TITLE:

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AUTHOR(S):

ITO, Ichiro; WAKAZONO, Yoshikazu; FUJINAKA, Yuzo

CITATION:

ITO, Ichiro ...[et al]. On the Causes of Misfires of Electric Detonators in Mines. Memoirs of the Faculty of Engineering, Kyoto University 1955, 17(1): 60-77

ISSUE DATE:

1955-03-31

URL:

http://hdl.handle.net/2433/280320

On the Causes of Misfires of Electric Detonators in Mines

By

Ichiro ITO, Yoshikazu WAKAZONO, and Yuzo FUJINAKA

Department of Mining

(Received November 1954)

Introduction

Inspite of the fact that the electric detonators are in good condition, misfires often take place which result in interference with blasting operations at the simultaneous firings such as millisecond blastings. These misfires are considered due to the following two causes: (1) leakage of igniting current and (2) lack of uniformity in ignitability of the fuse-heads. The former has been discussed by the authors in the previous report[1], and the latter will be discussed in the present work.

The lack of uniformity in the precision of ignitability of the fuse heads is due to the dispersed timing of ignition. The causes of the misfires which take place when several detonators are connected in series can be conceived as follows: whereas some of the fuse-heads of the detonators are ignited and their electric bridges are ruptured, the rest of the fuse-heads are not ignited.[2]

The ignition process of fuse-heads under various igniting currents was filmed by means of a 16 millimeter high speed motion picture camera in the hope that clarification of their ignition mechanism might be of value in discovering the specific causes of misfires. The experiments described in the present paper, the authors believe, have contributed to solve this problem to a considerable extent.

The number of the same experiments conducted at various phases ranged from ten to fifty depending on the objectives and the importance of the data anticipated.

Experiments

1. Material for Experiment

As shown in Fig. 1, the fuse-head employed was composed of a platinum bridge-wire coated with 5 milligram lead dinitrosoresorcinate as the first layer, and over it, with 5 milligram mixture of lead rhodanate and potassium chlorate as the second layer. The bridge-wire, SWG 49, is made of platinum alloy containing 10 % of iridium, 2 millimeters in length, with 0.9 Ω electric resistance and its tolerance is within

$\pm 0.1\,\Omega$.

Films were made on the ignition process both in the open and in the closed tubes. In the latter case, the fuse-heads were charged, as shown in Fig. 2, with delay composition in transparent quartz tubes of 6 millimeters in diameter. The device was purported to enable the authors to observe the ignition processes in a condition as close to those in the detonating caps as possible.

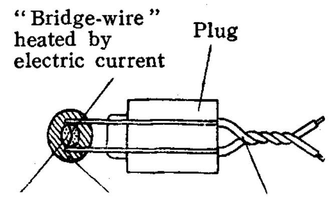

Fig. 1 Fuse-head

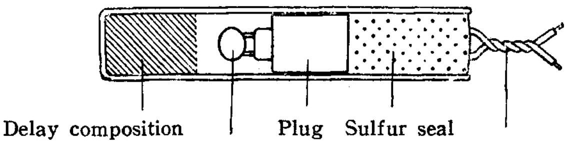

Fig. 2

2. Photographing

a. Apparatus

A 16 millimeter high speed motion picture camera of the Fukuhara style[3] was used for this experiment. As shown in Fig. 3, a small neon glow bulb (N_1) was employed as a time indicator and the electrodes of which were so designed as to flash alternately in an exact frequency based on a tuning fork oscillator.

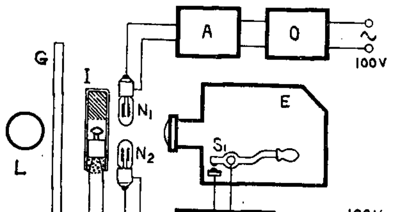

Fig. 3

E: 16 mm high speed motion picture camera
L: Background light for the bright field photographing
G: Background screen (frosted glass)
I: Testing fuse-head
N_1: Time indicating neon bulb
N_2: Switch-in-time indicating neon bulb
S_1: Starting trigger
O: Tuning fork oscillator
A: Amplifier
X: Power supply

For the purpose of marking the switch-in time, another neon bulb (N_2) was connected in parallel to the fuse-head circuit. Thus it was devised so that the ignition process and the two neon bulbs would be filmed together in the same frame.

b. Method

In this series of experiments, the methods of both bright field and dark field photography were employed because it was difficult to film the sparks by the bright field method. The cranking speed ranged from 2,300 to 3,200 frames per second.

3. Electric Current Applied

A storage battery (B_2) was used to supply the necessary current. Due to its low tension (6 volts) which was insufficient for indicating the switch-in time, however, the circuit, as shown in Fig. 4, was employed: that is, a thyratron (V) was adapted and a neon bulb (N_2) was connected to its anode circuit so that the former would be discharged by switching.

A relay (X_1) was used in order to regulate the time lag (0.1 to 4.0 seconds) between the moment of crank-in of the camera and the moment of the electrification of the fuse-head.

Further, in case of the fuse-heads in closed tubes, a device, as shown in Fig, 5, was employed so that time required for rupture of the bridge-wire could be measured.

Part I. Bright Field Photography

1. Ignition in the Open

The motion picture was taken of ignition processes in the open applying the currents of 0.7amp., 1.0amp., 1.5 amp., 2.0 amp., 3.0 amp., and 6.0 amp.

Generally speaking, the ignition process is classified into the following stages:

(a) When electrified, the fuse-head is caused to rupture partially and then a part of it is

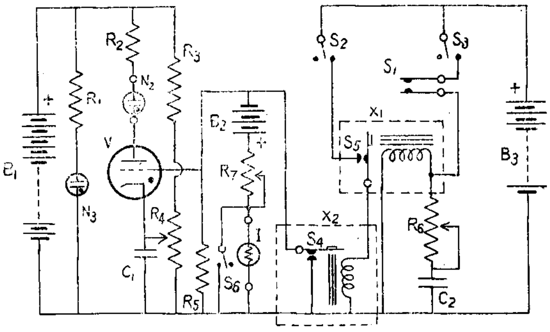

Fig. 4

B_1: Source for neon bulb (200 V)
B_2: Source for ignition (6 V)
B_3: Source for relay operation (24 V)
V: Thyratron (type 66-GT)
N_2: Switch-in-time indicating neon bulb
N_3: Pilot neon bulb
S_2, S_3, S_6: Ganged switches
S_4, S_5: Relay contacts
S_1: Contact point of high speed motion picture camera
R_1: Stabilizer for N_3 (100 KΩ)
R_2: Stabilizer for N_2 (10 KΩ)
R_3: Voltage dropper (50 KΩ)
R_4: Bias adjuster (10 KΩ)
R_5: Grid resistor (100 KΩ)
R_6: Time lag regulator (50 KΩ)
R_7: Igniting current regulator (10 Ω)
I: Testing fuse-head
C_1: Cathode by-pass condenser (10 μF)
C_2: Time delaying condenser (500 μF)
X_1: Primary relay
X_2: Secondary relay

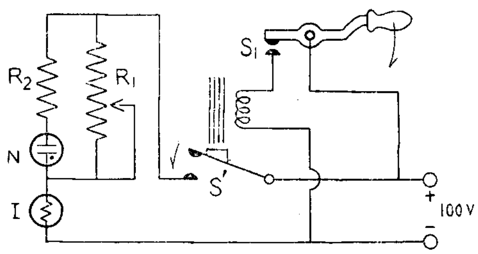

Fig. 5

S_1: Starting trigger
S': Relay switch
R_1: Igniting current regulator
R_2: Stabilizer for neon bulb
N: Switch-in and rupture indicating neon bulb
I: Testing fuse-head

blown away in powder. (For convenience, this stage is referred to as the "excitation time" and is marked with a "t_f" symbol. The time value has been obtained by measuring the time from electrification to the particular stage or step. The same shall apply hereafter with an exception that the prefix capital T, in place of small t, designates the case in the dark field photography.)

(b) At this moment, the flame appears for the first time and it gradually grows bigger. (This stage is referred to as the "inflammation time" shown with a symbol "t_i".)

(c) The flame reaches the maximum. This stage is referred to as the "maximum flame time" which is designated by a symbol "t_{max}".)

(d) The flame decreases and extinguishes. (This stage is referred to as the "extinguishing time" which is designated by a symbol "t_e".)

Photo. 1 shows the stages when 2.0 amp. was applied for ignition, and photo. 2 shows the case of 0.7 amp. The time values obtained under various igniting currents are shown in Table 1. and Fig. 6. The figures shown in the tables contained in this paper always show both the upper limit and the lower limit of the time values of individual stages.

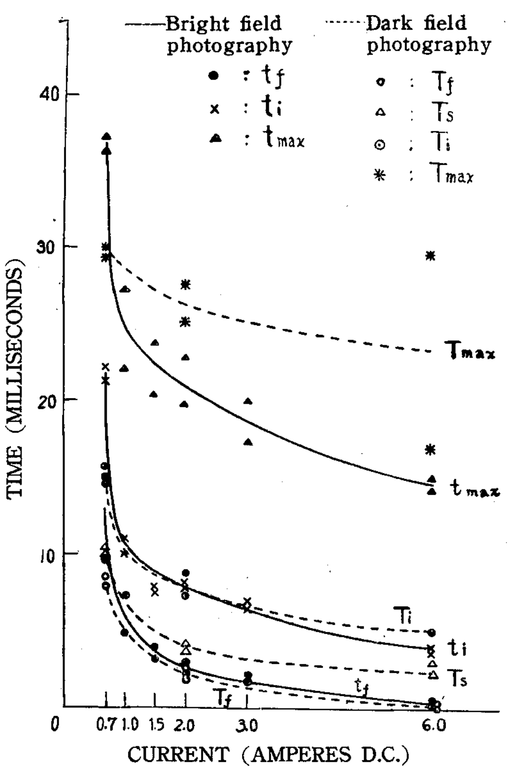

Fig. 6

Table 1.

Igniting current (A)	0.7		1.0		1.5		2.0		3.0		6.0	
Excitation time [t_f]	9.7	15.7	4.8	7.3	3.2	3.9	2.2	3.0	1.8	2.2	0.3	0.6
Inflammation time [t_i]	21.3	22.2	10.0	11.0	7.4	7.8	7.8	8.1	6.4	6.9	3.9	3.8
Maximum flame time [t_{max}]	36.3	37.2	27.3	35.2	20.4	23.8	22.8	19.8	17.3	20.0	14.2	15.0
Extinguishing time [t_e]	51.0	65.1	41.1	48.3	40.4	35.0	36.9	34.4	27.3	31.3	26.7	30.0

Unit of time: Milliseconds

Although the ignition caused by currents exceeding 0.7 amp. showed a similar tendency as described above in individual stages with the exception of a slight difference in time, in the case of 0.7 amp., it was observed that funnel-shaped gas or smoke gushed out (photos. 2-1 and 2).

The foregoing discussion and observation may be summed up in the following interim suggestion: When the amperage applied is below 1.5 amp., the time required for each one of the four stages is not uniform, whereas in case of 2.0 amp. or more, the influence exercised by the amount of amperage is relatively small and weak.

2. Ignition in the Closed Tube

The motion picture was taken of ignition processes of fuse-head in the closed tube applying the currents of 0.7 amp., 1.0 amp., 1.5 amp., 2.0 amp., and 3.0 amp.

The general tendency of the ignition processes is as follows:

(a) When electrified, the end of the fuse-head is blown up in fragments and powder. This stage corresponds to the "t_f" stage.

(b) A flame is caused and it grows bigger. This corresponds to the "t_i" stage.

(c) The flame reaches the delay composition. This stage shall hereafter be referred to as the "flame contact time" and be shown with a new symbol of "t_R".

(d) The flame reaches the maximum. This stage corresponds to the "t_{max}" stage. Halation is recognized in the photographs.

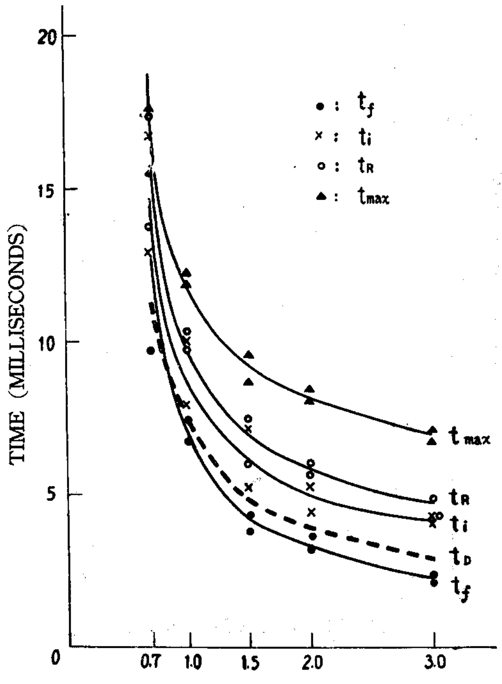

Fig. 7

(e) The flame decreases and extinguishes. This stage corresponds to the "t_e" stage.

Photo. 3 shows the ignition phenomena at each stage when 2.0 amp. is applied. The results obtained under various ignition currents are shown in Table 2 and Fig. 7.

Table 2.

Igniting current (A)	0.7		1.0		1.5		2.0		3.0	
Excitation time [t_f]	9.7	15.5	6.7	8.4	3.8	4.3	3.2	3.6	2.1	2.4
Inflammation time [t_i]	12.8	16.7	7.9	10.0	5.2	7.1	4.4	5.2	4.3	4.1
Flame contact time [t_R]	13.8	17.4	9.7	10.3	6.0	7.4	6.0	5.6	4.8	4.3
Flame maximum time [T_{max}]	17.6	19.8	11.8	12.2	8.6	9.5	8.0	8.4	7.1	6.7

Unit of time: Milliseconds

3. Consideration

Compared with the ignition in the open, the time required for ignition in the closed tube is shorter and halation caused by the flame at its maximum is shown on the film. By this, it is evident that deflagration (powder explosion) is caused by the fuse-head because of the ignition taking place in the airtight tube. Since the ignition of the fuse-head is the dominating factor over the blasting effect the igniting current exercises vital influence over the blasting.

From the above-mentioned experimental evidences, it is considered that in case igniting currents below 2.0 amp. are applied, the ignition is greatly affected by their amperage and even under the same amperage, the dispersion of time at the individual stages described in the preceding paragraphs is relatively large. Therefore, it is considered that the igniting currents of 2.0 amp. or more should be employed for simultaneous blasting.

Part II. Fuse-heads Incorporated in Electric Detonators

The blasting time, which is referred to as " t_D ", of the electric detonators equipped with fuse-heads of the same type as employed in the previous experiments described in the foregoing chapters, was measured by an oscillograph. The results are shown in Table 3 and in the broken line in Fig. 7. The ignition currents applied in these experiments were 0.7 amp., 1.0 amp., 1.5 amp., 2.0 amp., and 3.0 amp.

Table 3.

Igniting current (A)	0.7		1.0		1.5		2.0		3.0	
Blasting time [t_D]	10.0	12.0	6.7	8.0	4.0	5.4	3.5	4.3	2.7	3.1

Unit of time: Milliseconds

From the above experiments, a peculiar phenomenon was observed: that is, the curve indicating the blasting time was always found between the excitation time and the inflammation time. In other words, " t_D " always preceded " t_i ".

The experiments, described in the following part, were conducted for the purpose of investigating into this peculiar tendency by means of the dark field photography.

Part III. Dark Field Photography

1. Ignition in the Open

The ignition processes of fuse-heads in the open were filmed by the dark field photography with electric currents of 0.7 amp., 2.0 amp., and 6.0 amp. applied.

The process, when 2.0 amp. was applied, is shown in Photo. 4 and the observation can be summarized as follows; when the film was made by the bright field photography, the changes of the fuse-head on its surface was not clearly recognized, whereas it was clearly observed by the dark field photography that the body of the fuse-head itself was heated as shown by Photo. 4–1. This stage corresponds to that of the excitation time described in (a), 1. Part I.

It was also observed by the dark field photography that the matter blown away at the stage corresponding to that of the excitation time were numerous sparks and hot slags driven out of the body of the fuse-head. This is evidenced in Photos. 4–2 and 3. The phenomena observed at other individual stages were almost the same as in the case of bright field photography.

In the cases in which the amperage of igniting currents applied was low, for example 0.7 amp., the amount of sparks and hot slags was small, whereas in the cases where the amperage was relatively high, for instance 6.0 amp., the amount was large. Photos. 5 and 6 show the comparison.

It is suggested, therefore, that the dark field photography is more advantageous in observing slight changes during the ignition processes than the bright field photography, and that what is called the excitation time or "t_f" in the bright field photography can be divided in the dark field photography into the "excitation time in the dark field photography," or "T_f" and the "sparking time", or "T_s". For the discrimination purpose, the time values obtained by the dark field photography are prefixed by capital T's and are shown by dotted lines in Fig. 6.

2. Ignition in the Closed Tube

The ignition processes of fuse-heads in the closed tube were filmed by the dark field photography with electric currents of 0.7 amp., 1.0 amp., 2.0 amp., and 3.0 amp. applied. The ignition processes can be generally classified into the following stages:

(a) Several milliseconds after electrification, the surface of the fuse-head is heated (excitation time or "T_f").

(b) A part of the fuse-head is blown up in burning fragments (sparking time or "T_s").

(c) The hot slags or the burning fragments reach the delay composition (spark contact time or "T_r").

(d) A flame is caused from the body of the fuse-head (inflammation time or

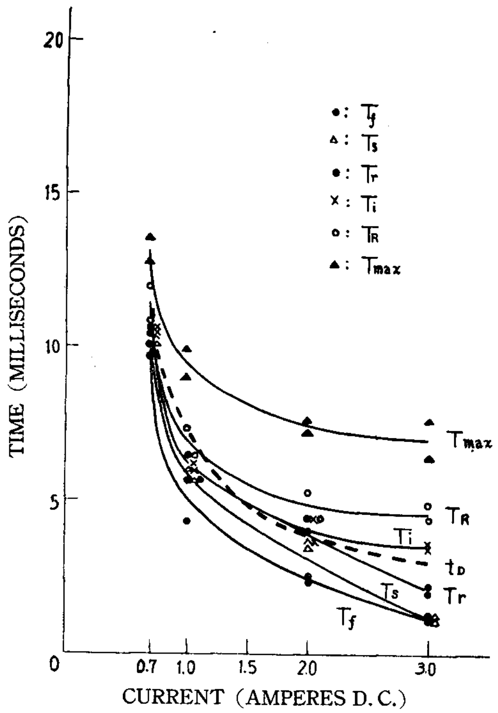

Fig. 8

" T_i ").

(e) The flame grows bigger and reaches the delay composition (flame contact time or " T_R ").

(f) The flame reaches the maximum and causes deflagration (maximum flame time or " T_{max} ").

(g) The flame decreases and is extinguished (extinguishing time or " T_e ").

Photo. 7 shows the process when 2.0 amp. was applied. The time values at each stage under various currents applied are shown in Table 5 and in Fig. 8.

3. Consideration

As described in the preceding paragraphs (1 and 2, Part III), the dark field photography revealed the fact that the blown powders and fragments as observed by the bright field

Table 4.

Igniting current (A)	0.7		2.0		6.0	
Excitation time [T_f]	7.9	8.5	2.0	2.4	0.4	0.5
Sparking time [T_s]	10.4	10.2	4.0	4.0	3.1	2.5
Inflammation time [T_i]	14.9	14.6	7.6	8.8	11.3	5.0
Maximum flame time [T_{max}]	29.4	30.0	30.4	25.2	29.6	17.0
Extinguishing time [T_e]	46.8	45.1	52.0	47.6	41.6	38.0

Unit of time: Milliseconds

Table 5.

Igniting current (A)	0.7		1.0		2.0		3.0	
Excitation time [T_f]	10.1	9.7	6.0	7.3	2.4	2.4	1.2	1.2
Sparking time [T_s]	10.1	10.1	7.3	7.7	3.6	3.6	1.2	1.2
Spark contact time [T_r]	10.5	10.5	7.3	8.1	4.0	4.4	2.0	2.0
Inflammation time [T_i]	10.5	10.5	7.7	7.7	3.6	4.4	3.6	3.6
Flame contact time [T_R]	12.0	10.8	8.1	9.0	4.4	5.2	4.4	4.8
Maximum flame time [T_{max}]	13.6	12.8	10.7	11.6	7.2	7.6	6.4	7.6

Unit of time: Milliseconds

photography were composed mostly of sparks and hot slags. And the two stages, namely, the excitation time (T_f) and the sparking time (T_s) which could not be distinguished by the bright field photography, were clearly distinguished by the dark field method.

Table 3 and Table 5 show the range of the blasting time (t_D) and the individual igniting stages included therein. They are interpreted as follows:

(a) When 0.7 amp. was applied, the blasting time (t_D) ranged from 10.0 to 12.0 milliseconds and within this range were included the excitation time (T_f), the sparking time (T_s), the spark contact time (T_r), the inflammation time (T_i), and the flame contact time (T_R).

(b) When 1.0 amp. was applied, " t_D " ranged from 6.7 to 8.0 milliseconds and " T_f ", " T_s ", " T_r ", and " T_i " were included within the range.

(c) When 2.0 amp. was applied, " t_D " ranged from 3.5 to 4.3 milliseconds and " T_s ", " T_r ", and " T_i " were included in the range.

(d) In the case 3.0 amp. was applied, " t_D " range was between 2.7 to 3.1 milliseconds and only the spark contact time (T_r) was included within the range.

From the above observation, it can be concluded that in the cases in which the currents of low amperage such as 0.7 amp. are applied, the dispersing range of the blasting time (t_D) is relatively wide and so is the dispersing range of time value at each stage of ignition; and, consequently, it is not evident at which stage the detonator is initiated.

It can also be concluded that the higher the amperage of applied currents are (as in the case of 1.0 amp. and 2.0 amp.), the narrower become the ranges of dispersion of the blasting time and the fewer stages are included within the ranges.

It is worthy of note that when the applied amperage reaches as high as 3.0 amp., the igniting stage included within the range of blasting time is nothing but " T_r " or the spark contact time. This particular phenomenon is interpreted as an evidence that the detonator can be initiated, not by the flame blown out of the fuse-head, but by the sparks and hot slags which have been observed by the dark field photography. Therefore, the fact that the blasting time preceded the inflammation time, as described in Part II, explains that the detonating caps are initiated by the jetting sparks and hot slags.

The ranges of dispersion vary depending upon the igniting stage where the initiator is initiated. The length of the blasting time also varies depending upon the stage where the ignition of the initiator occurs.

Part IV. Rupture of Electric Bridge and Simultaneous Firing

1. Rupture of Platinum Bridge-wire in Closed Tube

   a. Experiment

By means of the dark field photography, studies were made on the time required for rupture of platinum bridge-wire ("rupture time"——" T_w ") and on the condition of ignition thereat. Photos 8–11 are the results.

As indicated in Fig. 5, it was so designed that a neon glow bulb that indicates the switch-in time would be off at the instant the rupture of platinum bridge-wire occurred.

Photo. 8 shows the case when 0.7 amp was applied and the neon bulb was put off at its stage 5, which corresponds to the stage following the " T_{max} " as explained in the preceding part.

In the case of 1.0 amp., it was put off at stage 5 of Photo. 9, which corresponds to the stage of " T_{max} ".

In the case of 2.0 amp. as evidenced by Photo. 10, it was put off at its stage 3 which corresponds to the " T_i " stage.

In the case of 3.0 amp., the neon bulb was put off at the stage 2 of Photo 11, corresponding to the stage of " T_r ".

Table 6.

Igniting current	Time value (Photograph)	Time value (Oscillograph)	Blasting time
0.7	14.7	17.5	11.0
1.0	9.0	11.2	7.4
1.5	—	6.7	4.7
2.0	3.8	3.6	4.0
3.0	1.6	1.4	2.9

Unit of time: Milliseconds

b. Consideration

Table 6 shows the time value for rupture of the bridge-wires under various ignition currents. The values were obtained by the experiments described above. The table also shows the time values obtained by another series of experiments conducted in closed tubes and measured by an oscillograph. For comparison, it further includes the time values of blasting (t_D) of detonating caps obtained by experiments described in Part II.

From this table, it is observed that the higher the applied amperage is, the faster the time required for rupture of bridge-wire become. It is also observed that in case 1.5 amp. or below is applied, the value of rupture time (T_w) is larger than that of blasting time (t_D). This is because the bridge-wire is ruptured by the blasting of detonating caps rather than by the electrification of bridge-wire itself.

On the other hand, in case 2.0 amp. or more is applied, the value of rupture time (T_w) is smaller than that of the blasting (t_D). This is because the bridge-wire is cut off by its electrification rather than by the blasting of detonating cap. Despite such early rupture, the ignition of the fuse-head makes a smooth progress. This is because currents with higher amperage give larger igniting energy to the bridge-wire.

On the contrary, in case the currents of lower amperage are applied, elevation of temperature is slow; despite long application time, the igniting energy is small; consequently, the excitation time lasts longer. This results in larger dispersion of time values at individual stages as described in the foregoing part. Accordingly, if the currents of low amperage are applied, misfires at simultaneous firings are more frequent.

It is proposed, therefore, that the currents of high amperage are desirable for successful firing even though early rupture of the bridge-wire takes place. For practical purposes, it is further proposed that the currents of 2.0 amp. or more should be employed in order to prevent misfires.

2. Simultaneous Firing

The motion picture was taken by the dark field photography of simultaneous firing of fuse-heads within closed tubes which were set in six rows and connected in series. The igniting currents applied were 0.4 amp., 0.6 amp., 0.8 amp., 1.0 amp., 1.5 amp., and 2.0 amp.

The following results, shown in Table 7, were obtained by the experiments.

Table 7.

Igniting current (A)	Simultaneous firing of six fuse-heads					
	1	2	3	4	5	6
0.4	19.2	misfire	misfire	20.4	20.4	20.4
0.6	12.2	12.0	13.6	15.1	12.8	misfire
0.8	5.6	5.6	6.0	6.0	6.8	5.6
1.0	4.9	4.1	5.3	4.9	4.5	4.9
1.5	2.7	3.1	2.3	2.3	3.4	2.3
2.0	2.0	2.0	2.0	2.0	2.0	2.0

Unit of time: Milliseconds

When 0.4 amp. was applied, two of six fuse-heads caused misfire; and one of six, when 0.6 amp. was applied, resulted in misfire; but when 0.8 amp. was applied, no misfire took place, even though the dispersion of ignition time was observed.

Thus, in case the amperage of the applied currents is low, misfires take place, and even when successfully fired, the dispersion of ignition time marks a characteristic tendency. The above results also shows, as evidenced by the previous experiments, that in order to prevent the dispersion of the ignition time value, the application of higher amperage would be more advantageous.

Conclusion

In conclusion, the following points on the ignition processes of fuse-heads have been clarified by the high-speed motion pictures taken in both dark and bright field photography.

1. The fuse-heads with double coating of the lead dinitrosoresorcinate and the mixture of lead rhodanate and potassium chlorate are ignited in the following order:

 (a) The fuse-heads are heated.

 (b) Sparks and hot slags are jetted out.

 (c) A flame comes out and extinguishes.

2. The igniting process of fuse-heads conducted in closed tubes is different from that conducted in the open. Powder explosion is characteristic with the the ignition in the closed tubes.

3. When such a fuse-head is enclosed in detonating caps, it is considered that the electric bridge-wire causes rupture by its electrification under the applied current of 2.0 amp. or more, whereas, in case less than 2.0 amp. is applied, it is ruptured by blasting of the detonating cap.

4. In order to reduce the dispersion of the blasting time value of electric detonators, the kind of fuse-head that gives out powerful igniting energy at the early stage of ignition process is desirable.

5. Ignition of the initiator of electric detonator is more likely caused by sparks and hot slags which come out of the fuse-head prior to inflammation rather than by flames blown out of it.

6. When such fuse-heads are used, the currents to be applied should be 2.0 amp. or more, and less than that is liable to cause misfires at simultaneous firings.

Acknowledgements

The authors feel greatly indebted to Professor Rempei Goto for his facilitating us with the use of his camera in the early stage of these experiments. We must also offer our hearty thanks to Mr. Masayuki Yamada, superintendent, Nibuno plant, Nihon Kayaku Co., Ltd., for his kind cooperations in presenting us much of the necessary fuse-heads. Also for direct assistance in the experiments, our special thanks are due to our assistant, Miss Motoko Yoneda.

The parts of this investigation are indebted to the financial support of the Ministry of Education and thanks are also due to the Ministry of Education.

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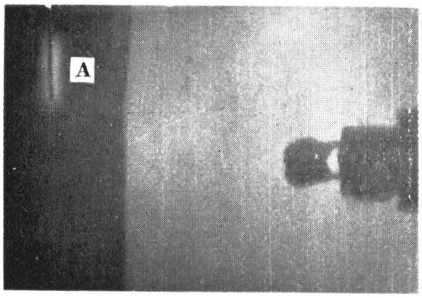
Photo. 1

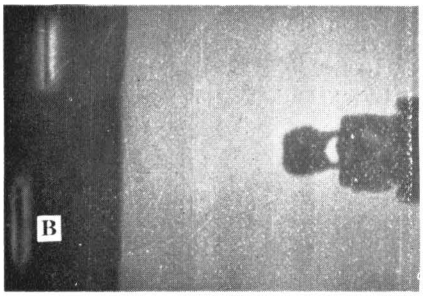
Bright field photography in the open
2.0A., 2,980 frames/second



1

Before firing

(A) Time indicating neon bulb

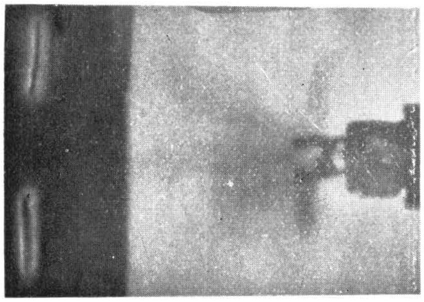


2

Switch-in time

Frame No. 1
0 ms

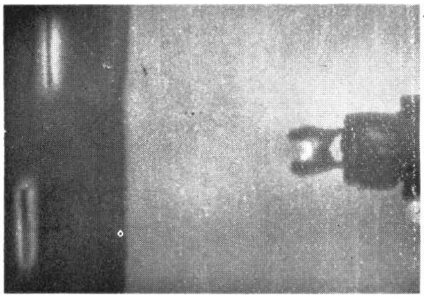
(B) Switch-in-time indicating neon bulb



3

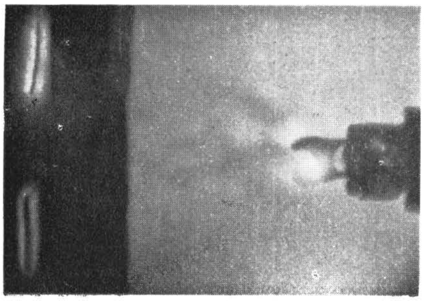
Excitation time

Frame No. 10
3.0 ms



4

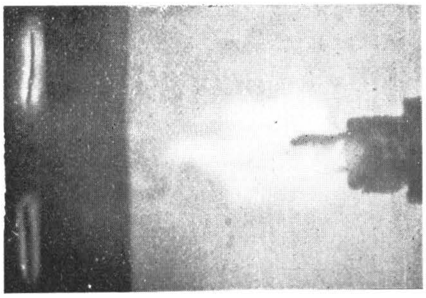
Frame No. 18
5.7 ms



5

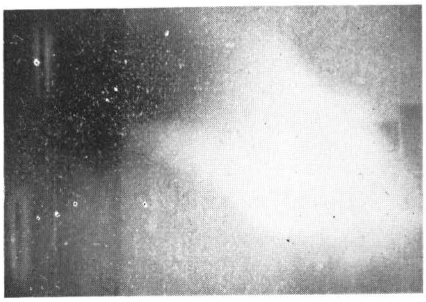
Inflammation time

Frame No. 26
8.4 ms



6

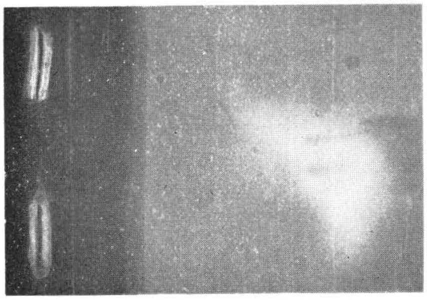
Frame No. 31
10.1 ms



7

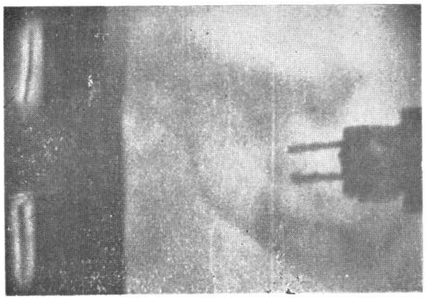
Maximum flame time

Frame No. 60
19.8 ms



8

Frame No. 89
29.6 ms



9

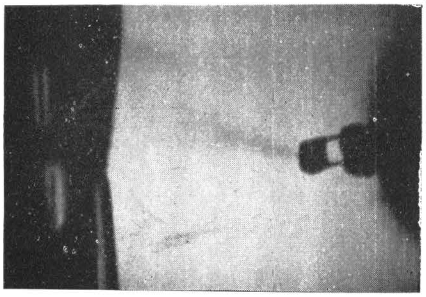
Extinguishing time

Frame No. 103
34.3 ms

Photo. 2

Bright field photography in the open
0.7A., 3,200 frames/second

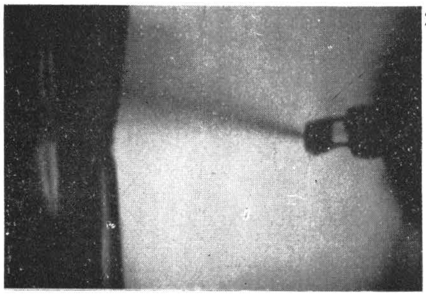
1



Excitation time

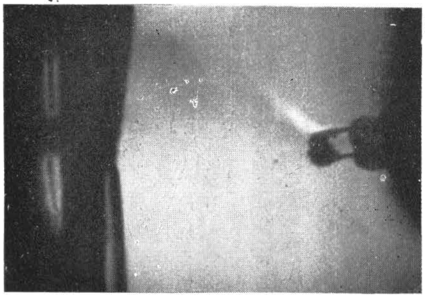
Frame No. 38
11.6 ms

2



Frame No. 41
12.8 ms

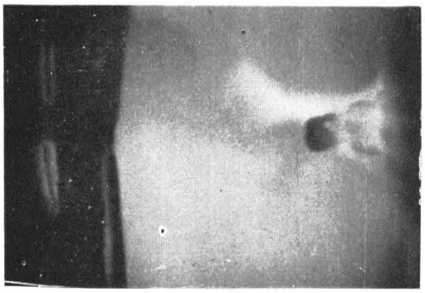
3



Inflammation time

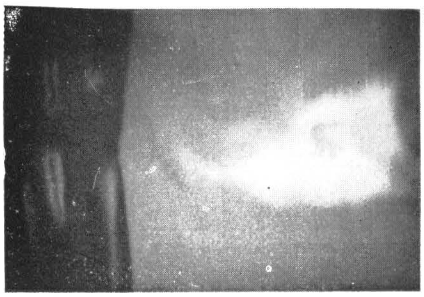
Frame No. 60
18.4 ms

4



Frame No. 74
22.8 ms

5



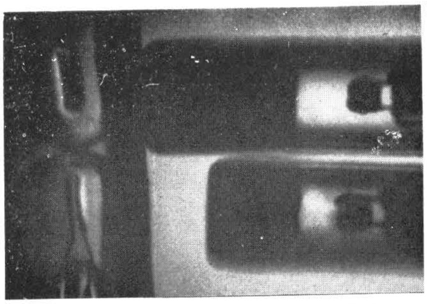
Maximum flame time

Frame No. 89
27.5 ms

Photo. 3

Bright field photography in closed tube
2.0 A., 2,330 frames/second

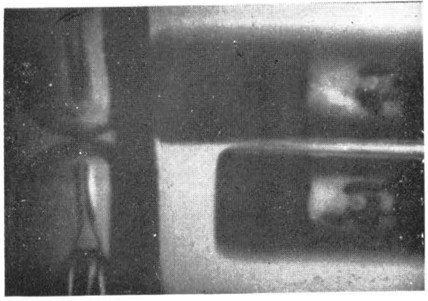
1



Frame No. 9
3.2 ms

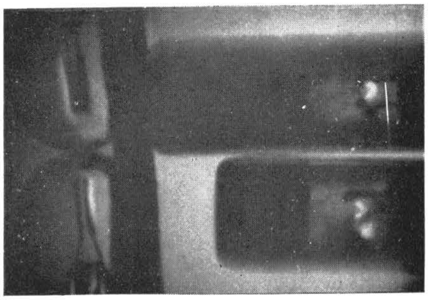
←Excitation time

2



Frame No. 10
3.6 ms

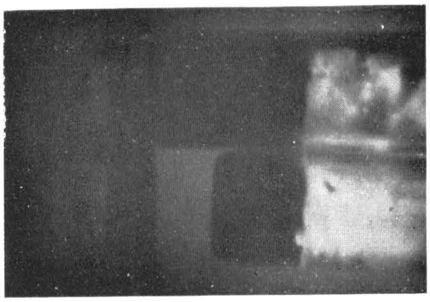
3



Frame No. 12
4.4 ms

←Inflammation time

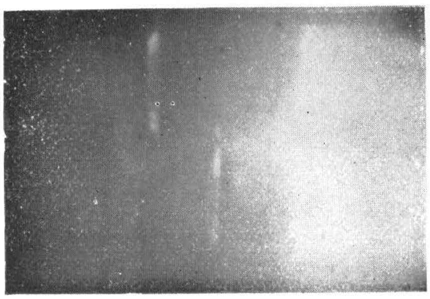
4



Frame No. 16
6.0 ms

←Flame contact time

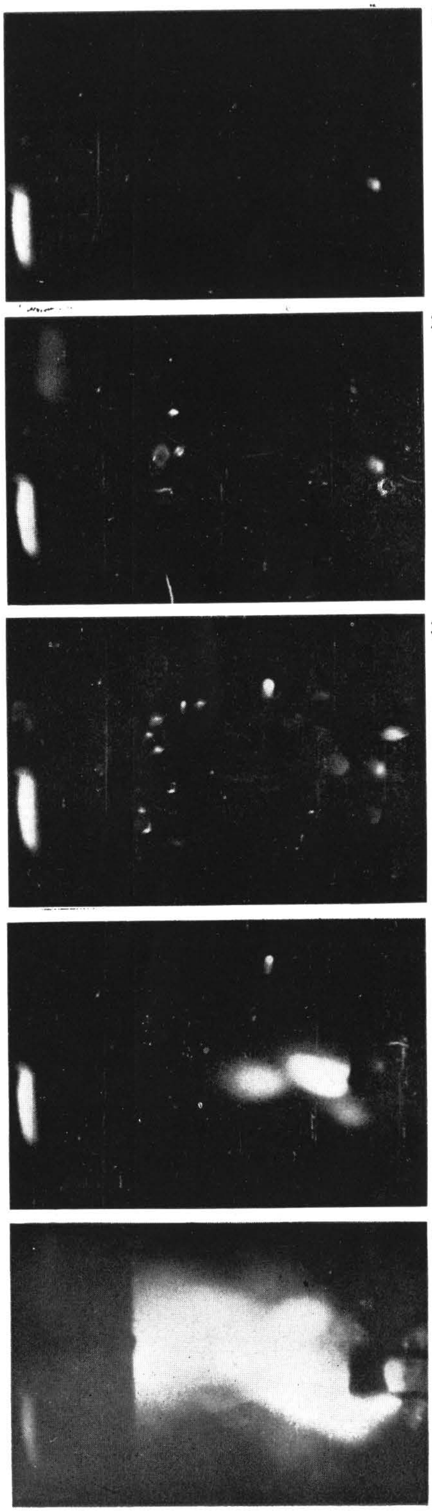
5



Frame No. 21
8.0 ms

←Maximum flame time

Photo. 4
Dark field photography in the open
2.0A., 2,500 frames/second



1 Excitation time
Frame No. 7
2.4 ms

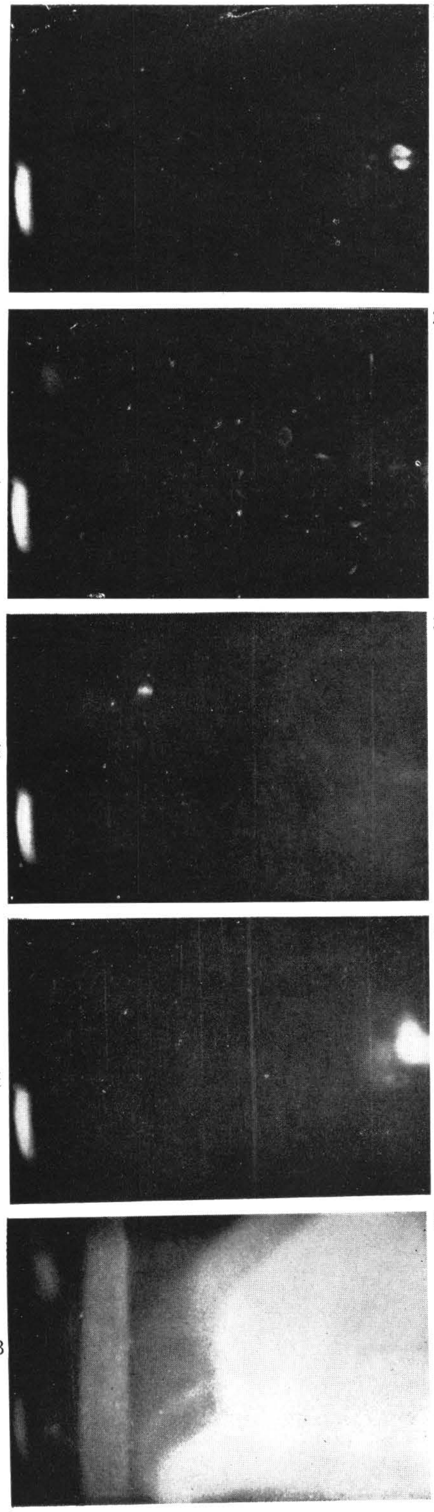
2 Sparking time
Frame No. 11
4.0 ms

3 Frame No. 19
7.2 ms

4 Inflammation time
Frame No. 23
8.8 ms

5 Frame No. 33
12.8 ms

Photo. 5
Dark field photography in the open
0.7A., 2,420 frames/second



1 Excitation time
Frame No. 20
7.9 ms

2 Sparking time
Frame No. 26
10.4 ms

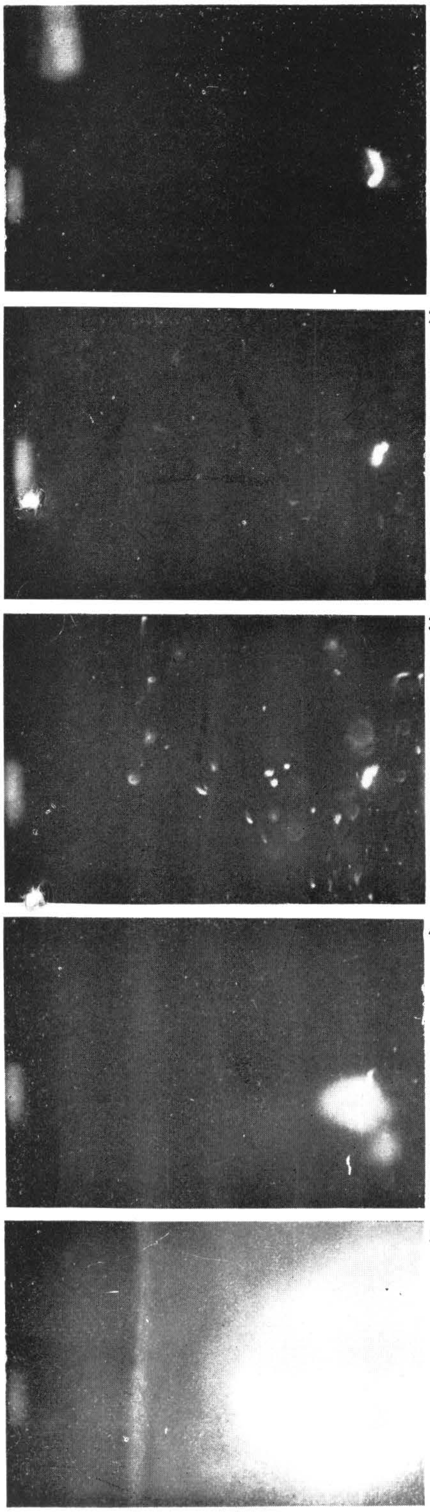
3 Frame No. 32
12.8 ms

4 Inflammation time
Frame No. 37
14.9 ms

5 Maximum flame time
Frame No. 72
29.4 ms

Photo. 6

Dark field photography in the open
6.0A., 2,570 frames/second



1 Excitation time
Frame No. 2
0.4 ms

2 Sparking time
Frame No. 9
3.1 ms

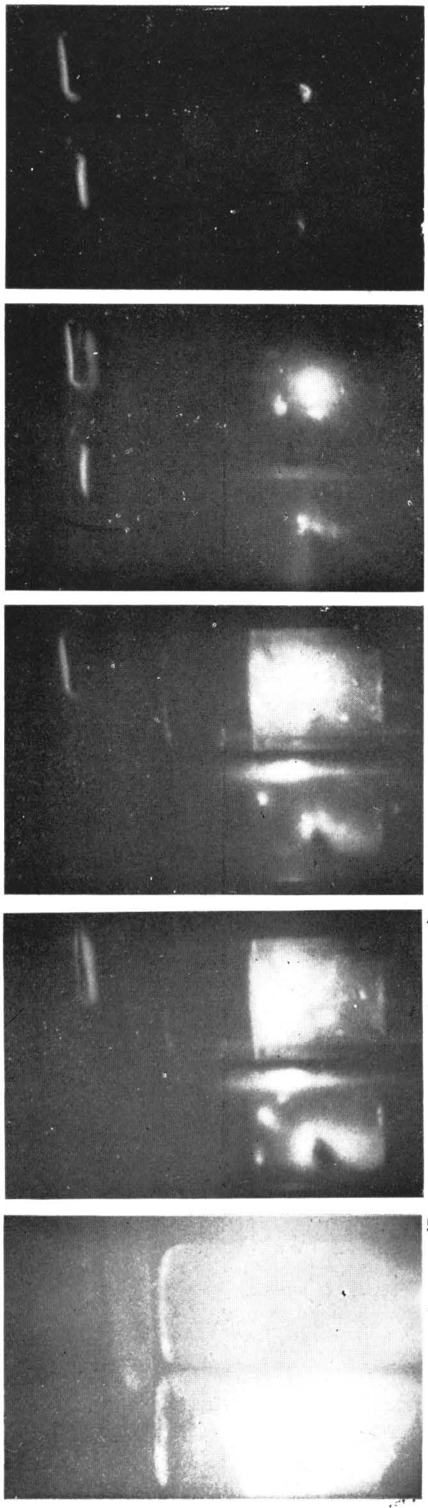
3 Frame No. 13
4.7 ms

4 Inflammation time
Frame No. 30
11.3 ms

5 Maximum flame time
Frame No. 77
29.6 ms

Photo. 7

Dark field photography in closed tube
2.0A., 2,500 frames/second



1 ←Excitation time
Frame No. 7
2.4 ms

2 ←Sparking time and inflammation time
Frame No. 10
3.6 ms

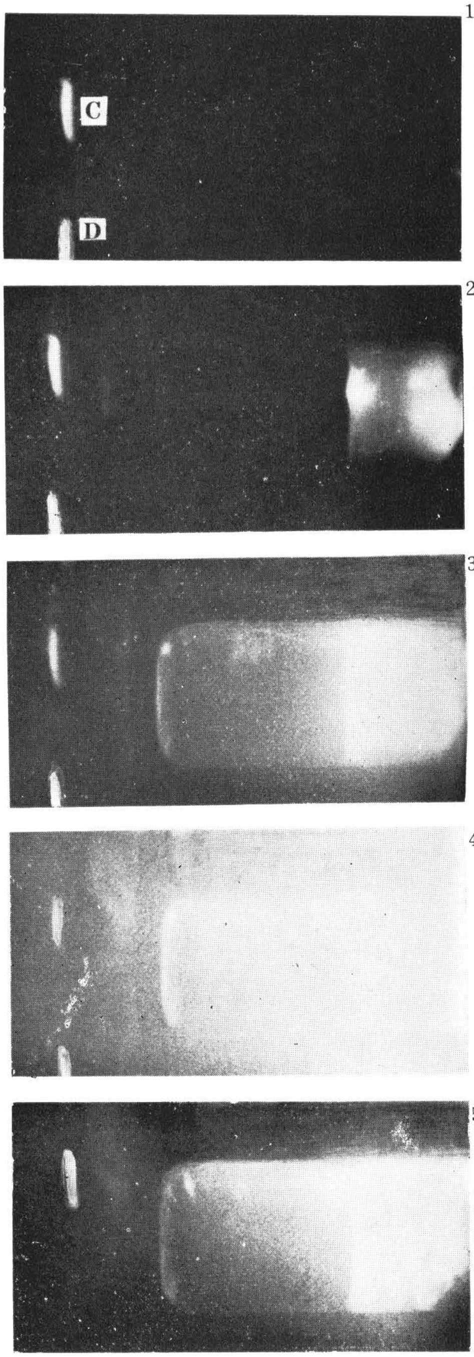
3 ←Spark contact time
Frame No. 11
4.0 ms

4 ←Flame contact time
Frame No. 12
4.4 ms

5 ←Maximum flame time
Frame No. 19
7.2 ms

Photo. 8

Dark field photography in closed tube
0.7A., 2,580 frames/second



1 Excitation time
Frame No. 26
9.7 ms

(C) Time indicating neon bulb
(D) Rupture indicating neon bulb

2 Frame No. 28
10.5 ms

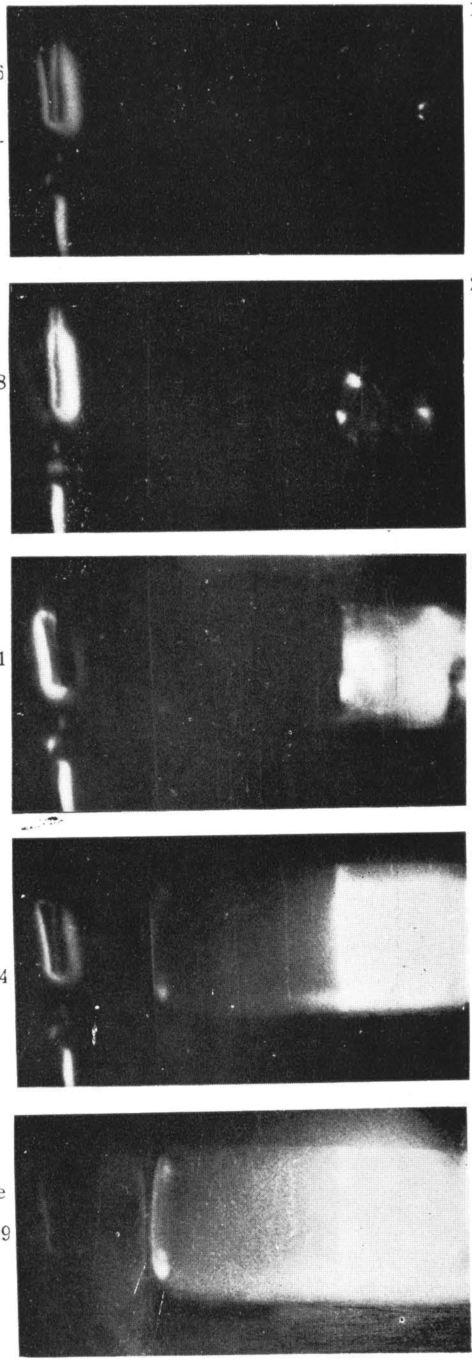
3 Frame No. 31
11.6 ms

4 Maximum flame time
Frame No. 34
12.8 ms

5 Rupture time
Frame No. 39
14.7 ms

Photo. 9

Dark field photography in closed tube
1.0A., 2,330 frames/second



1 Excitation time
Frame No. 15
6.0 ms

2 Frame No. 18
7.3 ms

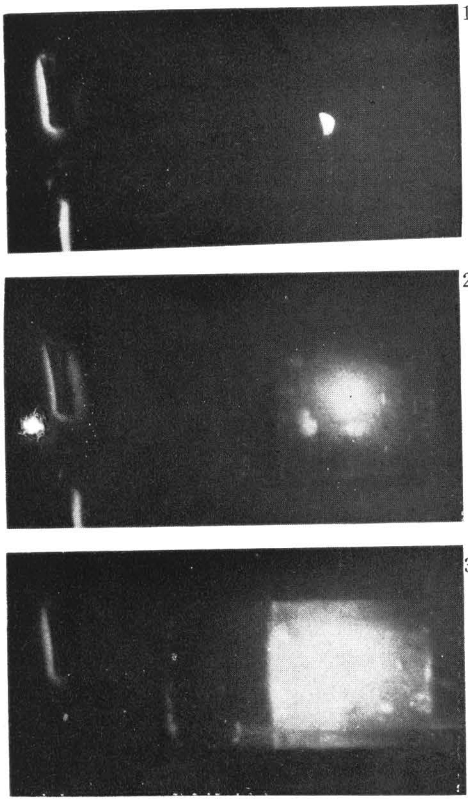
3 Frame No. 19
7.7 ms

4 Frame No. 21
8.6 ms

5 Maixmum flame time and rupture time
Frame No. 26
10.7 ms

Photo. 10

Dark field photography in closed tube
2.0A., 2,500 frames/second



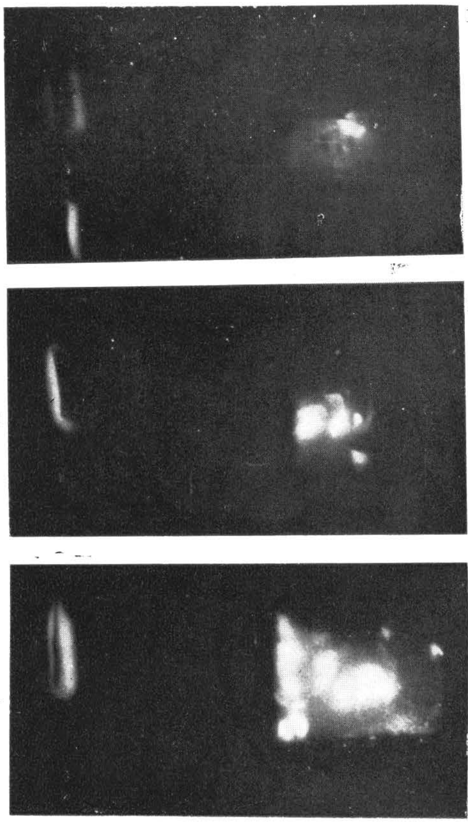
1 Excitation time
Frame No. 7
2.4 ms

2 Inflammation time
Frame No. 10
3.6 ms

3 Rupture time
Frame No. 11
4.0 ms

Photo. 11

Dark field photography in closed tube
3.0A., 2,500 frames/second



1 Excitation time
Frame No. 4
1.2 ms

2 Sparking time and rupture time
Frame No. 5
1.6 ms

3 Frame No. 10
3.6 ms