	26.5	3.816	64	53.8
31	29.8	4.291	65	54.7
31.4	30.2	4.348	65	54.7
37.6	36	5.184	66.5	55.8
37.8	36.2	5.212	66.5	55.8
47.2	45.2	6.508	66	55.4
48	46.1	6.638	66	55.4
6 TURNS - COMPRESSED				
13.7	13.3	1.915	45	36.3
13.9	13.5	1.944	46	37
38.4	36.7	5.284	62	50
38.4	36.7	5.284	62.5	50.4
47.5	45.5	6.552	60	48.4
47.5	45.5	6.552	61	49.2
5 TURNS - EXTENDED				
10.8	10.3	1.483	33	27.8
11	10.5	1.512	33.5	28.2
21.1	20.2	2.908	55	46.2

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading	Surge Crest Ammeter Reading 1200 Amps a-c
5 TURNS-EXTENDED (cont.)				
21.2	20.3	2.923	56	47
34.6	33.1	4.766	65	54.7
35	33.5	4.824	65	54.7
41.5	39.7	5.716	66	55.4
41.5	39.7	5.716	65.5	55
47.7	45.7	6.580	64.5	54.2
48	46	6.624	64	53.8
5 TURNS-COMPRESSED				
8.5	8.1	1.166	30	24.2
8.8	8.4	1.209	30	24.2
10.5	10	1.440	34	27.5
17	16.3	2.347	50	40.3
17	16.3	2.347	50	40.3
29.6	28.2	4.060	60	48.4
30	28.8	4.147	60.5	48.8
40	38.2	5.500	61	49.2
40.4	38.6	5.558	60.5	48.8
40.5	38.7	5.572	60	48.4
47	45	6.480	60	48.4
48	46	6.624	60	48.4
4 TURNS-EXTENDED				
7.6	7.2	1.036	22.5	19.8
8.4	8.0	1.152	23.5	20.7
8.4	8.0	1.152	23.5	20.7
23.3	22.6	3.254	56	49.2
23.4	22.6	3.254	56	49.2
31.5	30.3	4.363	64.5	56.6
31.8	30.6	4.406	65	57.1
41	39.3	5.659	68	59.7
42	40.2	5.788	68	59.7
48.3	46.3	6.667	68	59.7
48.4	46.4	6.681	68	59.7

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading	Surge Crest Ammeter Reading 1200 Amps a-c
3 TURNS-EXTENDED				
9	8.6	1.238	21.5	19.4
9.2	8.9	1.281	22	19.8
10.3	9.9	1.425	24	21.6
19.2	18.5	2.664	42	37.8
19.5	18.8	2.707	42.5	38.3
26.1	25.1	3.614	53	47.7
26.5	25.5	3.672	53	47.7
35.4	34	4.896	63	56.7
35.4	34	4.896	63	56.7
42.3	40.4	5.817	67	60.2
42.5	40.6	5.846	68	61.2
48.3	46.3	6.667	69	62
48.3	46.3	6.667	68	61.2
48.3	46.3	6.667	69	62
2 TURNS-EXTENDED				
7.2	6.9	.993	13.5	12.5
7.4	7.1	1.022	14	13
7.7	7.3	1.051	15	13.8
17.2	16.5	2.376	28	25.8
17.8	17.1	2.462	29	26.7
31	29.8	4.291	47	43.3
31.7	30.4	4.377	48.5	44.7
31.8	30.5	4.392	49	45.2
38.9	37.2	5.356	55	50.7
39	37.3	5.371	56	51.6
40.2	38.5	5.544	55.5	51.2
43.5	41.6	5.990	60	55.3
44	42.2	6.076	60	55.3
47.5	45.5	6.552	64.5	59.4
47.8	45.8	6.595	64	59
17-St. DURALUMIN, 0.125" with Single Rectifier in Loop				
4.2	4.0	.940	13.5	
4.2	4.0	.940	13.5	
5	4.8	1.128	16.5	

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading
17-St. DURALUMIN, 0.125" with Single Rectifier in Loop (cont.)			
7.5	7.2	1.690	26.5
8.9	8.5	1.996	33
9.1	8.7	2.045	34.5
12.0	11.5	2.700	46
12.8	12.4	2.915	55.8
12.9	12.5	2.935	55.8
16	15.3	3.595	68
16.7	16	3.760	74
17	16.4	3.750	79
17.3	17.6	4.130	off scale
19.5	18.6	4.370	83
22.2	21.3	5.000	95
22.5	21.6	5.075	92
23.4	22.5	5.280	off scale
24.0	23	5.400	100
25	24	5.640	off scale
25.2	24.2	5.680	off scale
25.5	24.5	5.750	off scale

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading Inner Link	Surge Crest Ammeter Reading Outer Link
17-St. DURALUMIN, 0.125" with two Rectifiers and Two Coils				
7.7	7.2	1.692	19.3	0
8.5	8.1	1.902	21.5	0
11.8	10.3	2.420	30.5	5
12	10.5	2.468	32.5	5
15.5	14.9	3.500	40.5	16
16	15.2	3.570	42.2	16
18	17.3	4.070	50.5	13.5

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading Inner Link	Surge Crest Ammeter Reading Outer Link
17-St. DURALUMIN, 0.125" with two Rectifiers and Two Coils (cont.)				
18.5	17.7	4.160	51	18.5
21.9	21	4.930	63.5	19
22.4	21.5	5.050	63.5	25
22.5	21.6	5.075	63.5	25.5
26.4	25.1	5.900	72.5	20.5
26.5	25.2	5.900	76.5	25.0
No. 8 COPPER COIL with Two Rectifiers and Two Coils				
3.8	3.5	0.822	0	10
3.9	3.7	0.869	0	10
7.1	6.7	1.573	0	21
8.1	7.8	1.831	0	24
11	10.5	2.465	0	31
11.6	11.2	2.630	0	30.5
15	14.4	3.385	10	44
15.4	14.8	3.475	10	42
15.8	15.1	3.545	11	44
20.8	20	4.695	16	52
21.5	20.7	4.860	24	53
22	21.2	4.975	22	54.5

DATA FOR LOOP CHARACTERISTICS

TESTED WITH AN OVERDAMPED TOWER CURRENT WAVE

(1 1/2 - 40)

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading
NEW LOOP			
12.8	12.4	240	8
14.4	13.7	266	10.5
14.6	13.9	269	10.5
23.5	22.4	434	15
24	23.1	448	15
24.2	23.3	452	16
30.2	29.1	564	19
30.3	29.2	566	19.5
30.5	29.4	570	20.5
30.6	29.5	572	20
32.5	31.2	605	19.5
32.8	31.5	611	20.5
39.5	37.8	733	24.5
40.2	38.5	747	24
40.2	38.5	747	24.5
43.4	41.5	805	26
43.7	41.8	811	27
43.8	41.9	813	26.5
45.8	43.8	850	26
46.2	44.2	857	26
OLD LOOP			
16.2	15.5	300	5
16.3	15.6	303	5
23.9	22.9	444	11
24.1	23.1	450	10.5
33.	32.6	632	14
33.3	32.9	638	15
41.6	39.8	772	18
41.8	40.	776	17.5
45.2	43.2	838	19
45.3	43.3	840	20

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading
NEW LOOP NO. II			
14.3	13.7	266	10
14.4	13.8	268	11
22.4	21.3	413	14.5
22.4	21.3	413	15
27.2	26.2	508	17.5
27.8	26.8	520	19
34.2	32.8	636	22
34.4	33	640	21.5
41.2	39.4	764	24.5
41.2	39.4	764	22
41.2	39.4	764	25
45.3	43.4	842	24
45.3	43.4	842	25.5
45.3	43.4	842	26.5
COPPER LOOP NO. 7			
16.6	16.	310	12.5
17.	16.4	318	12.5
26.3	34.6	671	22.5
26.4	25.2	489	17.5
26.5	25.3	491	18
36.2	34.5	669	21
42	40.2	780	24
42	40.2	780	26
45.2	43.2	838	26
45.2	43.2	838	27.5
HOME MADE			
20.4	19.5	378	10
20.5	19.6	380	10.5
35	33.5	650	15
35	33.5	650	17
45.2	43.2	838	18.5
45.2	43.2	838	19.5
STRESS REMOVED			
17.2	16.6	322	5
17.3	16.7	324	7

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading
STRESS REMOVED (cont.)			
27	25.9	402	12
27.4	26.2	508	12
36.2	34.3	665	16
36.7	35	679	16
41.4	39.5	766-	17.5
41.4	39.5	766	18.5
45.2	43.3	840	20
45.2	43.3	840	20
ORIGINAL LOOP			
15.1	14.6	1.567	20
15.2	14.7	1.577	19.5
25.3	24.5	2.629	36
25.5	24.7	2.651	35
38.4	36.7	3.939	49
38.4	36.7	3.939	49
38.2	36.5	3.917	48
38.6	36.9	3.939	49
38.6	36.9	3.960	49
45.4	43.5	4.669	54
45.5	43.6	4.679	54
NEW LOOP			
11.5	11	1.180	25.5
22.2	21.1	2.264	37
22.4	21.3	2.286	35.5
31.3	30	3.220	41
32.4	31.2	3.348	42
40.4	38.8	4.164	39
40.4	38.8	4.164	41
45.4	43.5	4.669	36
45.4	43.5	4.669	38

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading

THE FOLLOWING SOOPS WERE TESTED WITH 50%OSCILLATORY

CURRENT WAVE

NEW LOOP NO. 1

11.1	10.8	3.741	-17
11.3	11	3.810	-16
18.	17.4	6.027	-21
18.	17.4	6.027	-21.5
31.4	30.2	10.461	-16
31.4	30.2	10.461	-19
43.1	41.4	14.341	-21.5
43.2	41.5	14.375	-19.5

ORIGINAL LOOP

6.5	6.2	2.147	-13
6.5	6.2	2.147	-13
17.3	16.8	5.819	-24
17.3	16.8	5.819	-25
27.8	26.7	9.249	-23.5
27.8	26.7	9.249	-24
37.5	36.	12.470	-15
37.5	36.	12.470	-19

THE FOLLOWING LOOPS WERE TESTED WITH 7% OSCILLATORY

CURRENT WAVE

NEW LOOP

4.2	4.1	0.696	13.5
4.4	4.3	0.730	14.5
8.2	7.9	1.341	+ 20
8.2	7.9	1.341	+ 21
15.6	15.0	2.547	+ 24
15.8	15.2	2.581	+ 22
21	20.1	3.413	+ 24
21.1	20.2	3.430	+ 22
25.1	24.1	4.092	+ 23
25.2	24.2	4.109	+ 20.5

Tower Voltage in Kilovolts	Corrected Tower Voltage in Kilovolts	Current in Tower Leg in Kiloamperes	Surge Crest Ammeter Reading
NEW LOOP (cont.)			
33.7	32.5	5.518	0
33.8	32.5	5.518	0
42	40.2	6.826	-22
42	40.2	6.826	-22.5
ORIGINAL LOOP			
6.4	6.1	1.036	+11
6.4	6.1	1.036	+12.5
18.4	17.6	2.988	+28
18.5	17.7	3.005	+26
31.3	29.9	5.077	+29.5
31.3	29.9	5.077	+30
31.4	30	5.094	+29
31.5	30.1	5.111	+33
42	40.2	6.826	+23.5
42	40.2	6.826	+25
42	40.2	6.826	+27

APPENDIX F

RADIO FREQUENCY BRIDGE MEASUREMENTS

OF LOOPS TESTED

Loop No.	f in kilo-cycles	R in ohms	L in micro-heneries	$\partial = R/L$
1	500	0.7	1.0245	0.6832
1	500	0.7	1.0152	0.6894
2	1000	0.5	0.9013	0.5547
2	800	0.4	0.8705	0.4595
2	600	0.35	0.8543	0.4097
2	400	0.3	0.8704	0.3447
2	400	0.3	0.867	0.3460
3	500	0.69	1.0500	0.6571
4	500	0.3	0.8652	0.3467
5	500	0.5	0.9851	0.5075
6	500	0.3	0.9048	0.3315
7	500	0.3	1.0048	0.2985
8	500	0.1	0.885	0.0789
9	500	0.1	1.1613	0.0861
10	500	0.12	1.1253	0.1066
11	500	0.15	1.1626	0.1188
12	500	0.2	1.3649	0.1465
13	500	0.1	0.9716	0.1029
14	500	0.1	1.033	1.0968
15	500	0.7	1.0644	0.6576
16	500	0.7	1.0338	0.6770
17	500	0.16	0.9106	0.1757
18	500	0.18	1.0025	0.1796
19	500	0.1	0.9565	0.1045
20	500	0.22	1.0789	0.2039
21	500	0.15	1.232	0.1217
22	500	0.20	1.263	0.1583
23	400	0.1	0.860	0.1162
23	500	0.1	0.8389	0.1192
23	600	0.13	0.851	0.1527
23	700	0.15	0.855	0.1754
23	800	0.18	0.853	0.2110
23	900	0.20	0.850	0.2353
24	500	0.05	0.9357	0.0534
24	500	0.15	0.9189	0.1632
24	600	0.15	0.9375	0.1600
24	600	0.15	0.9685	0.1549
24	700	0.10	0.9636	0.1038
24	700	0.17	0.9545	0.1781

Loop No.	f in kilo-cycles	R in ohms	L in micro-henries	∂ = R/L
24	800	0.19	0.9169	0.2072
24	800	0.20	0.9453	0.2116
24	900	0.20	0.9311	0.2148
24	900	0.24	0.9395	0.2554
24	1000	0.24	0.9506	0.2525
24	1000	0.25	0.9540	0.2620
24	1000	0.25	0.942	0.2654
24	500	0.10	0.950	0.1053
24	400	0.1	0.940	0.1064
25	900	0.22	0.9277	0.2371
25	800	0.20	0.9234	0.2166
25	700	0.18	0.9129	0.1972
25	600	0.15	0.9367	0.1601
25	500	0.12	0.9060	0.1324
25	400	0.10	0.9377	0.1066

APPENDIX G

TABLE II

RESISTANCE AND INDUCTANCE MEASUREMENTS FOR IRON LOOP

Radio Frequency Bridge

f in kilocycles	R in ohms	L in microheneries
1000	1.0	0.9341
900	1.0	0.9341
800	0.9	0.9337
700	0.8	0.9334
600	0.7	0.8837
500	0.7	0.9428
400	0.6	1.027
300	0.5	1.028
200	0.4	0.771
1000	1.0	1.0148
600	0.8	1.0259
400	0.6	1.0729
200	0.4	1.0747
300	0.5	1.121

Universal Bridge

50	0.306	1.812
17	0.166	2.31
10	0.1285	2.64
7	0.109	2.96
4	0.0885	3.57
2	0.0711	4.62
1	0.0581	5.795
0.7	0.0516	6.95
0.4		8.97
0.2	0.0417	10.4
0.4		8.22

General Radio 1000 Cycle Bridge

1000	0.06	7
1000	0,07	7.5

Oscillographic Method

f in kilocycles	R in ohms	L in microheneries
60	0.0375	33.1
60	0.0331	31.0
180	0.0501	26.5
180	0.0508	22.6
180	0.0505	19.3
300	0.0826	26.4
300	0.0802	19.2
300	0.0758	16.5
420	0.0704	17.3

APPENDIX H

CALCULATIONS OF MINIMUM CURRENT THAT WOULD FLOW WHEN INSULATORS ARE FLASHED OVER ON A 230 KV LINE

The voltage necessary to flash-over a string of 16 insulators varies with the type of wave applied. The following values are those used in rating insulators for comparison:

Type of Wave	Flash-over Voltage
1 x 5 micro second	1,775 Kv.
1 1/2 x 40	1,425 Kv.
60 cycle	1,240 Kv.

If the line is struck at the midpoint between two towers, the line impedance (Z_g) plus the tower foot resistance (R_g), will be the opposition to the flow of current. At midpoint there are two paths for the current to flow, therefore, one half of Z_g is used. The equation for the tower current is:

$$I_T = \frac{E_o}{\frac{Z_g}{2} + R_g} \qquad \text{I-1}$$

Where:

Z_g = 500 ohms

R_g = 50 ohms

$$I_T = \frac{1.425 \times 10^3}{\frac{500}{2} + 50} \qquad \text{I-2}$$

I_T = 4750 amperes

Since there are four tower legs in parallel, the current through each leg will be one fourth of the total current.

$$\text{Current per leg} = \frac{I_T}{4} \qquad \text{I-3}$$

$$\text{Current per leg} = \frac{4750 \text{ amperes}}{4}$$

$$\text{Current per leg} \doteq 1188 \text{ amperes}$$

The second case, where the flash-over of the insulators is initiated by a foreign object, the obove equation will be used by the line peak voltage, to neutral, will be used.

$$\text{Peak Voltage} = \frac{E_{Line}}{3} \qquad \text{I-4}$$

$$\text{Peak Voltage} = \frac{230 \quad 2}{3}$$

$$\text{Peak Voltage} = 187.7 \text{ Kv.}$$

$$I_T = \frac{187.7}{300}$$

$$I_T \doteq 627. \text{ amperes}$$

or a current per leg of 156.5 amperes.

APPENDIX I

FIELD RESULTS

The following data were obtained by the Bonneville Power Administration. The loop used was made of 0.144 inch diameter iron guy wire. During the 1944 lightning season they had 1000 of these loops in service.

The following outages occurred and were located by the magnetic link:

Line	Tower No.	Phase	Link Charged	Remarks
Coulee-Spokane #3 & #4	359	Top	Yes	Insulators flashed on both lines.
4	253-254	Top	Yes	Tower 253 conductor pitted.
4	210-211	Top	Yes	
4	186-187	Top	Yes	Conductor pitted
3	187	Top	Yes	Spill gaps showed power burns.
	143	0	Yes	Direct Stroke to tower.
4	141	Top	Yes	
3 & 4	335-336	Top	Yes	Date 8-31-44
3	345-346	Top	Yes	Date 8-23-44

There were two other flashovers on these lines in which it appears that the links did not perform as anticipated.

APPENDIX J

EXPERIMENTAL PROCEDURE

Experimental tests were conducted for the purpose of studying the operation of loops under conditions simulating an actual lightning flash-over. The impulse generator shown in figure 1 was used for the surge tests. The impulse circuit consists of the following: surge capacitors connected to have one microfarad at 50 kv, damping resistor (adjustable), six foot section of transmission tower leg (5" angle iron), and non-inductive shunt. The damping resistor made possible the selection of desired wave shapes. The magnitude of the surge current was determined by calculations based on applied voltage and circuit impedance. Radio-frequency bridge measurements were used as a basis for all surge circuit calculations. As a check on the calculated surge currents an oscilloscope was connected across the non-inductive shunt through a coaxial cable. The measurements obtained in this manner checked favorably with the calculated currents so the latter were considered sufficiently accurate.

After the surge was applied and the amount of residual magnetism recorded the a-c follow-up current was impressed on the tower leg. Conditions simulating the a-c follow-up of a lightning flashover were obtained by passing heavy a-c currents through the tower leg. For this purpose a transformer, having a high current capacity, was connected directly across the tower leg. The transformer was fed by a variable voltage source so that the tower current up from zero to 1200 amperes and then reducing to zero again. Link readings taken before and after the a-c indicate how much magnetism had been removed.