# Experimental Study of Critical Cascading Flashove on Insulator Assembly Using Model Arrangements (Part 1)
## (The Influence of a floating Electrode, Placed in the Air at Mid-Gap, on the Formation of a Flashover Path)

by

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**Abstract**

This paper describes the phenomena of cascading flashovers in model arrangements for experimental analysis of critical cascading flashovers in an insulator assembly used on high voltage transmission lines.

The testing model used consisted of a 15 cm gap length of rod-rod electrode which was 1.0 cm in diameter with a hemispherical end, with a potentially floating electrode which was a copper wire of 0.16 cm diameter. The applied lightning impulse voltage of positive or negative polarity was much higher than the breakdown voltage when the flashover occurred for only a short time lag. The experimental results included V-t curve and 50% flashover voltage characteristics for a gap on the testing model, flashover path, pre-breakdown corona distributions, and cascading flashover rates.

The flashover phenomena in the air gap with a floating electrode clarified that the cascading flashover rate remained at a constant value whether the floating electrode existed or not. The coronas from the floating electrode were generated only when the coronas from the rod electrode reached the floating electrode. In order to form a cascading flashover, it was necessary that the bright leader coronas from the rod electrode grow toward the floating electrode, causing the coronas from the floating electrode to generate and meet the other coronas growing from the rod electrode.

## 1. Introduction

Ultra high voltage transmission lines, which can transmit great electric power at high efficiency and high density, must be sufficiently protected from lightning to avoid causing serious faults in the power system. Even if the aerial ground wire were to shield the transmission lines effectively from lightning, the insulator assembly might experience a flashover in the insulators. It could happen that because of a

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critical cascading flashover due to a reversible breakdown resulting from an impedance drop at the tower, the insulators could be broken and the transmission lines permanently damaged[1]. The authors have reported on the conditions for the occurrence of critical cascading flashovers in an earlier report[2].

In this series of fundamental experiments, we used a model insulator assembly consisting of a porcelain board, a potentially floating metal and rod-rod electrode.

The conditions of flashovers in the air gap of rod-rod electrode have been investigated in this series of experiments using a copper wire arranged in the mid gap, with the ends curled smoothly to obtain an undistorted electrical field, the wire being floated in potential. The applied impulse voltage must have a steep wave front, so a wave form (0.6×40 μsec.) was used here. This is because the critical cascading flashover phenomena on the insulator assembly occur in front of the voltage wave, as described in the earlier report. To test the model equipment, an over-voltage was applied to obtain a breakdown at the wave front. In this test, a 50% breakdown voltage, cascading flashover rate, pre-breakdown corona distribution and corona sequence phenomena were observed as follows.

## 2. Flashover Characteristics in Rod-Rod Electrode Gap

To investigate the effects of a floating metal and a porcelain board on the direction of the flashover path in the rod-rod gap, first, the breakdown characteristics were observed under experimental conditions in which the horn gap and connecting

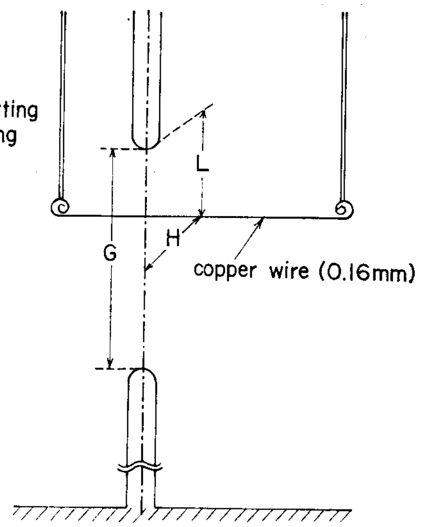



Fig. 1. Arrangements of the model insulator assembly (The horn gap and connecting metal fittings are replaced with rod-rod gap and copoer wire, without insulator)

metal fittings were replaced with rod-rod gap and copper wire, as shown in Fig. 1. However, an insulator had not yet been arranged.

a) Flashover voltage-time (V-t) curve and 50% flashover voltage ($V_{50}$)

The V-t curve and $V_{50}$ were obtained as fundamental flashover characteristics of the 15cm rod-rod gap as shown in Fig. 2. The $V_{50}$ of 137.2+3.2 kV resulted from the up-down voltage method being applied 40 times. In the figure, when a flashover occurred in front of the voltage wave, the instantaneous voltage was taken as the flashover voltage, and, the V-t curve was obtained by repeated voltage application. The curve did not rise in a short time range as it was saturated. Even when it was decided to apply a higher voltage than $V_{50}$, the instantaneous flashover voltage did not rise high but the wave rising time rate ($S_{ft}$) was steep. To obtain the V-t curve and the flashover probability, we used $S_{ft}$ which is defined by the following equation.

$$S_{ft} = V_p / T_f \qquad 1)$$

where, $V_p$ is the peak value of the applied voltage, and $T_f$ is the crest time.

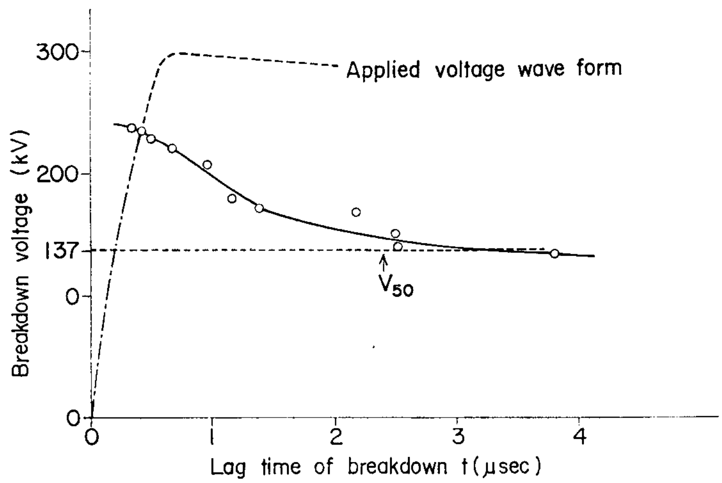



Fig. 2. V-t curve for rod-rod gap and 50% breakdown voltage (positive voltage, G=15 cm)

b) Flashover path distribution (F. P. D.)

Fig. 3 shows the F. P. D. obtained 300 times when positive or negative impulse voltages were applied to the 15 cm rod-rod gap. The highest number of flashovers were in a short time range, when the applied voltages were of a magnitude and steepness equal to 300 kV/0.6 μsec..

The F. P. D. s for the positive impulse voltage are shown in Fig. 3-(a). The number of F. P. D. s across each location at the distance (L) from the tip of the rod electrode inside of the applied voltage is shown by a histogram, in which the

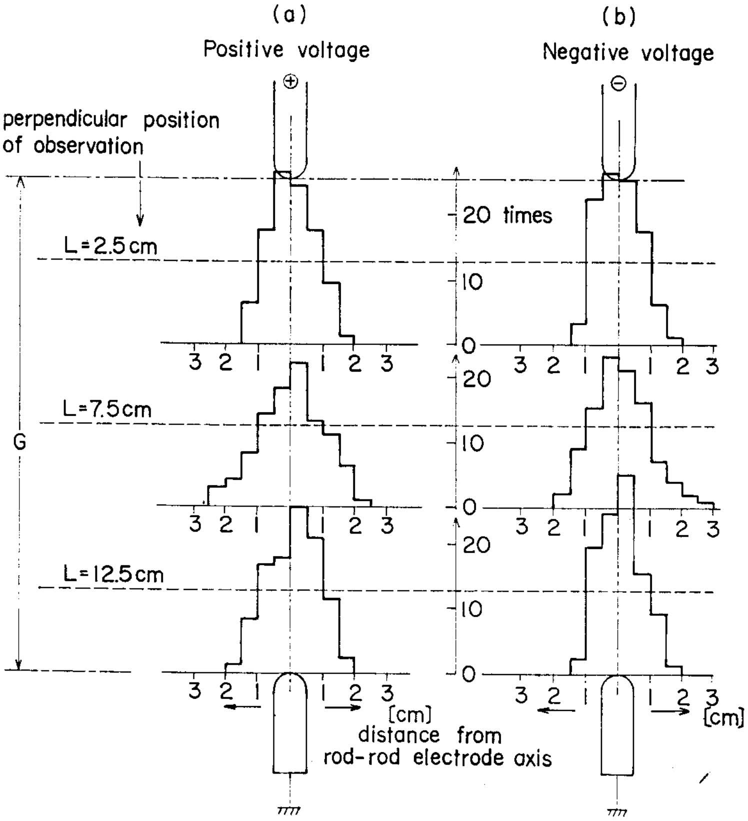



Fig. 3. Distribution of breakdown paths for rod-rod gap (G=15 cm)

abscissa is the distance (H) from the gap axis and the ordinate is the number of flashover paths. To observe these, specified locations were selected: L=2.5, 7.5 and 12.5 cm. The F. P. D. s for the negative impulse voltage are shown in Fig. 3-(b). There are no differences in these F. P. D. s for the positive and negative voltage. However, in the F. P. D. on location L=7.5 cm (half the gap length), the greatest deviation of the flashover paths from the electrode axis was 2.5 cm.

When the positive voltage was applied, on constructing the maximum F. P. D. on location L=2.5 cm with the maximum deviation of location L=12.5 cm, the latter was a little large. For the negative voltage application, the deviations in both locations were almost the same, though on location L=2.5 cm, the maximum deviation for the negative was a little greater than that of the positive. It was assumed that the F. P. D. s were related to the distributions of the pre-breakdown corona, which were observed next.

c) Pre-breakdown corona distribution

Fig. 4 shows the pre-breakdown corona distribution for the positive voltage, in

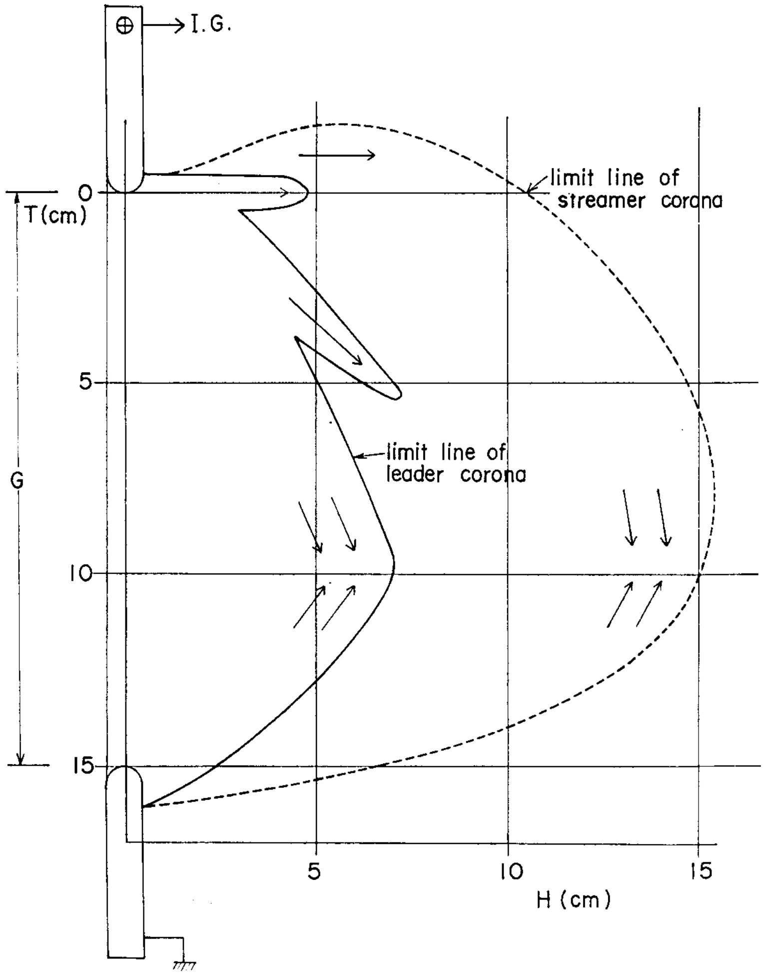


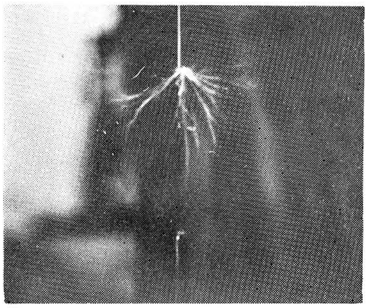

Fig. 4. Distribution of pre-breakdown corona for rod-rod gap (positive, G=15 cm)

which the corona distribution occurred just before flashover was obtained by means of the voltage-chopping method (chopping time: $T_c=0.28$ $\mu$sec.). The distributed corona in the gap, for example, the 4th developing stage in Fig. 5, was separated into two components of the corona distribution, as follows:

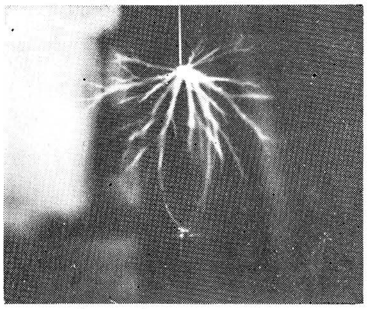
One of the two corona components was a leader corona that was bright and strong; the other was a fine streamer corona distribution which covered the leader coronas. These two corona components can be clearly seen as being separate at the 4th stage after the developing 3rd stage in the figure.

The dark streamer corona was photographed using a camera mounting an F. 1. 2 lens, and the film was overdeveloped using a high sensitivity technique. The streamer corona was broadly distributed, as shown in Fig. 4.

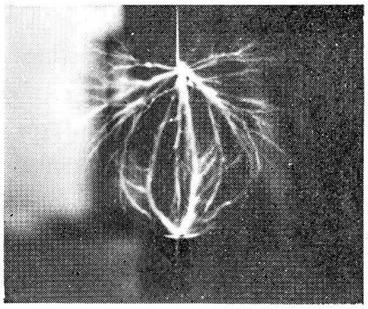
(a) positive voltage (300 kV/0.6$\mu$sec.)



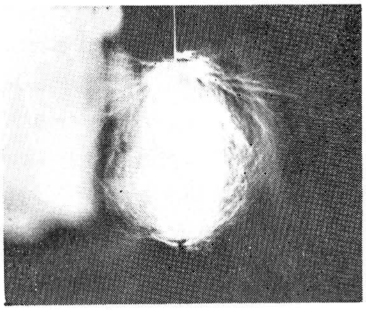
The 1st stage $T_c=0.17\mu$sec



The 2nd stage $T_c=0.19\mu$sec

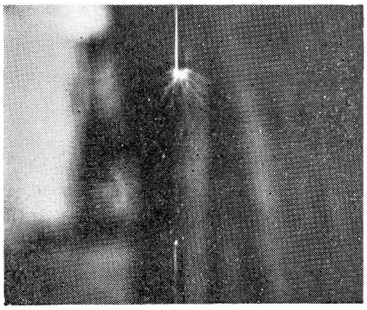


The 3rd stage $T_c=0.23\mu$sec

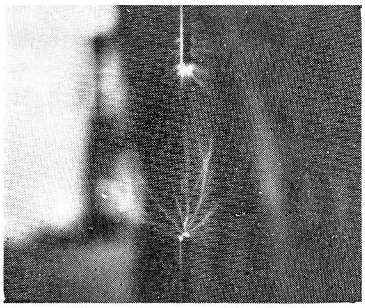


The 4th stage $T_c=0.28\mu$sec

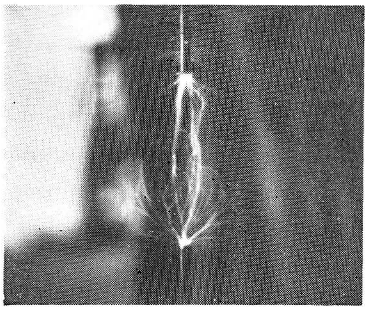
(b) Negative voltage (300 kV/0.6$\mu$sec.)



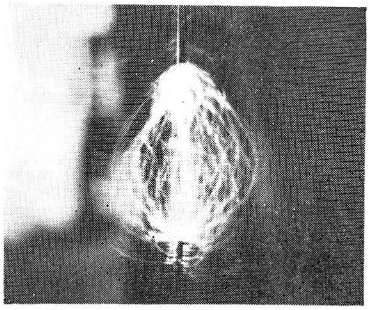
The 1st stage $T_c=0.17\mu$sec



The 2nd stage $T_c=0.19\mu$sec



The 3rd stage $T_c=0.23\mu$sec



The 4th stage $T_c=0.28\mu$sec

Fig. 5. Sequence of pre-breakdown corona for rod-rod gap (G=15 cm)

The distributed width in the horizontal direction was almost the same as the gap length. The distributed width of the leader corona was half of the width of the streamer corona, but the flashover paths were distributed to a maximum horizontal deviation of 2.5 cm.

d) Sequence of pre-breakdown corna

The sequence of the pre-breakdown corona was observed by means of the voltage chopping method as shown in Fig. 5. The chopping time ($T_c$) was set in steps as follows: 0.17, 0.19, 0.23 and 0.28 $\mu$sec..

The corona sequence for positive voltage is shown in Fig. 5-(a), in which at the 1st stage and 2nd stage ($T_c$=0.17 and 0.19 $\mu$sec.), the corona grew from the rod electrode on the applied voltage side as positive corona, and the negative corona was generated at the grounded electrode. The positive and negative coronas were connected to each other at two-thirds of the gap length (G) from the applied voltage side. At the 3rd stage of the corona sequence ($T_c$=0.23 $\mu$sec.), the positive and the negative leaders were already connected perfectly and becoming a main arc. At the 4th stage of the corona ($T_c$=0.28 $\mu$sec.), many bright coronas could be observed, but not in detail in this figure.

Finally, the corona phenomena at the 4th and final stage could be observed clearly by means of the camera technique mentioned above. The corona distribution of the two components is shown in Fig. 4.

The sequence coronas for negative voltage are shown in Fig. 5-(b). For negative voltage, the negative corona grew only a short length from the rod electrode on the applied voltage side. Following the negative corona, the positive corona leaving the grounded electrode grew long. These positive and negative coronas were connected together in the neighbourhood of the voltage applied electrode. At the 4th stage of the corona, there were many bright coronas but the pattern of the corona distribution was an inversion of that obtained for positive voltage.

It was clear that the flashover path mostly deviated at the location where the positive and negative coronas were connected.

## 3. Flashover Characteristics in an Air Gap with a Floating Electrode

Fig. 1 shows an air gap consisting of rod-rod electrode with a copper wire floated in the air at mid-gap.

The influence of the floating wire on the breakdown phenomena in the air gap was investigated only for a change in its location. A copper wire, with a diameter of 0.16 cm and a length of 50 cm, was used as a floating electrode. The wire was loop-like at both ends in order to weaken the electric field at a location far from the rod-rod electrode axis.

a) 50% flashover voltage

The location of the floating electrode was designated by the sign "(L, H)" which is shown in Fig. 6. $V_{50}$ was given for the following two locations:

$$\left.\begin{array}{l} 1),\ (L,\ H)=(2.5,\ 1.0)\cdots\cdots V_{50}=140.0\pm1.2\,\mathrm{kV} \\ 2),\ (L,\ H)=(12.5,\ 1.0)\cdots\cdots V_{50}=135.0\pm1.5\,\mathrm{kV} \end{array}\right\} \quad 2)$$

These were almost the same as the value for the air gap alone, that is, $V_{50}=137.2\pm3.2\,\mathrm{kV}$.

Thus, the $V_{50}$ for the rod-rod electrode gap with the potentially floating wire is not distingushed from the one for the rod-rod electrode gap only, whatever the location of the floating wire.

b) On the conditions of over-voltage application, the relation with a cascading flashover rate (C. F. R.) and the location of the floating electrode

The probability of a cascading flashover to the wire in the case of positive over-voltage having a steepness of 300 kV/0.6 μsec. is given in Fig. 6. In this figure, the location of the floating electrode is indicated " ○ ", and the fractions shown are numbers of cascading flashovers in 20 voltage applications. The fractions represent the C. F. R. s when the flashover cascaded to the floating metal. A curve was obtained by connecting the points at which the C. F. R. was zero. The shape of the curve resembles a gourd having its large part on the side of the voltage applied electrode. In the narrow part of the "gourd" where the positive and negative coronas join, it was not as easy to cascade to the floating metal, despite the fact that the corona distribution at this part was widest.

The coronas grown from both polarity electrodes were connected naturally at the narrow part of the "gourd" without the support of the corona grown from the floating electrode.

Next, the C. F. R. s obtained in our experimental results by changing the location of the floating metal along the electrode axis (H=0) are shown in Fig. 7. The C. F. R. s became lower the farther they were from the voltage applied electrode along the electrode axis. They reached their lowest rate of 75% at the distance L=8 cm, and then suddenly jumped to a high rate of almost 100%, at the distance L=9 cm.

The C. F. R. s of L=2.5, 7.5 and 12.5 cm are shown in Fig. 8. When the floating wire was set at L=7.5 cm, which is half of the gap length (G/2), and at a variable distance (H) from the electrode axis, the C. F. R. s were obtained as 80 to 0%. The C. F. R. s at L=2.5 and H=0 to 2.0 cm were 100%. From there, the C. F. R. s dropped suddenly to 0% at L=2.5 and H=3.3 cm. From H=3.3 cm on, the C. F. R. s continued at 0%. The C. F. R. s at L=12.5 and H=0 to 3.0 cm were 100%. From there, the C. F. R. s dropped suddenly to 0% at L=12.5 and H=4.2 cm. From H=4.2 cm on, the C. F. R. s continued at 0%. From these experimental

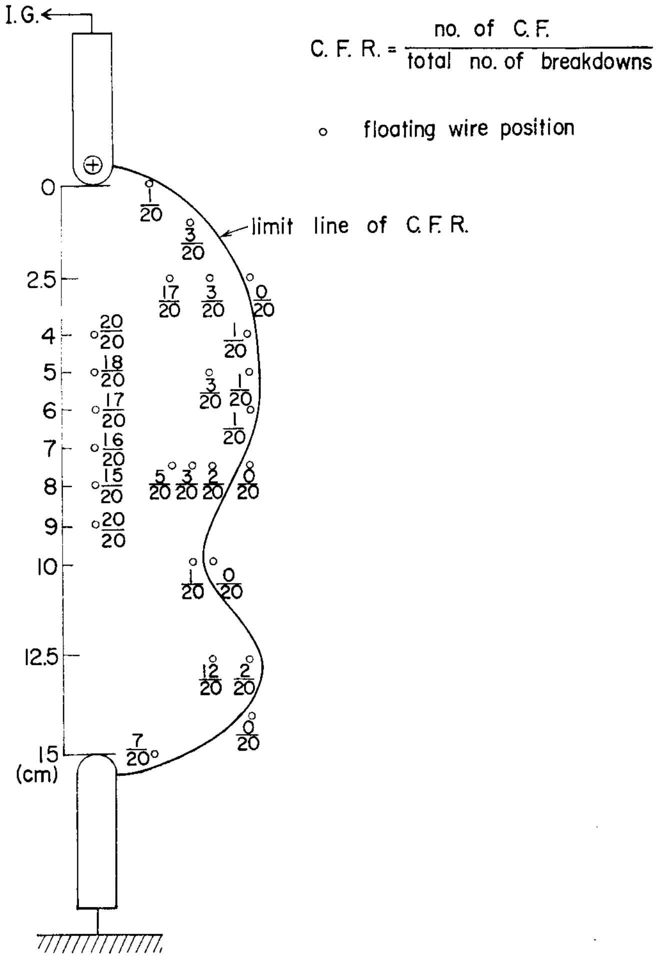



Fig. 6. The cascading flashover rata and the position of floating wire (positive over-voltage application)

results, it was clear that the flashover path cascaded to the floating wire when the positive and negative leader corona stages reached the wire.

In the case of negative voltage, the C. F. R. s resulting from the change in H are shown in Fig. 9. In the figure, the outer limit of the corona distribution formed of C. F. R. s zero points took the shape of a gourd. The narrow part was near the high voltage side in contrast to the positive applied voltage. In both the posiive and negative voltages, it was clear that the flashover path cascaded to the floating wire which was located in the range where the positive and negative coronas were distributed. Also the path did not cascade when the floating wire was located outside that range, and the flashover voltage was not changed by the presence of the floating

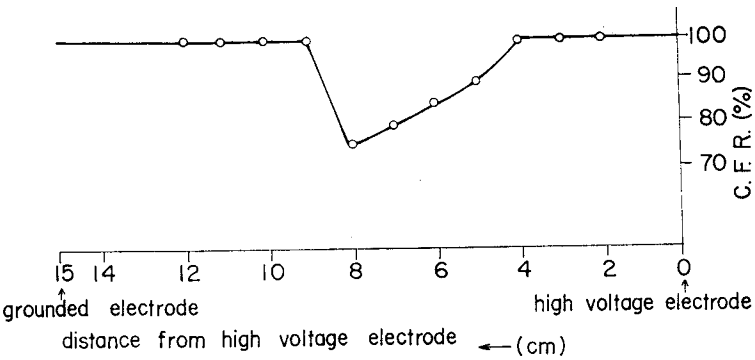



Fig. 7. Cascading flashover rate and position of floating wire on the rod-rod electrode axis (H=0)

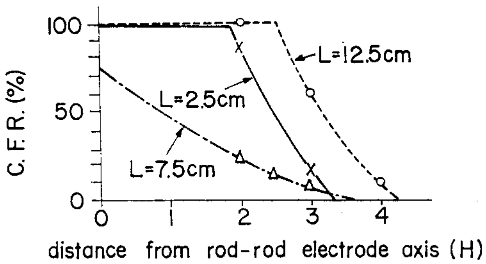



Fig. 8. C. F. R. and the horizontal distance of the floating wire from rod-rod electrode axis

wire.

c) Concerning the cascading flashover rate, and shape and dimensions of a floating electrode

First, when a copper wire with a large diameter (d=0.5 cm) was used as the floating electrode, the C. F. R. near the rod electrode was increased slightly more than the C. F. R. produced near the rod electrode while using a small diameter wire (d=0.16 cm). However, all the rates at locations farther from the rod electrode were almost the same as the C. F. R. when using the small wire.

Second, using a metal sphere, diameter 1.1 cm, as the floating electrode, the outer limit of the C. F. R. equal to zero was almost the same as the outer limit obtained using a fine wire. But, inside the outer limit of the corona distribution, the rates obtained using a metal sphere were slightly lower than those obtained using a fine wire.

The experimental results shown above were probably obtained for the following reasons. The corona distribution and the location of the floating metal in mid-gap are shown in Fig. 10 in an inside view. In the figure, it shows that when the cop-

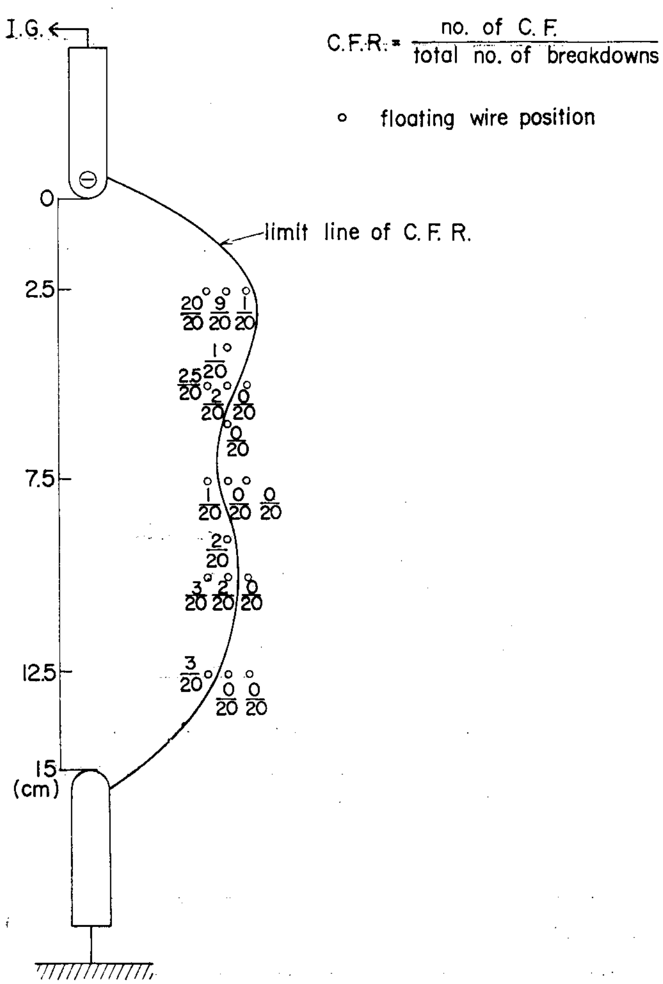



Fig. 9. The cascading flashover rate and the position of the floating wire (negative over-voltage application)

per wire was near the outer limit of the corona distribution, the area irradiated by the coronas was comparable with the area irradiated when using the metal sphere. On the inside of the outer limit of the corona distribution, however, the part irradiated by the coronas while using the wire was larger, as shown in Fig. 10, than that irradiated while using the metal sphere.

d) Concerning the corona distribution and the location of the floating wire in the air at mid-gap

Here, we treat the relation of the corona distribution, as pre-breakdown phenomena, to the location of the floating wire when the flashover is cascaded to it. In Fig. 6, it is understood that the area with a C. F. R., not equal to zero, is covered

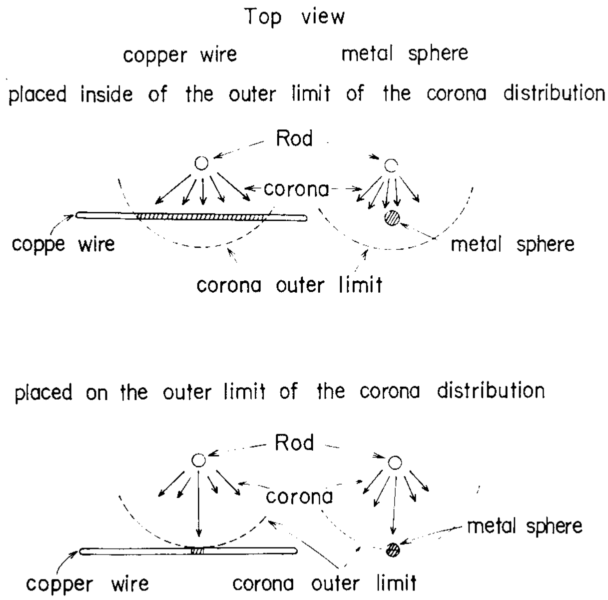



Fig. 10. The relation of the corona distribution to the shape and position of the floating electrode

by the area of the leader corona. (Cf. Fig. 4.)

The following observation was made to determine what changes in the corona distribution were caused by the presence of the floating metal. The corona distribution was observed in the rod-rod gap with the floating wire crossing the outer limit line. However, it was not confirmed whether the corona was distributed over a wide area or maldistributed around the floating wire placed far from the rod electrode.

It was made clear by the experimental results, however, that when the floating wire is in the air gap, the floating wire has no power to attract the corona grown from the rod electrode.

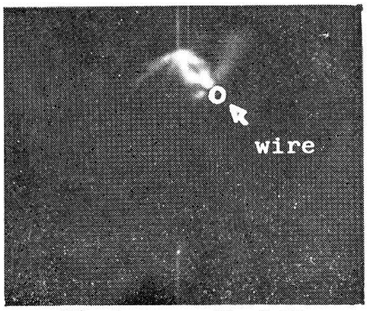
e) Development of pre-breakdown corona

In order to understand the developing behavior of the corona growing from the floating eletrode and the rod electrode, coronas developing to flashover by a positive voltage application were observed, using the voltage chopping method as shown in Fig. 11. The chopping times at the four stages were as follows : $T_c$=0. 17, 0. 19, 0. 23 and 0. 28 $\mu$sec.. At these four stages, the pre-breakdown corona was observed, with the copper wire at the following four locations.

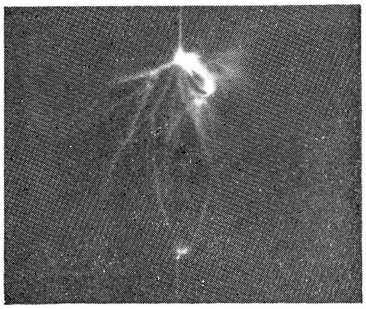
The C. F. R. s at the four locations of the floating wire are shown in Table 1. The applied positive voltage had a steepness of 300 kV/0. 6 $\mu$sec..

In contrast, the pre-breakdown coronas at these four locations of the floating

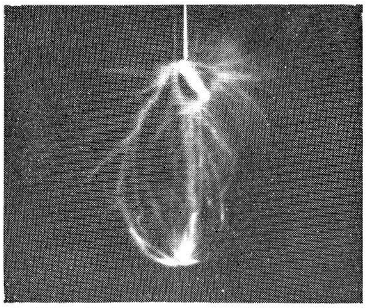
1) L=2.5 cm, H=2.0 cm



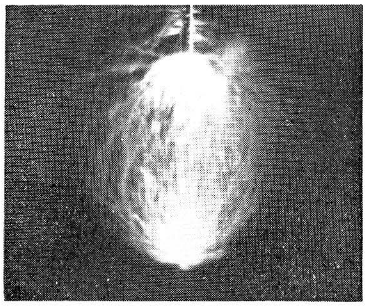

The 1st stage $T_c$=0.17μsec



The 2nd stage $T_c$=0.19μsec

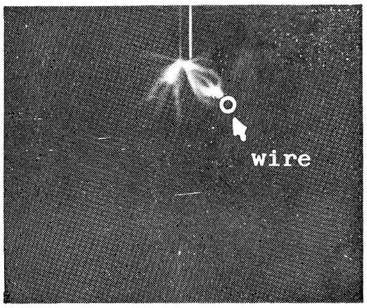


The 3rd stage $T_c$=0.23μsec

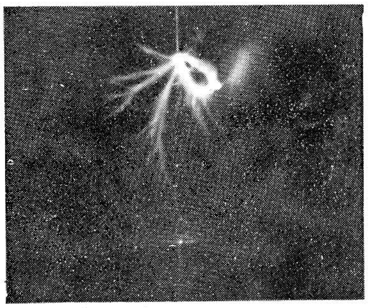


The 4th stage $T_c$=0.28μsec

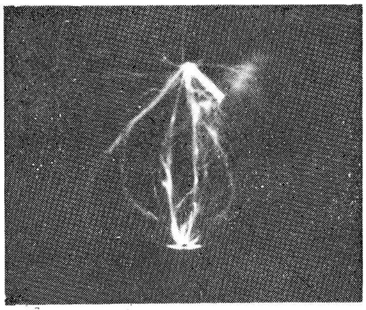
2) L=2.5 cm, H=3.0 cm



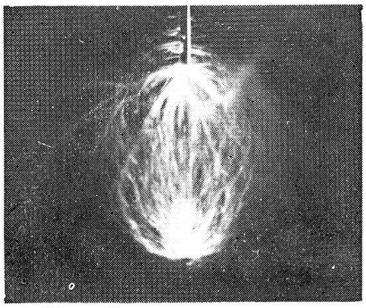

The 1st stage $T_c$=0.17μsec



The 2nd stage $T_c$=0.19μsec



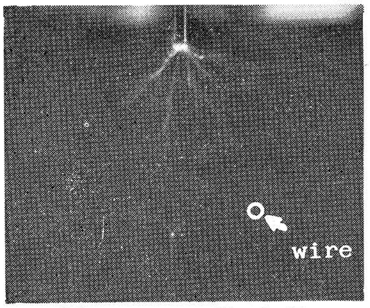
The 3rd stage $T_c$=0.23μsec



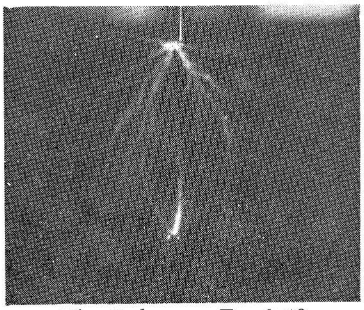
The 4th stage $T_c$=0.28μsec

Fig. 11-(a) Sequence of pre-breakdown corona for rod-rod gap and floating wire (positive voltage; G=15 cm)

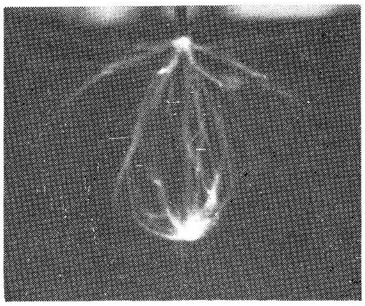
3) L=12.5 cm, H=4.0 cm



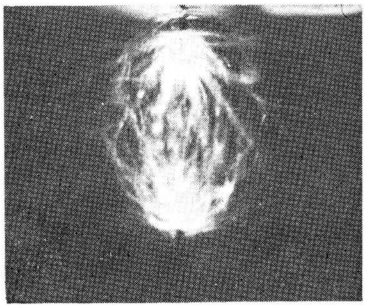

The 1st stage $T_c$=0.17$\mu$sec



The 2nd stage $T_c$=0.19$\mu$sec

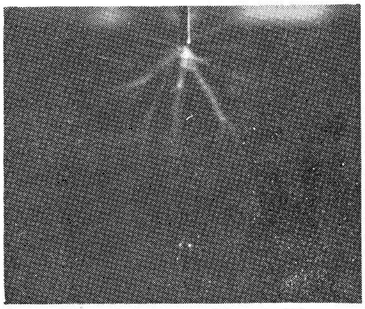


The 3rd stage $T_c$=0.23$\mu$sec

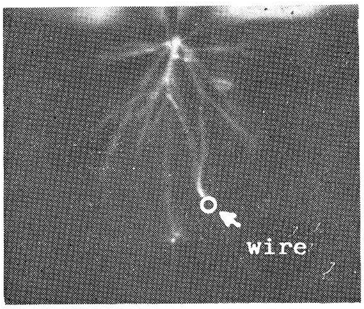


The 4th stage $T_c$=0.28$\mu$sec

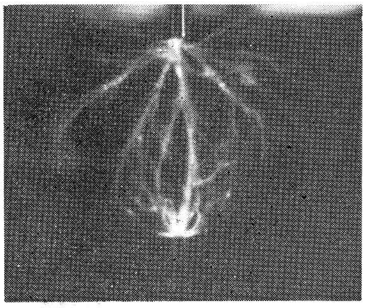
4) L=12.5 cm, H=2.0 cm



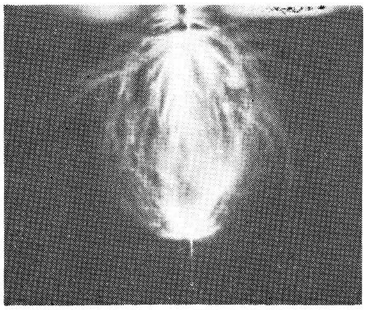
The 1st stage $T_c$=0.17$\mu$sec




The 2nd stage $T_c$=0.19$\mu$sec



The 3rd stage $T_c$=0.23$\mu$sec



The 4th stage $T_c$=0.28$\mu$sec

Fig. 11-(b) Sequence of pre-breakdown corona for rod-rod gap and floating wire (positive voltage; G=15 cm)

Table 1. The cascading flashover rates and locations of the floating wire.

| | location of copper wire | C. F. R. |
|---|---|---|
| 1) | (L, H) = ( 2.5, 2.0) | 85% |
| 2) | (L, H) = ( 2.5, 3.0) | 15% |
| 3) | (L, H) = (12.5, 4.0) | 10% |
| 4) | (L, H) = (12.5, 2.0) | 100% |

wire were observed and discussed by separating the two groups as follows:

(1) A comparison between locations 1) and 2) of the floating wire (as shown in Fig. 11-(a))

* The 1st stage ($T_c$=0. 17$\mu$sec.): At location 1) of the floating wire, the positive corona grow toward the floating wire from the voltage applied electrode became connected with the corona from the floating wire and became a bright corona. At location 2), the positive corona did not gather toward the floating wire, but developed the same as the positive corona in the gap without the floating wire. It was understood by the observation of these two phenomena that the positive corona did not cascade to the floating wire. Even though the floating wire location H was a little farther from the axis than before, the floating wire did not attract a corona from either electrode. There occurred only a small corona from the floating wire toward the corona emitted by the voltage applied electrode. In this early stage, the negative corona grew only slightly from the earth side electrode.

* The 2nd stage ($T_c$=0. 19 $\mu$sec.): At location 1) of the floating wire, the main bright corona of the leader stage was bridged in the gap from the voltage applied electrode to the floating wire, and the medium sized corona from the floating electrode reached the grounded rod electrode. Therefore, it was expected that the flashover path would cascade to the floating wire. At location 2), the main bright corona of the leader stage connected the voltage applied electrode and the floating wire just at this stage. Already, the main bright corona was bridged directly through the air without the presence of the floating electrode, and it appeared that the flashover path had not cascaded to the floating electrode. The flashover path had already been determined by this stage.

* The 3rd stage ($T_c$=0. 23 $\mu$sec.): At this stage, the coronas of the 2nd stage were continuing to develop.

* The 4th stage ($T_c$=0. 28 $\mu$sec.): At this stage, it was clear that the flashover path at location 1) had cascaded to the floating electrode, and the flashover path at location 2) had not cascaded.

As a result of the observations of the pre-breakdown coronas at the four stages above, it was concluded that at location 2), the C. F. R. was only 15%, because the cascading phenomena occurred when the leader corona was growing toward the floating wire at the early stage.

(2) A comparison between locations 3) and 4) of the floating wire (as shown in Fig. 11-(b))

* The 1st stage ($T_c$=0. 17 μsec.): When the floating wire was presented at locations 3) and 4), both corona phenomena were almost the same as those in the gap without the floating wire. The positive corona emitted from the voltage applied electrode grew to several centimeters in length. At the same time, the negative corona from the grounded electrode grew only a little. At this stage, a corona from the floating wire was not observed.

* The 2nd stage ($T_c$=0. 19 μsec.): At location 3), the positive corona from the voltage applied electrode clearly bridged through the air to the negative corona from the grounded electrode. Thus, no influence of the floating wire on corona sequence was seen. At location 4), the upward corona occurring at the floating wire, and the main bright corona occurring at the voltage applied electrode met clearly. A downward corona grown at the floating wire was observed at this stage.

* The 3rd stage ($T_c$=0. 23 μsec.): At location 3), the corona connection in this stage was stronger than the one in the 2nd stage and changed to a flashover path as expected. At location 4), the corona connection between the grounded electrode and the floating wire was stronger than the one in the 2nd stage. At the same time, the negative corona grown from the grounded electrode had been gathering uniformly and the main bright corona had cascaded to the floating wire.

* The 4th stage ($T_c$=0. 28 μsec.): At this stage, the flashover path could be seen. Thus, the flashover path cascaded to the floating wire at location 4), and did not cascade at location 3).

## 4. Summary of the Influence of a Floating Wire in the Air at Mid-gap on the Formation of Flashover Path

The influence of the floating wire on the formation of a flashover path will be summarized here based on the experimental results given above.

In the distribution of flashover paths without the use of the floating wire, the lateral growth of a corona from the electrode axis is maximum at H=2. 5 cm. However, extremely few flashover paths pass through this location. The lateral growth of the corona in the presence of the floating wire is at least 3. 0 cm or more. This indicates that the floating wire influences the flashover path to some degree. The degree of influence differs depending on the location of the floating wire.

When the floating wire is placed near the rod electrode where the corona density is high, a highly dense corona reaches thc floating wire, at the same time that another corona is generated from the floating wire. The coronas, thus, firmly meet in the space between the rod electrode and the floating wire. These coronas may change a part of the flashover path. When the floating wire is placed far from the rod electrode where the corona density is low, the flashover path forms regardless of the location of the floating wire. In rare cases, there is a flashover path through a much more remote location. The possibility is extremely low, but when main leader coronas reach the floating electrode at a remote point, the floating electrodegrown corona facilitates formation of the flashover path.

Cascading flashover phenomena occur when the floating wire is placed at a remote location, although the cascading flashover rate is low. The corona is generated from the floating wire, supported in the air, toward the highly dense leader corona from the rod electrode, thus connecting them and faciltating the formation of the flashover path. The floating wire does not change the growth direction of the initial corona from the rod electrode nor draw the coronas to the floating wire.

The electrostatic field around the floating electrode does not affect the cascading flashover rate, because of the electrostatic field distribution resulting from the applied voltage at the floating electrode, as shown by the test results in item b) in Section 3. It is also because of the electrostatic field difference depending on the size and shape of the floating electrode.

## 5. Conclusion

In this study, a fundamental research was conducted on flashover characteristics in an air gap with a floating electrode, using a model assembly consisting of rod-rod electrode and a floating electrode made of copper wire.

In order to form a cascading flashover, it is necessary that the bright leader corona grow toward the floating electrode, then coronas from the floating electrode generate and meet other coronas growing from the rod electrode.

The results are as follows:

(1) When a floating electrode has been placed anywhere in the rod-rod electrode gap, flashover voltage doesn't fluctuate and the cascading flashover rate remains constant whether the floating electrode is used or not.

(2) Flashover phenomena are affected neither by the shape of the floating electrode nor by the electrostatic field near the floating electrode.

(3) The coronas from the floating electrode are grown only when coronas from the rod electrode reach the floating electrode.

Finally, the authors have been fortunate to have the assistance of Mr. Kazuhiko Azumi who contributed his experimental skill, sustained effort, and grasp of objectives toward the accomplishment of this experimental program.

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