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Research on the Domain of Electric Discharge in Gases (I)

(Received October 30, 1952)

Tameyoshi MORI *

Abstract

In this report I describe the fact following the Townsend's theory that the discharge domain in gases is divided into two parts from the stand point of spark mechanism: that is the Townsend's domain of small p(Pressure) × I(gaplength) part in which Townsend mechanism is held, and the streamer domain, where the streamer formation is exhibited.

These facts are made clear experimentally and are shown as a function of pl and the percent over-voltageΔ.

I. Introduction

Regarding interpretaion of mechanism of the electric discharge in gases, Townsend established his basic theory, so-called Townsend Discharge theory, in the early nineteen hundred.

After that, there have been many developements, and now it has been Townsend's modified Theory taking into consideration of photo-electric effect in gases. The theory appears adequate to explain the sparking phenomena observed at appropriately low value of pl, the product of pressure p(mmHg) and the gap length I(cm).

However, considering the positive ion which is the basis of his theory, the transit time of positive ion cannot be less than 10^{-5} second. Thus the formative time lag for a discharge to build up must on Townsend's theory exceed about 10^{-5} second for the usual gaps used. However, by 1927 - 1928 many different types of measurement revealed that for sparks about atmospheric pressure the formative time lags were nearer 10^{-7} second than 10^{-5} second. In other words, Townsend's theory cannot apply in the domain where pl is large. These and many other experimental researches and theoretical researches, cooperating with each other, have proven the impossibility of assuming that mechanism of electric discharge generally remains the same independently to gap conditions, and an interpretation, has come to be made that the mechanism is divided into two which differ in discharge form, Townsend's and streamer mechanisms.

In the threshhold breakdown in uniform field such as occurs between two spheres or parallel plates, the criterion of both mechanisms is various by researchers from pl 150mmHg-cm to 1000mmHg-cm. And in the case of impression of a impulsive voltage, a breakdown in streamer mechanism is occured according to the

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supply of some over-voltage beyond the threshhold voltage, even if the gap condition pl belongs to Townsend discharge domain.

In other words, it is understood that the boundary between Townsend's and streamer discharge domain is given as a function of pl and the percent over-voltage ratio Δ. Regarding the boundary between the two discharge domains, Doctors S. Mochizuki and Y. Miyoshi in Japan, judging experimentally from the fact that discharge energy which is the transformation energy from glow to arc discharge makes a discontinuous change, decided the boundary of the two domains as a function of pl and Δ and represented it with one curve.

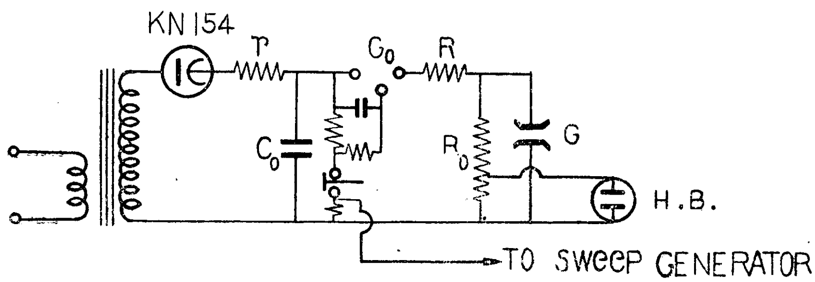
On the other hand, the so-called stepped discharge phenomenon in which breakdown voltage in the process of discharge falls by two steps as is illustrated in figure 6(A) or (B) was discovered and studied by Rogowski, Tamm and many others and was also researched much by Doctors S. Nomoto and Y. Miyoshi in Japan.

As the result, it has been recognized that the said discharge phenomenon cannot exist in streamer discharge domain but occurs in cases where it belongs to Townsend's discharge domain in terms of gap conditions and moreover when proper amount of series resistance is involved in the circuit.

The auther observed and photographed the wave form of breakdown voltage in the process of formation of spark by means of high speed Braun tube oscilloscope, and by these oscillograms examined the existence of stepped discharge phenomenon and the energy transfering from glow to arc, and so on. On the basis of these efforts, I intend to decide the boundary between the two discharge domains. Thus the aim of this paper is to decide the boundary between the two discharge domains by observing and considering it from the view point of Townsend's theory under the circumstances where Townsend's and streamer theory exist together.

II. Experimental Arrangement

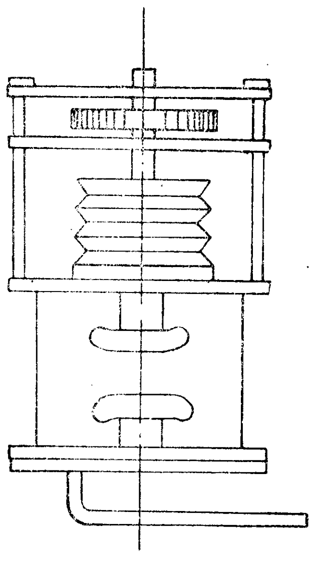
The connection diagram used in the present experiment is shown in Fig.1 (A).



(A)

Fig. 1. (A) Connection diagram of impulse-voltage generator

Impulse voltage is generated between the terminals of the test gap G by discharging the three-electrode trigger gap G_0. While G_0 is being discharged, the protective resistance r is made sufficiently large, and the capacity of the condenser C_0 is large ($16\mu F$), the charge of C_0 is independent of the condition of the rectifier supply circuit.



(B)

Fig. 1.
(B) Test gap g.

Since the steepness of wave front of impulse voltage must be made as steep as possible, much care was taken in wiring so that the inductance will be as small as possible over the whole circuit, and in parts of resistance manganin wire wound noninductively was used. As the result, the steepness could be able bellow 10^{-7} second. Moreover, since the time decrement of voltage is very small and almost rectangular as shown in Fig. 2 and the time needed for completion of the phenomenon, the subject of this research, is less than $30\mu S$ at the longest, voltage supplied from the power source can be regarded as constant during the duration of the phenomenon.

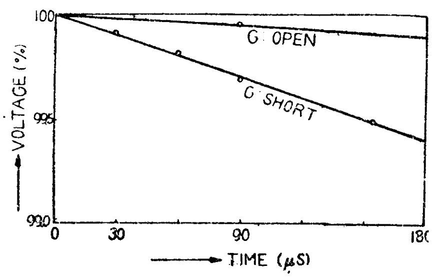


Fig. 2.
Time decrement of impulse generator

Moreover, as the statistical time lag of spark discharge increases rapidly as the decrease of pressure, and the experiment is undertaken at a various pressure from 760 mmHg to few mmHg, a constant photo-electron current is supplied to G by illumination of certain ultra violet light from the outside in order to decrease the statistical time lag.

In this case, if photoelectron current is too small in amount, it will increase the statistical time lag, causing inconvenience in carrying ont the experiment.

On the contrary if it is too large, space charge field by it is produced between electrodes, field distortion is caused and breakdown voltage also changes there by making it meaningless to impress rectangular impulse voltage. Therefore, it is necessary to select a suitable value of photoelectron current. By using the circuit as shown in Fig. 3, photoelectron current was measured. According to the result of the measurement, I adjusted by slit the amount of ultra-violet light given to the electrode so that about 10^{-12} Ampere initial photoelectron current may be supplied throughout all pressures as shown in Fig. 4.

The space charge field produced by 10^{-12} Ampere is almost negligible according

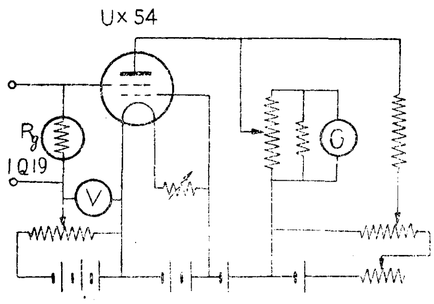


Fig. 3. Connection diagram for measuring the initial photoelectron current

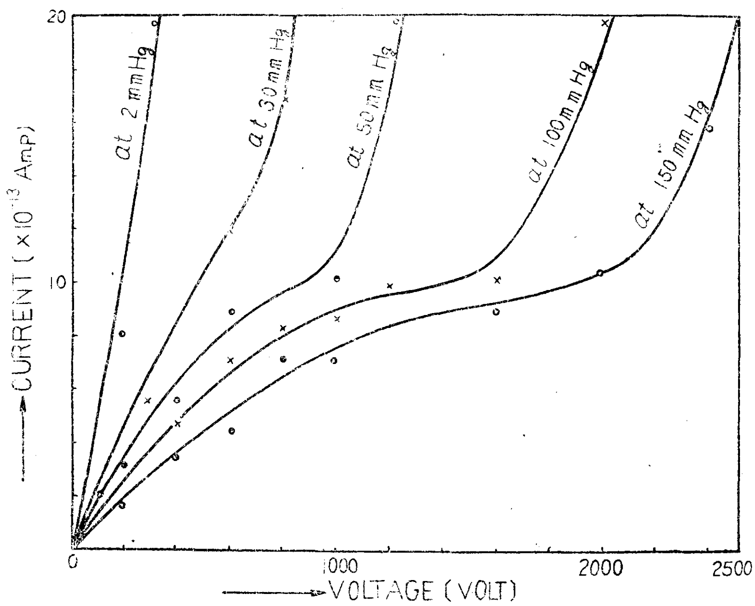


Fig. 4
Voltage-current characteristics of initial photoelectron current

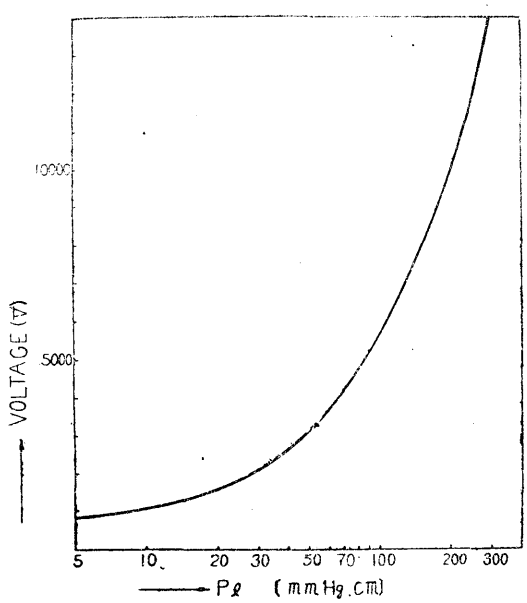


Fig. 5
Static breakdown votage for various pl.

to calculation, and the experimental results show in Fig. 5 that it does not change the threshhold voltage at all.

Since this study concerns uniform electric field, parallel plate electrodes, so-called Rogowski's electrodes of Nickel were used as the gap *G*. The reason why *Ni* was used, is mainly due to its small spattering of cathode material to the wall at breakdown discharges. If the wall is attached much by metal molecule, the photoelectron current by illumination of ultra violet light becomes less owing to its absorption or reflection at the wall.

As for construction of the *G* part, bellows is attached to one of the electrodes as is shown in Fig. 1 (B), so that gap length may be changed arbitrarily. The outside wall is made up of quarz glass to enable ultra violet light to pass through.

Three electrode trigger circuit is adjusted to synchronize with the time axis circuit of the high speed Braun tube oscilloscope. As soon as the switch *S* is closed, the axis starts the sweep, and at the same time G_0 is closed, and the rectangular impulse voltage is impressed to *G*.

III. Experimental Results

It is found that if the supplied impulse voltage increases gradually over the threshhold voltage under the gap conditions pl which are considered naturally to belong to Townsend domain in static breakdown, the discharge mechanism shifts at a constant over-voltage ratio from Townsend's to streamer domain.

Fig. 6 shows the voltage wave forms of discharge under various conditions of p, 1, Δ. These forms can be roughly classified, through observation, into four, (A) (A)′ (B) (C) of Fig. 6. As Δ is increased under an arbitrary gap condition pl, the discharge wave form progresses from (A) or (A)′ first, then to (B) and (C) at the end.

For example, we consider now at the gap condition p_1l_1 in Fig. 11. When Δ is increased under the condition $p_1 l_1$, wave form such as (A) or (A)′ is always formed in the domain between $0\sim\Delta_1$. In case Δ is increased further, two forms exist in the domain between $\Delta_1\sim\Delta_2$, one taking (A) or (A)′ wave form and the other (B) wave form. And the probability of forming (B) wave form increases as Δ becomes greater.

Then (B) or (C) wave form co-exist in the domain between $\Delta_2\sim\Delta_3$, and in this case, too, the probability of forming (C) wave form increases as Δ increases. Finally, when the over-voltage becomes over Δ_3, (C) wave form alone is observed.

From these wave form oscillograms, the duration of stepped discharge and energy transfering from glow to arc were measured and calculated, and through these results, the boundary between the two discharge domains was defined.

Begining with the conclusion first, the discharge which forms (C) wave form is accomplished by streamer mechanism, the discharge of (A) (A)′ or (B) form is

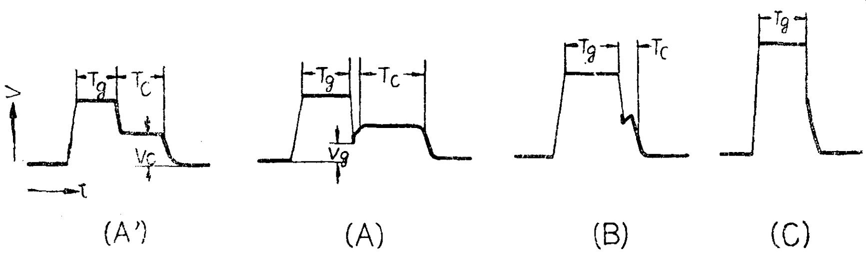


Fig. 6 B. Typieal voltage wave forms of breakdown. See Fig. 6 A

Gap conditions	Applied overvoltage ratio	Voltage wave form
p_1l_1	$0-\Delta_1$	(A) or (A)′
p_1l_1	$\Delta_1-\Delta_2$	(A) and (B) co-exist
p_1l_1	$\Delta_2-\Delta_3$	(B) and (C) co-exist
p_1l_1	above Δ_3	(C) alone

The classification of wave form at p_1l_1 in the series resistance is 2000Ω.

by Townsend's mechanism, and so the belt-form part hatched in Fig. 11 is the boundary between the two domains.

The boundary does not form a line as was advocated by doctors S. Mochizuki and Y. Miyoshi but is a domain in which the two discharge formulas co-exist over a considerable range. It is due that since it is impossible, as a matter of fact, that conditions of the cathode are always completely the same, the discharge domain cannot generally be represented by a single line.

The reason why these conclusion were made is as follows.

Regarding the discharge wave form as shown in Fig. 6, the time lag of discharge from impression of voltage to arc discharge is composed of two parts which are *Tg* and *Tc*.

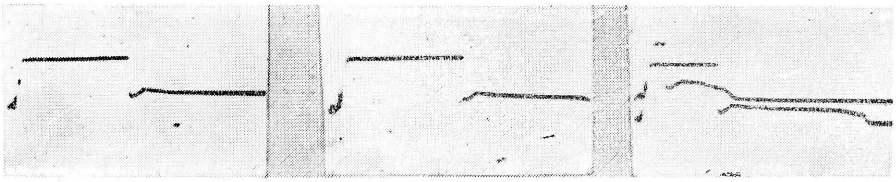
The time *Tg* represents the discharge construction time needed for breaking gases. Needless to say, the so-called statistical time lag is contained in it, and in some cases this time lag may occupy a major part of it.

The time *Tc* means the discharge construction time needed for destroying the cathode namely, the time necessary for forming cathode spot and contains less statistical elements.

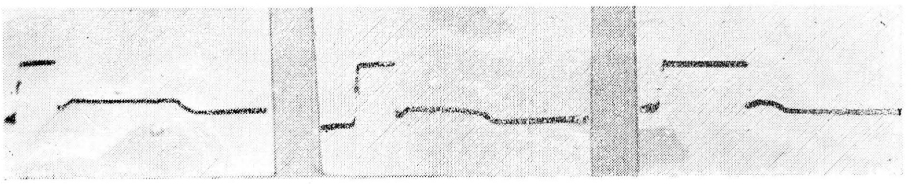
In other words, *Tg* and *Tc* are times required for completing separate phenomena which are independent to each other.

There can exist no relations. Experimental results also prove, as shown in Fig, 7. Fig. 7 is an example where p was set at 30 mmHg and l at 0.5 cm. Even when pl is given by other values, similar results are made.

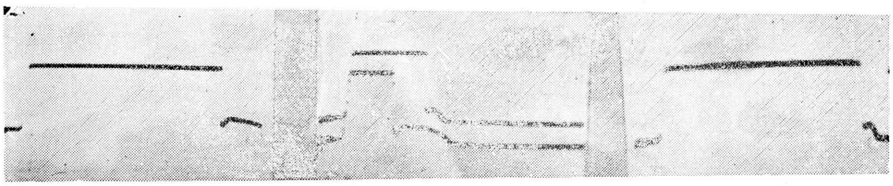
When the boundary of the discharge domains is discussed on the basis of Townsend's theory, glow discharge occurs semi-stably in the process of breakdown



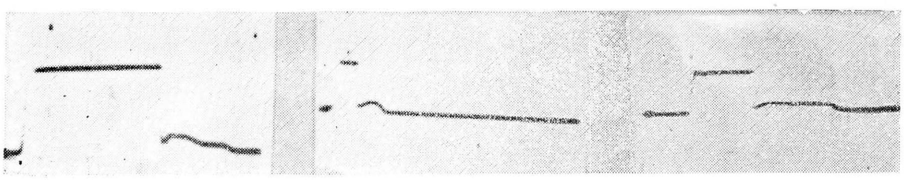
50mmHg 40% 50mmHg 50% 50mmHg 60%



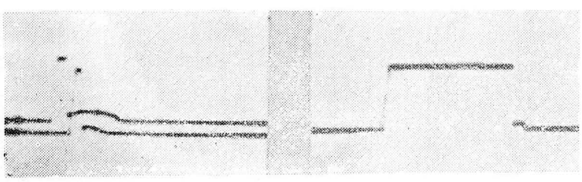
50mmHg 40% 50mmHg 80% 50mmHg 80%

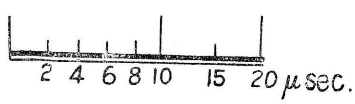


50mmHg 90% 50mmHg 100% 50mmHg 120%



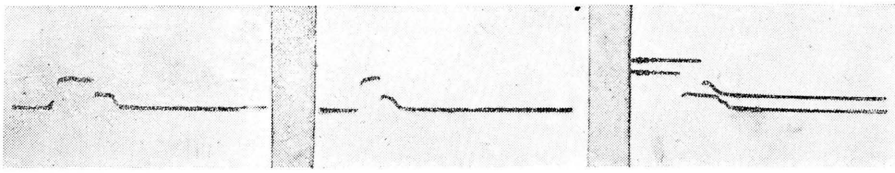
50mmHg 150% 50mmHg 170% 50mmHg 200%



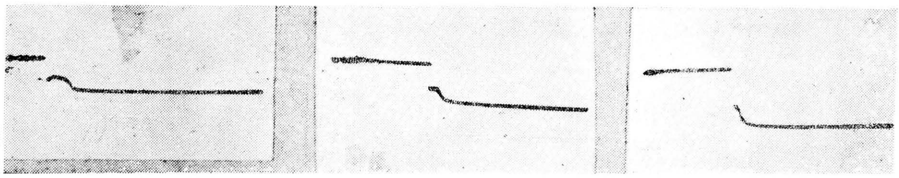


50mmHg 240% 50mmHg 240%

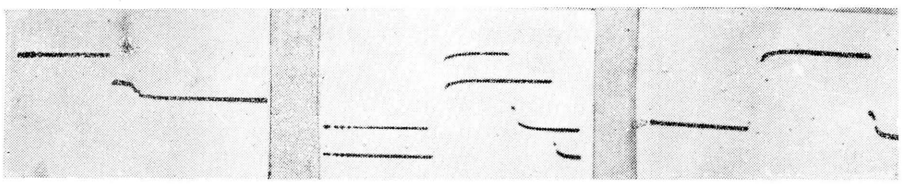
pl = 50 × 0.5 = 25mmHg cm, Series resistance R = 2000Ω



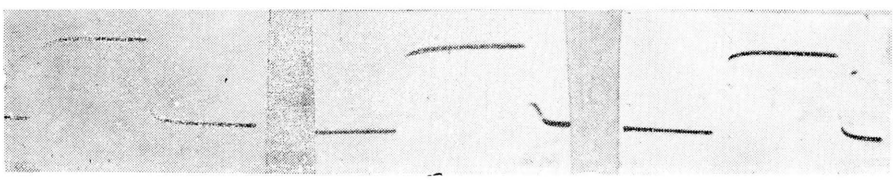
s00mmHg 40%　　100mmHg 50%　　100mmHg 60%



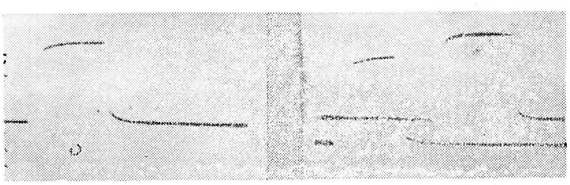
100mmHg 70%　　100mmHg 70%　　100mmHg 100%

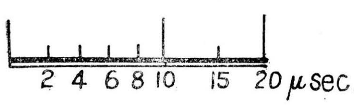


100mmHg 100%　　100mmHg 150%　　100mmHg 160%



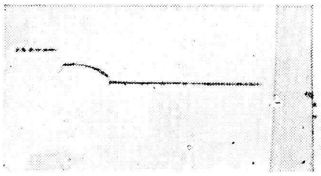
100mmHg 170%　　100mmHg 170%　　100mmHg 180%



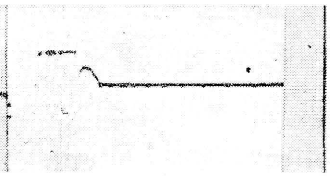


100mmHg 180%　　100mmHg 200%

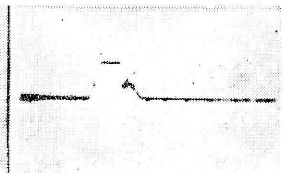
Pl = 100 × 0.5 = 50mmHg cm, Series resistance R = 2000Ω



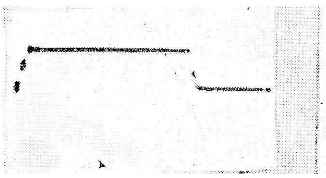
200mmHg 20%



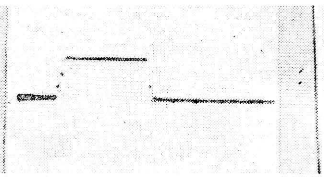
200mmHg 20%



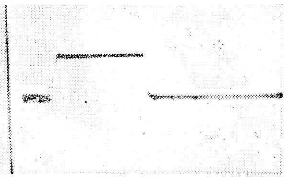
200mmHg 30%



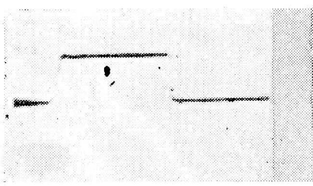
200mmHg 30%



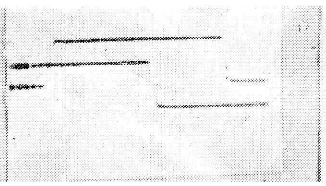
200mmHg 40%



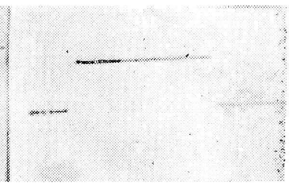
200mmHg 50%



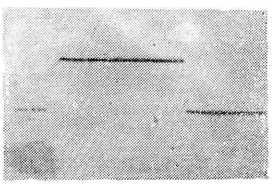
200mmHg 60%



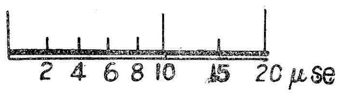
200mmHg 50%



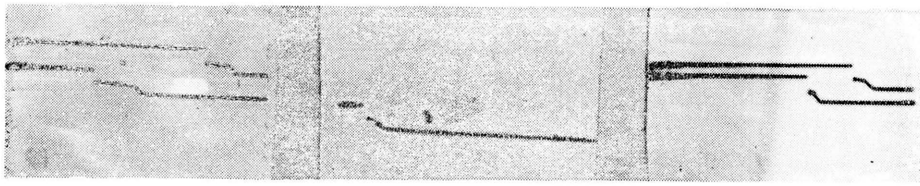
200mmHg 70%



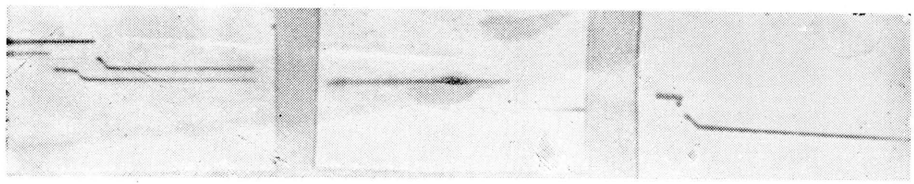
200mmHg 80%



pl = 200 × 0.5 = 100mmHg cm, Series resistance R = 2000Ω

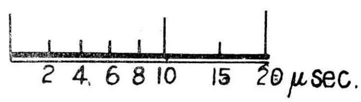


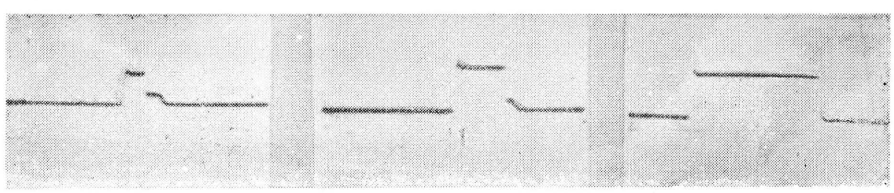
400mmHg 5%　　400mmHg 10%　　408mmHg 15%



400mmHg 20%　　400mmHg 30%　　400mmHg 30%

pl = 400 × 0.5 = 200mmHg cm Series resistance R = 2000Ω





600mmHg 2.5%　　600mmHg 10%　　600mmHg 10%

pl = 600 × 0.5 = 300mmHg cm, Series resistance R = 2000Ω

Fig. 6A. Oscillograms of voltage wave form of breakdown for various p,l,Δ.

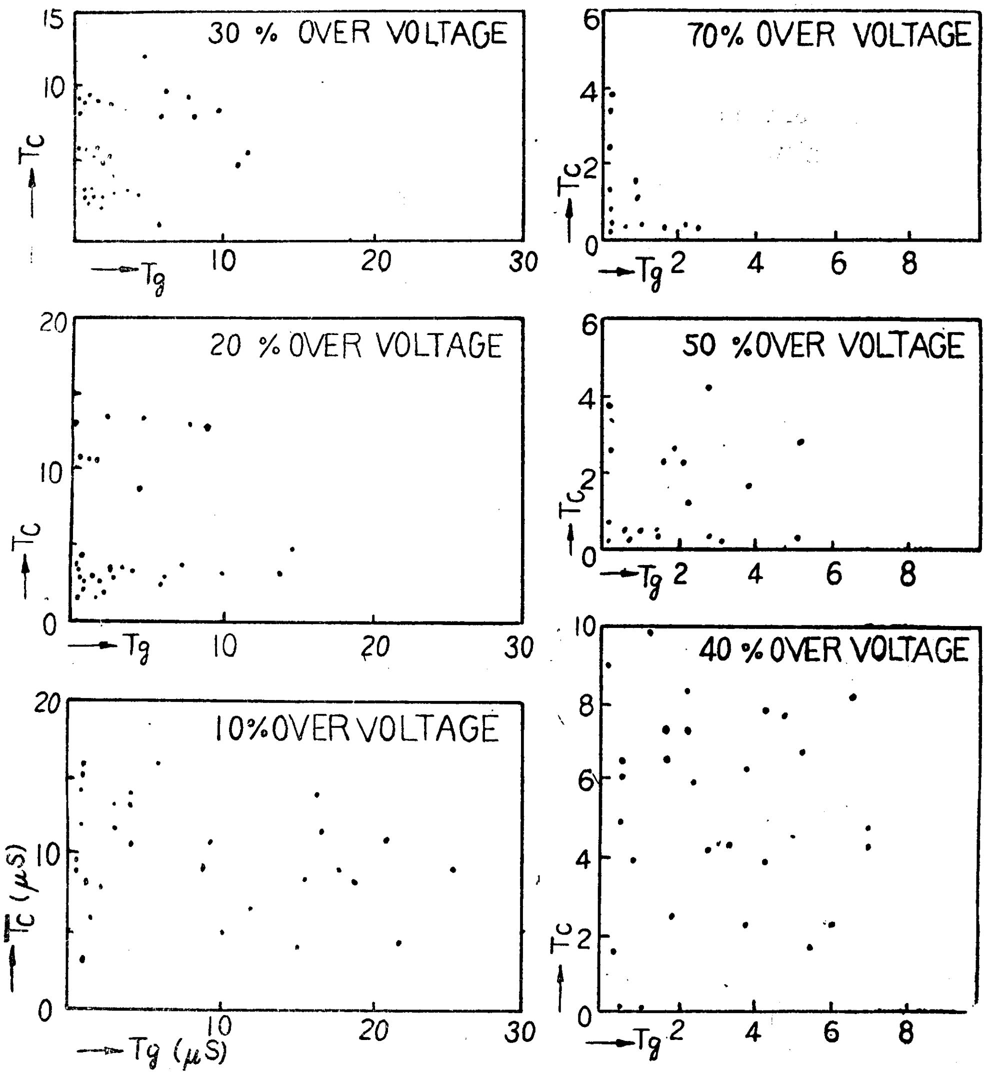


Fig. 7. Distribution of the time T_g and T_c. pl=30mmHgcm

in Townsend's domain, and arc discharge is brought about only when some energy stored during glow discharge is supplied to electrode as transfering energy from glow to arc. Accordingly, it can be interpreted that streamer is formed in case this transfering energy is zero, namely, when breakdown occurs without passing glow discharge to bring to arc.

Thus the energy during the time *Tc* and the existence of *Tc* part decide the discharge domoin.

On the other hand, even when the phenomenon is considered from the view point of streamer theory, in cases where only one electron avalanche is sufficient to make breakdown of positive streamer, the phenomenon belongs to streamer domain.

And in cases many avalanches are required, the phenomenon belongs to Townsend's domain. It cannot be considered at least that the phenomenon belongs to streamer domain in case where glow discharge occurs in the process of discharge.

On the basis of the above observation, the experiments were adjusted. First, the energy during glow discharge is calculated as follows.

$$W=\int_0^{T_c} v_c \frac{v_0-v_c}{R} dt$$

where v_c : gap voltage value at stepped discharge.
v_0 : supplied voltage, constant
R : series resistance 2000Ω

In case wave form is (A) or (A)′, the above equation turns out to be as follows.

$$W=v_c\frac{v_c-v_c}{R}\times T_c$$

The result of calculation is shown in Fig. 8, energy is generally constant in case wave form is (A) or (A)′ and energy begins to reduce rapidly and discontinuously when wave form becomes (B) and falls to zero when wave form is C. Thus it can be deduced that the part T_c represents the time needed for producing the cathode spot, judging from the fact that energy during the time is constant.

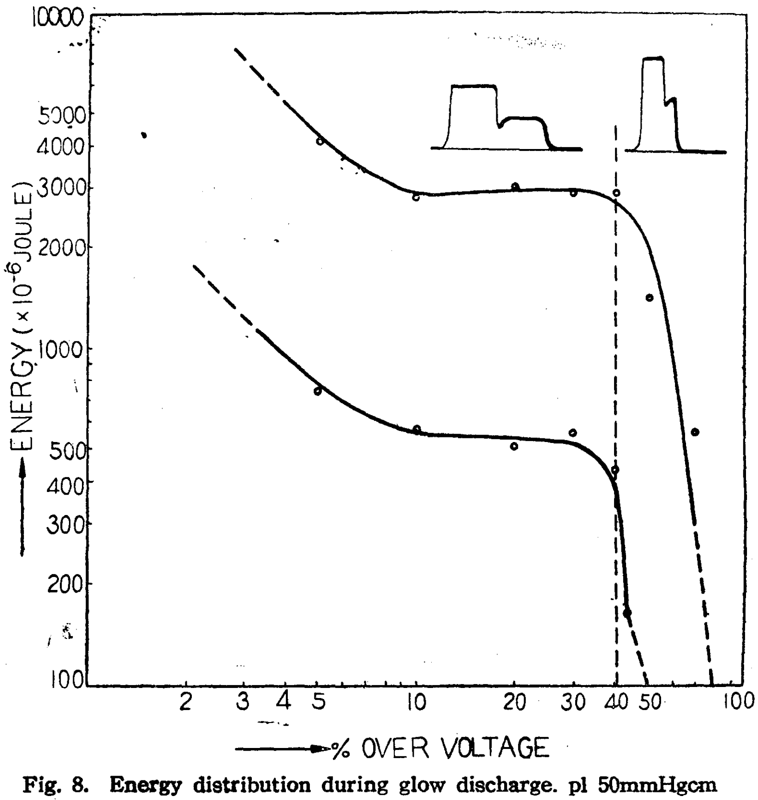


Fig. 8. Energy distribution during glow discharge. pl 50mmHgcm

Accordingly, from such a view point alone, it can be considered that (A) wave form and (B) represent the boundary between the two discharge domains, namely the discharge of form (A) represents Townsend's discharge and form (B) streamer discharge.

However, when we further examine the voltage (v_c)—current(i_c) characteristics of both discharges, the so-called positive characteristic is revealed throughout the both discharges as is shown in Fig. 9 or Fig. 10.

This clearly indicates that both forms take abnormal glow characteristic.

Accordingly, (B) wave form appears in case duration time of stepped part of (A) form is extremely small, and as discharge mechanism, both (A) (B) take the same and cannot but be considered to belong to Townsend discharge domain.

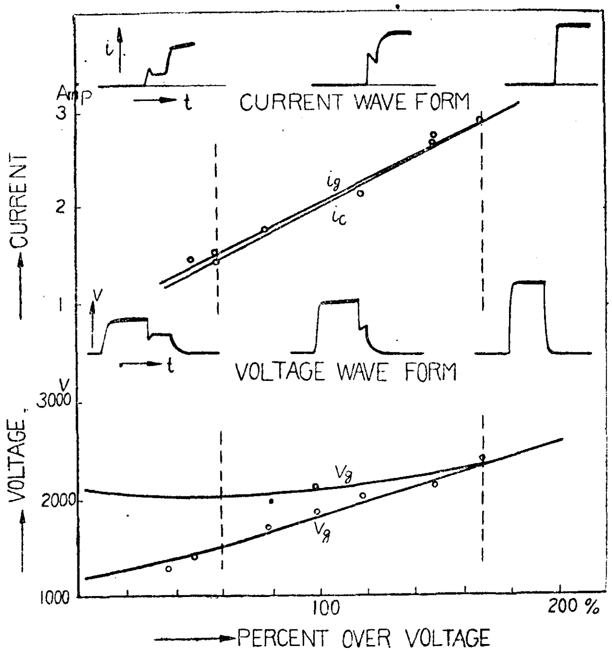


Fig. 9. Voltage and current characteristic of v_g, i_g, v_c, and i_c according too pereene over voltage ratios Δ. pl=50mmHg cm

From the above experimental and theoretical considerations, (B) and (C) wave forms constitute the boundary of both domains as stated above. By arranging experiments made under various pl and Δ conditions at series resistance 2000Ω, the hatched part in Fig, 11 was defined as the boundary between Townsend's and streamer discharge domains.

As is clear from the same figure, it is expected that the value of the critical pl of both discharge mechanisms takes considerably high in the breakdown of threshhold voltage, that is at Δ equal zero.

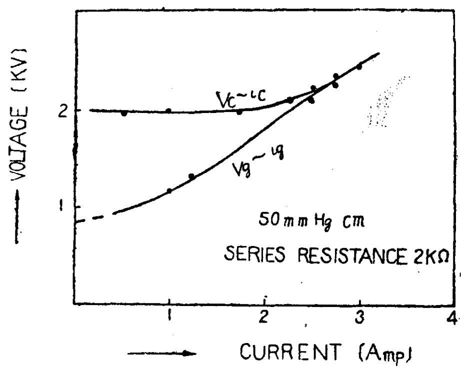


Fig. 10. Voltage-current characteristic of v_g—i_g and v_c—i_c. Pl=55mmHg cm

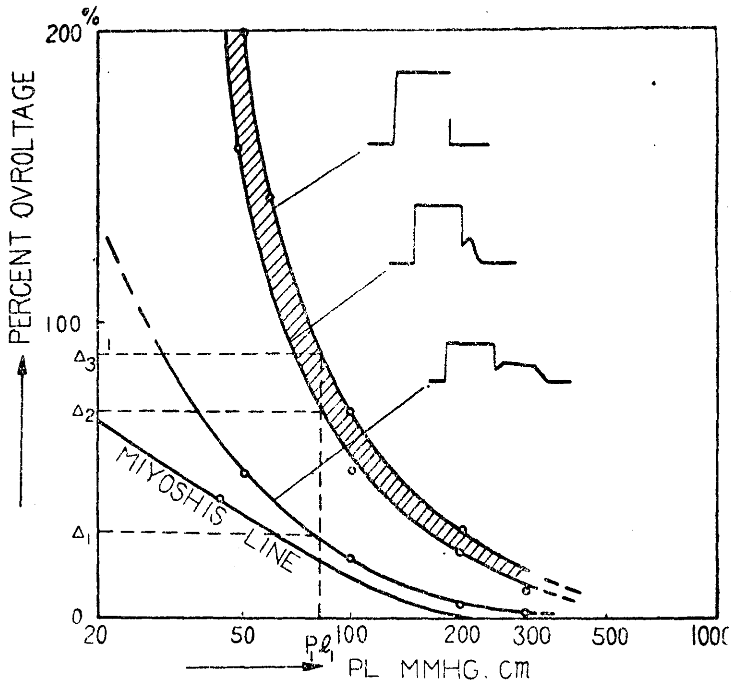


Fig. 1. Boundary between Townsend and streamer discharge mechanisms in air, series resistance R=2000Ω

IV. Discussion

This paper deduced its conclusion from Townsend theory alone. Therefore, it is premature to conclude that the boundary of the domains defined here immediately coincides with the conclusion deduced from streamer theory.

Regarding the critical value of pl of the two domains in static breakdown, about 2000 mmHg cm is the critical value according to the calculation on the basis of Meek's or Raether's equation for calculating sparking potentials. I will report on this point on another opportunity.

However, in any case, it is expected that the critical value of pl shown by this experiment will also be of very high. Thus I believe that the result will be better than when the boundary is sought only from the energy transfering from glow to arc discharge.

Furthermore, this paper deals only with results in air of series resistance R= 2000Ω., and so the research is not completed yet.

I will report on these effects on the next opportunity.

V. Acknowledgement

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