THE DIELECTRIC RECOVERY
OF PARALLEL ARCS

Thesis by
Robert Herman Shennum

In Partial Fulfillment of the Requirements
For the Degree of
Doctor of Philosophy

California Institute of Technology
Pasadena, California
1954

ACKNOWLEDGMENT

The author wishes to express his sincere appreciation for the guidance and interest of Professor G. D. McCann. He acknowledges the many helpful suggestions and generous cooperation of Mr. J. E. Conner during the early phases of the work and acknowledges the valuable assistance rendered by Mr. R. W. Thompson and Mr. H. E. Johnson in obtaining the data.

Appreciation is also expressed for the interest of Mr. O. Ackerman who made arrangements to supply lightning arrestors for the work through the courtesy of the Westinghouse Electric Corporation.

The work was supported by the Department of Water and Power of the City of Los Angeles, the Kelman Electric and Manufacturing Company and the Southern California Edison Company. The research was made possible through their interest in dielectric recovery research. The author wishes to express his appreciation for their assistance.

The author is indebted to his wife Doris for valuable help in the preparation and typing of this thesis.

ABSTRACT

A study of the factors which influence the stability of simultaneous, distributed arcs on power lines is reported. The types of arcs studied were through air between iron electrodes, flashover along a wood-air boundary between copper electrodes and arcs confined in expulsion-tube lightning arrestors.

Variations of line geometry influence line characteristic impedance, series and shunt impedances and equivalent length. The studies indicate that of these factors, only the series impedance between the simultaneous arcs is important unless the line length separating the two arcs is very short.

The analysis illustrates that it is possible to calculate approximate critical spacing of a test gap in terms of the geometry and material of arc electrodes and the potential at the gap. This potential was shown to depend upon both the power frequency conduction characteristics of the remainder of the circuit and upon the nature of the surge initiating the arc. The relative importance of these two factors was estimated.

The studies show that it is possible for arcs to rob one another after they have been independently initiated on power distribution systems. Consequently, with appropriate placement of lightning arrestors it is possible to protect a system so that even though a direct stroke of lightning may initiate an arc at a location remote from the arrestors, the arrestors can still rob the open arc of current and hence extinguish it.

INTRODUCTION

The stability of simultaneous arcs which are separated on distribution lines by various distances is of prime importance to the electrical distribution engineer. A fundamental understanding of the various factors influencing this stability is therefore desirable.

The difficulties associated with lightning have been many and varied since the earliest days of electrical power transmission and distribution by use of open wire lines. A great deal of research has been carried on to study various phases of the problem and an excellent bibliography of recent work in this field has been prepared under the direction of the American Institute of Electrical Engineers.* Much remains to be learned of the action of lightning and its influence on power systems and these experiments and analyses were performed to study basic properties of protection of distribution lines. It has been found that when lightning arrestors protect a line there usually will be a breakdown of the protective gap of the arrestor due to induced potential on the lines prior to the actual strike of the main lightning surge. Usually the strike occurs at a point remote from the nearest arrestor since arrestor density is frequently low, being in the order of one per mile on many rural lines.

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* For an extensive list of recent articles, see reference 1. For all numbered references see the bibliography at the end of this thesis.

The situation which results following a direct strike of lightning is that of two simultaneous arcs on the system, separated by an appreciable distance, and the studies of this research were planned to investigate the system and basic arc properties which influence the stability of the two arcs.

The negative resistance characteristic of an arc is well known and as a result of this property it is apparent that where two dissimilar arcs are in direct parallel, one is unstable and the other, which has the greater stability while conducting, robs the first and continues to carry the entire current of the system. When the arcs are separated by an appreciable impedance, but are still energized by the same electrical source, it is possible to have stability of both without the occurrence of the robbing mentioned above.

On distribution lines many factors could influence the stability of the arcs, among which are line impedance and propagation time, delay time between initiation of the two arcs, arc lengths and the mediums in which the arcs are formed, nature and magnitude of the lightning discharge, a variety of terminal conditions and the material of the electrodes between which the arcs are established. Each of these factors was investigated in the experiments described later.

Dielectric recovery rates have been studied by McCann, Conner and Ellis (2) in the California Institute of Technology High Potential Laboratory for arcs with current as high as 800 amperes and with length as long as 11 inches. Much of the equipment developed during that study was used and modified as required by the writer in the experiments described in this thesis.

Several studies have been made of distribution systems in connection with lightning problems, among which are studies by Witzke (3), Harder and Clayton (4) (5) and MacCarthy, Stan, Edge and McKinley (6). Much very valuable information has been obtained but certain limitations of the studies are apparent. Witzke, Harder and Clayton and others have used analog computers to perform their experiments and in the general study were confronted with the problem of providing a satisfactory analog for a lightning arrestor. Since an arrestor is non-linear and has the property of introducing harmonics of power frequency voltage into the system when conducting, a completely satisfactory analog is difficult if not impossible to obtain. Recent studies by Harder and Clayton (5) have been made using a battery in series with a rectifier; however this is far from ideal as it cannot simultaneously represent the effect of the arrestor to surges and to power frequency currents.

Other writers such as MacCarthy, Stan, Edge and McKinley have collected data which describe actual operating characteristics of the lines in use by various companies. This is, of course, a slow and costly process and has the disadvantage of not allowing control of conditions pertaining to the lightning and, in addition, basic line parameters are usually fixed so that only length can be varied.

As a combination of these methods it was decided that experiments on an artificial or analog line would be conducted but at current and potential levels equal to those used on real lines and that real arrestors and arcs of lengths actually found in practice would be used. The High Potential Laboratory is uniquely suited to this type of experiment since two surge generators capable of producing one million volts each, as well as a sixty-cycle source which could be adjusted to obtain a variety of potential and power ratings, were available.

The purpose of the research reported in this thesis was to determine how variation of line and arc parameters influenced the stability of the system of parallel arcs and to establish criteria for which the arrestor would rob the open arc. This condition on a line would, of course, result in satisfactory performance since a lightning arrestor is self-extinguishing at the first current zero.

No attempt has been made to investigate economic factors of the desirability of certain arrestor spacings along lines, nor has a statistical study of lightning performance been included. It was felt that the former was a matter for the power companies to consider, while the latter has been investigated by many writers in the past and tables and charts have been prepared which give the probable number of lightning strikes per mile of line per year for various areas of the country, as well as the approximate range of charges and voltages likely to be encountered.

The studies have been limited to distribution systems in the 3.0 kilovolt class and have included only expulsion-tube arrestors of the type normally used on distribution lines. While higher voltage levels might introduce special problems it was felt that the fundamental properties would be very similar to those found at 3.0 kilovolts. Station type arrestors were not studied since in the past they have been too costly to use on distribution lines in large numbers.

APPARATUS AND TEST TECHNIQUES

APPARATUS

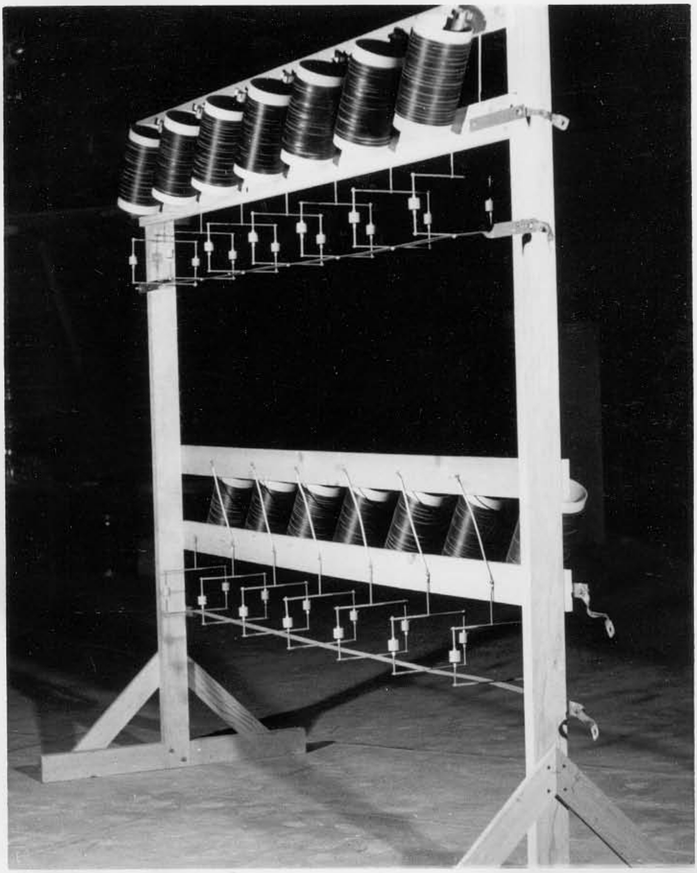
The research was performed on an artificial line which simulated as nearly as practical actual conditions found in distribution systems. Since a pulse of lightning has a very wide range of frequency components, it was necessary to arbitrarily specify some upper value of frequency as the highest which would be freely transmitted along the simulated line. Smythe (7) has shown that frequencies below the cut-off value $f_c = \frac{1}{\pi\sqrt{L\ C}}$, where f_c is a critical frequency and L and C are inductance and capacitance per line section respectively, are freely transmitted; with this as a criterion a frequency of 1 megacycle was taken as a reasonable figure for f_c. Many of the tests were conducted with the line arranged to allow a critical frequency greater than this value.

The capacitors used were built up of combinations of basic 609 micromicrofarad units which would withstand a surge test of 50 Kv with a $1\frac{1}{2}$ x 40 microsecond wave. These were arranged in series and parallel combinations as were required to provide the desired total capacitance.

The coils were wound on 5 inch inside-diameter micarta tubing with #12 AWG copper wire and had an average inductance of 193 microhenry each. Single layer solenoid winding was used to obtain maximum insulation with minimum cost and size.

The coils were mounted in two rows on wooden racks and were placed at an angle of 60° from the horizontal to minimize the mutual inductance between coils and thus to insure that propagation would follow the line as desired and not result from instantaneous induction effects. The spacing of coils along the rack was at 12 inch intervals for which measured mutual inductance was less than 0.2% of the self inductance per coil. Fig. 1 shows the physical arrangement of the coils and capacitors with common ground bus and illustrates the hardware used to obtain various values of total capacitance per section by the series and parallel connections. Appendix A describes tests made on this line analog to determine how accurately it represented an actual line and includes oscillograms showing propagation characteristics.

Most of the data presented in this thesis were obtained from tests conducted with the circuit arranged as shown in Fig. 2, in which the blocks show the functional elements of the test apparatus. Two surge generators were used and were connected to be tripped in sequence with the time interval determined by a binary counter used in connection with an audio oscillator and square-wave generator. The latter instrument was used to insure accuracy of the time in each cycle at which the counting occurred. The counter was arranged so that it could be used as a 4 stage or a 10 stage unit and tests were conducted with time delays from 10 microseconds to several thousand microseconds by appropriate changes of the frequency and number of stages.



LINE STRUCTURE WITH

L = 193 μhenry/section

C = 1218 μμF/section

FIG. 1 PHOTOGRAPH OF LINE ANALOG

USED IN EXPERIMENTS

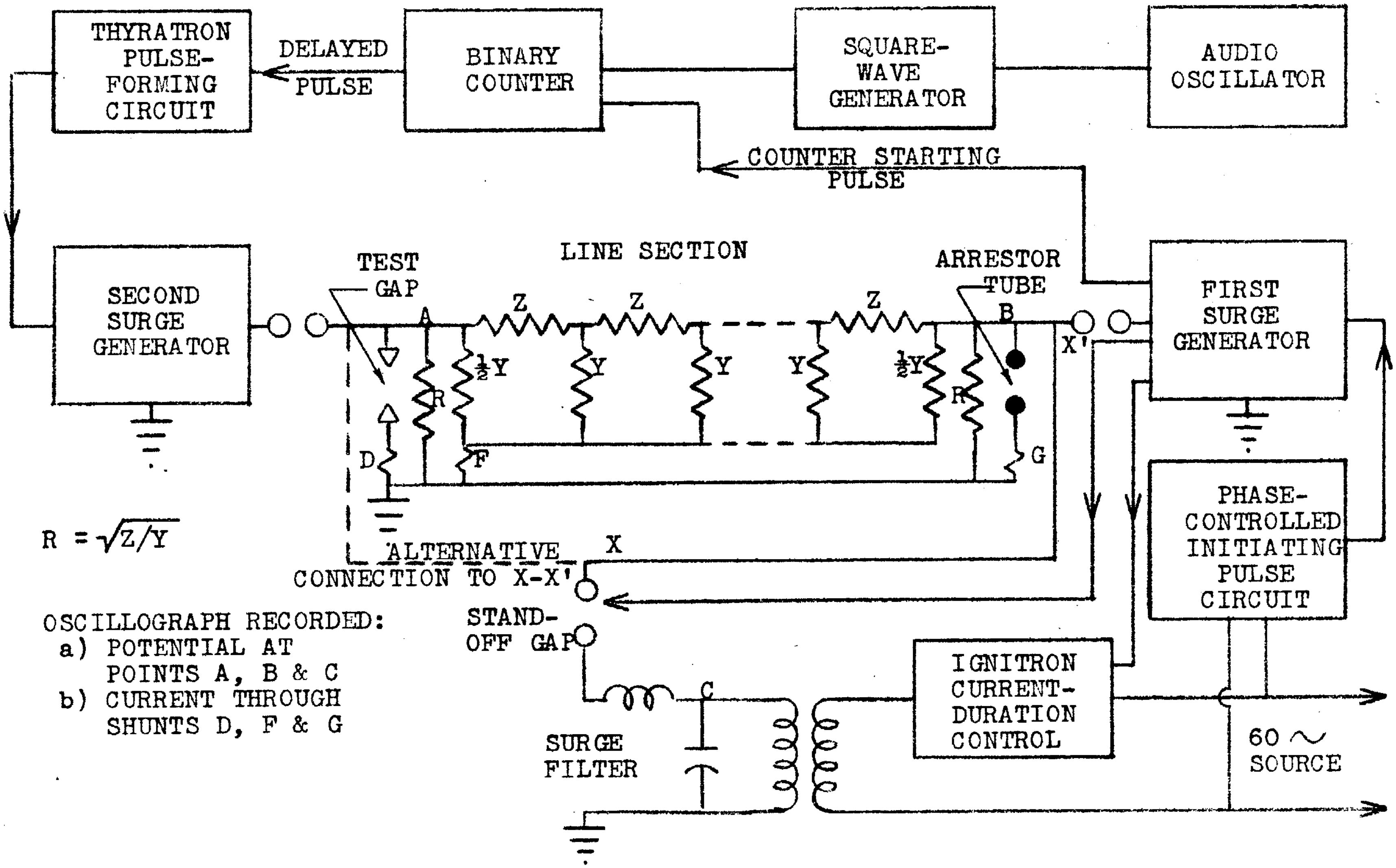


FIG. 2 SCHEMATIC BLOCK DIAGRAM OF ARC STABILITY EXPERIMENTS

A sixty-cycle power source was connected through a $\frac{1}{4}$ inch stand-off gap to the line and, as is illustrated in the circuit diagram, was arranged so that the duration of current flow could be controlled to allow any number of half-cycles that were desired. Most testing was done with this control set to allow two cycles of conduction. It was limited in that manner since most of the valuable data were recorded during the first half-cycle; however, it was important to know the long time conduction properties of the arcs also.

Records were made simultaneously with three instruments in most cases, and with at least two instruments for all tests. A magnetic oscillograph recorded three voltages and three currents as indicated on Fig. 2 and gave a complete record of the long-time characteristics of the system. A sample of one such record is shown in Fig. 3, where a description of the test conditions is given. A total of approximately 3000 such records were made during the course of the experiments.

In addition to the magnetic oscillograph, a cold-cathode electronic oscillograph was used at various points in the system for many of the tests to obtain a detailed record of the short-time variations of currents and voltages. These records were made by the electron beam directly impinging upon the photographic film which was under vacuum.

A third instrument, a hot-cathode single-sweep elec-

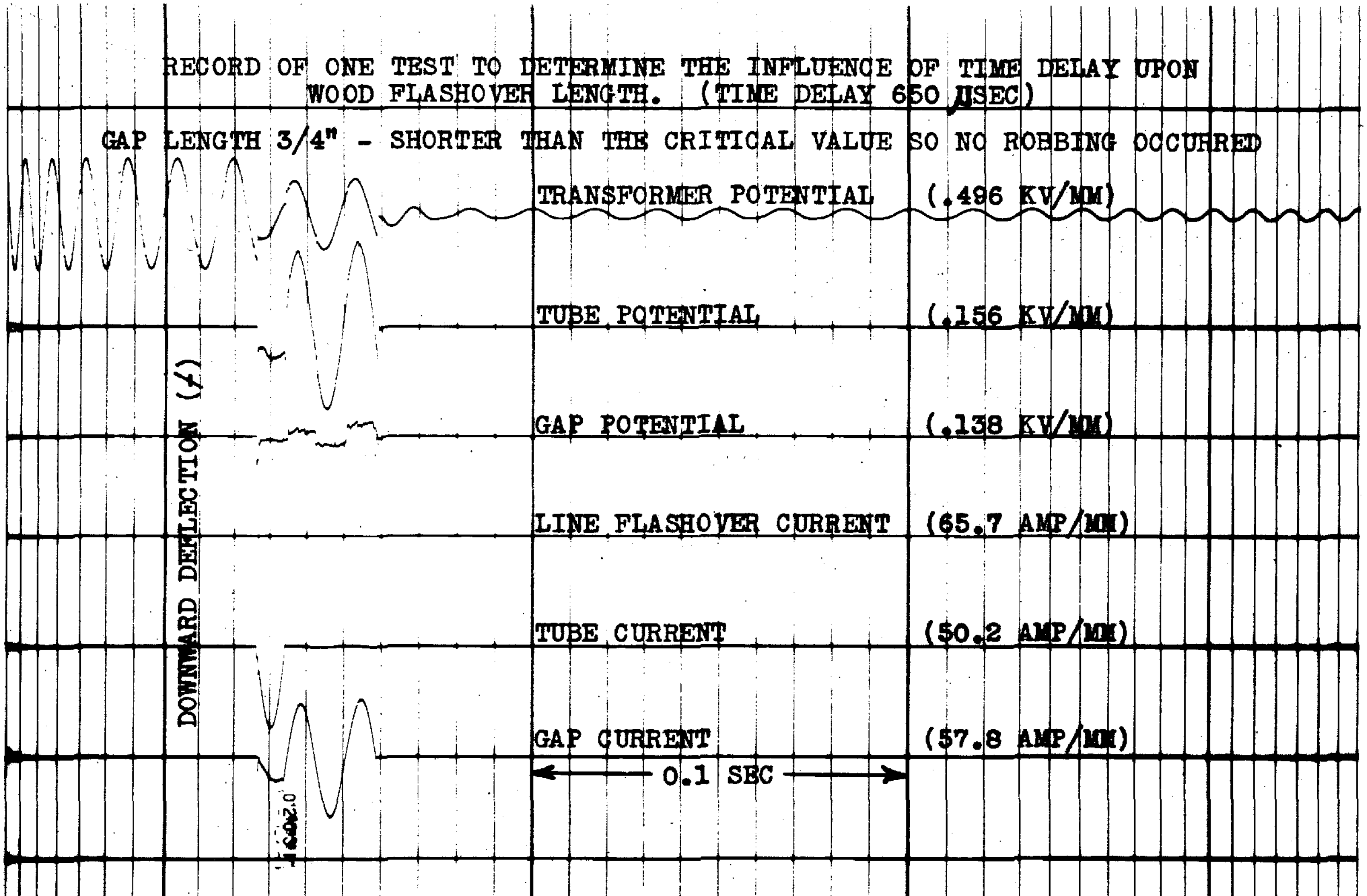


FIG. 3 TYPICAL OSCILLOGRAM SHOWING SYSTEM POTENTIALS AND CURRENTS

tronic oscillograph, was used as a visual monitor and to keep continuous records of the time delay for each test.

TEST TECHNIQUES

As outlined earlier in this thesis the operation of arrestors on a line is such that the tube is usually already conducting when the surge strikes the line. To simulate this the first surge generator was tripped, discharging most of its energy through the tube to ground. The sixty-cycle power-follow current continued to flow as the standoff gap became conducting at the discharge of the #1 generator and at the end of the preset time delay, the second surge generator was tripped. This discharged its energy through the test gap to ground and at the same time initiated a traveling wave on the line with a shape determined by the wave front of the applied wave and magnitude limited to the flashover potential of the test gap being used. This wave traveled down the line to the tube where, due to the very low impedance of the conducting tube (less than 1 ohm), it was reflected with inverted polarity for the potential wave.

Several series of tests of this type were conducted with a wide variety of line and terminal conditions to determine which of the factors was most influential in determining the stability characteristics of the two arcs and, wherever possible, curves and functional relationships were obtained.

In later series of tests the sixty-cycle power source was moved to the test gap and connected to the end of the line at the terminal of the #2 surge generator. The only important circuit change required for this arrangement was that of adding a third tripping electrode to the stand-off gap which isolated the sixty-cycle system from the line, since the time delay of the line was usually so great that power-follow did not result in the tube unless flashover occurred in the stand-off gap and tube simultaneously. In all cases the magnitude of this tripping surge was limited to a value too small to produce flashover of the main test gap to which it was connected.

Since the arrestor was one of the main elements of the test circuit, every effort was made to keep uniformity of results. One arrestor was checked new on a five "π" section line and was re-checked periodically, as it was being used in the regular tests, under the original conditions to determine aging characteristics and variations due to erosion. Appendix B shows the results of these tests and clearly indicates that during the first 15 discharges changes of characteristics were so rapid that these are not usable for comparative purposes.

It was found necessary to replace the core of an arrestor about every 100 tests, when current had a crest magnitude of approximately 900 amperes, with a replacement core made of the same fiber used in new arrestors; these were constructed in our own shop.

Fig. 4, in the upper photo, shows a complete arrestor ready to mount on an exposed line, a cut-away section

ARRESTOR TUBE STRUCTURE

TEST GAP STRUCTURE

FIG. 4 ARC ELECTRODES AND CONFIGURATIONS showing internal construction and cores to illustrate the type of erosion which occurred. Each tube was used with four or more cores and it was found that after about five tests, with a new core in a used barrel, a stability of arc conditions was reached.

It should be noted that the tubes identified by numbers one through three were of an older and slightly different design than those numbered four through seven. This difference is reflected in a slightly higher arc potential during conduction for the older type; however the characteristic trends measured with the two types are the same. Fig. 6 and Fig. 8 are based on the early tubes and have somewhat higher values of test gap length than would have been found had the later tubes been used, as can be seen by comparison with corresponding points on other curves.

TEST SEQUENCE AND RESULTS

The test plan was developed to discover as much basic information as possible concerning the phenomena found in nature in connection with the simultaneous parallel arcs. Andrews and McCann (8) had found that arrestors frequently become conducting as much as 50 to 250 microseconds prior to the direct stroke of lightning to the system. The investigation of the influence of the variation of this delay time was carried out over a range somewhat wider than this to cover all probable delays, and a total delay varying from 10 to 650 microseconds was used. The time interval was measured with a cathode-ray oscillograph and photographic records were made of each test using a 35 mm camera photographing the pattern on the screen of the tube.

Variations of time delay resulting from inherent errors in the counting system, due to random phase relation between the audio oscillator of the counter and the firing point, occurred with a total spread of ± 3%. The basis of comparison of characteristics of the arc stability was that of the length of the test gap.

The test gap used in the initial phases of the research was a standard rod gap, made of $\frac{1}{2}$ x $\frac{1}{2}$ inch square-cut steel rods mounted in the fashion prescribed by AIEE standards for high potential testing. In later work flashover along wood and flashover between additional modified copper-tipped rod gaps were tested in order to simulate conditions found on distribution systems in which flashover occurs along crossarms between various pieces of hardware.

The lower part of Fig. 4 shows the mechanical arrangement of the three types of test gaps and illustrates how the seven foot section of fir crossarm material was moved along the supports so that an undamaged section was available for each new series of tests. Electrodes were resurfaced by machining after every 20 tests in all cases and wood sections were used for a similar number of shots.

TIME DELAY TESTS

The procedure followed was that of starting each series of tests with a short test gap so that in both the tube and test gap stable arcs would be established. The test gap was then lengthened until a critical length was determined for which a test had equal probability of resulting in parallel stable conduction or of the arrestor robbing the test gap during the first few microseconds with power-follow being appreciable only in the tube. Since tests were conducted at time intervals of as much as several minutes, and as the conduction properties of air and of tubes are highly variable, some spread of data was to be expected. While the total number of tests required to establish a critical level varied, ordinarily from 20 to 40 tests were made. The critical level was established as is customary in critical flashover characteristics from a plot of length versus test number and a mean length was determined from these points. One such typical plot is shown in Fig. 5. These tests were not taken in a series as numbered

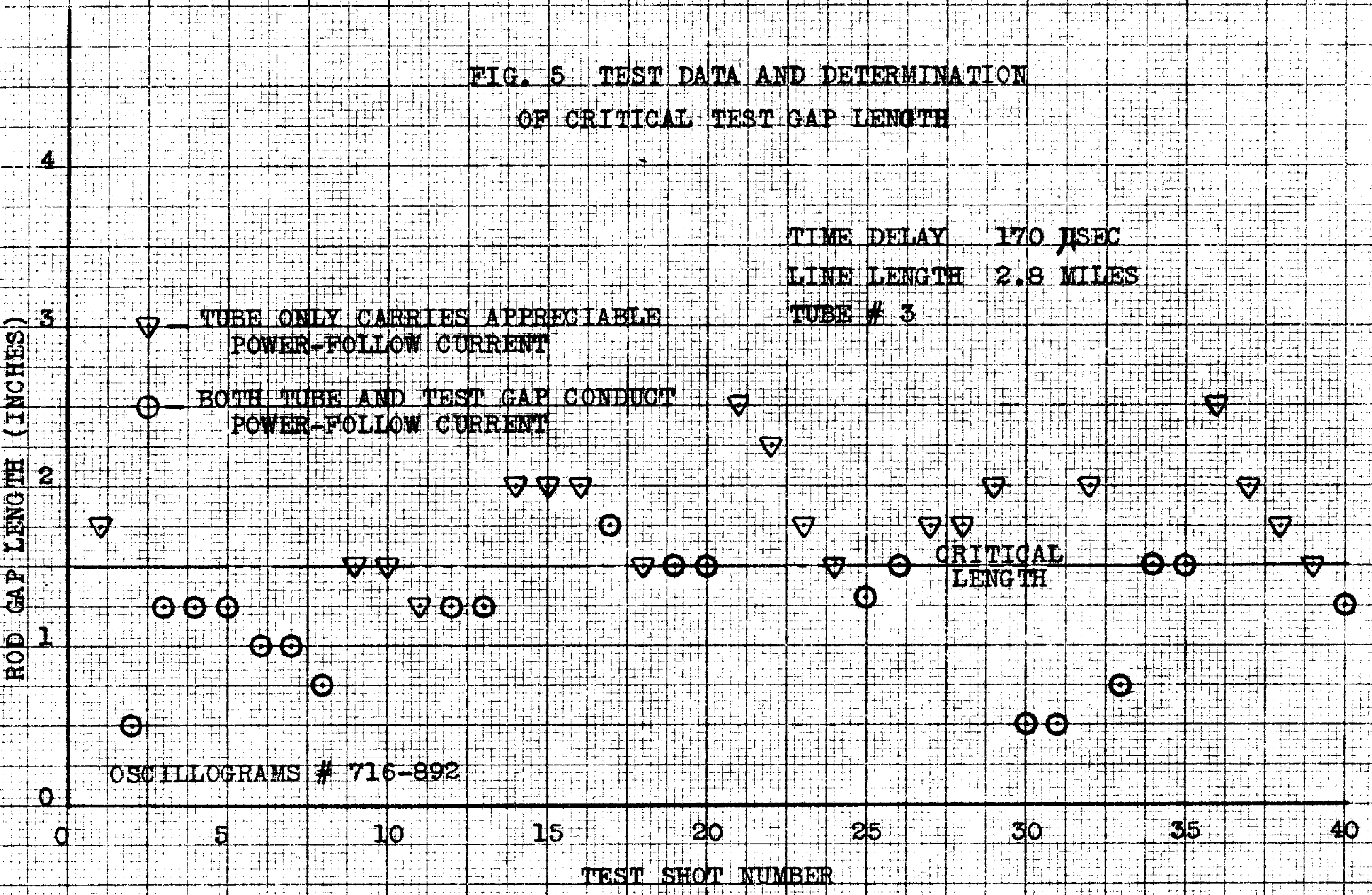


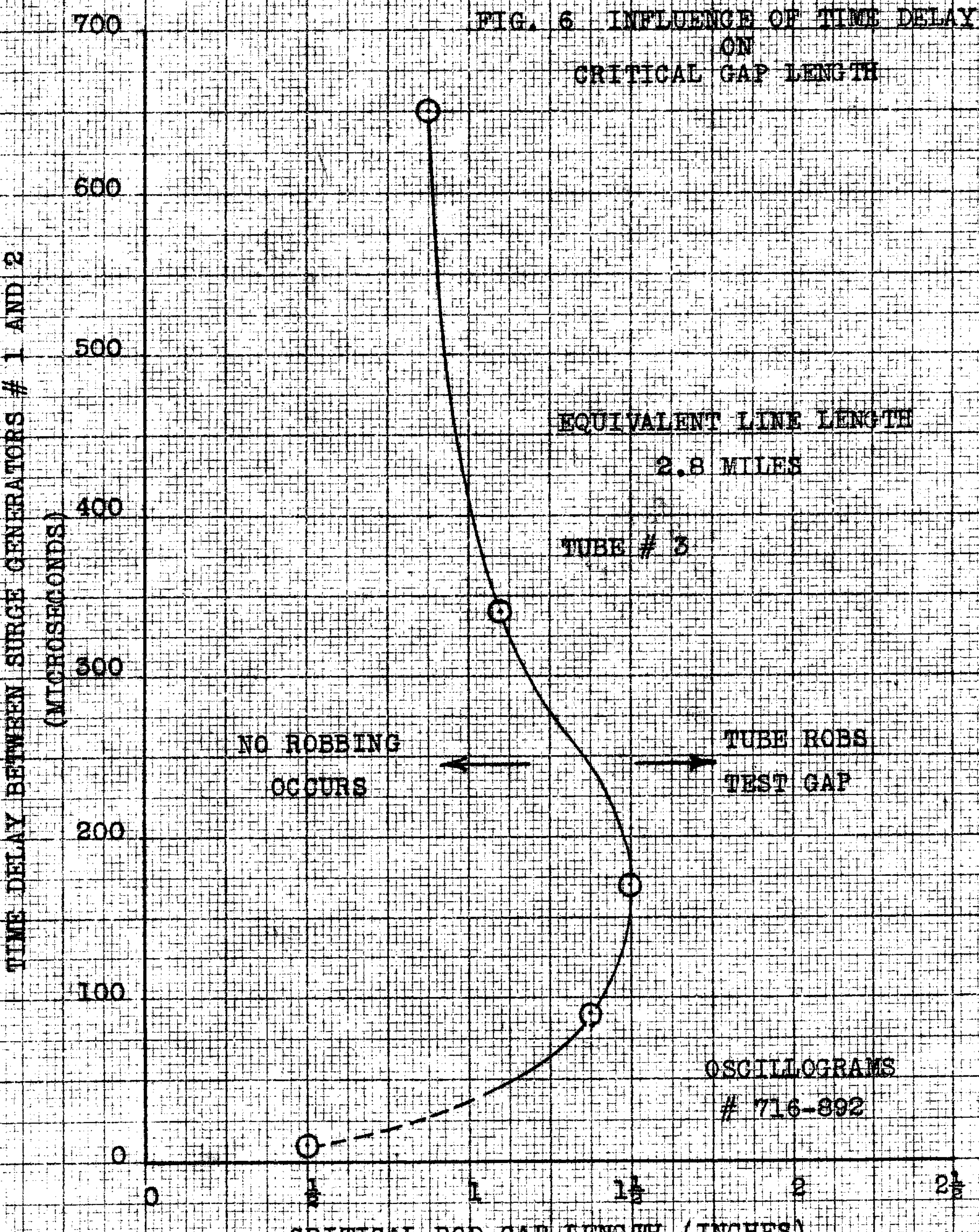
FIG. 5 TEST DATA AND DETERMINATION OF CRITICAL TEST GAP LENGTH

but were interspersed with tests at other time delays in order to reduce systematic errors which might have resulted from tube aging or system changes over the several days time required to obtain data for the entire time delay curve. This accounts for tests at very long and very short spacings on Fig. 5 which might otherwise not seem to be appropriate.

Check tests were made, to definitely establish the influence of the tube on the system, by removing the tube. In all cases the test gap then carried power-follow current for all gap lengths up to 7 inches, which was the longest gap used, clearly showing that the tube was robbing the test gap of current and that the test gap was not extinguishing due to the natural recovery properties of the system.

The total curve of time delay as a function of test gap spacing is shown in Fig. 6 and shows relatively small variation except at very short times for which the two surges existed simultaneously on the line. For times in excess of 50 microseconds such as are likely to be found on real systems, the influence of the first surge generator on the system had been damped out and the system was stable with the tube carrying sixty-cycle power-follow current. Since in actual distribution systems the arrestor flashover results from induced potential which rises relatively slowly, the mechanism used here to initiate the arc in the arrestor is not a true duplicate of practice and hence

FIG. 6 INFLUENCE OF TIME DELAY
ON
CRITICAL GAP LENGTH



values for very short times, below 50 microseconds, are probably not applicable to explain line phenomena.

Throughout the remaining tests on the system the time delay used was 170 microseconds. This was a typical value measured in distribution systems and since Fig. 6 indicates that this value is not in a region of rapid change, small variation in delay about this value would thus not be serious.

LINE LENGTH TESTS

The length of the line section between the two arcs was known to be a rather important parameter and the next tests were made to determine the nature of this influence on test gap length. The procedure followed that used in the time delay series with variation in test gap length being the parameter for which a critical value was found corresponding to each line length used. The range of distances covered by the tests corresponded to approximately three miles of typical distribution line.

With the circuit arranged as shown in Fig. 2, tests were conducted from the maximum line length to as short a line as was possible while still allowing the two arcs to be initiated independently. Since connection of the test gap and the tube at the same spot always produced a single arc with both surge generators being discharged through the same weaker dielectric path, it was necessary to limit length to a minimum value. That value was such that the transit time of the line section was sufficient to allow the potential to build up at each arc position so that flashover occurred only from the surge generator connected at that point. For the tubes and spacings used in these experiments this distance corresponded to approximately 400 feet of line or a propagation time of about 0.4 microsecond. This short transit time was possible because for test conditions near the critical gap spacing the dielectric strengths of arrestor tube and test gap were nearly equal.

The tests were continued with the sixty-cycle power source connected to the test gap and with the tube on the open end of the line, corresponding in a practical distribution system to a lightning strike occurring between the isolated arrestor and the power source. The curve obtained for this series is a smooth continuation of the one found for the earlier series of line length tests with an increasing critical gap length as the line length was increased. The complete curve of line length as a function of critical gap spacing is shown in Fig. 7. The critical gap spacing was carried to 5-3/4 inches with individual tests having been made for spacings as long as 7 inches. This value is 3½ times the equivalent rod gap spacing for basic impulse level at 3 Kv and was considered to be well above any probable value which would occur on a system.

CHARACTERISTIC IMPEDANCE AND LINE CAPACITANCE TESTS

Although there is fair uniformity of line construction on distribution systems, there is a considerable variation in estimates of line characteristic impedance due to

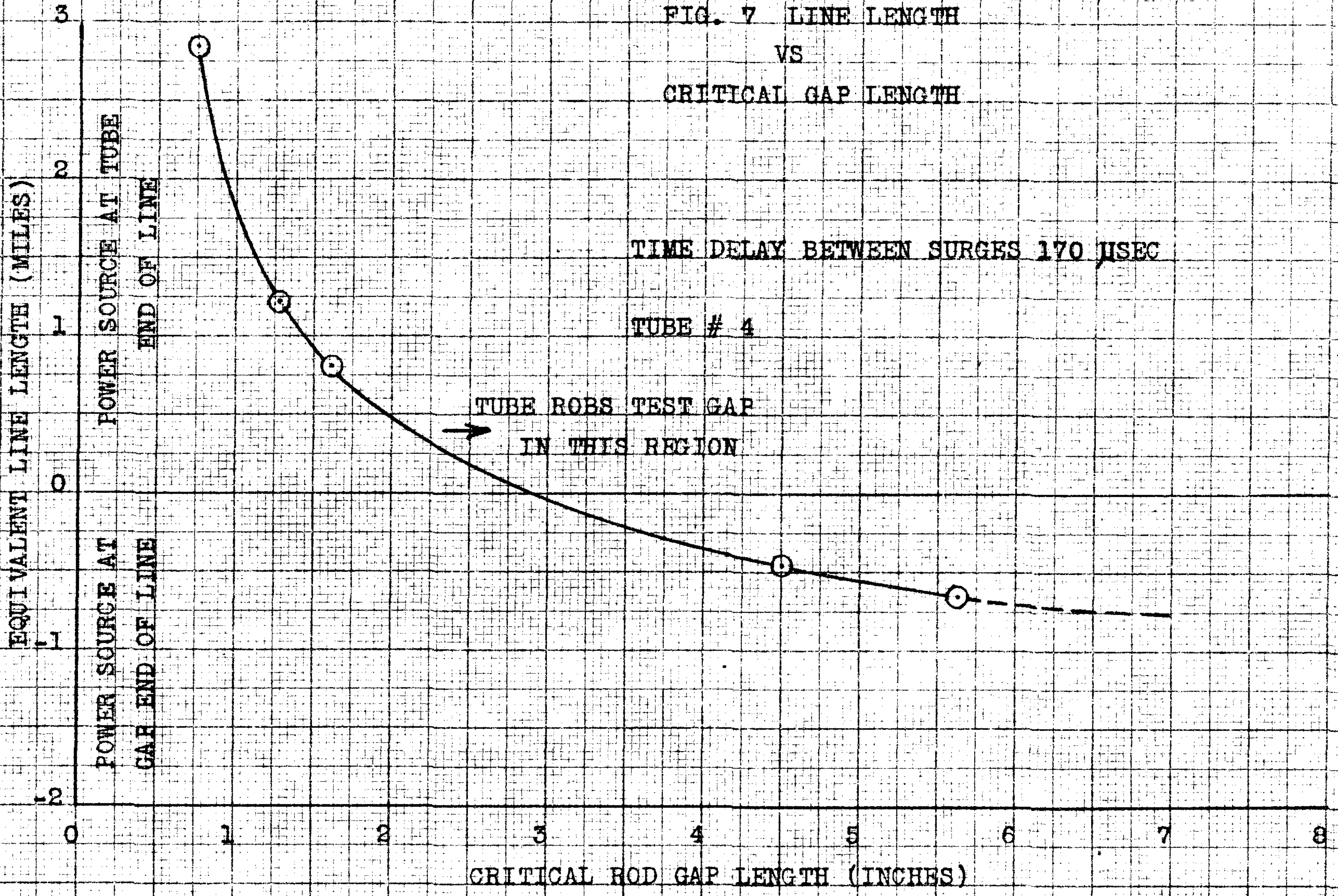


FIG. 7 LINE LENGTH
VS
CRITICAL GAP LENGTH

TIME DELAY BETWEEN SURGES 170 µSEC

TUBE # 4

imperfect knowledge of actual line geometry; therefore it was felt that this factor should be carefully investigated to determine if variations in line geometry would materially influence the arc stability. The model line was arranged so that inductance and capacitance could readily be varied independently of one another; however in a real system the two are both determined by line spacings. The next tests were performed keeping inductance per section constant and keeping the same number of sections but varying the capacitance per section. This had the effect of varying both characteristic impedance and equivalent length since length of the model line was based upon propagation velocity of the highest frequency components of surges being equal to the velocity of light. These tests were performed since it was convenient to vary capacitance and because it was thought that the dominant factor in determining stability was the series impedance between the arcs. Tests were made on a line of 2.8 miles equivalent length with capacitance variation in the ratio of 16 to 1. The curve of Fig. 8 shows the results of this series of tests and indicates that the capacitance of the line is a relatively unimportant factor in determination of arc stability within the range which would be encountered on actual distribution lines.

Associated with this series of tests, check points were taken in which the equivalent length was held fixed and characteristic impedance was varied. This was based upon line length being measured in terms of propagation

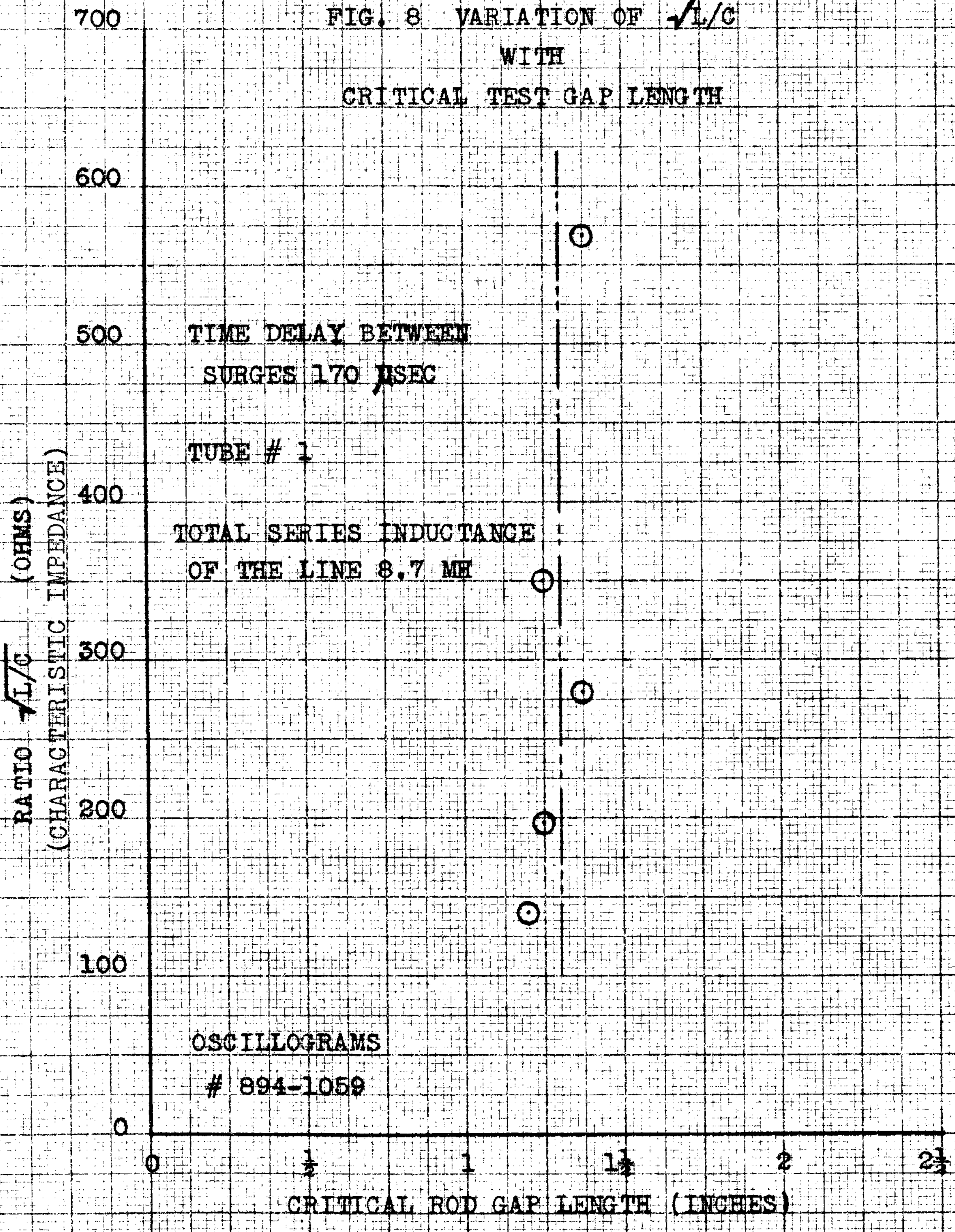


FIG. 8 VARIATION OF $\sqrt{L/C}$ WITH CRITICAL TEST GAP LENGTH

time on the line. Since the highest frequency components of the surges propagate with a velocity approaching that of light, and since the velocity in units of line "π" sections per second is $v = \frac{1}{\sqrt{L\,C}}$ where L and C are inductance and capacitance of each line section, the total equivalent line length was taken as $N \times \sqrt{L\,C} \times c$. N represents the number of sections and c is the velocity of light, 984 feet per microsecond in British units.

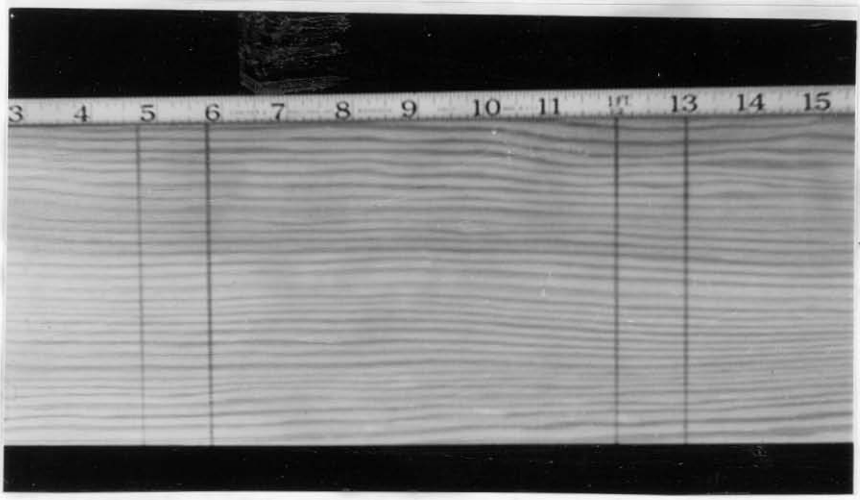
Three check points were evaluated by series of tests in which the product L x C was fixed by doubling C and halving L first, and then using factors of $1\frac{1}{2}$C and 2/3L and $2\frac{1}{2}$C and 2/5L respectively. To maintain constant total transit time the number of line sections was also constant so that the total inductance was varied accordingly. This gave a range of Z_o of 2.5:1 total. These points were compared with the curve of Fig. 7 and were found to correspond to values on this curve for the same total series impedance (i.e. same total number of coils in the series line) but were apparently independent of line shunt impedance. This clearly indicates that except for very short lines where transit time is so small as to not allow the two arcs to be independently initiated, the line characteristic impedance and transit time effects are small and for variation of line geometry the dominant factor in determining arc stability is that of the series impedance.

In actual lines, since wire size and spacing influence both series and shunt impedance, the physical arrangement of the line is thus apparently of importance only in-so-far as it controls series impedance. In the laboratory model series impedance is affected by both physical length and characteristic impedance.

ARC CONFIGURATION TESTS

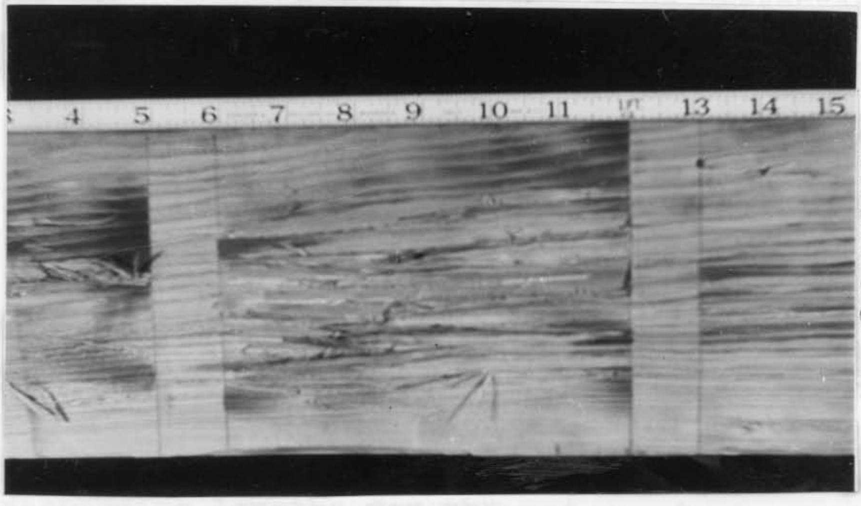
The next tests investigating arc dielectric material were made by changing from a standard rod gap as the test gap to investigation of wood flashover between copper electrodes. The photograph in Fig. 4 illustrates the mechanical arrangement used in these tests. Seven foot lengths of clear Douglas Fir, free from knots and other grain irregularities, were used; the width of the material was five inches. Copper straps were attached to one side of the wood and arranged so that the contact pressure was uniform over the entire series of tests. Preliminary tests on splintering and physical damage to the wood indicated that as many as 50 tests, using a surge simulating a lightning discharge of crest current magnitude of 4000 amperes and a charge of .02 coulomb while doing considerable mechanical damage, caused no measurable change of electrical flashover characteristics. With power-follow of one-half cycle at 800 amperes crest magnitude, damage was much greater and electrical characteristics began to change appreciably after 25 tests, so an arbitrary limit of 20 tests per wood section was imposed. Fig. 9 shows the effects of surges only and of surges combined with power-follow to wood surfaces.

The test procedures used with the test gap being a



NEW
UNTESTED
WOOD

SAMPLE AFTER
20 SURGE TESTS
(4000 AMPERES
CREST)



SAMPLE AFTER
20 POWER-FOLLOW
TESTS. (BOTH
SURGE & $\frac{1}{2}$ CYCLE
OF POWER FRE-
QUENCY CURRENT)

FIG. 9 PHOTOGRAPHS SHOWING DAMAGE TO WOOD SURFACE
CAUSED BY SURGE AND POWER-FOLLOW CURRENTS

standard rod gap were duplicated for the wood flashover test gap using the same type of arrestor tubes and similar line arrangements.

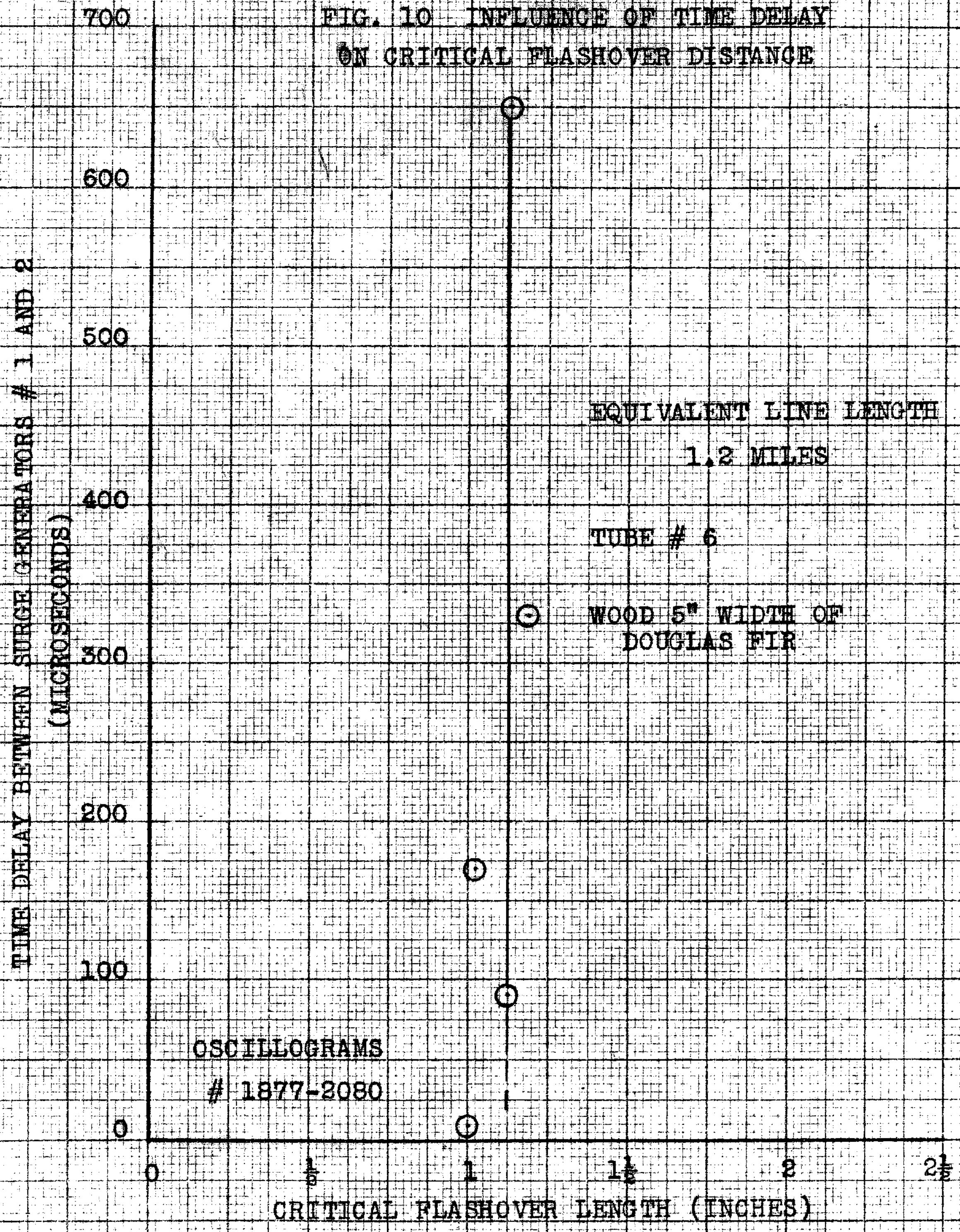
Since the influence of time delay and line shunt impedance had been found to have small influence on the stability of the parallel arcs for the rod gap test gap it was decided to make these corresponding tests using wood flashover distance as the comparison parameters for slightly different line conditions in order to make the scope of the investigation as wide as possible. This was justified on the basis that the fundamental arc characteristics of the wood flashover and of the rod gap were similar.

The time delay variation was investigated over the same range of time that had been used in the case of the rod gap but with an equivalent length which was somewhat shorter, being 1.2 miles, whereas with the rod gap the equivalent line length was 2.8 miles.

The results of these tests are presented in the curve of Fig. 10 and show that no appreciable variation of critical gap length as a function of time delay exists, except at very small time delays.

The dependence of arc stability upon line length was investigated with the power source connected first to the tube end of the line and later with it connected to the test gap. Line parameters were identical to those used for corresponding lengths for the rod gap tests so that direct comparison could be made. The curve of Fig. 11 shows this

FIG. 10 INFLUENCE OF TIME DELAY ON CRITICAL FLASHOVER DISTANCE



EQUIVALENT LINE LENGTH
1.2 MILES

TUBE # 6

WOOD 5" WIDTH OF
DOUGLAS FIR

OSCILLOGRAMS
1877-2080

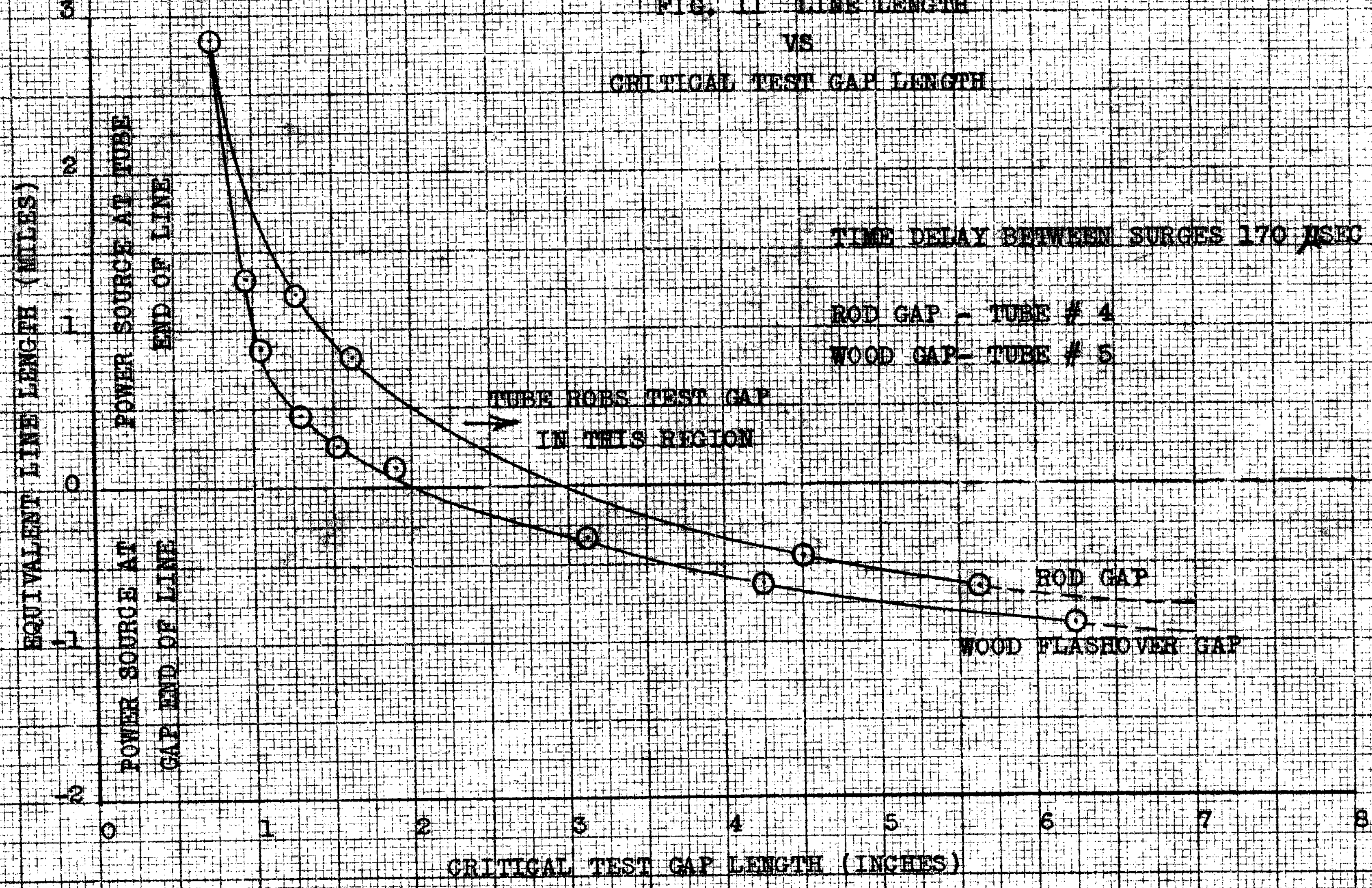


FIG. 11 LINE LENGTH
VS
CRITICAL TEST GAP LENGTH

dependence, and shows the curve presented earlier as Fig. 7 for the rod gap, for comparison. The two curves are similar in shape and differ chiefly in magnitude of the critical spacing. The ratio of spacing at a particular line length is in the range 0.6 to 0.8 for line lengths up to $\not-$ 1-3/4 miles and approaches unity for longer line lengths.

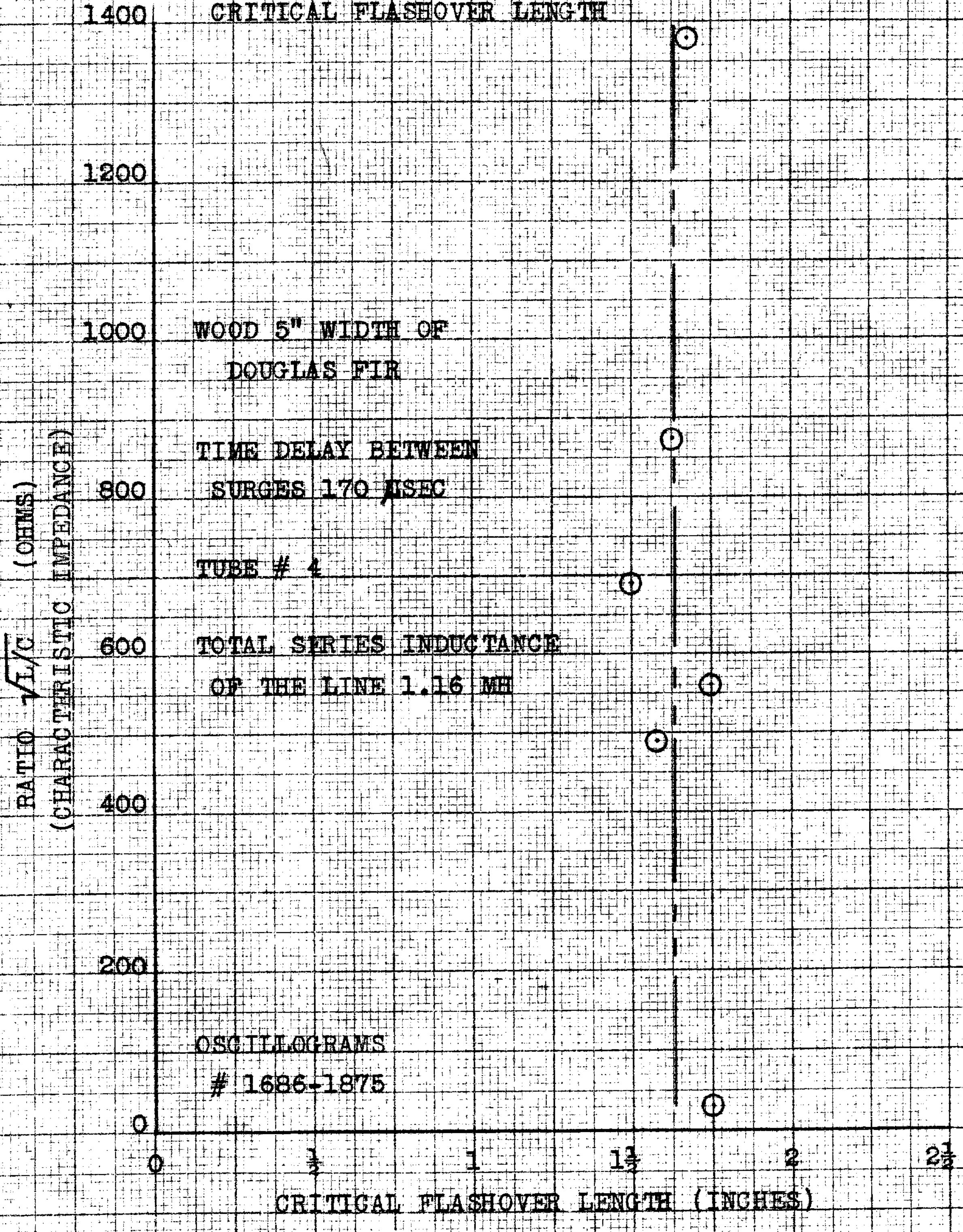
The results of tests made by varying the line shunt impedance per section as a function of critical gap length are summarized by the curve of Fig. 12 and indicate no appreciable dependence of arc stability upon shunt impedance. As was the case for the rod gap tests, check points were made with constant effective line length and variable characteristic impedance with the same result as discussed earlier, that the stability is apparently dependent upon series impedance only and not basically upon transit time or shunt impedance.

The difference in performance of the rod gap and wood with reference to line length gave a means of discovering the basic criterion of arc stability. The difference of dielectric recovery rates of the two materials offered one possible explanation, while the longer-time arc-burning characteristics offered a second. The dielectric recovery rates were next investigated.

DIELECTRIC RECOVERY RATES OF ROD GAPS, WOOD FLASHOVER AND ARRESTOR TUBES.

The rate of dielectric recovery of arcs in standard rod gaps following various types of discharges has been

FIG. 12 VARIATION OF $\sqrt{L/C}$ WITH CRITICAL FLASHOVER LENGTH



investigated by several experimenters. McCann and Clark (9) developed a technique using two surge generators and investigated recovery rates of 6 and 11 inch rod gaps following predischarges of several types of surges. McCann, Conner and Ellis (2), using a similar method, extended this work to include 3, 6 and 11 inch rod gaps and measured dielectric recovery rates following conduction of sixty-cycle power-follow current for a variety of current magnitudes and durations. Although there has been a great deal of experimental work on wood flashover characteristics, for example Bellaschi (10), no comparative and well tabulated recovery rate data are available on wood sections of a length such that quantitative comparison to rod gaps is possible.

The lightning simulating surge generator which had been used throughout these experiments had a discharge characteristic of 4000 amperes crest with a total charge of 0.02 coulomb. Using this predischarge tests were performed to determine recovery rate curves for rod gaps of 3 and 6 inch lengths and for wood flashover for the same lengths, as well as rates for the special strap electrodes shown in Fig. 4 and for the expulsion tube.

These experiments were conducted in a fashion similar to that used by McCann, Conner and Ellis with much of the same equipment and modifications were made as were required by the new and special conditions. The time interval between surges was varied from 80 to 15,000 microseconds so that a binary counter suitable for these time delays was arranged. The tripping system for the surge generators which had been used by the earlier experimenters had proved to be very critical to adjust and difficult to maintain over the wide ranges of potential required. A triple gap had been used which was constructed with a pair of 10 centimeter diameter spheres with a third smaller sphere adjacent to the other two. These gap structures were replaced by a pair of gaps constructed of hemispheres with a needle point coaxial with the hemisphere axes and insulated from one by an appropriate fiber sleeve. The initiating pulse from a 4C35 thyratron circuit produced flashover of the insulator from the needle point to the ground hemisphere, supplying sufficient ionization to very rapidly initiate an arc between the two hemispheres. This arrangement had the advantage of operating over a very wide range of potentials without mechanical readjustment.

The special copper-tipped strap electrodes described earlier were constructed to investigate the influence of electrode size and material on dielectric breakdown, recovery rate and arc conduction characteristics. Ellis (11) had investigated the influence of electrode material on recovery rate with use of iron and carbon electrodes under identical conditions. It is his conclusion that the material with the lower boiling point and ionization potential has the lower dielectric recovery rate; consequently arcs between copper electrodes should recover more slowly than between iron electrodes due to slight differences from both of these effects.

The possibility existed that the difference in the material and mechanical arrangement of the rod gap and the electrodes for the flashover along the wood might be so influential in change of recovery rate that it would completely obscure the differences between air and a parallel air and wood dielectric. Comparison of the recovery rates between the special strap electrodes in air and rod gaps in air over several hundred tests as plotted on Fig. 13 show no appreciable differences however, so the effect of slightly reduced rate of recovery of copper relative to iron, due to lower boiling point and lesser ionization potential, is apparently exactly compensated for by the increased recovery rate produced by the cooling effect of the larger area of electrode and change of shape. Therefore differences between the rates of recovery of rod gaps and wood flashover were caused by the wood only and not by the electrodes.

The curves of Fig. 13, in addition to eliminating material and configuration as variables to be considered, illustrate that for both the 3 and 6 inch length test gaps the wood recovers more slowly than does air for the same spacing.

A second series of dielectric recovery tests was conducted following power-follow current of one-half cycle duration and 800 amperes crest magnitude for rod gaps of 3 and 6 inch spacing, for wood flashover of 3 and 6 inch

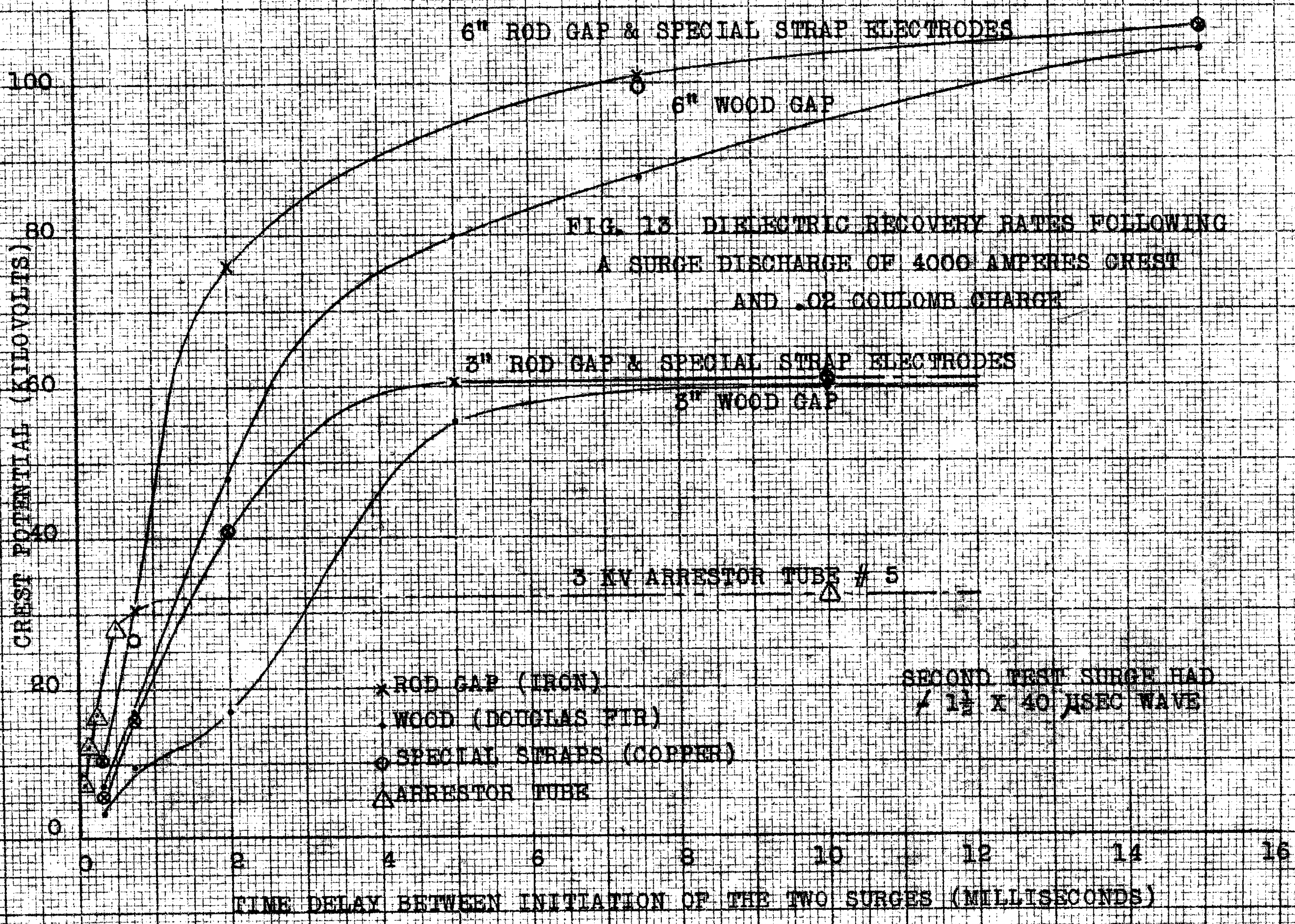


FIG. 13 DIELECTRIC RECOVERY RATES FOLLOWING A SURGE DISCHARGE OF 4000 AMPERES CREST AND .02 COULOMB CHARGE

electrode spacing and for the 3 Kv arrestor tube used throughout this research. The one curve of the six inch rod gap was compared to work done by Ellis (11) as a check and agreement was within 2 Kv at all points. Fig. 14 shows the points determined during these tests, as well as points determined by Ellis, together with the points for the other four curves.

The results of relative rate of recovery for the three inch rod gap and wood flashover are the same as those found in the surge predischarge case for which the air was found to recover more rapidly than the wood. The long time recovery of the six inch gap shows the wood to recover more rapidly than the air for times in excess of 30 milliseconds; however this is not important in the present research since the stability of the two arcs had been established prior to a time corresponding to a half-cycle of sixty-cycle power frequency which is only 8.33 milliseconds.

The time delay for each curve was reduced to as short a value as was possible for which a definite recovery voltage existed. The "long-tail" flashovers discussed by Ellis (11) were encountered in testing the wood flashover and tubes as well as for the rod gaps and established the minimum recovery time for all curves on both Fig. 13 and Fig. 14.

The results of these curves clearly indicate that the lesser stability of wood as compared to an air rod gap arc found in the line length series of tests and plotted in Fig. 11 is not accounted for by faster dielectric recovery

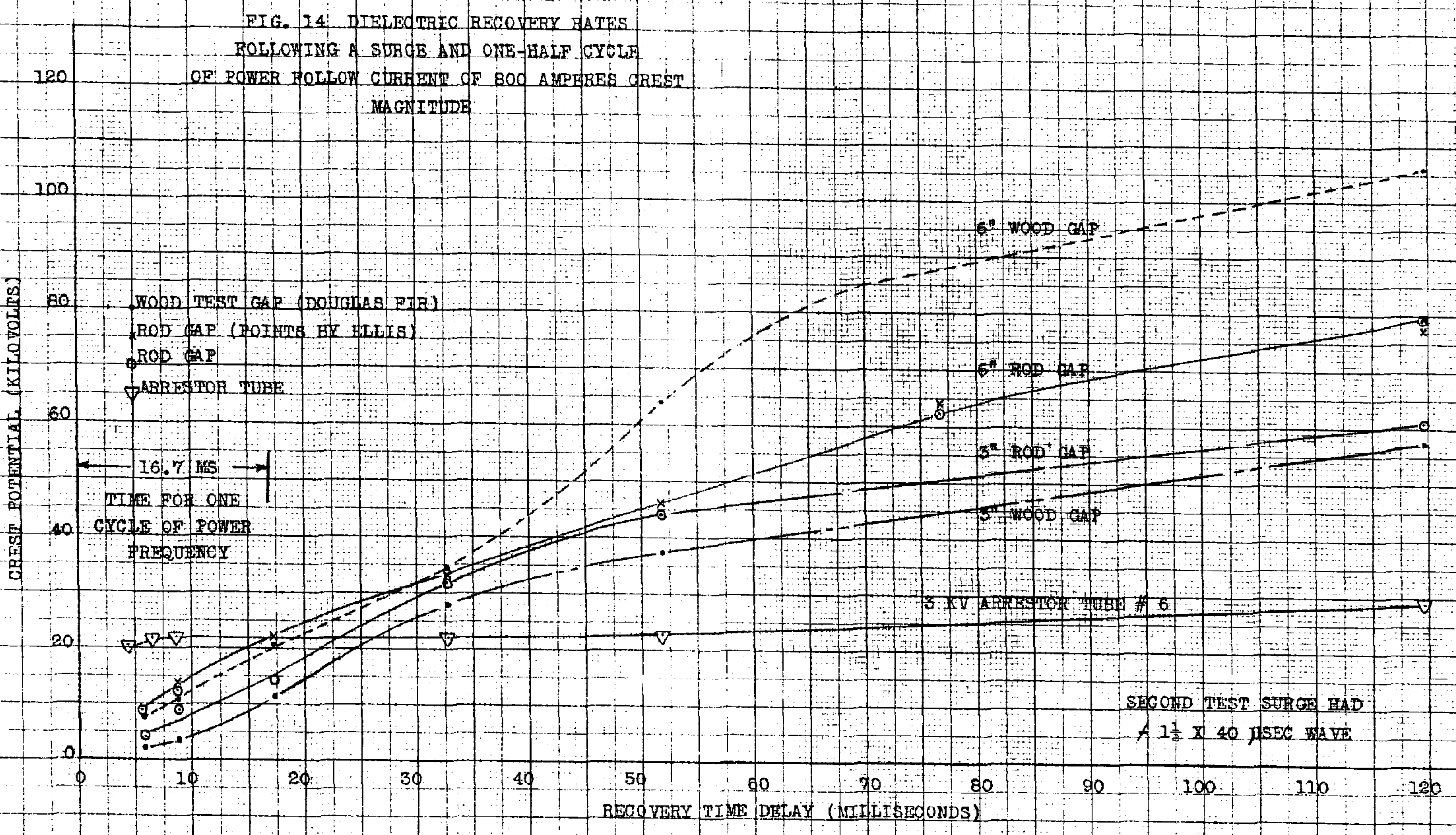


FIG. 14 DIELECTRIC RECOVERY RATES FOLLOWING A SURGE AND ONE-HALF CYCLE OF POWER FOLLOW CURRENT OF 800 AMPERES CREST MAGNITUDE

since actually the rod gap is found to recover faster. Consequently the explanation of lesser stability of wood must be accounted for by the second of the factors suggested earlier, namely that of difference of long-time arc-burning potential.

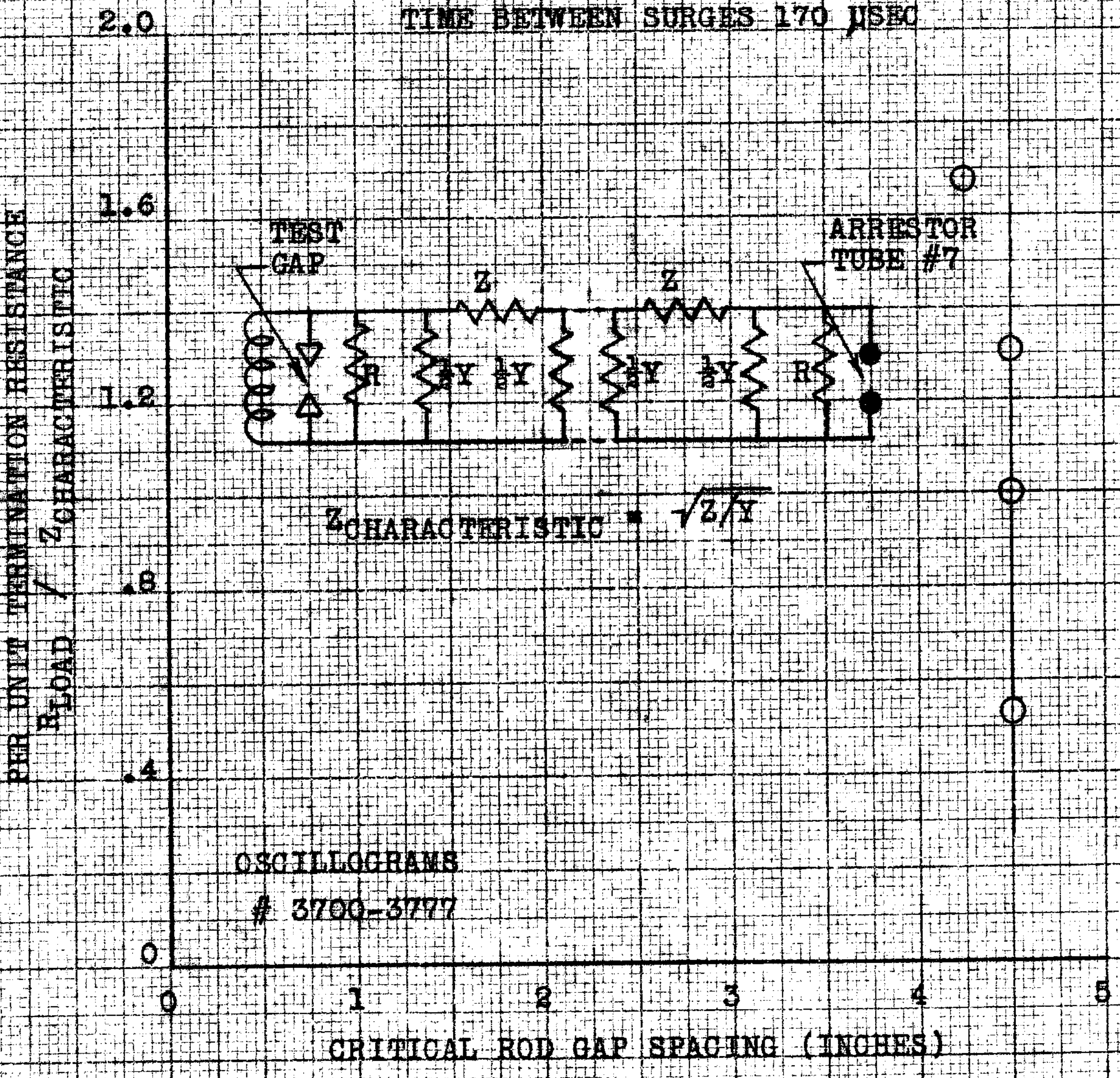
While the dielectric recovery rate tests were not directly applicable to explain the phenomenon encountered in the line length tests, the data are none the less valuable to power distribution engineers in connection with general studies of line design.

LINE TERMINATION RESISTANCE TESTS

The next tests were conducted to evaluate the influence of line termination impedance upon the arc stability. In the earlier tests, as stated in the introduction, the line section was terminated at either end by a resistance approximating the characteristic impedance of the line, so that the test section then was equivalent to a segment of an infinite system. Since in practice lines are often terminated at power transformers, it was desirable to investigate the influence of various termination resistances. A range of resistances from 53% to 168% of the characteristic impedance of the line was used.

Fig. 15 shows the results of these tests and indicates that line termination has negligible influence on stability. This is explained by the fact that at either end of the section the conducting arc represents an impedance of less than 1 ohm in the steady state condition and since the

FIG. 15 PER UNIT LINE TERMINATION RESISTANCE
VS
CRITICAL TEST GAP SPACING


TIME BETWEEN SURGES 170 μSEC

$Z_{CHARACTERISTIC} = \sqrt{Z/Y}$

OSCILLOGRAMS
3700-3777

stability is a function of the arc-burning characteristic and not of the time rate of dielectric recovery this result would be expected. The impedance of the arcs during ignition and during the first few microseconds of conduction is difficult to define but it is undoubtedly large since this impedance changes from a value approaching infinity to a value of less than 1 ohm during the ignition time.

LIGHTNING SURGE VARIATION TESTS

In order to investigate the influence of variation in lightning surges the crest magnitude and wave shape of the second surge was varied on a system using a 7 "π" section line with a rod gap as test gap connected to the sixty-cycle power source. The wave shape of discharge current was characterized by a very high short pulse near the front of the wave, which was largely dependent upon the test gap length, followed by a second and lower peak and then by an exponential decay. Table 1 below shows the time to decay to one-half of the lower peak as well as the magnitude of this peak for the waves used and compares their influence on the system in terms of rod gap critical spacing.

Table 1

Surge-Charge Constant at .02 Coulomb

Wave Shape	Time to decay to half crest	Crest Current	Approximate Critical Rod Gap Length
A	10 microsec	1660 amperes	4½ inches
B	17 "	862 "	5½ "
C	27 "	431 "	4¼ "
D	61 "	220 "	3½ "

The range of time to half crest measured on direct strokes of real lightning is approximately 15 to 90 microseconds so the wave shapes described in Table 1 cover most of the usual range. AIEE tests for distribution lightning arrestors include voltage tests with wave shape of $1\frac{1}{2}$ x 40 microsecond and current tests with 5 x 10 and 10 x 20 microsecond waves.

The critical test gap length does not follow any progressive trend with change of wave shape but has a maximum deviation from the mean of 26% over the range tested. This indicates that while the differences in lightning account for a part of the variation of stability found in nature, they are not the dominant factor as variations of line length, and arc electrode and dielectric materials are of much greater importance.

MATHEMATICAL DESCRIPTION OF STABILITY THEORY

The characteristics of arc discharges in air have been studied by many experimenters and Loeb (12) has collected and summarized much of the best data and verified theories of arc conduction.

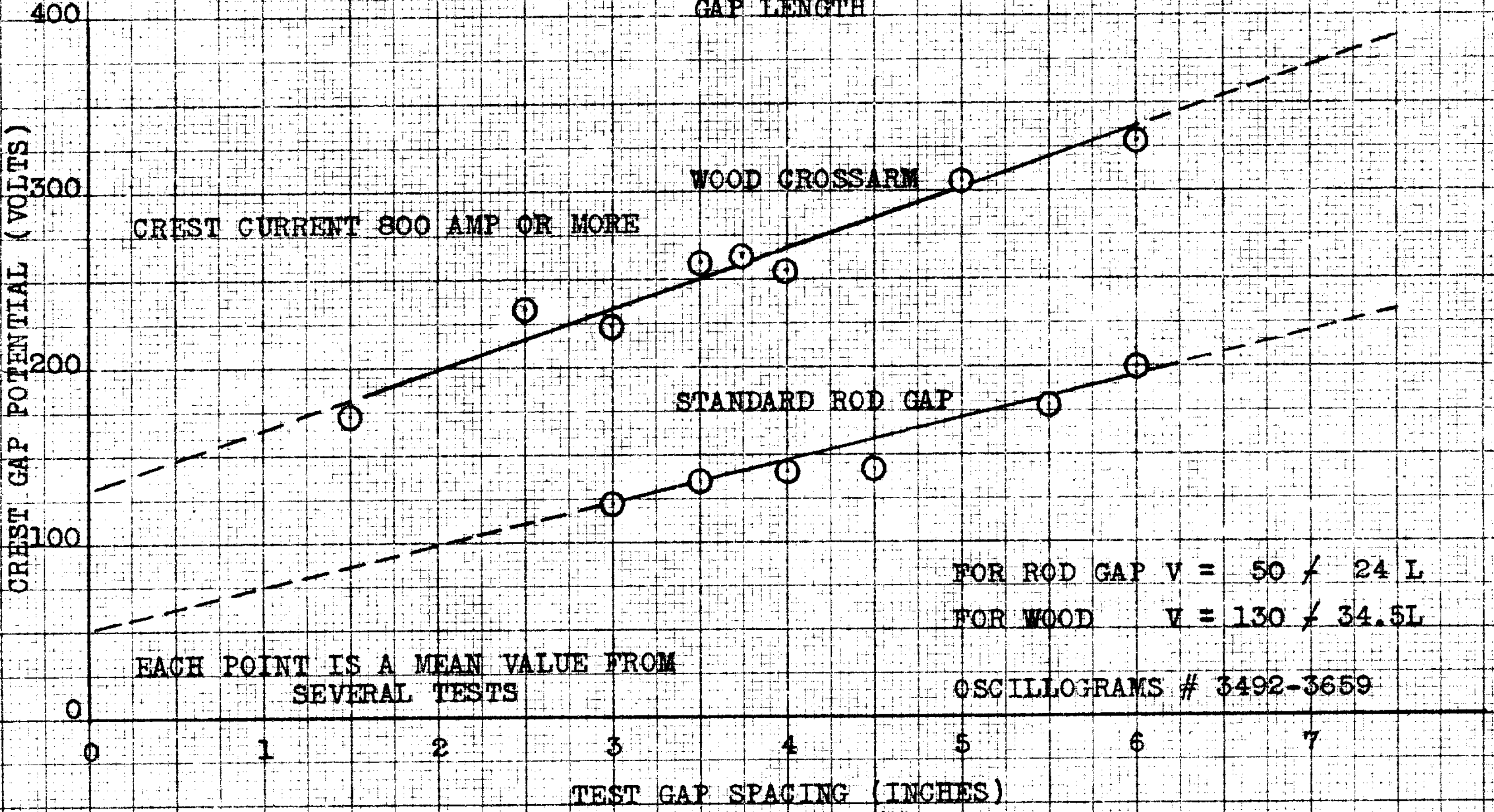
An acceptable relationship between d-c arc potential and current for arcs of various lengths is given by Loeb as

$$(1)\quad v = \alpha + \beta L + \frac{\gamma + \delta L}{i}$$

where L is the arc length, v and i are arc potential and current and the four constants α, β, γ and δ are the Ayrton constants which depend upon electrode material and shape, and upon the gaseous medium in which the arc occurs. For arc conditions with current in excess of 100 amperes it is usually possible to neglect the last term of equation (1) completely and describe the arc potential in terms of electrode conditions and length. Fig. 16 shows the results of data collected to determine α and β for the rod gap and wood flashover. In all tests made to obtain these curves the crest current exceeded 800 amperes so the γ and δ terms were neglected.

The arc robbing mechanism can be described by consideration of the case in which the arrestor is mounted at the end of the line remote from the sixty-cycle power source. With this arrangement the arrestor conducts power-follow current 170 microseconds prior to the second or lightning surge and the level of sixty-cycle potential at the test gap is fixed by the tube current and arc voltage, the system

FIG. 16 GAP POTENTIAL
VS
GAP LENGTH



CREST CURRENT 800 AMP OR MORE

EACH POINT IS A MEAN VALUE FROM
SEVERAL TESTS

FOR ROD GAP $V = 50 + 24 L$

FOR WOOD $V = 130 + 34.5L$

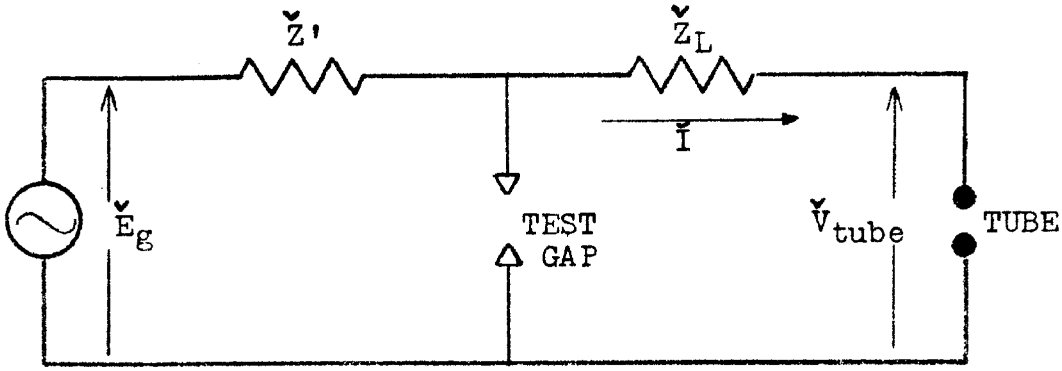
OSCILLOGRAMS # 3492-3659

impedances and the source potential. The diagram of Fig. 17 shows the circuit layout, complete with impedance values for the components effective at power frequency.

Tripping of the first surge generator was arranged to be synchronized with the sixty-cycle source such that maximum severity of current through the arrestor would be obtained and in most of the work this was at 60 electrical degrees after source potential zero.

For low magnitudes of current the arrestor acted as an arc with negative resistance characteristic; however as the current increased to the order of 500 amperes and above the oscillograms indicate that potential began to rise with increased current showing that above that level the arrestor had the characteristic of a positive but nonlinear resistor. In view of this fact it was possible to evaluate the potential at various points in the system in terms of usual phasor notation. The following equations are thus valid only in time intervals for which currents and voltages are large and would not apply, for example, at or near voltage zero. Since power-follow current through an arrestor does not result for surge application near voltage zero however, use of these equations is appropriate as an approximation to estimate the potential levels throughout the circuit.

The instantaneous potential at the test gap is thus given by the following equations using the rms alternating current circuit notation of Fig. 17.



SOURCE RATING 3.0 KV RMS AT 300 KVA

PER UNIT SYSTEM Z RATED = $\frac{1000(KV)^2}{KVA}$ = 30 OHMS

VOLTAGE REFERENCE $\check{E}_g = 1\angle 0^\circ$ PU

$\check{Z}'$ INCLUDES TRANSFORMER IMPEDANCE, SURGE FILTER IMPEDANCE AND IMPEDANCE OF INDUCTION REGULATOR AND SUPPLY LINES.

$= .0612 + j\ .153$ PU

$\check{Z}_L$ REPRESENTS LINE IMPEDANCE

$= N(.00436 + j\ .00241)$ PU WHERE N IS NUMBER OF LINE SECTIONS.

FIG. 17 EQUIVALENT POWER FREQUENCY CIRCUIT DIAGRAM

(2) $$\frac{\check{E}_g - \check{V}_{tube}}{\check{Z}' + \check{Z}_L} = \check{I}$$

(3) $$\check{E}_g - \check{I}\,\check{Z}' = \check{V}_{test\ gap} = V'_{test\ gap}\,\underline{/\theta}$$

(4) $$v_{instantaneous} = V'_{test\ gap}\sqrt{2}\,\sin\left\{w\,(T + \Delta t) + \theta\right\}$$

where wT gives the relative firing angle of the first surge generator with respect to the phase angle of the power source and Δ t gives the delay time between # 1 and # 2 surge generator discharges.

The foregoing equations thus allow calculation of the potential which exists at the test gap at the instant the stability of the two arcs is determined, for a given system and a known arrestor arc potential and current. Both tube potential and current values are required since $\check{V}$ and $\check{I}$ are not, in general, in phase through the tube.

Slepian (13) in his discussion of the extinction of long a-c arcs bases the extinction or reignition criterion upon energy balance in which heat losses in the arc due to conduction, convection and radiation are compared to electrical energy input. The arc extinguishes if heat losses exceed input and is stable if electrical input exceeds total heat losses. In equation form stability is insured if $P_e \geqslant \frac{dW}{dt}$ where P_e is electrical power input and $\frac{dW}{dt}$ is rate of loss of thermal energy.

Duesterhoeft (14) states that in the conductive state an arc is maintained by thermal ionization even though the average molecular energy is much less than the ionization potentials of the gases present. This is possible since collisions are so frequent that those molecules which do have sufficient energy produce ionization. In the course of his work Duesterhoeft has prepared a curve giving an estimate of energy content of air per cubic centimeter above that contained at 300° K as a function of temperature.

In order to apply this information to the present calculations it is necessary to estimate the volume and temperature of the arc region at the instant following the surge discharge and to estimate the initial rate of change of temperature. This is done in Appendix B.

From equation (1) the electrical power input can be evaluated as a function of current, i, and length of gap, L,

$$(7) \quad P = vi = i(\alpha + \beta L) + \gamma + \delta L$$

and equating this to the power required to sustain the arc due to thermal losses as estimated by Duesterhoeft

$$(8) \quad P_{critical} = k \text{ volume} = kAL$$

where A = effective arc area and k is time rate of change of volume energy density. Equating the powers from equations (7) and (8) and solving for the arc length, L,

$$(9) \quad L = \frac{\gamma + i\alpha}{kA - \delta - i\beta}$$

and for long arcs such as used in this research γ is very small so solving for L in terms of v

$$(10) \quad L \approx \frac{v\left(1 - \frac{\delta}{kA}\right) - \alpha}{\beta}$$

which shows how the critical length increases with current available, and how length depends upon arc potential.

In the physical system used here, as noted before, the test gap potential is largely fixed by the sixty-cycle current flow through the tube after the transients of the surge are attenuated so that the gradient in the test gap is determined by this potential and the gap length. The arc conduction is maintained chiefly as a result of ionization by collision and the energy of the collisions depends partially upon the electrical gradient. Therefore for a fixed gap potential there exists a maximum gap length for which the gradient is sufficiently high to sustain the required current following the surge discharge to maintain the arc.

When the arc does continue, the current rises rapidly with time causing the potential to fall due to impedance drop in the system and at the same time reduces the potential at the arrestor to a value too low to sustain its conduction. The entire current is thus transferred to the test gap is a few hundred microseconds as is verified by the oscillogram records. The longest transfer time observed was about 1000 microseconds but most were much shorter, being in the order of 100 microseconds or less.

Appendix B shows calculation of critical gap length by use of the preceding equations for lines of 5 and 10 "π" sections and gives data on typical conduction characteristics of the tubes used in these experiments.

While the conditions required for arc stability in this situation are somewhat different from those encountered in most system recovery analyses, the basic criteria are similar. In the studies of Ellis (11) the time rate of dielectric recovery was measured by variation of applied potential as a function of time after current zero. In the present research, however, the potential is largely fixed by the system and stability can be determined in terms of current flow through the arc space as carried by the ionized gases, and the gradient required to maintain this current.

Several factors influence the time variation of arc current in the test gap following the surge, among which are the rapid air motion caused by pressure waves produced during the surge generator discharge, the shape, material and spacing of the test gap and the temperature and ion density in the gap produced by the initial discharge.

The case for which the circuit is inverted, with the power source connected at the tube, is somewhat different and the previous equations are not directly applicable. Since the tube current is, in that case, not drawn through the line the potentials at the tube and test gap are the same for times in which the second surge is not supplying energy to the system and when the test gap is not carrying current.

The discharge of the first surge initiates power-follow current through the tube and the level of line potential is then fixed by tube conduction characteristics. The discharge of the second surge, 170 microseconds later in this case, changes the potential at the gap, and any small power-follow current which is started through the test gap is in a direction such as to lower the potential at that point. As a consequence the longer the line, the lower the potential at the test gap for a particular arrestor, so the shorter the critical test gap length becomes.

For this situation the general trend can be predicted but calculations of even very approximate values of critical gap length appear to be impractical due to the lack of knowledge of temperatures and rate of change of ion density in the gap following the second surge discharge.

This research has been limited to an investigation of the influence of system conditions on the arc stability and to a preliminary investigation of actual arc conditions. Further research investigating the properties of arcs would be valuable in explaining this and many other arcing phenomena in the power transmission and distribution field.

CONCLUSIONS

Evidence has been given that the stability of two arcs existing simultaneously on a distribution line at positions separated by various distances is essentially independent of line termination impedance, of transit time and line capacitance and is only slightly influenced by the time which elapses between the initiation of the two arcs. The time between initiation of the two arcs must be sufficient to allow the first to stabilize prior to the striking of the second in order that time delay have small effect on stability.

The influence of line length and characteristic impedance on the stability has been shown to be important due to their influence on series impedance of the system. The line series impedance, source impedance, source potential and arrestor arc drop, and current together with the nature of the second surge, determine the potential at the test gap and consequently are of prime importance in the determination of stability.

Data for critical potential as a function of time were found to describe the time rates of dielectric recovery of wood flashover and to extend the knowledge of dielectric recovery rates of rod gaps for various conditions of predischarge. Although these data do not serve to directly explain the phenomena here encountered, they are none the less valuable in the engineering field.

The basic theory of recovery of long arcs as first outlined by Slepian was applied to the system and general agreement with the mechanism was found. The critical stability criterion was found to be maintenance of a minimum current following the surge discharge to provide sufficient electrical energy to the arc space to maintain conduction.

A detailed study of the physics of the arc space with regard to ion density and rate of ion loss has not been included since it is outside the scope of this research. The work done in this field by Duesterhoeft and others has been applied, however, to substantiate the development of the explanations of the phenomena here described.

APPENDIX A

LINE ANALOG TESTS

A series of tests were made on the analog line to determine how accurately it represented a real line for transmission of surges of the type used in these experiments. A recurrent surge oscillograph which had been developed in the High Potential Laboratory was used. The instrument was constructed so that pulses of various shapes could be generated repeatedly every 1/60th of a second and with a recurring sweep at the same rate a standing-wave pattern of transients could be obtained.

Fig. 18 shows in the top row a series of three double exposure oscillograms for which the wave shapes at the sending and receiving ends of the line are shown. The sweep scales shown are in microseconds. For these oscillograms the line was terminated by a resistor equal to the calculated characteristic impedance of the line. The oscillograms numbered 1 and 2 were taken with identical line conditions but with two different sweeps to show the details of the wave front and to show the over-all shape of the waves. The transit time of the $1\frac{1}{2}$ mile line was calculated to be approximately 8 microseconds and the oscillograms verify this value. The applied wave shape was 2 x 50 microsecond and had a crest magnitude of approximately 150 volts. The slight irregularity in the wave of oscillogram # 2 at 16 microseconds shows the result of imperfection of line termination and results from a small reflected wave.

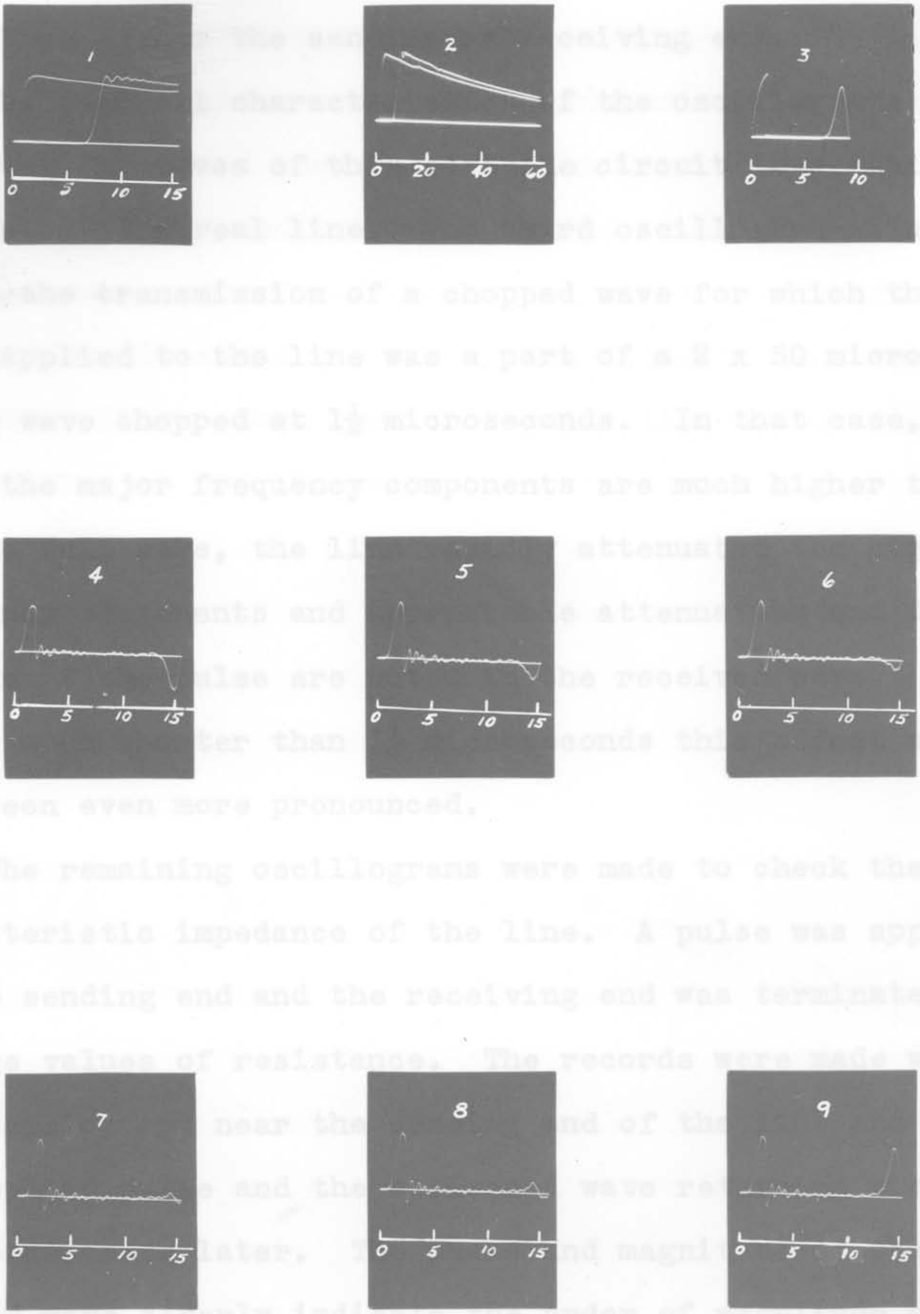


FIG. 18 RECURRENT SURGE OSCILLOGRAMS SHOWING LINE ANALOG CHARACTERISTICS

This is evident in both waves as slight reflections could occur from either the sending or receiving end.

The over-all characteristics of the oscillograms indicate that for waves of this sort the circuit is a satisfactory analog of a real line. The third oscillogram illustrates the transmission of a chopped wave for which the pulse applied to the line was a part of a 2 x 50 microsecond wave chopped at 1½ microseconds. In that case, since the major frequency components are much higher than for the full wave, the line rapidly attenuated the high frequency components and appreciable attenuation and distortion of the pulse are noted in the received wave. For pulses much shorter than 1½ microseconds this effect would have been even more pronounced.

The remaining oscillograms were made to check the characteristic impedance of the line. A pulse was applied at the sending end and the receiving end was terminated in various values of resistance. The records were made with the oscillograph near the sending end of the line and show the applied pulse and the reflected wave returning about 16 microseconds later. The phase and magnitude of the reflected wave clearly indicate the order of magnitude of the characteristic impedance relative to the load impedance connected.

Oscillogram # 4 shows the reflected wave with receiving end of the line shorted and oscillograms # 5, 6, 7 and 8 show results of tests with the ratio $R_{load}/\sqrt{L/C}$ equal to

.4, .6, 1 and 1.6 respectively. Oscillogram # 9 shows the reflection which occurred with an open-ended line.

The oscillograms verify the calculations of characteristic impedance and show how well the line analog represents a real line. The small irregularities in the waves are chiefly the result of reflection set up at the junction of the "π" sections and are due to the "lumpy" character of the analog line. Some small irregularities may be due to noise pickup on the line also.

APPENDIX B

CALCULATION OF APPROXIMATE CRITICAL TEST GAP LENGTH

The equivalent circuit of the system to power frequency current is shown in Fig. 17. The curves of Fig. 19 show crest values of tube current and voltage as a function of test number and illustrate the effect of erosion of the core and tube barrel. In Table 2 are tabulated average stabilized values of current and voltage for both the 5 section line from the curves of Fig. 19 and also for the 10 section line from similar curves for another tube.

Table 2

Conduction Characteristics of 3.0 Kv Expulsion Tubes

Source Potential 3.0 Kv rms

Series Impedance	Crest Current	Crest Arc Potential
5 section line $.083 + j\ .165$ PU*	720 amperes	600 volts
10 section line $.105 + j\ .177$ PU	700 amperes	350 volts

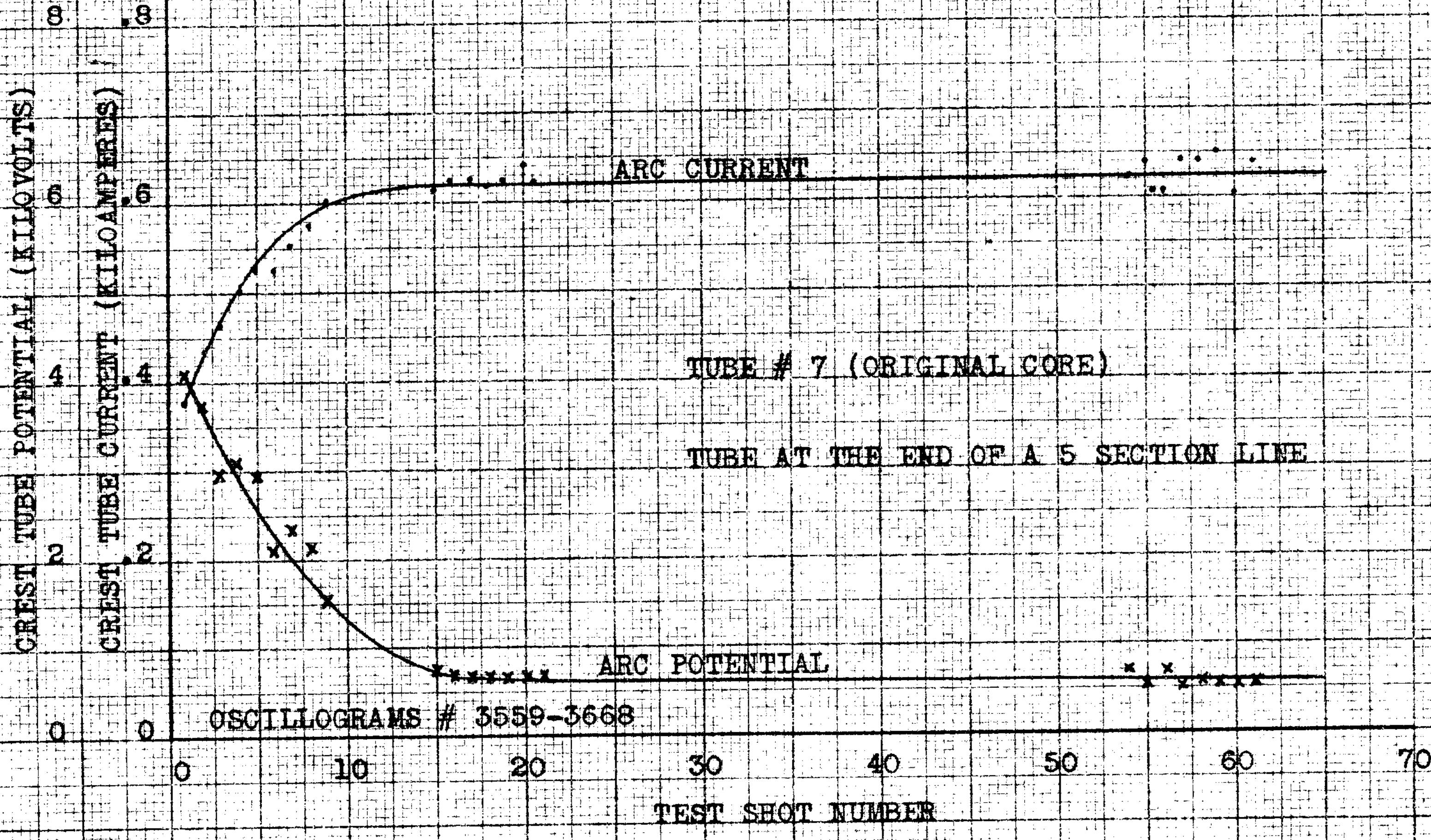
*Per unit quantities based on 3.0 Kv and 300 Kva.

The equations developed earlier can be applied to evaluate test gap potential and to calculate the approximate critical length of the test gap for the circuit configuration of Fig. 17.

From equation (2) the phase angles of $\check{V}_{tube}$ and $\check{I}$ with respect to the applied line potential can be determined and from equation (3) the test gap potential is obtained.

For the 5 section line $V_{tube} = .14$ and $I = 5.1$ per unit.

FIG. 19 TUBE CONDUCTION CHARACTERISTICS AND AGING PROPERTIES



From these values $\check{V}'_{\text{test gap}} = .25\ \underline{/-45^\circ}$ can be calculated and with $wT = 60^\circ$ and $\Delta t = 170$ microseconds, equation (4) can be used to evaluate $v_{\text{instantaneous}} = 340$ volts.

The arcs used in these experiments were all "long" in the electrical sense so equation (10), in which the parameter γ is neglected, is applicable.

$$L = \frac{v\left(1 - \frac{\delta}{kA}\right) - \alpha}{\beta}$$

Values of α and β can be obtained from Fig. 16 for both the rod gap and wood flashover but values of δ and kA are not available with a satisfactory degree of accuracy. The dimensionless ratio $\frac{\delta}{kA}$ is calculated by taking a known critical test gap length for one circuit condition and once established, this value can be applied to calculate other test gap lengths for comparison with measured values.

Fig. 11 shows a critical rod gap length of 4 inches and a critical wood flashover length of 3-1/8 inches for the 5 section line, which is equivalent to 1680 feet. From equation (10) rearranged

$$\left(1 - \frac{\delta}{kA}\right) = \frac{\beta L + \alpha}{v} = \frac{24 \times 4 + 50}{340} = .43$$

for the rod gap, and

$$\left(1 - \frac{\delta}{kA}\right) = \frac{34.5 \times 3.13 + 130}{340} = .70$$

for the wood flashover, which results in values of $\frac{\delta}{kA}$ of .57 and .3 respectively.

The 10 section line current and tube arc voltage are 4.95 and .083 PU respectively, so from these values and a new equivalent circuit similar to Fig. 17, but with larger impedances appropriate to the increased line length, the test gap voltage is calculated as

$$\check{V}'_{\text{test gap}} = .284 \,\underline{/-43^0} \quad \text{from which}$$

$$v_{\text{instantaneous}} = 425 \text{ volts.}$$

Using the values of $\frac{\delta}{kA}$ determined previously, the new critical lengths are calculated from equation (10) as

$$L = \frac{v(1-\frac{\delta}{kA}) - \alpha}{\beta} = \frac{425\ (.43) - 50}{24} = 5.5 \text{ inches}$$

for the rod gap and $L = \frac{425\ (.70) - 130}{34.5} = 4.8$ inches for the wood flashover. These values compare satisfactorily with the measured values of 5-5/8 inches and 4-1/4 inches, respectively.

An order of magnitude estimate of the value of $\frac{\delta}{kA}$ can be obtained from information given by Duesterhoeft (14) and from photographic and oscillographic records made during the present research. An arc in air at normal pressure and at a temperature of 5000° K was found by Duesterhoeft to have an initial cooling rate following current zero of 10^5 degrees per second and can be shown to be described by $k = 1.87 \times 10^8$ ergs per second per cubic centimeter. Photographic records show that the initial flashover has a region of highly luminous gas of fairly uniform cross section of about 0.9 inch diameter following the surge used through these experiments. The value of kA in British units is thus 195 watts per inch.

The oscillographic records indicate that the minimum current for arcs which were sustained had a value, for tests at the 4 inch critical rod gap spacing, between 1 and 10 amperes. The best average value estimated from these records would be about 3 amperes.

The critical voltage for this rod gap was known to be 340 volts, hence the value of σ can be determined from $v = \alpha + \beta L + \frac{\sigma L}{i}$ from which $\sigma = 145$ watts per inch. From these values $\frac{\sigma}{kA} = .74$ which is in the same order of magnitude as the value .57 calculated by the earlier method, which was based on the power balance criterion proposed by Slepian.

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