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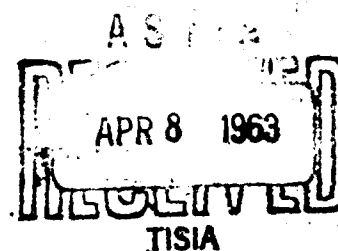
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NEW MATERIAL ON THE DEVELOPMENT OF A
NEGATIVE SPARK AND ITS COMPARISON TO LIGHTNING

by I. S. Stekol'nikov and A. V. Shkilev

- USSR -

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NEW MATERIAL ON THE DEVELOPMENT OF A NEGATIVE SPARK AND ITS COMPARISON TO LIGHTNING

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[Following is a translation of an article by
I. S. Stekol'nikov and A. V. Shkilev in the
Russian-language periodical Doklady Akademii
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782-785.]

The authors have investigated the development of a spark produced by pulse voltage in gaps -rod+plate (-r+p) and -rod+rod on plate (-r+r/p) by means of an electron-optical converter (EOP) with light amplification (1). A rounded rod, 20mm in diameter, was used as the negative electrode. In the case of -r+r/p, a rounded rod, 10mm in diameter with a height of from 2.5 to 50cm, was installed on the plate. In the case of -r+p the length of the discharge gap was varied from 100 to 300cm and for -r+r/p $S_0=270$ to 300cm. The voltage wave had the shape of 1.5x1,000 microsec with an amplitude U close to the minimum discharge voltage ($k=U/U_{min} \approx 1.0$). The electron-optical converter was used with the following objectives: 1) quartz ($D=3.5$), 2) "Jupiter-3" ($D=1.5$) and 3) "Jupiter-12" ($D=2.8$). The EOP shutter was operated on the "open-closed" principle which made it possible to obtain, on the photograph film, a static picture of the discharge processes developed at the start of the time scan. The synchronization of the EOP and the oscilloscope recording was ensured by connecting their time plates to one source of scanning voltage. The current was registered by means of a shunt connected to the measuring plate $3 \times 3m^2$. The latter was installed at a height of 15cm from the $8 \times 8m^2$ grounded plate. In order

to analyze in detail the time picture of the spark development obtained by means of the EOP, the discharge processes were photographed simultaneously by a stationary camera with a quartz objective ($D=4.5$) for which a known voltage "cutoff" method from S_0 was used by means of another gap $S_1 < S_0$.

Results of the experiments. The examples of the records obtained in gaps $-r+p$ and $-r+r/p$ are correspondingly shown in Figures 1 and 2 [See Note]. The connection of time scanning in Figure 1B occurred at instant t_0 after the front of the voltage wave. Therefore, there is first seen a static picture of discharge processes (channels ab_1 , ac_1 and others) developed up to t_0 . It is of interest to note the step character of the propagation of the channels into the gap with an average effective velocity equal to 1.1×10^7 cm/sec. The process has a complex structure: at the lower ends of the channels are observed bright flashes (possibly the stems of the pulse corona) from the bottom of which go off luminous channels in the form of "branches" of the pulse corona, and at the top of which there is a widening diffused glow. The brightness of the glow becomes weaker in the direction of the rod electrode. It ends on the tip of the common leader (line e_1-e) which develops with a velocity of 4.2×10^6 cm/sec. After t_1 branches from the bright flashes begin to touch the plate. The value of the current does not change essentially at this time (see Figure 1C). At the same time bright flashes continue to propagate towards the plate up to t_2 when there is formed a brighter branch and increase in brightness of the previously ionized channel occurs. There is a slight increase in the current at this time. Leader (kg) from the plate begins to grow only after it is touched by the stepped leader (t_3). Its initial velocity is 2×10^7 cm/sec. A "bundle of threads" (2) starts on the tip of the leader and ends on the tip of the negative leader. With the appearance of the positive leader the current rises rapidly. With the appearance of leader (kg) the velocities of both leaders become approximately equal and begin to grow rapidly. The closing of the shutter of EOP occurred at instant t_4 prior to instant t_5 of the voltage cutoff.

[Note]: In time scans the angle $> 90^\circ$ between the direction of the scan and the axis of the gap is dependent upon the characteristics of the given EOP.

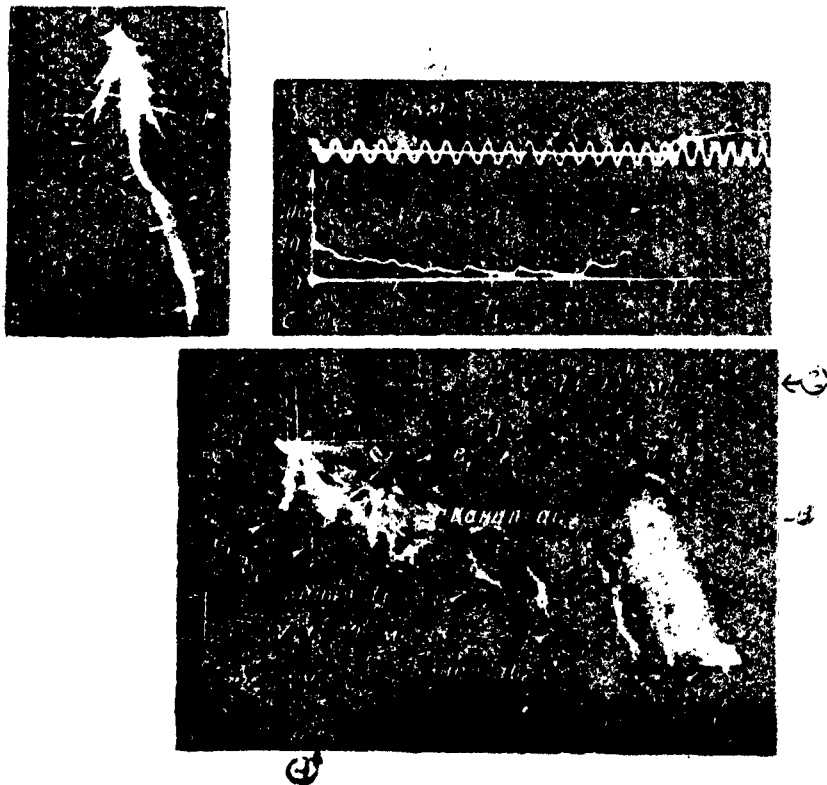


Figure 1 - Optical picture of the discharge in gap interval $-r+p$ for $S_0=2.7m$ and $k=U/U_{min} \approx 1.0$.

A-Static photograph (quartz, $D=4.5$); B-Time scan (EOP with objective "Jupiter-12", $D=4.5$); C-Current oscillogram (1), timing trace (2) and voltage pulse (3) for shutting off EOP.

Legend: 1-megacycles; 2 - cm/ sec; 3 - Channel
4-microsec

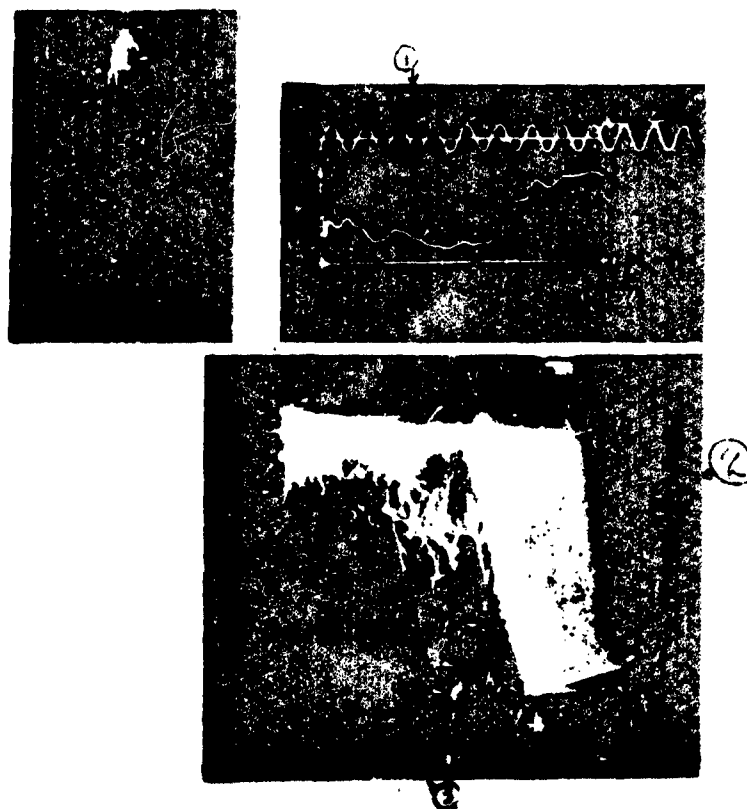


Figure 2. The same as Figure 1 except in gap $-r+z/p$ for $S_0=2.9m$ and $h=10cm$.

Legend: 1-megacycles; 2 - cm/sec; 3 - microsec

It may be concluded from Figure 1B that when voltage is applied to the gap thin channels (ab_1b , ac_1c , adf) propagate in steps in several directions from the rod electrode after the pulse corona (rod zone mm) to the plate. We shall call this process the stepped leader of the spark (See Note). The bright flashes at its ends we shall call steps and the channels going off downward from them we shall call branches of the pulse corona.

(Note): The concept of the jerky or stepped movement of the leader has been noted by several writers studying the spark by other methods (3,4).

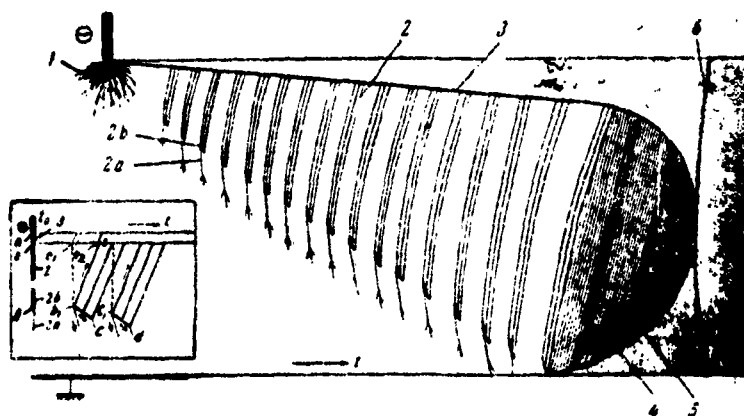


Figure 3. The arrangement for spark development in gap -r+p. 1-Pulse corona; 2-Stepped leader; 2a-pulse corona branch; 2b-step; 3,4-negative and positive leaders; 5-thread-like glow; 6-main channel; In the rectangle is shown the arrangement of the development processes for the course of elongation of the stepped leader (aeb is the static picture prior to scanning, e_2b_1c is the scan).

The spark development in gap -r+r/p is shown in Figure 2. At first the spark develops in a manner similar to the case -r+p, i.e., stepped leader (bc) propagates towards the plate. When it approaches within a certain distance of the rod installed on the plate, from the rod at instant t_1 begin to develop branches (kd) typical of branches of the positive pulse corona with an average velocity $\approx 7 \times 10^7$ cm/sec. The current thereby does not essentially change. As these branches approach the stepped leader their velocity increases. Afterglows are

comparatively small in the region passed by the tips of the branches and they are not always fixed. In the region passed by stepped leaders the brightness of the branches increases considerably. Only after the merging of the positive pulse corona branches (t_2) with the stepped leader is there observed a bright glow along the entire gap, leader ($k_1 g$) begins to develop from the grounded rod and the current increases sharply.

In a number of cases in the channel of the stepped leader there were observed disconnected leader-like channels the tips of which develop in both directions with a velocity close to that of the leader at the electrode.

Figures three and four show arrangements of spark development in the gaps $-r+p$ and $-r+r/p$. The negative pulse corona forms a zone of excess charge. At U_{min} the zone radius does not exceed $1/3 S_0$. At the zone boundaries of negative space charge there are created conditions for its penetration in one or several directions towards the plate in the form of stepped leaders. The effective velocity of propagation of stepped leaders lies within limits of $(0.8-2) \times 10^7$ cm/sec. In the course of elongation of the stepped leader there take place three processes (see insert in Figure 3): 1) a branch of the pulse corona in the form of one or several thin channels 25-50 cm long grows towards the plate with a velocity of $(1-3) \times 10^8$ cm/sec; 2) the tip of the step (full length of step equal to 5-15 cm) also propagates towards the plate with a velocity in the order of 5×10^7 cm/sec; 3) the glow which is brighter in its lower portions propagates with a velocity of $\approx 10^8$ cm/sec upward along the previously formed channel of the stepped leader. During the time of the step development this process may be repeated several times but always from the propagating tip of the step. Between the step of the leader there occur pauses in the order of one microsecond. Each succeeding step usually starts at the end of the previous step. Simultaneously with the propagation of the stepped leader towards the plate there develops from the rod a common leader with a velocity of $(1-5) \times 10^6$ cm/sec. Stepped leaders create ionization of the air and carry into the gap a negative charge which changes the initial gradient distribution along the gap increasing them to the critical values near grounded objects. This, in the case of $-r+r/p$ leads to the development of a counter process from the grounded rod of height h in the form of branches of positive pulse corona. The average velocity of their

tips is $\approx 5 \times 10^7$ cm/sec. The process originates at a certain critical height S_{cr} of the stepped leader. As the branches approach the stepped leader the velocity of the tips of the branches rises. At the moment of their merging with the stepped leader the glow flashes along the entire gap and the positive leader begins to develop from the rod. S_{cr} depends, to a great extent, on the h of the rod and its displacement with respect to the axis of the gap. S_{cr} decreases with the decrease in h . At the limit, in the case of a smooth surface ($h=0$), the stepped leader reaches the plate and from the point of contact along its channel there develops a counter positive common leader with an initial velocity of $\approx 10^7$ cm/sec. With the appearance of a positive leader for $-r+p$ as well as for gap $-r+r/p$ the velocities of both leaders become approximately the same and increase rapidly. Jumps may occur in the development of the leaders and their junction is made by a final jump (5). The latter leads to the main channel and to the completion of the breakdown.

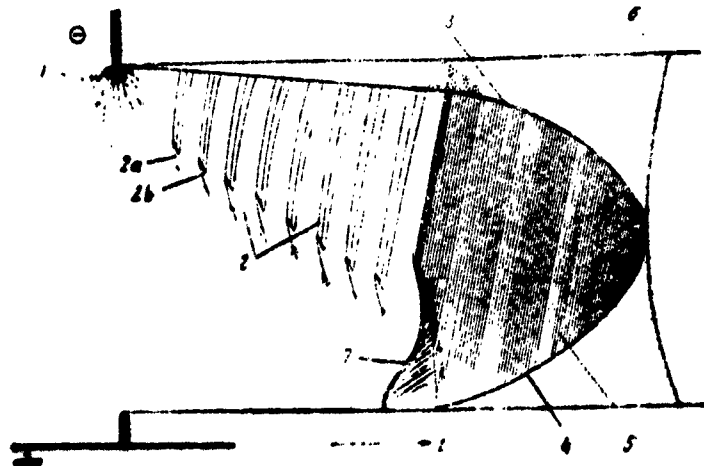


Figure 4. Spark development in gap $-r+r/p$.
 7-Branches of positive pulse corona. Remaining designations are the same as in Figure 3.

Discussion of the Results

1. The analysis of the data makes it possible to explain qualitatively the higher values of discharge voltage (U_d) in the gap $-r+p$ as compared to U_d for the gap $-r+r/p$. Actually, the introduction into the gap of a negative discharge by the pulse corona and the stepped leader reduces the potential gradients near the high voltage electrode and makes it more difficult to develop a leader from it. To continue the spark development it is necessary either to raise the voltage across the gap or to decrease the negative space charge. This latter function is accomplished by the positive leader. The positive leader originates in gap $-r+p$ only after the stepped leader touches the plate after passing the entire distance S_0 . In the case of $-r+r/p$ the positive leader originates after the stepped leader passes only part of the gap ($S_0 - S_{cr}$). This explains the lower discharge voltage.

2. The development of the negative spark is often compared to the mechanism of the formation of lightning which, in the vast majority of cases, also has a negative polarity. If, following along this line of reasoning, a comparison is made of the arrangement in Figure 3 with a known arrangement (6) based on photographic scanning of lightning made by Boys cameras or with its more recent theoretical varieties (7,8), it becomes clear that they are far from being the same. Thus, while in the case of a spark after the stepped leader touches the plate, as was noted, there does not occur immediately a formation of the main channel and a breakdown, in the case of lightning striking a plate there is assumed a development of the main channel immediately upon the arrival to the earth's surface of the stepped leader, the channel of which is considered highly conductive. The further development of the process of the stepped leader elongation of the spark does not correspond to the described mechanism of the step leader of lightning. Our photographs made by apparatus with high optical sensitivity have not discovered a "pilot-leader" in the manner postulated by Schonland (9,10). Turning to the history of this question, we shall note that in 1938 Allibone (11) made static photographs which showed clusters and diffused glows at the ends of the split-off leaders and their branches. Aside from that, Lichtenberg fig-

ures were obtained from the electrodes when voltage was cut off across the discharge gaps. In 1948, Allibone (12), referring to this data, concluded that the glows represent the "pilot-leader" in lightning. This conjecture was supported by Schonland (10).

Recently, Hagenhood, in a discussion of (7), expressed the opinion that a glow which he has photographed in a gap r-r for $S_0 = 500\text{cm}$ must be assumed to be a "pilot-leader". In view of our data the above-mentioned glows represent stepped leaders and "bundles of threads" from the tip of the developing positive leader (2). Finally, Liao and Anderson (13) confirm that on breakdown of gap r-p ($S_0 \approx 7\text{cm}$) placed in oil, there is seen an "equivalent pilot streamer" which develops downward from the end of the "initial streamer" towards the grounded plate by a method very similar to that postulated for lightning. However, the quality of the photographs and the velocity of their time scan does not provide the proper bases for such a conclusion.

There is also an essential difference in the process of spark development in gap -r+r/p (Figure 4) from proposed processes of lightning striking metallic poles (lightning rods). This case has important significance in the calculations of overvoltages which originate when electric transmission lines are struck by lightning.

From the data obtained it may be assumed that the process of lightning development based on photographs made by Boys cameras requires further clarification.

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