Reducing Effect in Footing Resistance Against Heavy Impulse Current

(Observation of Streamer in the Soil).

By

Tatsuro OKUBO* and Muneaki HAYASHI*

(Received August 31, 1963)

The streamer in the soil, which is considered to cause the reducing effect in footing resistance against heavy impulse current can be observed directly by means of an embedded film, intermediate electrode or chopped wave. By these observations, the form, size, propagating step and velocity of streamer in the soil have become clear.

1. Introduction

In the design of long transmission line, it is important to consider both the high efficiency of power transmission and reliable insulation of the line. Especially, the problem of insulation has become more important because of the increase of the electric power, voltage and length of the line.

Generally, an impulse flash-over of the line rarely occurs from switching surge, but very often from direct stroke of lightning. Because, the outage of the line with higher voltage influences more the capacity necessary for the margin or spinning reserve of the system, we must consider the design for protecting super high voltage transmission line against lightning as one of the most important matters.

The potential rise of a line tower by lightning, depends chiefly on the product of its footing resistance and the lightning current. The footing resistance of the tower may be much reduced if the wave front of the incoming lightning stroke is steep and of high crest value.

An explanation of these phenomena, i. e. the so called "reducing effect of footing resistance", is given chiefly by the increase of effective area of electrode and also by the decrease of contact resistance between electrode and soil, and soil particles with each other, due to the streamer which shows "the breakdown

* Department of Electrical Engineering

of the soil" in the vicinity of footing electrode. The calculation of the potential rise of the tower by a lightning stroke may be taken into consideration in regard to the reduction of footing resistance.

This paper concerns "the streamer in the soil", the presence of which was hypothetically recognized hitherto as the cause of these phenomena. The authors have tried to contribute direct observation of the streamer in the soil by means of X-ray film in the vicinity of earth electrode embedded in the soil, intermediate electrode or chopped wave and obtained many favourable results regarding its shape, size and variation with elapsed time, considering many factors such as the resistivity and breakdown voltage of the soil, the crest value and wave form of the applied impulse voltage.

As a footing electrode has its opposite infinitely apart on the field, the streamer in the soil does not bridge over both electrodes and so dissipates on the way. In this paper, the authors tried an experiment about the streamer under the conditions where the streamers do not arrive at the vessel filled with soil, and more over the equivalent radius of the footing electrode, i.e., the radius of hemispherical discharge is made much smaller than the radius of the vessel filled with soil which acts the external electrode in order to match the practical field.

2. Observation of Streamer in the Soil by Embedded Film

As the streamer in the soil appears and dissipates instantly in an opaque space, it may be difficult to observe the streamer exactly.

In the authors' experiment, the X-ray film is embedded vertically under the spherical center electrode as shown in Fig. 1, and the impulse voltage of the standard form ($1\times 40\,\mu s$) with positive polarity is applied to this center electrode for the vessel filled with soil as external electrode. The tests were carried out with regard to many parameters such as the earth resistivity (ρ), crest value and wave form of the applied impulse voltage, size of the electrode etc.. The shape and size of the streamer in the soil have been studied by the figure on the film.

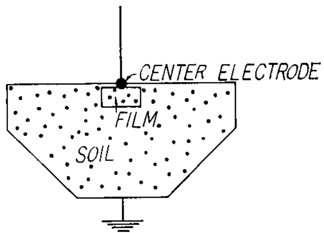


Fig. 1. Arrangement of center electrode and embedded film in the vessel filled with soil.

(1) The relation between streamer and earth resistivity

Fig. 2 shows that the figure on the film has a circular form like Mr. Petropoulos' assumption where the earth resistivity (ρ) is 2 kΩ-cm, the radius of the center electrode (r_0) is 2 cm and the crest value of the applied impulse voltage is 25~60 kV with positive polarity.

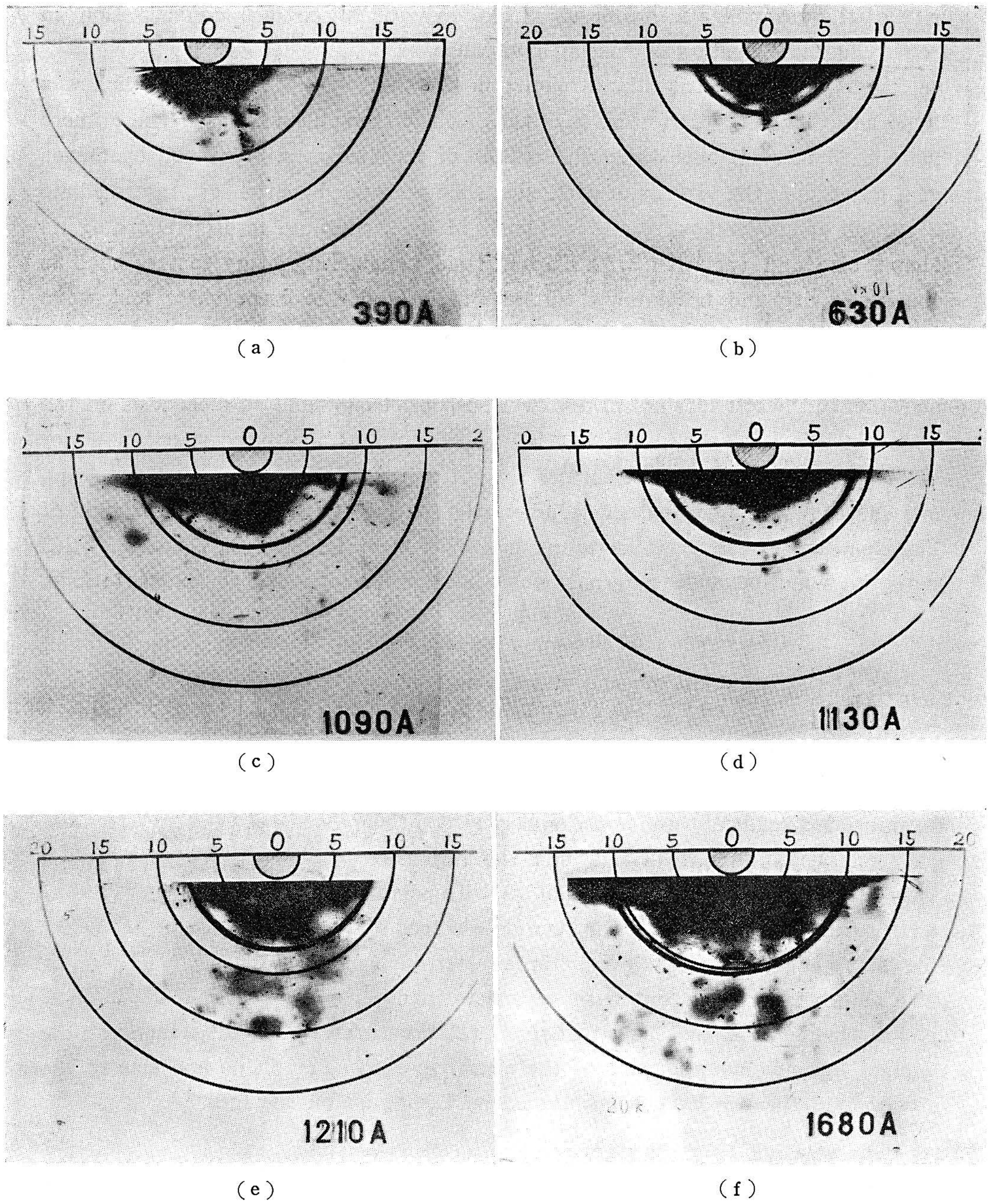


Fig. 2. Figure on the film.
ρ : 2 kΩ-cm

Measuring the impulse voltage and current by an oscillograph, let g_0 denote the inherent breakdown voltage of the soil, then

$$g_0 = \frac{I_m \cdot \rho}{2\pi r^2} \quad \text{(kV/cm)} \tag{1}$$

where I_m : crest value of impulse current (A)
ρ : earth resistivity (kΩ-cm)
r : maximum radius of streamer (cm)

The radius of streamer calculated by equation (1) as shown in Table 1 approximately equals the radius of the streamer figure obtained on the film (Fig. 2).

Table 1. Radius of Hemispherical Discharge.
ρ : 2 kΩ-cm g_0 : 5 kV/cm

E_m (kV)	I_m (A)	r (cm)
26.8	392	5.0
32.6	632	6.4
38.0	1090	9.5
39.8	1133	9.3
43.4	1210	9.2
56.5	1679	10.0

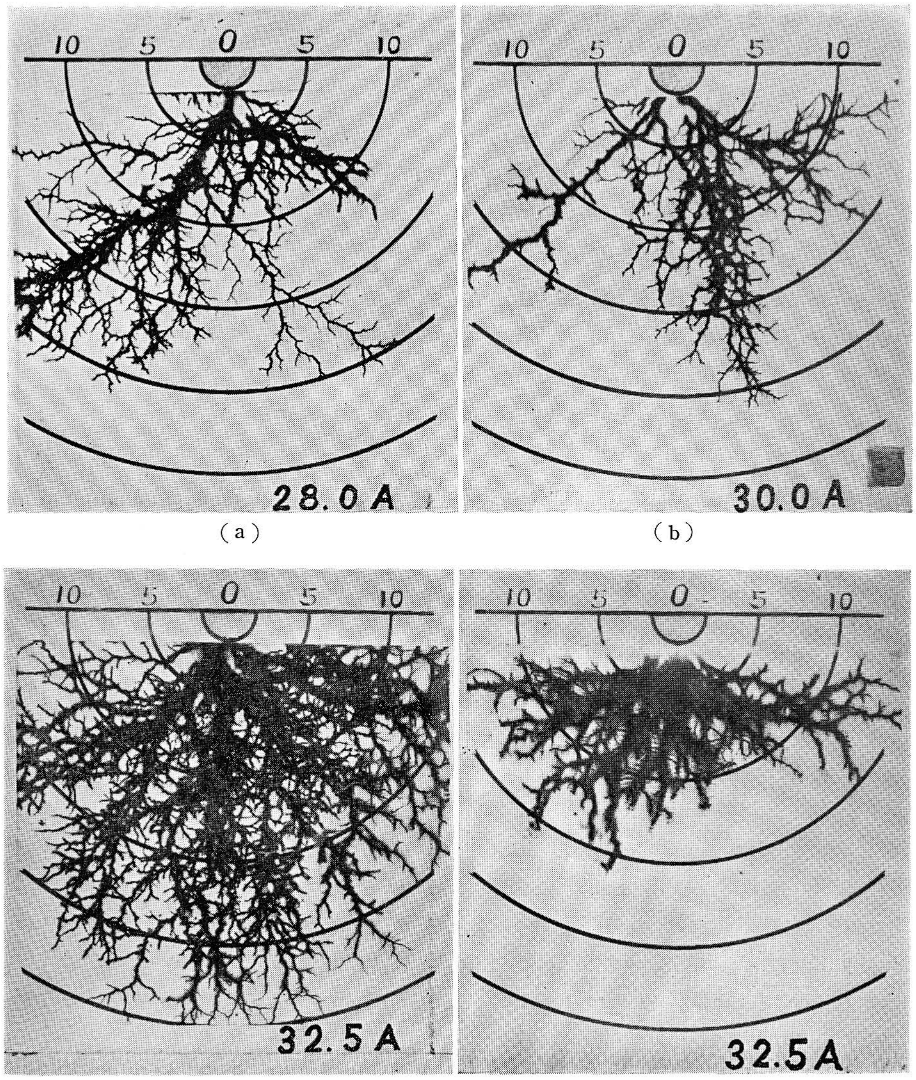
Note E_m : Crest value of impulse voltage
I_m : " " current
r : Radius of hemispherical discharge

While the figure on the film obtained by the same conditions except the earth resistivity is 30 kΩ-cm, has a tree form as shown in Fig. 3 (a), (b) and (c), and the length of the streamer is not equal to the radius calculated by equation (1). Generally where ρ is about 2.5 kΩ-cm, the figure on the film is often either circular or tree formed, while where ρ is more than 2.5 kΩ-cm, the figure always has a tree form.

As a result of these tests, it is evident that the shape and size of the streamer vary with the earth resistivity, and the size of the streamer obtained on the film does not always equal the equivalent radius of the earth electrode.

For negative polarity, the size of the figure on the film is rather smaller than for the positive one with similar form as shown in Fig. 3 (d), but the degree of reduction of earth resistance is the same in both cases.

This is because it is more difficult for the streamer with negative polarity to run on the film than positive one, i.e., only when the negative streamer is restricted by means of two sheets of film arranged in parallel vertically as shown in Fig. 4, can the streamer figure be obtained on the film.



(a) (b)

(c) (d)

Fig. 3. Figure on the film.
ρ : 30 kΩ-cm

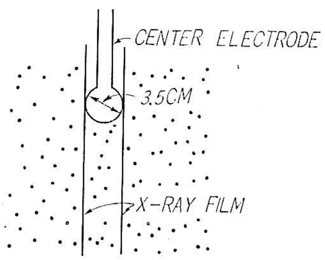
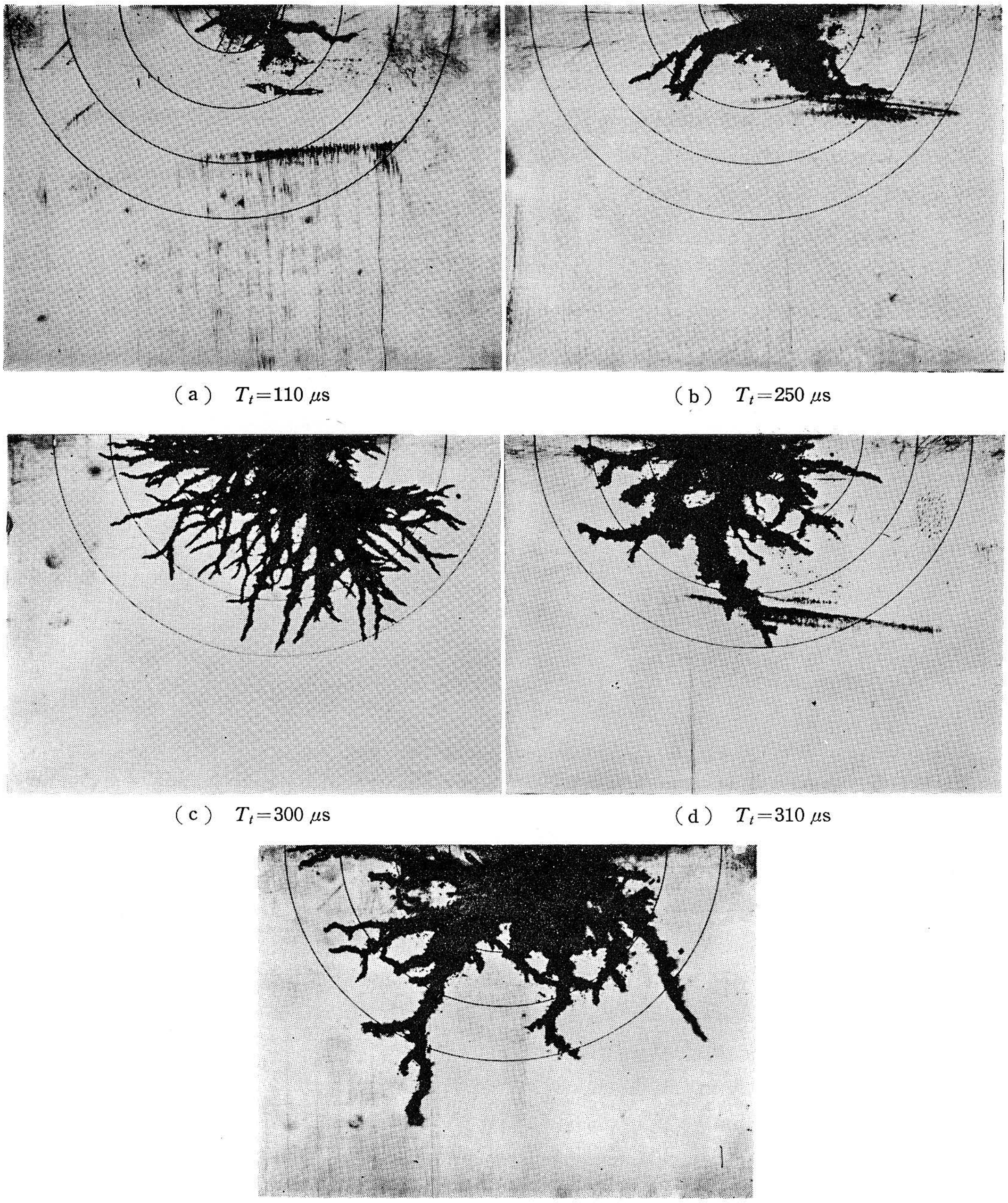


Fig. 4. Arrangement of center electrode and two sheets of parallel arranged film.



(a) T_t=110 μs (b) T_t=250 μs

(c) T_t=300 μs (d) T_t=310 μs

(e) T_t=400 μs

Fig. 5. Figure on the film with various kind of wave tail length of applied impulse voltage.

Diameter of center electrode : 3.5 cm
V : 20.8 kV ρ : 10 kΩ-cm

(2) The relation between streamer and length of impulse voltage wave tail

The above tests were given in a condition where the applied impulse voltage has a standard form (1×40 μs), but when the wave tail length (T_t) varies, the figures on the film are shown in Fig. 5. From these figures, the streamer length (l_s) is proportional to wave tail length as shown in Fig. 6.

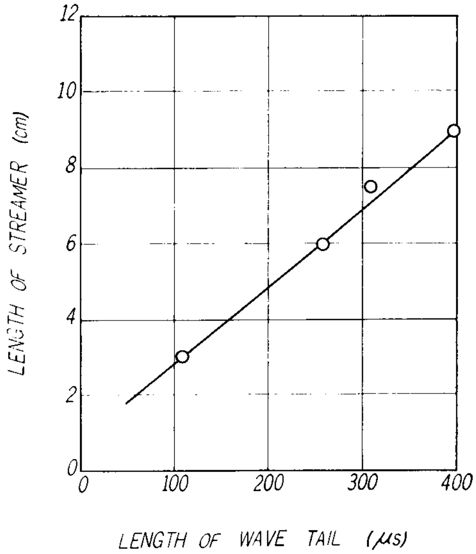


Fig. 6. Length of streamer against wave tail length of applied impulse voltage.

Diameter of center electrode : 3.5 cm
V : 20.8 kV ρ : 10 kΩ-cm

(3) Influense on the streamer by the embedded film

The figure on the film has a circular form in the test of (1), but has a tree form in the test of (2), so it is feared this may be a "Richtenberg Figure", that is, a corona dischage creeping on the surface of the film.

This question is studied as follows.

(a) The film with many holes of 0.7~1.0 cm diameter as shown in Fig. 7, is used as one of embedded films described above. Then the streamer figure on the film penetrates the holes and does not take the round about way along the edge of the holes. From these phenomena, it is considered that the streamer propagates independently of the embedded film.

(b) By the existence of the embedded film, the propagation of the streamer may be forced to deviate from the natural direction. But as the film is in the symmetric center of the applied electric field, deviation is considered to be

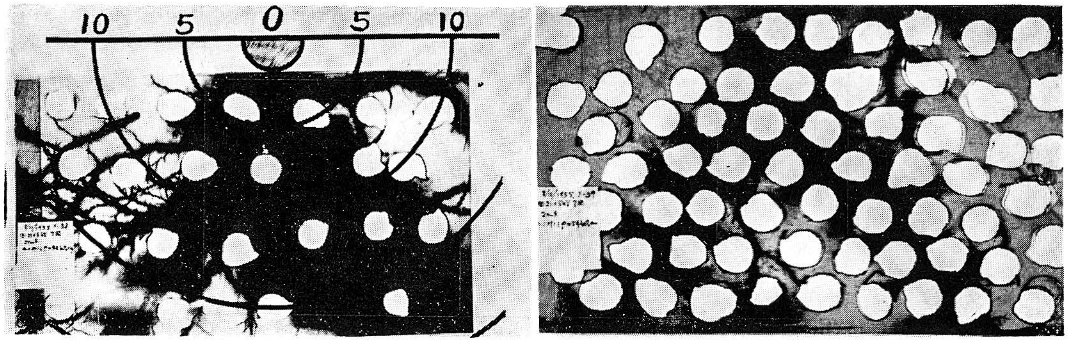


Fig. 7. Figure on the perforated film.
ρ : 30 kΩ-cm

very small, and the fact that voltage-current characteristic on the oscillogram shows independent of the existence of the embedded film, supports this assumption.

(c) The streamer figure on the film often dissipates discontinuously on the way, which suggests that the path of discharge is separated from the film with three dimensions.

(d) In some cases the edge of the film becomes black, or the streamer reflects at the film edge etc.. But they are phenomena of little worth because the amount is negligibly small.

3. The propagated Distance of Streamer in the Soil

As shown in Fig. 8 (a), seven sets of intermediate hollow hemispherical electrodes as shown in Table 2 are arranged like shell in a concentric position with the center electrode, the gap between the electrodes is filled with soil, and the impulse voltage is applied to the center electrode.

Then as shown in Fig. 8 (b), when the streamer starting from the center

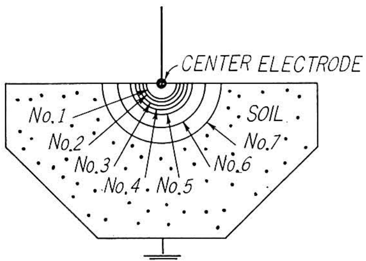


Fig. 8 (a). Arrangement of center and intermediate electrodes formed like shell.

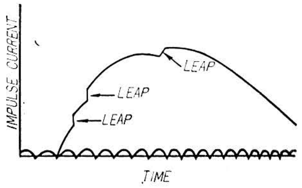


Fig. 8 (b). Leaps of current by means of intermediate electrodes.

Diameter of center electrode : 3.5 cm
" intermediate " : 20, 30, 40 "
V : 105 kV ρ : 10 kΩ-cm

Table 2. Diameter of Intermediate Electrode.

No.	Diameter (cm)	Remarks
1	20	copper, 1 mm thick
2	25	〃 〃
3	30	〃 〃
4	35	〃 〃
5	40	〃 〃
6	60	zinc, 〃
7	80	〃 〃

electrode arrives at each intermediate electrode (used only No. 1, 3 and 5 in the Fig. 8 (a)), the current leaps up.

Especially, where the earth resistivity is high, the leap of current is sharp, while where the resistivity is low, the voltage drop is remarkable.

One of these intermediate electrodes is chosen that is suitable for the impulse voltage, and on increasing the crest value of the applied voltage, we can find the minimum voltage necessary to leap in the wave form. In this condition,

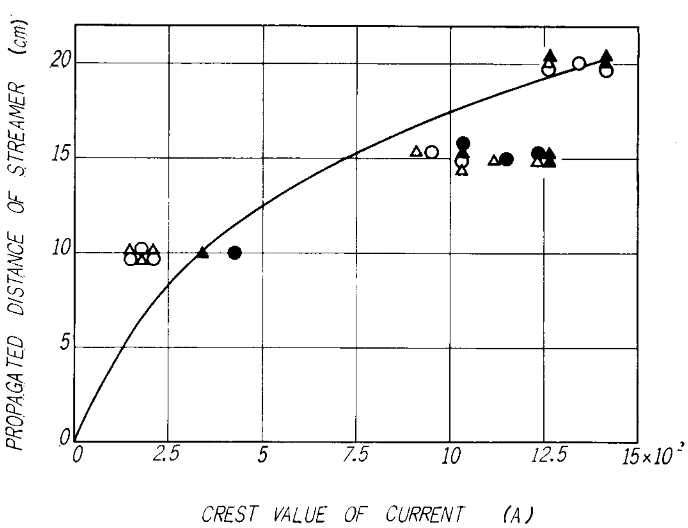


Fig. 9. Propagated distance of streamer against crest value of applied impulse current.

▲ : Positive polarity } Case when streamer has
● : Negative 〃 } arrived at intermediate electrode
△ : Positive 〃 } 〃 has not
○ : Negative 〃 } 〃 〃 〃
Diameter of center electrode : 4 cm
〃 intermediate 〃 : 20, 30, 40 〃
ρ : 1.2~1.6 kΩ-cm

the leap appears in the wave tail and not in the wave front.

Then the radius of the intermediate electrode can be considered as the propagated distance of streamer for measured voltage, which also can be made by the embedded film described above. The results obtained by both methods are consistent.

In this test, the earth resistivity (ρ) is 1.2~1.6 kΩ-cm, 2.3~2.6 kΩ-cm or 30 kΩ-cm, and the intermediate electrode is suitably chosen from Table 2, the polarity of applied impulse voltage being either positive or negative.

The testing result is shown in Figs. 9~11. The value of impulse current corresponding to the propagated distance is the mean value of the two critical currents, when the leap of current appears in one test and does not in another test.

It is evident by these results that the length of the streamer (l_s) varies not only with the crest value of the impulse current (I_m) but also the earth resistivity (ρ). When as shown in Fig. 12, $I_m \cdot \rho$ is taken as the abscissa, many of these curves for the various parameters are nearly consistent in simple form, and the propagated distance of the streamer becomes greater as the resistivity becomes higher.

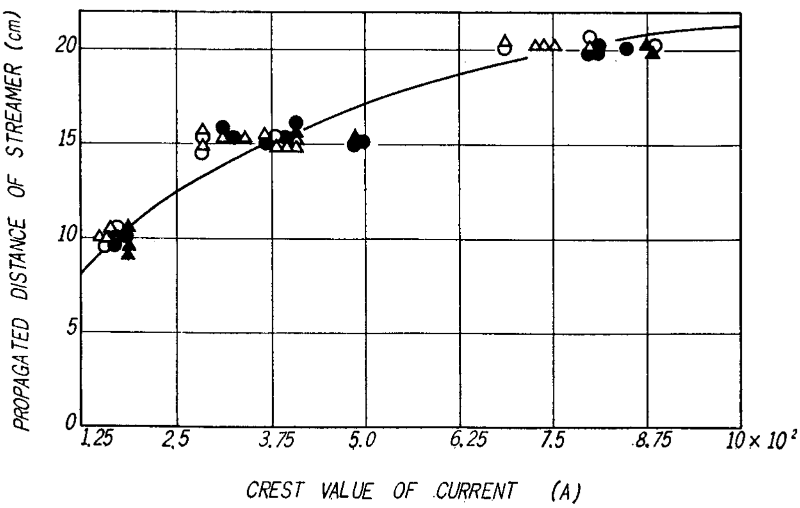


Fig. 10. Propagated distance of streamer against crest value of applied impulse current.

▲ : Positive polarity } Case when streamer has
● : Negative " } arrived at intermediate electrode
△ : Positive " } " has not
○ : Negative " } " " "

Diameter of center electrode : 4 cm
" intermediate " : 20, 30, 40 "
ρ : 2.5 kΩ-cm

As described above, where the streamer has a tree form, its length (l_s) is not equal to the equivalent radius of the center electrode (r_{eq}). To find the relation between l_s and r_{eq}, in the measurement, the result of which is indicated in Fig. 12, the equivalent radius of the center electrode is calculated by the crest value of current (I_m) from equation (1) as shown in Fig. 12, by a dotted line, by which it is roughly said that l_s is twice as long as r_{eq}.

In the same way, the relation between $I_m \cdot \rho$ and r_{eq} are indicated over a wide range in Fig. 13.

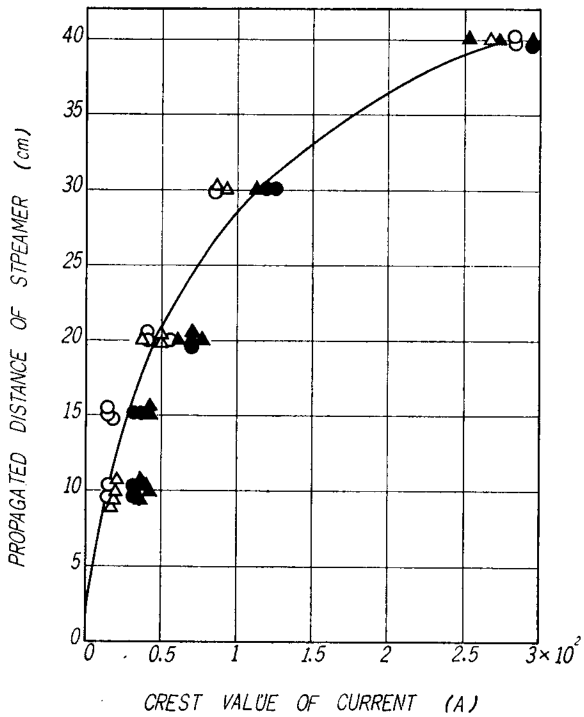


Fig. 11. Propagated distance of streamer against crest value of applied impulse current.

▲ : Positive polarity } Case when streamer has
● : Negative " } arrived at intermediate electrode
△ : Positive " } " has not
○ : Negative " } " " ".

Diameter of center electrode : 4 cm
" intermediate " : 20, 30, 40 "
ρ : 30 kΩ-cm

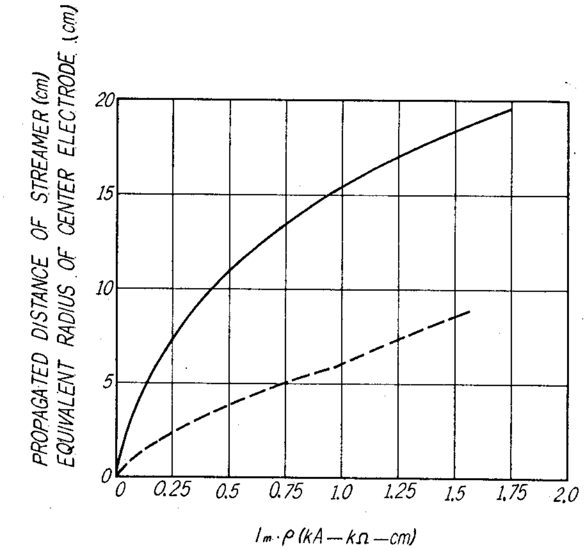


Fig. 12. Propagated distance of streamer in various kind of soil.

— Propagated distance of streamer
··· Equivalent radius of center electrode
Diamter of center electrode : 4 cm
ρ : 1.2~30 kΩ-cm

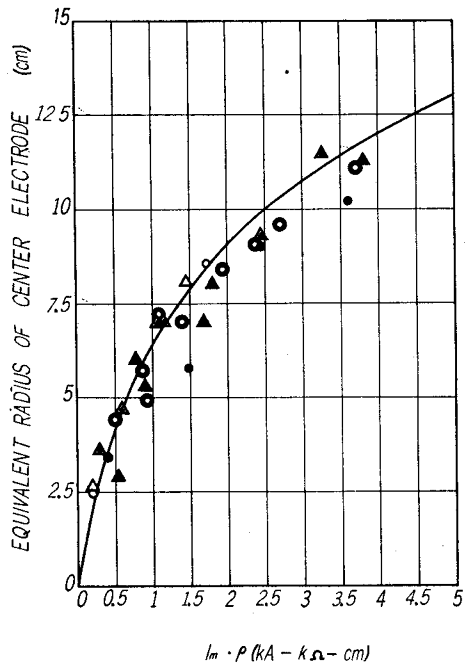


Fig. 13. Equivalent radius of center electrode against $I_m \cdot \rho$.

△ : Positive polarity } ρ : 1.2~1.6 kΩ-cm
○ : Negative ″
◬ : Positive ″ } ″ : 2.3~2.6 ″
◎ : Negative ″
▲ : Positive ″ } ″ : 55 ″
● : Negative ″
Diameter of center electrode : 4 cm

4. The Mean Propagating Velocity of Streamer in the Soil

The propagating velocity of the streamer in the soil greatly affects the variation of the earth resistance with elapsed time. Mr. Petropoulos estimated that its velocity was about 10 cm/μs. In order to measure this velocity directly, the authors adopted a method by means of an intermediate electrode embedded in the soil formed like shell, as described in the preceding section, and recognized the time from the instant the impulse voltage is applied, to the instant the leap in the current wave is observed, as the time that the streamer needs to arrive at the intermediate electrode. As the propagating velocity of streamer (v_s) varies with the elapsed time, the result obtained by this method is a mean value. By this test, the mean propagating velocity where the amount of water contained in the soil is 4.4~16.0% and ρ is 0.88~6.0 kΩ-cm, is shown in Fig. 14.

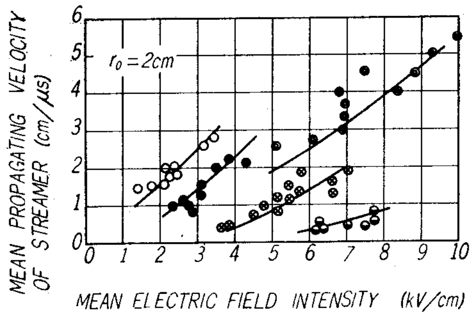


Fig. 14. Mean propagating velocity of streamer in the soil.

	Diameter of intermediate electrode (cm)	Amount of water contained in the soil (%)	Earth resistivity (kΩ-cm)
◎	20	4.4	6.000
⊗	30	"	"
◒	40	"	"
●	"	10.0	1.225
○	"	16.0	0.880

The mean propagating velocity of the streamer varies with the diameter of the intermediate electrode, and so generally decreases with the enlargement of the diameter of the intermediate electrode.

Figs. 15~22, show the propagating time and mean propagating velocity of streamer against the crest value of impulse current for the various kind of soil and various sizes of intermediate electrode and if $I_m \cdot \rho$ is taken as the abscissa as described above, these results can be shown in one graph. Then, Figs. 23~25 show one single curve approximately arranged for the various diameters of intermediate electrode for the above measured value.

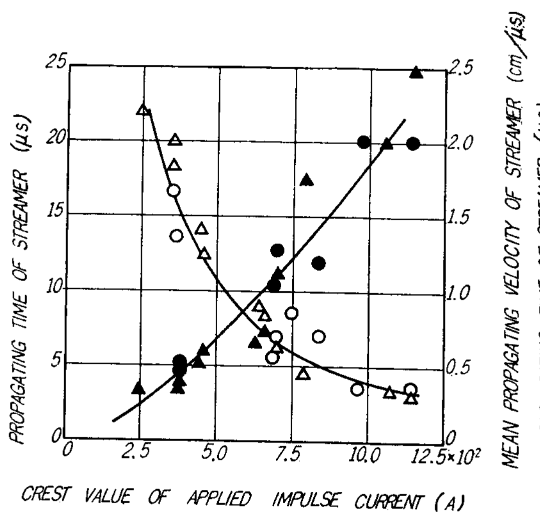


Fig. 15. Mean propagating velocity of streamer.

△ : Propagating time for positive polarity
○ : " " negative "
▲ : " velocity for positive "
● : " " negative "
Diameter of center electrode : 4 cm
" intermediate " : 20 "
ρ : 1.6 kΩ-cm

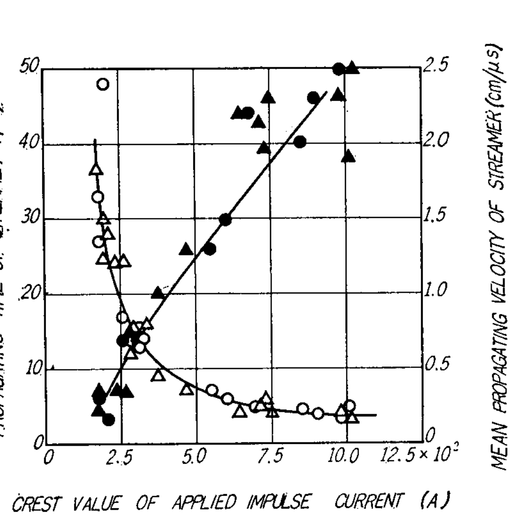


Fig. 16. Mean propagating velocity of streamer.

△ : Propagating time for positive polarity
○ : " " negative "
▲ : " velocity for positive "
● : " " negative "
Diameter of center electrode : 4 cm
" intermediate " : 20 "
ρ : 2.5 kΩ-cm

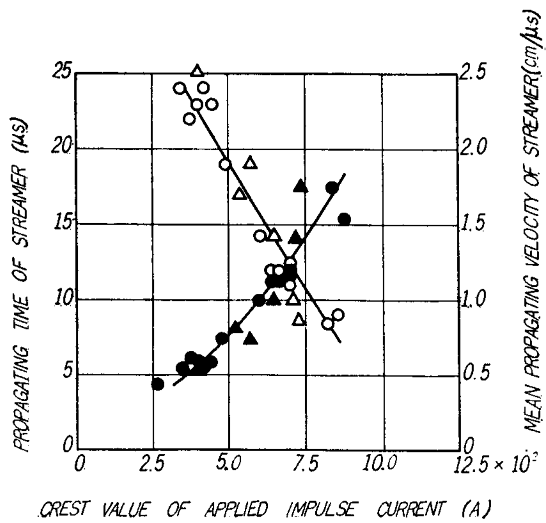


Fig. 17. Mean propagating velocity of streamer.

△ : Propagating time for positive polarity
○ : " " negative "
▲ : " velocity for positive "
● : " " negative "
Diameter of center electrode : 4 cm
" intermediate " : 30 "
ρ : 2.4 kΩ-cm

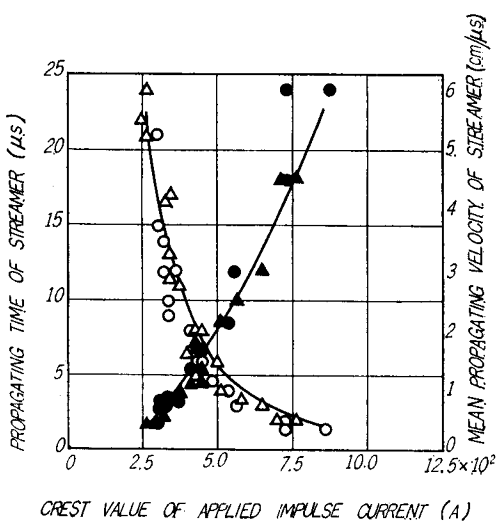


Fig. 18. Mean propagating velocity of streamer.

△ : Propagating time for positive polarity
○ : " " negative "
▲ : " velocity for positive "
● : " " negative "
Diameter of center electrode : 4 cm
" intermediate " : 20 "
ρ : 30 kΩ-cm

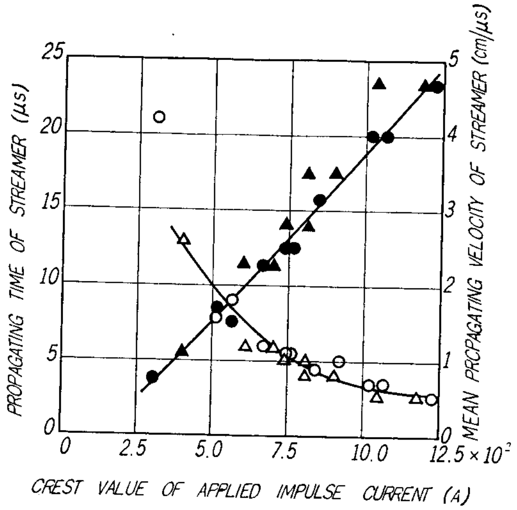


Fig. 19. Mean propagating velocity of streamer.

△ : Propagating time for positive polarity
○ : " " negative "
▲ : " velocity for positive "
● : " " negative "
Diameter of center electrode : 4 cm
" intermediate " : 30 "
ρ : 30 kΩ-cm

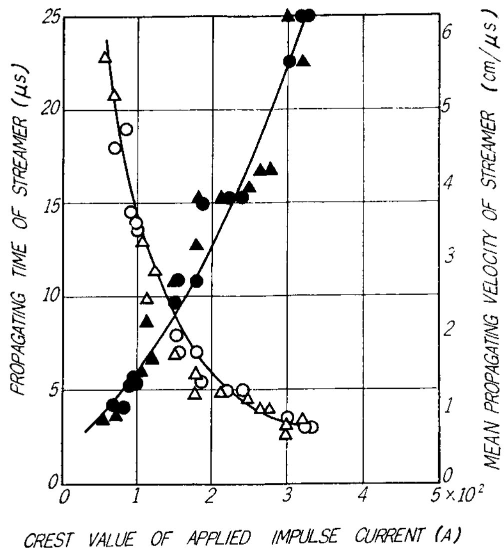


Fig. 20. Mean propagating velocity of streamer.

△ : Propagating time for positive polarity
○ : " " negative "
▲ : " velocity for positive "
● : " " negative "
Diameter of center electrode : 4 cm
" intermediate " : 40 "
ρ : 30 kΩ-cm

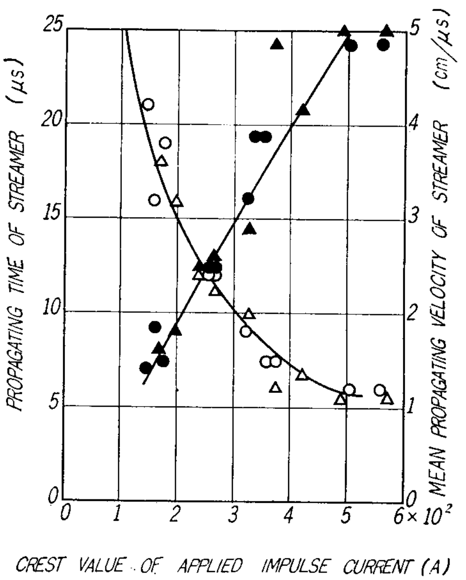


Fig. 21. Mean propagating velocity of streamer.

△ : Propagating time for positive polarity
○ : " " negative "
▲ : " velocity for positive "
● : " " negative "
Diameter of center electrode : 4 cm
" intermediate " : 60 "
ρ : 30 kΩ-cm

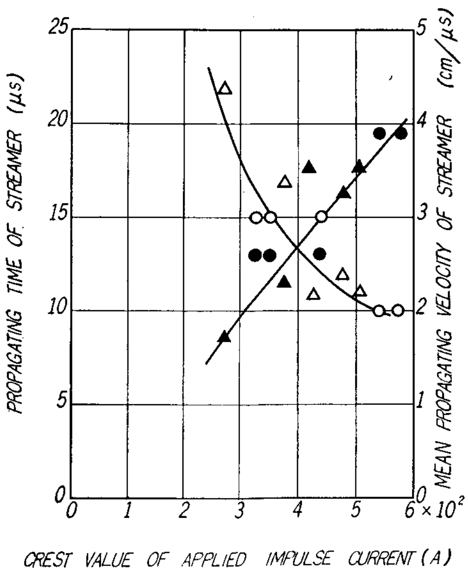


Fig. 22. Mean propagating velocity of streamer.

△ : Propagating time for positive polarity
○ : " " negative "
▲ : " velocity for positive "
● : " " negative "
Diameter of center electrode : 4 cm
" intermediate " : 80 "
ρ : 30 kΩ-cm

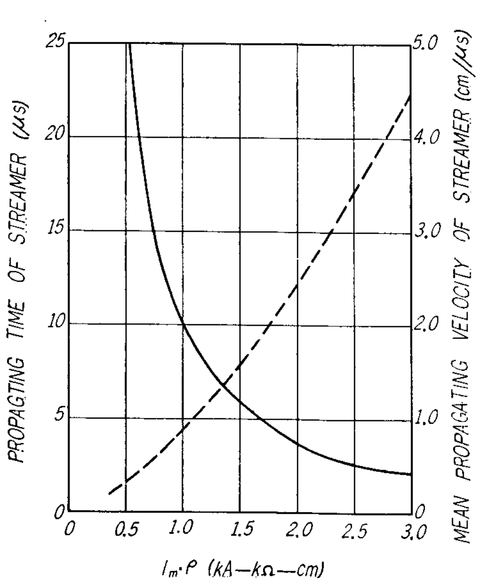


Fig. 23. Mean propagating velocity against $I_m \cdot \rho$.

— : Propagating time } for positive and
··· : 〃 velocity } negative polarity
Diameter of center electrode : 4 cm
〃 intermediate 〃 : 20 〃
ρ : 1.2~30 kΩ-cm

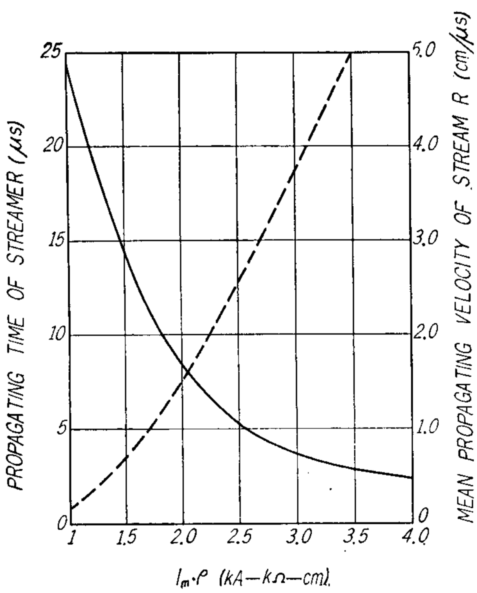


Fig. 24. Mean propagating velocity against $I_m \cdot \rho$.

— : Propagating time } for positive and
··· : 〃 velocity } negative polarity
Diameter of center electrode : 4 cm
〃 intermediate 〃 : 30 〃
ρ : 1.2~30 kΩ-cm

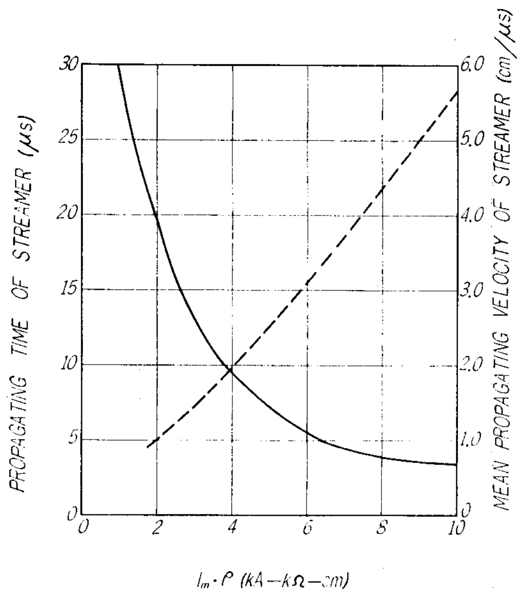


Fig. 25. Mean propagating velocity against $I_m \cdot \rho$

— : Propagating time } for positive and
··· : 〃 velocity } negative polarity
Diameter of center electrode : 4 cm
〃 intermediate 〃 : 40 〃
ρ : 1.2~30 kΩ-cm

5. The Potential Drop of Streamer in the Soil

In the flash-over in an air gap, there is almost no potential difference between the electrodes, while some potential difference is observed during the bridge-over across the same gap in the soil as shown in Fig. 26 where a gap length is 15 cm between the rectangular bar electrode in the soil of 30 kΩ-cm resistivity.

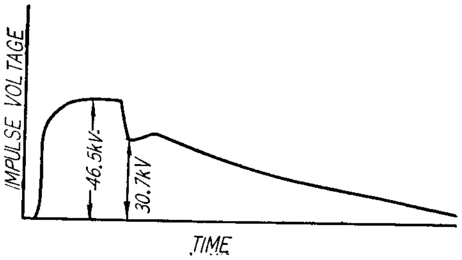


Fig. 26. Potential drop between gap in soil against elapsed time.

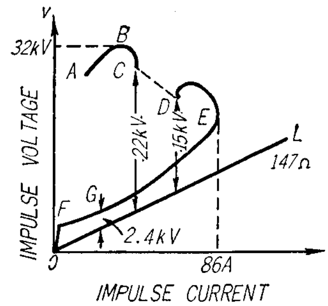


Fig. 27. Method of measuring the potential drop of streamer.

Table 3. Potential Drop of Streamer in the Soil.
(Diameter of center electrode : 3.5 cm ρ: 30 kΩ-cm)

Positive polarity				Negative polarity			
Crest value of applied impulse voltage (kV)	Crest value of applied impulse current (A)	Potential drop (kV)	Potential drop per unit length (kV/cm)	Crest value of applied impulse voltage (kV)	Crest value of applied impulse current (A)	Potential drop (kV)	Potential drop per unit length (kV/cm)
Intermediate electrode No. 3 (Diameter : 30 cm)							
29.0	41.0	3.3	2.2	29.5	37.5	3.3	2.2
33.0	50.0	3.0	2.0	32.0	49.0	3.3	2.2
38.0	73.0	2.0	1.3	38.5	71.5	3.3	2.2
59.5	125.0	2.2	1.5	62.0	121.0	2.8	1.9
Intermediate electrode No. 5 (Diameter : 40 cm)							
38.5	71.0	3.3	1.7	38.5	96.0	3.3	1.7
48.5	153.0	1.7	0.9	48.5	157.0	1.7	0.9
53.5	195.0	1.7	0.9	53.5	190.0	1.7	0.9
62.0	255.0	1.7	0.9	62.0	245.0	1.7	0.9
Intermediate electrode No. 6 (Diameter : 60 cm)							
50.0	170.0	5.0	1.7	50.0	165.0	4.2	1.4
55.0	235.0	3.3	1.1	54.0	250.0	3.3	1.1
63.5	325.0	3.3	1.1	63.5	325.0	3.3	1.1
72.5	522.0	1.7	0.6	73.5	522.0	1.7	0.6

Fig. 27 is an oscillogram of the voltage-current characteristic (OABCDEFO) where the impulse voltage is applied on the center electrode of 3.5 cm diameter, with the intermediate electrode of 30 cm diameter, embedded concentrically in the soil of 30 kΩ-cm resistivity. The leap at CD in the figure shows the arrival of the streamer at the intermediate electrode. Furthermore it shows also a straight line (OL) which is the voltage-current characteristic where the impulse voltage is applied directly on the intermediate electrode. The reason why OL is straight is that the soil outside the intermediate electrode is not broken down electrically, and the inclination of straight line OL shows the earth resistance of the intermediate electrode of 147 Ω, while 153 Ω is obtained for 60～a. c., these two values being almost consistent.

However the curve EF which shows the wave tail after the streamer arrives at the intermediate electrode, is different from OL. It seems to be due to the potential drop of the streamer the amount of which is shown in Table 3 for various kinds of intermediate electrodes measured by this method. From this result, it is evident that the potential drop decreases with the increase of the crest value of the impulse current, and may be negligible under the actual lightning discharge.

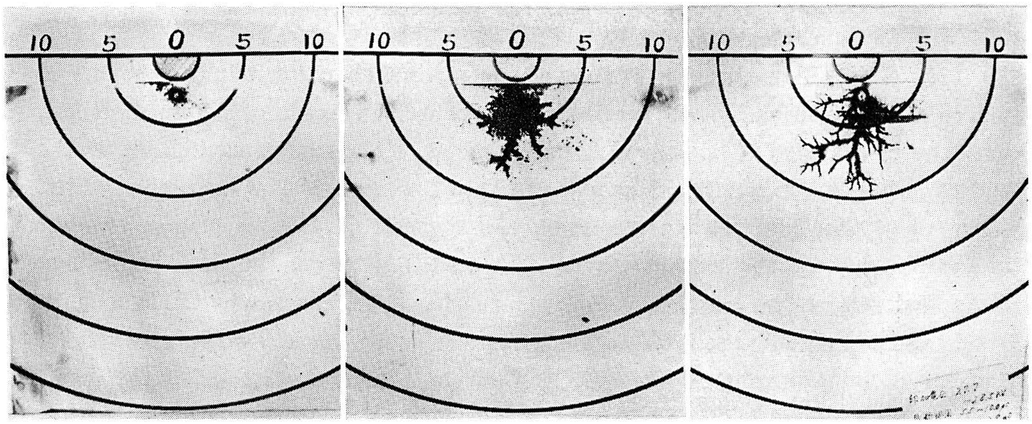
6. The Variation of the Streamer Form with the Elapsed Time

As described in section 2, the form, length and so on of streamer in the soil depend on the crest value and wave form of the applied impulse voltage, the shape of electrode and the earth resistivity and furthermore they vary with the elapsed time from the initiation to the dissipation of the streamer. In this section, the variation of the streamer form with the elapsed time is observed by the following method.

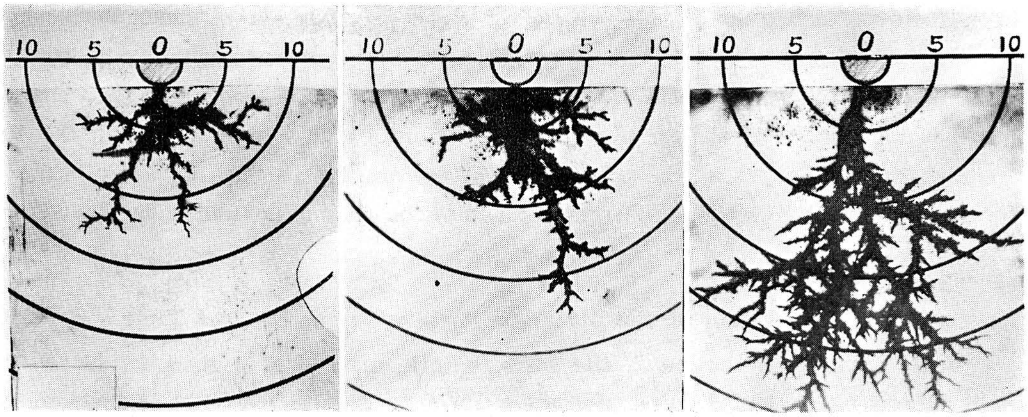
The streamer figure in the soil observed by the embedded film mainly shows the shape in the state where the streamer has propagated enough, that is, at the moment when the impulse current arrives at the peak. Therefore it is impossible to observe the propagation of the streamer with the elapsed time only by this method.

To observe the variation of the streamer with the elapsed time, the embedded X-ray film and a chopped wave are used together. For instance, a chopped impulse voltage is applied to the center electrode whose chopping time (T_c) equals the length of its wave front (T_f), then the figure of the streamer at the peak of the impulse valtage can be obtained.

An impulse generator, which is able to generate chopped waves with an arbitrary T_c, is used in this test, and T_c is changed successively. Then the



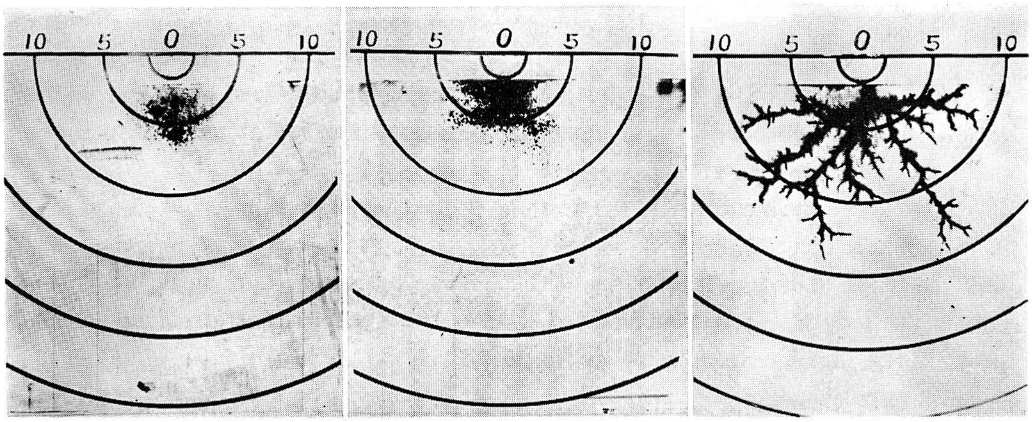
(a) T_c=7.5 μs (b) T_c=10 μs (c) T_c=15 μs



(d) T_c=20 μs (e) T_c=25 μs (f) FULL WAVE

Fig. 28. Figure on the film by means of chopped wave.

Diameter of center electrode : 3.5 cm
T_f : 10 μs ρ : 15 kΩ-cm V : 35 kV



(a) T_c=2.5 μs (b) T_c=5 μs (c) T_c=10 μs

Fig. 29. Figure on the film by means of chopped wave.

Diameter of center electrode : 3.5 cm
T_f : 5 μs ρ : 15 kΩ-cm V : 35 kV

instantaneous form, length, and velocity of streamer can be measured for T_c.

Figs. 28 and 29 show the variation of the streamer with elapsed time under the conditions of Table 4.

Table 4. Form of Chopped Wave.

	Fig. 28	Fig. 29
Crest value of voltage (kV)	35	35
T_f (Length of wave front) (μs)	10	5
T_c (Chopped time) (μs)	7.5~25	2.5~10

By means of this method, for two kinds of impulse voltages of equal crest value but not of equal length of wave front, the length of streamers is plotted against the elapsed time (i. e. T_c) on a semi-log.-graph as shown in Fig. 30.

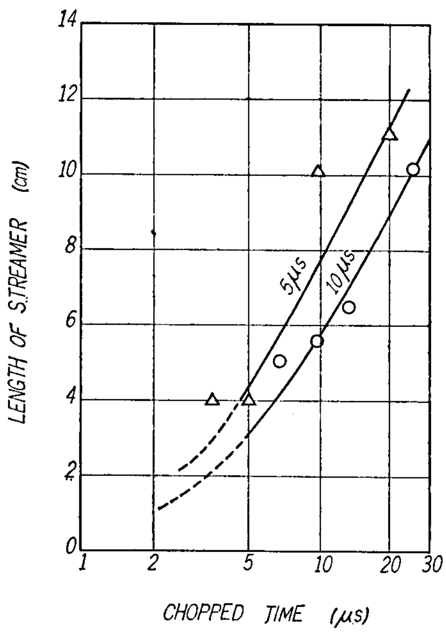


Fig. 30. Length of streamer against elapsed time.

Then these data are approximately indicated as two parallel straight lines. Then the experimental formula is obtained as follow,

$$l_s = A \log_{10} t + B \qquad (2)$$

where l_s : length of streamer (cm)

t : chopped time (μs)

A, B : constants chosen by the condition

From above equation, the instant propagating velocity of streamer v_s is as follow,

$$v_s = \frac{C}{t}, \qquad C = A \log_{10} \varepsilon \tag{3}$$

These two equations are correct in $0<t<T_t$ (length of wave tail), and for $t>T_t$ the streamer dissipates and these equations can not be applied and the figure of the streamer in this state can not be taken by this method.

By many experiments using a chopped impulse voltage and an embedded film, the conclusion is obtained as follows.

(1) According to Figs. 28 and 29, it is evident that the streamer formed by the wave front of an impulse voltage is spherically concentrical to the center electrode. Therefore, it is concluded that, though the streamer formed by a full wave of the impulse voltage has a tree form, the one in the first stage is spherically concentrical in all cases.

From the view point of the time of impulse flash-over of insulation, the reduction of footing resistance is impotant in the wave front where the streamer in the soil at tower footing is spherical.

(2) When two impulse voltages have the same crest value and different length of wave fronts as shown in Fig. 30, the two lines, which show the relation between the length of the streamer and chopped time, are parallel and the streamer from the steeper voltage precedes the other by a finite length of wave front.

7. Conclusion

The experimental results described above are summarized as follows:

(1) The figure of streamers in the vicinity of the center electrode can be obtained by X-ray film embedded vertically in the soil under the center electrode, and this leads to the following conclusions:

(a) The streamer in the soil with the earth resistivity of less than 2.5 kΩ-cm has a spherical form concentrically to the center electrode, and its radius approximately equals the equivalent radius of the center electrode which Mr. Petropoulos proposed, while the streamer in the soil with the resistivity of more than 2.5 kΩ-cm has a tree form, and its length is not equal to the equivalent radius of the center electrode.

(b) The longer the wave tail of the impulse voltage becomes, the longer the streamer propagates, at a constant crest value.

(c) By using the film with many punched holes the figure may show the natural form of the streamer independent of the embedded film.

(2) By means of the intermediate hollow hemispherical electrodes embedded in the soil which are arranged in the concentric position with the center electrode, the propagated distance and mean velocity of the streamer are able to be simply and plainly indicated on the graph against the product of the crest value of the impulse current and earth resistivity.

(3) By means of both embedded film and chopped wave, the propagation of a streamer is observed as follows:

(a) The streamer appears spherically and concentrically with the center electrode as far as the wave front of the impulse voltage, then it propagates in a tree form.

(b) The propagating velocity of the streamer is inversely proportional to the elapsed time after the application of the impulse voltage.