IGNITION CRITERIA AND FLAME KERNEL DEVELOPMENT
BETWEEN BREAKFLASH ELECTRODES IN EXPLOSIVE GAS MIXTURES

by

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Thesis presented for the degree of Master of Philosophy
in the faculty of Electrical and Control Engineering
of the University of Surrey, Guildford.

1969
## Contents

<table>
<thead>
<tr>
<th>Preface</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>1</td>
</tr>
<tr>
<td>1. General approach to ignition studies.</td>
<td>2</td>
</tr>
<tr>
<td>1.1. Introduction.</td>
<td>2</td>
</tr>
<tr>
<td>1.2. The criteria of ignition.</td>
<td>2</td>
</tr>
<tr>
<td>1.3. Ignition by electrical discharges.</td>
<td>6</td>
</tr>
<tr>
<td>1.4. The importance of breakflash tests.</td>
<td>7</td>
</tr>
<tr>
<td>2. Review of previous work</td>
<td>9</td>
</tr>
<tr>
<td>2.1. Definitions</td>
<td>9</td>
</tr>
<tr>
<td>2.1.1. Minimum igniting energy.</td>
<td>9</td>
</tr>
<tr>
<td>2.1.2. Minimum igniting current.</td>
<td>10</td>
</tr>
<tr>
<td>2.1.3. Minimum igniting duration.</td>
<td>10</td>
</tr>
<tr>
<td>2.1.4. Critical quenching distance</td>
<td>11</td>
</tr>
<tr>
<td>2.1.5. Critical time</td>
<td>11</td>
</tr>
<tr>
<td>2.2. Probability theory</td>
<td>11</td>
</tr>
<tr>
<td>2.4. Low voltage moving contact discharges (Work by Guenault, Berz, Thomas).</td>
<td>15</td>
</tr>
<tr>
<td>2.5. The investigation of discharges by oscillography (Work by Gordon, West, Widginton)</td>
<td>18</td>
</tr>
<tr>
<td>2.6. The effect of the electrical parameters and duration of discharge (Work by Riddlestone, Bertels, Nethercot, Rose, and Priede).</td>
<td>19</td>
</tr>
<tr>
<td>2.7. Tabular review of work on criteria of ignition</td>
<td>27</td>
</tr>
<tr>
<td>3. Experimental equipment</td>
<td>28</td>
</tr>
<tr>
<td>3.1. Preliminary considerations.</td>
<td>28</td>
</tr>
<tr>
<td>3.2. The firing circuit</td>
<td>30</td>
</tr>
<tr>
<td>3.3. The spark-gap</td>
<td>34</td>
</tr>
<tr>
<td>3.4. The optical system</td>
<td>36</td>
</tr>
<tr>
<td>3.4.1. The shadow system</td>
<td>36</td>
</tr>
<tr>
<td>3.4.2. Recording of the voltage diagram.</td>
<td>37</td>
</tr>
<tr>
<td>3.5. Trigger pulses</td>
<td>38</td>
</tr>
<tr>
<td>3.6. Synchronisation</td>
<td>39</td>
</tr>
<tr>
<td>3.7. Specification of the experimental apparatus.</td>
<td>40</td>
</tr>
</tbody>
</table>
4.1. Experiments with resistive circuits.
4.2. The electrical power transfer function in a resistive circuit.
4.3. The electrical power transfer function of the model electrode system.
4.4. Photographic records.
   4.4.1. Detailed description of the voltage diagrams.
   4.4.2. Observed developments.
   4.4.3. Light emission
   4.4.4. Effect of compounds
   4.4.5. Control experiment with platinum electrodes.
4.5. Cine photographs.
4.6. Discussion.

5. Summary and conclusions

6. References

7. Appendix
Preface

This thesis is submitted for the degree of Master of Philosophy in the faculty of Electrical and Control Engineering of the University of Surrey.

The research was carried out in the intrinsic safety laboratory of the Mining Research and Development Establishment at Isleworth from April 1967 to April 1969 under the direction of Mr. I Berz to whom I wish to express my sincere gratitude for his constant encouragement and advice.

The thesis was written in the Electrical and Control Engineering Department of the University of Surrey under the supervision of Dr. B. W. Ward to whom I am indebted for his continual interest in this work and for many helpful discussions.

I should also like to thank the Mining Research and Development Establishment and the University of Surrey for making available facilities for the research and other work involved.

Grateful acknowledgement is made of the assistance of the department staff and photography group.

Department of Electrical and Control Engineering.

University of Surrey.

August 1969.
A general survey is given of the work connected with investigation of the criteria of ignition by electrical discharge in methane - air mixtures. A suggestion is made for a theoretical approach to the problem and on the basis of this approach past work is evaluated and future experiments planned. It is suggested that the energy distribution in time is of primary importance in the process of ignition and hence should be the subject of investigation.

Details are given of the design and construction of a versatile experimental apparatus which was used to register the development of the ignition kernel until it reached the self-propagation stage and which recorded the relevant voltage diagrams in order to calculate the energy - time function of the discharge.

With this equipment detailed investigation was made of the characteristics of the German breakflash used for testing sensitive circuits and, besides the kernel development, 'bubble' development and light emission were observed. The energy distribution, i.e. power consumption of the discharge as a function of the discharge voltage and indirectly of time is examined theoretically and from the experimental data the power function of the relevant photographs have been calculated. It was found that the kernel appears when the electrical power from the resistive circuit is at a maximum.

On the basis of these findings the operation of the German breakflash is elucidated. It was shown that for resistive circuits by considering the surplus energy available during the development to self-propagation, energy values of the order of three tenths of a milliwatt can be calculated which are very near to the minimum energy values quoted by other authors for inductive and capacitive circuits.
1. General approach to ignition studies

1.1. Introduction
The beginning of research on intrinsic safety goes back to the nineteen twenties when the introduction of electrical equipment into mines gave rise to the urgent question as to its safety in explosive atmospheres. Because of the urgency of the problem the first approach was mainly practical and was based on simulation in a safe experimental chamber of the worst possible electrical discharge conditions in the presence of the most dangerous atmosphere occurring underground. The results of such experiments were decisive in the question of safety. On the basis of empirical data standards were laid down and if a given circuit met these standards it was considered suitable for use underground.

Besides the practical approach to intrinsic safety more and more thought was given to the theoretical explanation of the problem of ignition. The necessity of a clear understanding of the fundamental processes involved was emphasised by the fact that during the development of different testing equipments and procedures the results were not in agreement, the energy levels or current levels at which ignition occurred were different. Also with the improvement of the experimental apparatus lower and lower ignition values were achieved. This fact is disturbing because it indicates that the tests and regulations currently in use do not give satisfactory assurance regarding safety. The safety regulations may be valid only for given test conditions and not for an actual equipment.

1.2. The criteria of ignition
The theoretical approach to the problem of ignition is very difficult because of the many factors involved and several theories have been proposed (Blanc et al. 1947). Neglecting losses (See Section 1.3), the following process takes place: energy is needed to raise the temperature of a small volume of gas, called the kernel, and when the temperature exceeds the ignition temperature the gas starts burning. Heat will then be liberated according to the chemical reactions of the process. There is at the same time another effect to be considered. The kernel is surrounded by cold gas which exerts a cooling effect. However, owing to heat flow from the kernel, the temperature of the outer layer reaches the ignition level, the chemical reaction takes place and more heat is liberated.
In this way a combustion wave will be formed and propagate outwards. At any instant, owing to the interaction of different effects, the energy balance consists of the following components:

- the energy gained (a) from an external source $E_{so}$ and (b) from the chemical reaction $E_{ch}$.
- the energy lost $E_l$ due to the heat flow to the ambient unburnt gas.

This heat loss depends on the temperature difference between the kernel and the ambient gas and on the size of the surface where the chemical reaction takes place. Part of this energy is useful because it brings the next layer of gas to ignition temperature and thus makes the continuity of the chemical reaction possible. One can assume that the temperature dependent rate of liberation of chemical energy $P$ increases with the radius. There comes a point at which the energy loss per second to the ambient gas is equal to the chemical energy released per second. At this point the process becomes self-propagating. Before this point there is an energy deficit which has to be supplied by an external source. However, if the rate of energy supplied by the source and the rate of heat liberation within the more or less spherical zone of chemical reaction are insufficient to compensate for the rate of heat loss to the outer zone of pre-heated unburnt gas, then the temperature decreases throughout the reacting volume and the combustion wave is extinguished.

In other words there is a minimum energy which has to be transferred to the gas in order to initiate and support the chemical reaction until the kernel reaches a certain geometry and becomes self-supporting. This minimum energy depends

(a) on the mixture as it will influence the amount of energy liberated in the chemical process by burning a given volume of gas,
(b) on the ignition temperature of the gas because this temperature has to be maintained against the ambient temperature,
(c) on the ambient temperature which, together with the temperature inside the kernel, influences the rate of heat loss,
(d) on the pressure because this affects the density,
(e) as a secondary factor, on the turbulence of the gas.

In previous discussions turbulence has been assumed to be negligible but several attempts have been made to investigate the other parameters (Blanc, Guest, von Elbe, Lewis 1947, Calcote, Gregory, Barnett, Gilmer 1952).

A further parameter which the present author feels should be considered in more detail is the time or, more precisely, the time dependence of the above parameters. If it is accepted that combustion is the propagation
In a chemical reaction, i.e. the growth of a kernel, it has to be acknowledged that the energy liberated by the chemical reaction is also a function of time. Also it is worth noting that Norrish et al. (1953) has found that there is a delay of the order of 100 μs between the beginning of the combustion process and the release of energy. Furthermore, owing to the change in the geometry of the burning layer, the rate of energy loss must also change with time. Consequently, unless energy is transmitted from an external source to the gas in a relatively short time (in which case it will be stored presumably as heat and used as required), the rate of energy input must be of importance. As well as a minimum energy for ignition, the rate of energy input is important, as this rate plus the rate of energy generated chemically must be greater than the rate of heat loss in order for a kernel to develop and lead to ignition.

Let us suppose that the chemical energy liberated per second and the energy loss per second are represented by the curves $P_{ch}(t)$ and $P_{l}(t)$ respectively (Fig. 1.1). The rate of energy liberation and loss reach the same value at $t = t_0$ which is called the critical time, when the kernel has reached the critical size. For $t = t_0$ the process becomes self-propagating and for $t < t_0$ energy has to be supplied from outside the system. The shaded area would represent the energy deficit which is the minimum energy required by the gas for ignition after the start of the chemical reaction.

If the duration of the energy input is negligible compared to the critical time the rate of energy input must be higher thus leading to higher temperatures and increased rate of loss. The optimum situation would be achieved if the energy input together with the liberated heat were enough to maintain the kernel at ignition temperature. Ideally a high rate of energy input is needed at first to quickly heat up the gas to ignition temperature, thereafter energy should be supplied at the effective loss rate $(P_{l} - P_{ch})$ until the energy rate from the chemical reaction equals the loss rate and the process becomes self-supporting.
Fig. 1.1. Rate of energy loss $P_l$ and rate of liberation of chemical energy $P_{ch}$ in the growth of an ignition kernel.
1.3. Ignition by electrical discharges

In order to get a better understanding of the ignition process by electrical discharges it is important to consider the various energy-loss mechanisms which tend to mask the true energy required for ignition.

Basically ignition by a spark discharge is a phenomenon in which electrical energy is transformed into heat and eventually into a chemical reaction. It is well known that when a system is subjected to external action and converted from one state to another the total energy of the interacting systems remains constant. However, this does not mean that all the energy in one system can be converted into another because no conversion is perfect. There will always be losses when injecting energy into a system in a particular form. The case of ignition by electrical discharges can be broken down into two distinct problems. Firstly the conversion of electrical energy from a given circuit into a discharge and secondly the conversion of a discharge into the chemical ignition process.

The electrical system provides according to the circuit parameters a certain amount of energy for the discharge mechanism. There is immediately a loss involved, because only a certain part of this energy (of the source energy) which is available in principle will go into the discharge mechanism, the remainder will be lost, i.e. retained in the circuit. This loss can be taken into account by introducing an electrical transfer factor \( T_e \).

\[
T_e = \frac{E_o}{E_s} = \frac{\text{output energy}}{\text{source energy}}
\]

Where \( E_s \) is the source energy available in principle and \( E_o \) is the energy going out of the circuit into the discharge.

Obviously this \( T_e \) factor is a function of the circuit parameters \( (L, C, \pi, V, I, ...) \) and of the impedance represented by the discharge mechanism, which entails the discharge itself and any other losses occurring in connection with it (i.e. energy used for raising the temperature of the electrode tips to form a hot spot, heat conduction by the electrodes from the hot tips during the discharge, light radiation, etc.). From the point of view of ignition only that part of the \( E_o \) will be useful which, in fact, will be transferred to the gas in the form of heat. Let us here take these losses into account by the introduction of a discharge factor \( T_d \).

\[
T_d = \frac{E_d}{E_o}
\]

Where \( E_d \) is the energy which is transformed into heat and transferred to the gas. It is important to take account of the distribution of heat in the gas. Depending on the type of the discharge the size of the discharge channel will vary and hence the energy density and local gas temperature will vary. In other words the ignition efficiency may be associated with
the discharge regime. (Riddlestone, Nethercot 1962).

If the electrodes or any other heat-conducting bodies interfere with the developing kernel they will exert a quenching effect by conducting heat from the gas. Consequently only a part of the energy transformed into heating the gas will in fact be available for maintaining the required temperature of the kernel until the energy liberated from the chemical process is able to take over. This quenching effect could be represented by the use of a quenching factor $T_{qu}$ which is given by the ratio of the energy $E_k$ used strictly for the development of the ignition kernel and the discharge energy $E_d$.

$$T_{qu} = \frac{E_k}{E_d}$$

Summarising the above discussion, if an electrical discharge occurs, only a fraction of the electrical source energy $E_s$ will be used directly for the growth of the kernel $E_k$, the ratio of which $T_{ign}$ will be characteristic of the efficiency of the igniting system.

$$\frac{E_k}{E_s} = T_c \cdot T_d \cdot T_{qu} = T_{ign}$$

It should be borne in mind that the process is dynamic and that the rate of supply and rate of loss of energy are important. Although it is usual to think in terms of a minimum igniting energy, a minimum power will be required to overcome the continual losses which are inherent in a practical system. It is useful in fact to consider transfer factors in terms of power ratios (Section 4.2).

### 4.4. The importance of breakflash tests.

From the safety point of view the most important problem is to ensure that a given item of equipment is unable to cause ignition. Every effort should be made to prevent discharges occurring, but one should also design a system such that ignition will not occur even when there is a discharge and all parameters are set to their most dangerous values. Unfortunately in many practical cases this would result in such strict conditions that the equipment would have no chance of serving a useful purpose. Therefore, in most cases it is usual to consider carefully the importance of individual parameters, determine their limiting values within the given circumstances and test the equipment within these values. There is no point in the present work in discussing the detailed regulations and specifications relating to the testing of equipment but it is emphasized that careful evaluation of the results of breakflash tests is necessary.

Tests are generally made with the internationally accepted parameters $T_{amb} = 20^\circ C$, $p = 760$ mm Hg and an $8.3\%$ methane - air mixture. Although the $8.3\%$ methane - air mixture is regarded as the most dangerous it is only true if the oxygen/oxygen + nitrogen ratio is the normal air value of $0.21$ by volume.
If due to any reason the oxygen content increases a significant drop in the minimum energy $E_k$ for kernel development can be expected (Blanc, Guest, von Elbe and Lewis 1947). For example if the oxygen/oxygen + nitrogen ratio is 0.5, $E_k$ would be six times smaller. Also higher pressures or higher temperatures would lead to a reduction in $E_k$ (King, Calcote 1955).

It should be noted that, although tests are carried out to determine the igniting energy at normal temperatures and pressures etc., in adverse circumstances the practical value of the igniting energy could be lower. Therefore, standard tests may not be relevant to the worst possible conditions; hence after careful consideration or the working environment of equipment additional tests may be necessary. Furthermore each type of breakflash apparatus is characterised by its transfer factors which influence the value obtained for the minimum igniting energy and it is possible that an equipment could prove to be safe with one type of breakflash and unsafe with another. Because it is impossible not to include transfer factors in the test results, care should be taken in selecting a breakflash apparatus and interpreting the results.

It should be mentioned at this stage that the work reported here is mainly concerned with the German type of breakflash (Section 4) used in conjunction with a resistive circuit. Compared with inductive and capacitive circuits it is easier with a resistive circuit to follow the power input into the spark as a function of time. Also as the German breakflash was being considered as an international standard for ignition tests it was important to investigate this type in some detail.
It will be attempted to give a review, though by no means an extensive one, of the work carried out in connection with the problem of ignition by electrical discharges, and to evaluate this work in the light of the considerations discussed in section 1.

It should be emphasized that, because of the complexity of the problem, it is very difficult to survey all the factors involved and their possible effects. Therefore the experiments carried out by different authors can only be compared qualitatively, if at all, because

(a) not all the decisive parameters were controlled,
(b) the relevant parameters were different,
(c) the values of some parameters were not recorded and hence the experiments are not always fully defined,
(d) the definitions of the variables were not identical.

First of all there are often inconsistencies in the basic definitions. Different concepts are introduced and discussed without being properly defined. Even numerical values are attributed to these not properly defined ideas. They can be found quoted and sometimes related without justification.

2.1. Definitions

As the experiments were governed by the idea of safety it is understandable that in the course of investigations the emphasis was placed on the determination of the extreme values relating to the most dangerous situation, hence the introduction of the concepts of minimum igniting current, minimum igniting energy, critical time, etc.

2.1.1. Minimum igniting energy

From the transfer function concept discussed in the previous section it can be seen that without defining where the energy was measured and under what circumstances there is no real meaning attached to any energy values.

In the literature the following incomplete definitions can be found:

(a) In the experiments of Blanc, Guest, von Elbe and Lewis (1947), the minimum igniting energy \(^1\) (m.i.e. \(^1\)) is the energy stored in their capacitive spark system, calculated as \(0.5CV^2\) from the capacitance and voltage values at which ignition occurred with a particular item of equipment for given conditions. Apparently this is an \(E_1\) value in which the \(T_2\) transfer factor is fairly small.

(b) Gordon, West and Widginton (1962) obtained simultaneous oscillograms of current and voltage waveforms for every discharge and calculated the minimum igniting energy \(^2\) (m.i.e. \(^2\)) from them. These energy value
should be regarded as \( E_0 \) values related to a wire breaking test equipment where emphasis was put on the supposition that \( T_d \) was independent of every other parameter but time, and the influence of the length or discharge on the required energy was investigated.

(c) The minimum igniting energy \( (m.i.e.) \) and minimum igniting duration were introduced by analogy with the definition given by Berz (1959) for the minimum igniting current \( m.i.c. \) (see later).

2.1.2. Minimum igniting current

The introduction of the minimum igniting current concept can be attributed to the suggestion that the current has priority and plays a decisive role in the determination of ignition, especially in the case of inductive circuits. Of course, the value of the minimum igniting current has no meaning without fixing the other circuit parameters, discharge and gas parameters. The difficulty of comparing minimum igniting current values is increased by the fact that, even with closely controlled conditions for the electric circuit and the gas (there was no mention of the discharge being controlled), the ignition at a given current was uncertain (Thomas 1964). To overcome this uncertainty in the experiments the concept of ignition probability was introduced.

With this concept in mind the "British definition" of minimum igniting current \( (m.i.c.) \) was given arbitrarily by Allshop (1940) and others as follows: After a current at which ignition of the gas mixture readily occurs has been found, the value of the current is progressively decreased by amounts of 5 per cent to 10 per cent until a value is reached at which the passage of 100 sparks fails to give ignition. The minimum igniting current is taken as the mean between this value and the value immediately above, at which ignition is obtained.

Other British authors have used various other definitions. For instance the minimum igniting current values \( (m.i.c.) \) quoted by Berz (1959) are the values at which at least one ignition was obtained, and below which no ignition was obtained in 10 tests, where the levels were chosen in 5mA steps.

In Russia the term minimum igniting current \( (m.i.c.) \) is defined in terms of ignition probability, the value of which is chosen as \( p = 0.001 \).

\[ p = n_1/n \]

where \( n_1 \) is the number of ignitions in \( n \) tests (Serov 1960).

2.1.3. Minimum igniting duration

This concept was introduced by Gordon, West and Widginton (1962) experimenting with arc discharges of controlled constant current value.
2.1.4 Critical quenching distance

The definition of critical quenching distance was made on the basis of the quenching curves and indicates that gap distance at which the $E_s$ energy was the same with and without flanges. Below this distance the required minimum $E_s$ energy increases abruptly with flanged electrodes and gradually with point electrodes. This distance is assumed to correspond to the critical diameter of the kernel.

2.1.5 Critical time

According to Lintin and Wooding's (1959) definition the critical time ($c.t.$) is the time expired until a difference can be noticed between the kernels leading to explosion and kernels going to be extinct (about 100 µs). Widginton (1965) relates the definition of critical time ($c.t.$) to the energy required for ignition and defines it as a discharge duration time, beyond which the energy required for ignition increases with time (about 300 µs).

2.2 Probability hypothesis

The probability of ignition is widely used particularly in Russia. It is assumed that there is a relation between the incendivity of electric discharges and the value of the current obtained as a result of a large number of experiments (Serov 1960).

This relationship in logarithmic coordinates is expressed by inclined straight lines. When other parameters (e.g. inductance) are varied the relevant straight lines change their position in the $p = f(I)$ diagram, but they remain straight and parallel to each other. This feature suggested that the straight lines could be extended into the experimentally unverified region of low current values, and thus the boundary of safety could be determined as the current belonging to the nominal probability of ignition $p = 10^{-8}$.

A probability approach had extensive support as it gave a very simple way out of the problem of inconsistency. It was thought that the inclination or angle of these lines is characteristic of the physical and chemical processes, i.e. that these processes are responsible for the width of the boundary within which the ignition fluctuates.
This was attacked by Furmanov (1965), who suggested on the basis of experiments carried out with the same circuit values but with greater accuracy, that the angle of the probability lines depends on the quality of the test; hence with more carefully controlled tests lines nearly perpendicular to the current axis can be produced. From this he concludes that the low angle of inclination, i.e. the fluctuating nature of the ignition, arises mainly from the imperfect conditions in the apparatus used. Moreover if the inclination of the probability lines is dependent upon the apparatus and accuracy of the experiment, then the safe value of the current extrapolated from the probability lines has no validity at all. According to Furmanov 'the low values for ignition probability are evidence not so much of a high degree of safety as of the low quality of the experiment'.

By applying the linear co-ordinate system for plotting the probability function he points out that the points of \( p = 1 \) and \( I = I_{\text{safe}} \) values are well defined in this system, whilst the shape of the curves can vary considerably and is governed by the quality of the experiment, see Fig. 2.1.

![Fig. 2.1. The probability of ignition versus current according to Furmanov.](image-url)
Consequently though the $I = I_{\text{safe}}$ clearly exists its value cannot be determined by extrapolation from higher probability values plotted in logarithmic co-ordinate system.

2.3. High voltage capacitive discharges

One of the first experiments related to the ignition of gases was carried out by Blanc, Guest, von Elbe and Lewis in 1947. They used a capacitive system for producing the sparks. The voltage at which the spark occurred, and the relevant capacitance value were used to calculate the source energy $0.5CV^2$. Since the d.c. resistance of the circuit was less than 0.1 ohm, it was felt that the losses ($T_e$ and $T_d$ factors) were kept at the possible minimum. By changing the distance of the electrodes and using glass flanges on them the influence of the gap distance on the required minimum source energy and hence indirectly the $T = f(\text{electrode distance})$ relation was investigated. After determining the minimum value of this function, the gap distance was set to this value. The gas parameters were 8.3% methane - air mixture, 760 mmHg pressure, and an unspecified ambient temperature. The claim was made that the energy (source energy) measured under these circumstances is the absolute minimum igniting energy which according to the present author's terminology would be equivalent to the kernel energy $E_k$. Although a control experiment was made by increasing the d.c. resistance in the circuit and the increase up to 50 ohms made no difference in the energy required for ignition, it does not mean that the value of the transfer factors would have been equal to one. Therefore, the $E_k$ value must be lower than this minimum value of $E_s$ determined in their experiment. However it should be noted that their values seem to be the lowest energy values measured for a long time.

Experiments were also made with this apparatus to see the effect of the composition of the air and of the pressure of the mixture on the ignition energy ($E_s$).

Basically the same type of experiments were carried out at the Bureau of Mines by Litchfield, Hay, Kubala and Monroe in 1967, but with a different type of apparatus. Their gaps were variable, cleaned every time and had glass flanges of different sizes. The gas composition was determined by partial pressures and the reaction vessel was evacuated to better than 1mmHg before filling. The initial temperature in the chamber was maintained by built-in heaters and the interval between successive tests was made several times greater than the thermal relaxation time. Hence single-spark conditions were assured. The charging of the capacitor was continuous and the potential was measured by an electrostatic voltmeter in connected parallel with the power supply. Although not indicated, it is
assumed that the energy values were calculated from the expression 
\[ E = 0.5CV^2 \] - i.e. source values were determined. The type of discharge 
was not controlled. Initial pressures were varied from 10 mmHg to 3 
atmospheres, temperature from -78°C to 198°C. It was stated that ignition 
energy values of as low as 10^{-7} joules were measured, but unfortunately 
further details were not published. Their paper only shows a quenching 
diagram from which \( E_s = 0.3 \) mJ (at 8.5 per cent methane-air mixture, 
760 mmHg pressure, temperature unknown, presumably laboratory temperature).
This is similar to the value of \( E_s = 0.48 \) mJ (at 8.3 per cent methane-air 
mixture, 760 mmHg, temperature also not mentioned) measured by Blanc, Guest, 
von Elbe and Lewis (1947).

The experiments made by Lintin and Wooding (1959) using a photographic 
system for the investigation of the kernel development and geometry, 
represented a further major step in the understanding of ignition phenomena. 
They used a pointed gold tipped electrode system with a fixed 0.2-mm gap 
distance. The electrical energy was obtained from a Hackethal delay cable 
previously charged to several kilovolts. It was estimated that the igniting 
spark released about one mJ of electrical energy during a period of about 
0.5 μs. (It is not quite clear whether this energy was a source or an output 
value). As regards the other transfer factors, it can be assumed that they 
were low.

A photographic system was set up to take shadow photographs of the 
electrode area. Only one photograph could be taken of a given ignition, 
but the time interval between the ignition spark and the taking of the 
photograph was varied. The minimum delay was 23 μs.

The main purpose of the experiment was to investigate the geometry 
of the kernel growth. Owing to the temperature differences (\( T_{\text{kernel}} \) and 
\( T_{\text{amb.}} \)) and the consequent light refraction, the ignition kernel appeared 
on the photographs as a dark area surrounded by a lighter line. By 
varying the delay time, the growth (size and shape) of the kernel could 
be deduced. An apparent difference was found in the growth of the kernel 
dependent on whether it developed into an ignition or collapsed. The 
kernel radius and the relevant time when this difference became detectable 
were defined as critical radius and critical time.

Experiments were made to elucidate the effect of gas composition on 
the critical radius and time. At the beginning (23 μm) the shape of the 
kernel was oblong and parallel to the discharge path, later it became 
approximately circular with some corrugations in the electrode axis, but 
these disappeared by 4 ms if the kernel developed into ignition.

- 14 -
In the case of unsuccessful ignition the kernel could still be seen at 1.3 ms although the boundary had become diffused, but it had completely disappeared by 4 ms.

2.4. Low-voltage moving contact discharges

Though the capacitive discharges are of theoretical interest, from a practical point of view the kilo-voltage range is not as important as the lower range; from 5-10V to a few hundred volts. At these voltages discharges are most likely to occur when the circuit is broken.

In order to investigate and test the criteria of ignition in this low-voltage region a large number of different types of apparatus were developed. (A good survey of this can be found in a review by Thomas published in 1964. See Section 6)

Basically, however, these equipments can be classified into two groups:

(a) wire breaking equipment, in which wires of different length, diameter and material were broken at different speeds.
(b) contact making equipment, where the electrodes were brought into contact, and then separated. Again there was a wide variation in the shape and material of the electrodes, in the speed of separation and in the mode of bringing the electrodes into contact. The making of a contact inevitably included some relative sliding of the electrodes. Sometimes this sliding effect was deliberately made use of (German breakflash).

It was assumed that the value of the current in the circuit before the break was an easily measurable and decisive factor in incendivity. Therefore this was chosen as the independent variable, and by deliberately postulating the concept of a minimum igniting current, experiments were performed to measure the effects of variations in the other circuit parameters \( V, L, R, C \) electrode configurations, materials, and speed of separation on the incendivity (Widginton 1963, 1965, Seki et al. 1964).

These experiments resulted in numbers of different curves, all of which were specific to a given equipment and are difficult to correlate. (e.g. for 20mH inductance the No. 3 breakflash curve gave 0.43 A m.ioc. at 24 V, Müller's stein brush electrode system gave 0.26 A m.ioc. at 25 V, whilst Berz's tungsten wire breaking system gave 0.18 A at 24 V belonging to \(10^{-1}\) probability, at the same time the value calculated from the expression \(0.5 L I^2 = 0.28 \text{ mJ} \) was 0.16 A. These data are quoted in Fig. 16 of the review by Thomas (1964).

For the sake of future reference some of these experiments will be described in detail.
Circuits with very low inductances were investigated by Guenault in 1952. Using an intermittent breakflash apparatus he plotted the lowest igniting current - circuit voltage diagram, which was used afterwards for making safety assessments (Fig. 2.2.).

The interpretation of these corresponding current and voltage values is rather difficult as there is no indication of the duration of the energy input, nor is it recorded what proportion of the energy went into the discharge. The energy or power input conditions are simply not defined.

It is known that a dielectric circuit is characterised by its source voltage \( V_s \) and shortcircuit current \( I_s \). It has an internal resistance \( R_i = V_s / I_s \), and in case of optimum matching conditions the maximum power \( P_s \) which can be supplied to the load resistance \( R = R_i \) is given by \( P_s = V_s I_s / 4 \).

By plotting the relevant \( P_s \) in the diagram (Fig 2.2.) it can be concluded that the values of the transfer functions must be changing in the same way as \( P_s \) does, since power required by the kernel \( P_k \) cannot be dependent on the circuit voltage.

This \( P_s \) curve suggests that between 10 and 40V the transfer function \( T_{\text{ignition}} \) is particularly low, whilst above 200V it increases rapidly. As it is not likely that the voltage \( V_s \) would have an effect on the quenching factor \( T_{\text{quench}} \) the variation of \( T_{\text{ignition}} \) must be due to the change in the values of \( T_e \) and \( T_d \). It is not possible to determine \( T_e \) because the voltage and current functions \( c \) the discharge were not recorded, hence no further information about the transfer factors could be derived from this experiment.

The importance of measuring the discharge current and discharge voltage became obvious to Guenault and made him start work on taking oscillographic records. He also investigated the effect of electrode materials on the minimum igniting current (m.i.c.) - inductance relation.

The minimum ignition energies obtained with inductive circuits were about an order of magnitude greater than the values determined for capacitive circuits. This phenomenon was examined by Berz (1959), who suggested that the discrepancy was due to the different quenching factors involved. The main difference between the capacitive static tests and the inductive break tests was that in order to achieve low energy levels in the capacitive case the electrodes were set above the critical quenching distances, whilst in the inductive tests the electrodes were within this distance for a long time as they were separating. Consequently they were acting as 'heat sinks' and tended to retard the development of the kernel.
Igniting current versus source voltage for resistive circuit according to Guenault
Berz concluded that if this quenching effect was minimised by reducing the size of electrodes and increasing the speed of their separation, substantial reduction should be achieved in the value of minimum igniting current and hence in the minimum igniting energy. (It is to be noted that the energy values quoted by him were \( E \) values as they were calculated as \( 0.5 I^2 \) from the minimum igniting current (m.i.c.)).

Berz modified a standard breakflash equipment for his experiments. The smallest diameter of wire that could be used satisfactorily was 0.005 in, though some tests were made with 0.0005 in, whilst the speed of separation could be varied between 250 and 12,000 cm/s. The reduction of the electrode diameter proved to be effective in reducing the minimum igniting current. For the case of 0.0005 in tungsten wire, 24 V and 95 mH an energy of 0.3 mJ was calculated from the relevant minimum igniting current value. The increase in the speed of separation did not seem to be particularly effective in the case of these very thin electrodes, but Gordon, Lord and Wilginton (1961) have experienced substantial reductions in minimum igniting energies for a thicker wire (0.012 in diameter) when a speed of separation of 2000 cm/s was used.

The voltage and current oscillograms taken by Berz in connection with these wire-breaking tests showed mainly multiple spark patterns, and seldom the appearance of an arc.

2.5. The investigation of discharges by oscillography

The importance of the investigation of the discharges by oscillographic methods became more and more apparent.

Firstly from the voltage and current oscillograms the output energy \( E_o \) could be calculated and hence the problem of determining the electrical transfer factor \( T_e \) was eliminated.

The experiments carried out with electrodes of different diameter and different speeds of separation elucidated the question of quenching, and indicated techniques for reducing the effect of quenching, i.e. for achieving a quenching factor \( T_{cu} \approx 1 \).

Secondly the importance of the discharge conditions become obvious. From the oscillograms it was apparent that in most cases the discharge characteristic was very unpredictable and unstable. Hence it was assumed that the probability nature of the ignition could be associated with the inconsistency of the discharge.

The types of discharges observed during the investigations of break discharges can be divided into three groups: arc, spark (multiple) and glow.
The arc discharge is characterised by a relatively low voltage level and a high current. The channel of the discharge is rather concentrated.

As opposed to the arc, the glow discharge appears at higher voltages and lower currents. There is a cathode fall and because of the high 'inner resistance' the glow discharge is very sensitive and can readily change to a spark discharge. The discharge channel covers a larger area and is therefore less effective for ignition.

The spark discharge which is a breakdown pulse can be single or multiple. It is connected with the discharge of a capacitance, generally the electrode capacitance, and frequently occurs when the circuit current is below the minimum arcing current.

2.6. The effect of the electrical parameters and duration of discharge

In order to investigate the dependence of the minimum energy necessary for ignition on the discharge time Gordon, West and Widginton (1962) set up an experiment in which the duration of the arc discharge was controlled by a silicon-controlled rectifier. The circuit parameters were chosen so as to provide a current of constant amplitude within the 10 - 30 μs region where the system operated. However, owing to the separation of the electrodes (a wire-breaking electrode system was used), the discharge voltage was probably not constant as suggested but rose with increasing separation of the electrodes. In this way an approximately linear increase in power input \( P_0 \) was provided. It was stated that the energies quoted in the paper were calculated from the V – I diagrams, but neither the accuracy or the method were given.

The outcome of the experiment was that the calculated energy appeared to remain constant within the range 2.3 - 2.6 mJ, in spite of the change in discharge duration between 10 - 30 μs.

The experiments included taking photographs of the developing kernel. Using a high-voltage spark light-source a sequence of about 20 photographs of the kernel were obtained with the means of a drum camera. The interval between the pictures was given as over 100 μs. Though the photographs gave useful information regarding the development of the kernel and the relationship between the kernel and the electrodes - unfortunately they were not appropriate to the study of the influence of the arc duration because of the different timescales.

The author considers it necessary to discuss the possible implications of these results on the basis of the energy considerations, discussed in section 1.
As can be seen from the photographs the quenching of the growing kernel was continuous. Because the wires were rather thick $D = 0.22$ in, the energy loss from the kernel due to the cooling effect of the electrodes must be substantial. The rate of this energy dissipation should depend on the relative position of the electrode tips and the flame envelope. In these experiments the electrodes were penetrating into the kernel during the whole time taken by the kernel to become self-propagating. This energy loss could be regarded as being fairly constant in the sense that it would not be influenced by the change in the duration of discharge from $10\mu s$ to $30\mu s$. The discharge losses used to maintain the electron emission and visible radiation, etc., are obviously present as long as the arc lasts. As the arc is fairly stable to a first approximation the losses can be represented as a continuous power consumption — thus the energy lost into the discharge should be proportional to the length of the arc.

The igniting energy value $E_i \approx 2.5$ mJ (output energy) obtained with the above experiments, compared to the output energy figures $E_c \approx 0.3$ mJ resulting from capacitative discharges under minimum quenching conditions, suggests that the energy difference must be due to the quenching and discharge losses. It is obvious that the kernel energy $E_k$ must be smaller even than $E_c$. Therefore if $E_i$ proves to be independent of the discharge time, it could be assumed that most of $E_i$ must be used up by quenching because this is independent of the discharge duration, and $E_d$ which is dependent on it must be comparatively small.

Consequently, the finding that the necessary output energy was not dependent on the duration of the arc suggests that this energy was used mainly to cover the quenching losses which are likely to be independent of the arc duration within the $10 - 30\mu s$ period.

Wigdinton considered it desirable to extend the duration of the controlled discharges, but because the arc discharges under 3 A current — corresponding to discharges longer than $30\mu s$ — were not stable, he decided to carry out the investigations with glow discharges. However, the production of stable glow discharge between separating electrodes proved unsuccessful. Eventually a high-voltage electrode system with fixed electrode distances was used. After the initial breakdown during which the energy due to the capacitance of the gap is released, a stable glow discharge was obtained, in which the current could be adjusted by the external circuit resistance and the duration of the glow by a thyatron.
The required igniting energy (presumably $E_o$, although no clear indication is given) increased with decreasing electrode distance. For the purpose of comparison the experiment was repeated with capacitive spark discharges instead of glow discharge, by adding a capacitor parallel to the gap. For the same conditions the capacitive discharge generally gave a lower energy value. It is suggested that the differences in energy were caused by the differences in the discharge properties. With the increase of the gap distance the energy difference apparently decreased and even reversed sign at gap distances greater than 0.09 in.

It is difficult to interpret this behaviour, but it could be explained partly by the fact that at smaller gap distances the discharge time (given as a parameter) for glow discharge was getting longer and consequently the discharge losses increased.

The effect of changes in the electrical parameters ($R$, $Q$) on the ignition have been under investigation by Riddlestone and co-workers (1962) at the E.R.A. Experiments were made with capacitive discharges and as well as the discharge energy ($E_o$), the stored energy ($E_s$) was calculated from the $V-I$ diagrams by the summation of the products of the instantaneous voltages and currents, and plotted against the series resistance in the circuit.

It was noted that polishing the tungsten hemisphere electrodes with carborundum paste (grade 600) after every spark, made a great difference to the required stored and discharge energy. The polishing did not make much difference up to 1 kohm, but above this value with unpolished electrodes there was discontinuity for ignition energy and just above 10 kohm there was a vertical rise, i.e. beyond this resistance value no ignition was achieved. In case of polishing the electrodes the igniting energy decreased above 1 kohm and after reaching a minimum at about 100 kohm, sharply increased again suggesting that there was a limit in series resistance value above which ignition could not occur.

The curves illustrating these findings can be seen in Fig. 2.3 where
- $E_s$ is the stored energy, with unpolished electrodes,
- $E_s$ is the stored energy with polished electrodes,
- $E_o$ is the discharge energy with polished electrodes,
- $T_e$ is the electrical transfer factor $T_e = E_o/E_s$ for polished electrodes.

The electrical transfer factor function was calculated by the author in order to interpret Riddlestone's findings in the light of the transfer function theory. As it can be seen $T_e$ appears to be ~1 up to 5 ohms then decreases.

It can be seen in Fig. 2.3 that $T_e$ decreases slightly in the region of 200 - 500 ohms where the discharge energy shows a sudden tenfold rise and then decreasing again reaches its minimum value of ~0.015 at about 800 ohms, above which the transfer
gradually improves again. From these curves important conclusions can be drawn. Bearing in mind that the $T_\text{qu}$ factor cannot be influenced by the series resistance $R$, the sudden rise of the required $E_0$ energy between 200 and 500 ohms suggests that the change in the value of the $T_d$ factor is responsible for this rise, i.e. the losses in the discharge system are increasing presumably owing to the change to a less effective type of discharge.

The fact, that simultaneously there is an improvement in the $T_e$ factor suggests that this other type of discharge represents a higher inner resistance towards the electric circuit, hence the improvement in the electrical transfer.

From the V-I diagrams it can be seen that the output (discharge) energy as a function of time is quite different on the two sides of this region. With resistance values less than 200 ohms the rate of input is high, about $10^4$ J/s and the duration of the discharge is short, less than 61 $\mu$s, as opposed to the discharge at circuit resistances over 300 ohms where the rate is $10^2$ J/s at the start and gradually increases during a few hundred microseconds to about $10^5$ J/s. The reason for this change from short discharges to long discharge is not clear, but it is feasible that in the case of a long discharge the overall energy output required must be higher because of the continuous presence of the discharge and quenching losses. These findings suggested that the rate of energy input might play an important part, and thus gave rise to further investigations.

The effect of the duration of the discharge was studied by several other workers as well (Widginton 1965, Komarov 1965). According to Komarov provided the quenching effect is small, the required energy remains constant and thus independent from the discharge duration until a critical time, thereafter it increases rapidly. In other words the required power is inversely proportional to time within this critical period and after that remains constant, thus there is a minimum rate of energy input under which no ignition can be achieved.

Further experiments were made by Riddlestone and Methercot (1962) using artificial lines to produce constant current discharges. It was found that the magnitude of the current and its rate of rise has important effects on the necessary discharge energy. The sudden rise of the required output energy which was observed with capacitive discharges also appeared in the case of constant current pulses supplied by artificial lines. It was found that at 23 A discharge current for duration of 2.3 $\mu$s the required output energy was only 3.7 mJ, whilst at 22 A the duration was 40 $\mu$s and the energy 29 mJ. It was felt that this difference is associated with a change...
in the discharge phenomenon.

In order to get a better understanding of this transient period further investigations were made by Bartels and Riddlestone (1966) the result of which was published in E.R.A. report No. 5135. Besides the V-I diagrams the growth of the incipient flame kernels was studied by taking schlieren photographs of successive sparks at progressively later instants of time. The current diagram showed that the higher ignition energies were associated with lower rates of discharge energy. The properties of the discharge and the radial and axial temperature distribution are expected to depend on the rate of energy dissipation. Since these physical characteristics will affect the geometry and growth rate of the expanding flame kernel, the ignition process must also be dependent upon the rate of energy dissipation. The schlieren observations proved this, and showed, that the geometry and rate of propagation are related to the energy level rather than to the circuit parameters. The short duration, low-energy discharge starts with a cylindrical kernel that at first seems to be separated from the anode. In contrast to this the flame kernel that develops from a long-duration high-energy discharge is of cylindrical shape and is in contact with both electrodes for the whole time and simply increases its radius. In the intermediate or transition region there is a gradual change from one type of kernel to the other. There seemed to be no obvious difference between kernels produced by capacitive discharges or artificial lines.

The increasing contact with the electrodes must result in a greater thermal loss from the kernel which could account for the increased output energy required for ignition but the non-adherence of the low-energy kernel to the anode cannot be explained satisfactorily. One of the possible explanations of the variation in kernel shape was thought to be that the energy distribution along the discharge column varies. Consequently a qualitative examination was made by means of colour photography which showed a significant difference in the shape and colour of the different types of discharges. The low-energy discharge was filamentary in nature with an intense white channel surrounded by a narrow yellow sheath. The discharge becomes pink as the circuit conditions approach the transition region, beyond which the discharge broadened into a crimson core surrounded by a diffuse blue glow. As the rate of energy dissipation was further reduced there was a gradual reduction in the diameter and intensity of the crimson core, which eventually disappeared leaving a uniform conical discharge.
It was found that the discharges struck in air appeared to be at a lower temperature than the corresponding ones in the methane-air mixture and the relevant photographs showed rather faster decay due to the absence of the exothermic reaction.

Though the report did not include sufficient information about the duration of discharges related to the cylindrical and disc-shaped kernels, it seems that the kernel shape is cylindrical as long as the discharge persists, and then (as a consequence of the quenching effect of the cooling electrodes) it takes up the disc form.

A detailed investigation of the electrical characteristic and transfer functions of capacitive discharges was carried out by Rose and Priede (1959). They found that the capacitive discharges normally employed in ignition experiments are of an oscillatory nature. Under such conditions the gap resistance seems to be virtually constant over the greater part of the duration and dependent on the impedance of the electrical circuit. The empirical equation found for the gap resistance \( R_g = k \cdot e^\gamma \), where \( k \) and \( \gamma \) are the functions of the electrode configuration and \( Z = (L/C)^{1/2} + R \) is the circuit impedance. If the series resistance \( R \) is increased the discharge becomes aperiodic. In this case the relationship \( R_g I^r = \text{const.} \) holds well for a wide range of variables. In the aperiodic range as the resistance is increased the discharge time tends to increase and the output power decreases rapidly. The gap resistance is constant at a value determined by the circuit impedance only for a very short period, this phase is followed by an arc-like discharge. For the purpose of calculation the whole process can be treated as a conventional arc discharge.

It was found that the proportion of the total stored energy released at the spark-gap depends upon the ratio of the gap resistance to the series resistance in the circuit. As the stored energy is in fact the source energy, and the energy released at the spark-gap is equivalent to the output energy, the diagrams given by Rose and Priede actually present the electrical transfer function \( T_e \) as a function of the series resistance and capacitance. From these diagrams it can be seen that at a given capacitance value the increase in the series resistance results in a decrease in \( T_e \), i.e. the transfer becomes less efficient. This result is not unexpected since, although the gap resistance increases with \( R \), the \( R_g/R \) ratio is reduced, consequently a smaller proportion of the source energy is dissipated in \( R_g \). At the same time with a given resistance \( R \) the transfer can be improved by decreasing the circuit capacitance.
many experimental circuits a circuit resistance of less than 0.1 ohm is practicable, and in such cases the electrical transfer factor can be taken as 1.0, i.e. the output energy released at the gap can be calculated as $0.5 CV^2$.

Bearing the above result in mind the measurements of Blanc, Guest, von Elbe and Lewis can be re-interpreted. As in their experiments the circuit resistance was less than 0.1, the relevant electrical transfer factor $T_e \approx 1$, consequently the energy values measured with electrode distance greater than the minimum quenching distance ($T_{qu} = 1$) include only the discharge factor multiplied by the kernel energy.
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<th>Current</th>
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<th>Impedance</th>
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3. Preliminary considerations

As can be seen from the general review there have been several attempts to make the very beginning of the ignition process, that is the kernel growth, visible. The most obvious suggestion is to make use of the high temperature difference between the kernel and its surroundings. The temperature difference is accompanied by a density difference which causes deflection of the light going through it. This light deflection can be recorded on film in the form of lighter and darker areas and will be characteristic of the ignition.

Basically there are two different techniques based on this principle, i.e. the shadow and schlieren methods.

Without going into the details of these methods, which can be found in great detail in the literature (B. Lewis and G. von Elbe: Combustion, flames and explosion of gases, 1961; F. J. Weinberg: Optics of flames, 1963) it should perhaps be mentioned that as a method of visualization the shadow method has the great advantage of simplicity. On the other hand it is far less sensitive than the schlieren method and sometimes is susceptible to ambiguous interpretation.

Shadowgraphy is more sensitive to density changes parallel to the light beam and less sensitive to changes that are oblique than the schlieren method. However, it was thought that for informative investigations the shadow method would be adequate and perhaps later when necessary the system could be modified into a schlieren system.

From the two possibilities within the shadow methods, i.e. the parallel beam and divergent beam system, the parallel system was chosen as it is superior to the divergent one on almost every count.

Several workers used photographic techniques for the investigation of the incipient flame kernel. Lintin and Wooding (1959) employed a photographic flash tube which was triggered by the spark via a delay unit. The light was then made parallel by lenses and was recorded after passing through the kernel onto a photographic plate. This system enabled them to take one single picture of a kernel with a predetermined and adjustable delay.

Gordon, West and Widginton (1962) applied a more advanced system, where a tungsten gap was used as a point source of light and the shadowgram was recorded with a drum camera. In this way a sequence of about 20 photographs spaced not less than 100 µs apart of the growth of a single flame kernel was obtained.

Bartel and Riddlestone applied the schlieren technique for their
investigations. The light was produced by a capacitor breaking down through series gaps, one of which was triggered by an ultraviolet light source and thus caused the breaking down of the other gap. The light of the main gap was made parallel and after passing through the kernel was collimated, cut with an iris diaphragm and recorded with an Exa II camera. By means of a delay circuit the taking of the photograph could be delayed between 15 µs and 2.2 ms, for shorter delays up to 2 µs artificial lines were used. This system gave again only one photograph per kernel. Therefore, the growth of the incipient kernel could be studied only by observing successive sparks at progressively later instants in time.

The one photograph per kernel technique is rather long-winded for investigating the growth of the kernel and further has the disadvantage that every picture belongs to a different kernel. As the ignition at the critical conditions is not easily reproducible, every kernel has an individual history and although a comparison of the different phases of the different kernels can yield some information, it is not really satisfactory. In particular this method is not adequate when the energy input takes a longer time, i.e. the input and the growth of the kernel are simultaneous. Consequently it was decided to develop a system which would be suitable for taking 50 – 100 pictures of the same kernel. In the interest of observing the rate of growth it was aimed to reduce the spacing between the successive picture frames to about 40 µs.

In order to obtain information about the energy input the voltage and current should be simultaneously recorded. When the subject of investigation is a resistive circuit, it is adequate to record the discharge voltage only, as there is a simple relation between the current and voltage in a resistive circuit.

At the beginning a separate polaroid film was used for this purpose, but this solution had several weaknesses. Firstly the ratio of the resolution and the duration of the event on the oscilloscope screen was not satisfactory. Secondly the handling and comparing of the two different records (polaroid photographs and high-speed film) were rather difficult, not to mention that there was always a chance of error in the synchronising either in the system itself or later at the evaluation of the records. Therefore, an attempt was made to improve the method and eventually resulted in recording the voltage diagrams and the kernel photographs on the same film.

The work involved in setting up the experimental apparatus for the given requirements can be conveniently considered in the following parts:
The circuit diagram of the final version of the experimental apparatus is shown in Fig. 3.1., whilst the layout of the system can be seen in photographs Fig. 3.2. and Fig. 3.3.

3.2. The firing circuit

The principle used to obtain a series of repetitive sparks is the repeated charging of the discharge capacitor (18 on Fig. 3.3.) from a storage capacitor (21) through an inductance (20) and a charging resistance (19) which serve to isolate the discharge circuit from the power supply during the spark, and provide quick charging up of the discharge capacitor to the required voltage in the interval between sparks.

The H.T. power supply has generally a high source impedance, and hence is not able to provide the necessary current for recharging the discharge capacitor during the time intervals between discharges, therefore, a storage capacitor has to be used as a buffer.

The value of the storage capacitor limits the energy available for photography and for a given discharge capacitor influences the length and envelope of the light pulse train. The maximum repetition frequency required determines the time constant of the charge circuit and thus the values of the inductance and charging resistance. A detailed discussion on calculation of the firing circuit is given by L. Whitlow (1961).

The discharge capacitor is discharged via the spark-gap (2 on Fig 3.2.) and the thyatron (16). During the charging-up period the anode of the thyatron rises up to 10 kV through the bridge resistance (23), thus the electrodes of the spark-gap are both at 10 kV relative to earth. The discharge takes place when the trigger pulse appears on the grid of the thyatron. Then the thyatron breaks down and by earthing one side of the spark-gap (the high value of the bridge resistance hinders the dropping of the voltage on the other side as well), owing to the sudden voltage difference between the electrodes of the gap, the gap breaks down, short-circuiting the discharge capacitor via the conducting thyatron.

The energy dissipated in the discharge is proportional to the stored energy \( \frac{1}{2} CV^2 \). The voltage of the power supply (22) was 10 kV. The minimum value of the discharge capacitor was determined experimentally by setting up the shadow system and measuring the light intensity falling on the film. There was no appropriate lightmeter which could have been applied for such a fast and low intensity light, therefore, a photomultiplier
Fig. 3.2
The layout of the experimental apparatus
Fig. 3.3
The layout of the experimental apparatus
The photomultiplier was placed into the opening (11) originally intended for holding the lens system. In this way the light pulses coming through the film were recorded, by displaying the signal of the photomultiplier on an oscilloscope. A typical light distribution can be seen in Fig. 3.4, where the first curve was recorded without using an argon flush in the gap, the second one using argon. The scales are 17/cm, 1 ms/cm.

It was very difficult to screen the photomultiplier from picking up the pulses of the spark-gap, in which at the time of the discharge approximately 0.5-μs pulses of several hundred amps were flowing. Eventually this difficulty was solved by using a steel chamber which incorporated the multiplier, its H.T. power supply and the battery feeding the supply. This photomultiplier was very useful as it enabled the study of the exact shape of the light pulse train and by this several checks could be made regarding the firing system, gap, synchronisation, etc.

3.3 The spark-gap

It can be proved that the smaller the light source, the nearer it can be to the object without loss of definition. This in turn reduces the amount of light required, since the light reaching the plane of the lens follows the inverse square law. Therefore, the main requirement towards the spark-gap is the smallest possible size. Stability is also essential.

Basically there are two main types of spark-gap, the open gap and the constricted gap.

At first, because of its simplicity, the experiments were started with an open gap consisting of two stainless steel rods with conical ends. The axis of the gap was perpendicular to the optical axis. Therefore the increasing distance between the electrodes due to erosion increased the size of the effective light source. An attempt to use an extra lens in order to focus the spark-gap into a pinhole of given size and thus to reduce the size of the effective source was unsuccessful because of the loss in intensity. Therefore, it was decided to turn to the application of a constricted gap of a spherical anode and a flat cathode with a central 0.5 mm diameter pinhole in it acting as the effective source. The axis of the spark-gap was in line with the optical axis.

The unevenness of the subsequent pulses in intensity was improved by using a 2-mm wide insulator tube between the electrodes. The hole in the tube determined the space where the sparks had to occur and thus the light pulses become more even. The other advantage of this constricted gap was that owing to the small hole in the insulator and in the electrodes, the pressure increased during the spark and this way the discharge took
Fig. 3.4
Light pulses train recorded by photomultiplier
1. with argon flush
2. without argon flush
The time displacement of the traces is of no significance

Fig. 3.5
Break-off discharge V-I diagram
Top: voltage 10V/cm
Bottom: current 2V/cm
Time: 50 $\mu$s/cm
Circuit: 50V, 2A. resistive
A 'break-off discharge' occurs when the tungsten wire breaks away from the cadmium segment
place in a high pressure gas, which had the effect of increasing the luminosity of the discharge.

A further improvement in luminosity was achieved by using argon gas emitted slowly through the central hole in the spherical electrode. According to Whitlow (1961) by using argon gas at atmospheric pressure the intensity and the duration of the discharge can be increased noticeably, though in our experiments the improvement was not so marked. The comparison of sparks with using argon flush (1) and without argon (2) can be made on the basis of the Fig. 3.4 which was taken by using the photomultiplier.

The improvements achieved by the constricted gap made it possible to reduce the value of the discharge capacitor by about half. Consequently the duty in the firing system diminished and the length of the pulse train increased.

3.4 The optical system

3.4.1 The shadow system

For reasons of simplicity the parallel shadow system was preferred. The layout of the optical system can be followed on Fig. 3.2. The arc light-source (1) was used only for lining up the optical system and checking the position of the electrodes before firing the gap. The light pulses used for shadow photography were generated by the spark-gap (2). The pinhole of the spark-gap was in the focus of a lens (3) of 17-in. focal length. The parallel light pulses passed through the parallel windows of the chamber (4) which is removed in Fig. 3.2, but can be seen in Fig. 3.3.

For the experiment an intermittent breakflash equipment was used, the electrode arrangement (5) of which was modified according to the requirements. The breakflash chamber was blackened in order to prevent reflections and disturbances and two parallel windows were inserted in the way of the light beam. The breakflash equipment was evacuated and filled with an 8.3% methane-air mixture at 760 mmHg pressure via the tube (6) from the breakflash testing station (7) with automatic sequence control, developed by K.R.E.

The elements of the optical system, except the camera, were mounted on an optical bench (8). During the experiments it proved necessary to fix the camera stand as well by slippers screwed to the floor in order to avoid the meticulous lining up process before every shot.

The camera (9) used was an Eastman Kodak high-speed cine camera (16mm film) designed for normal cine-photography with a top speed of 3200 frames per second. As the separation of the pictures was provided by the pulsing nature of the light, the light pulses had to be recorded on the film without
going through the rotating prism, which would have framed it again. Therefore, the opening originally designed for recording continuous oscilloscope beam was used for projecting the light pulses into the film via a prism (10) placed at 45° to the optical axis. The prism was later replaced by a metal-plated surface-mirror in order to get better reflection.

Several types of film were tried out. Eventually the Ilford Mark V film was used with emulsion turned inwards, towards the mirror.

The opening (11) normally applied for holding the lens system was used for checking the lining up of the optical system (the rotating prism was set to be parallel with the film during this check), and for measuring the intensity of the light source by the photomultiplier.

The speed of the film was set to the maximum value of 3200 frames per second. Each frame was 7.6 mm, i.e. the film speed was 24.3 m/s or 2.43 mm per 100 μs. Since the speed was predetermined, in order to record pictures of different repetition time, the height of the picture had to be changed correspondingly by masking to avoid overlap. The masking was done by metal plates of different slot size inserted in front of the film.

3.4.2 Recording of the voltage

At the beginning only the kernel development was recorded on the cine-film, the relevant voltage was observed on the oscilloscope, or simultaneously recorded by taking a polaroid photograph of the screen. For the observation of break off discharges such as in Fig. 3.5 this was adequate, but when the complete sliding period was recorded with the model electrode system imitating the conditions of the German breakflash, then either just a small part of the complete voltage could be recorded on the screen, or if the time-scale was altered so as to cover the whole event, then the resolution was very poor.

To solve this problem an attempt was made to extend the length (improve the resolution in time) of the voltage trace by using another film running synchronously for recording the voltage. The idea was to modify the sawtooth form of the horizontal deflection into a triangular form and stop the suppression during the return of the beam. In this way the beam would have been plotting the voltage continuously from left to right and right to left. The screen would have been photographed on a film running vertically, resulting in a voltage trace along a time axis going in zig-zag. Though the system was working the evaluation of this zig-zag voltage diagram was difficult and, though the resolution in time was much better, the permissible vertical deflection was reduced and limited by the speed of the film.
Therefore it was thought that the voltage should be recorded on the same film together with the kernel photographs. The main obstacle to the use of the opening (11) was the rotating prism which could not be removed and which was not required as part of the optical system in these experiments. Several arrangements were tried out to get the oscilloscope beam via different mirrors onto the film. The problem was threefold. First the intensity of the oscilloscope beam was not adequate; second the size of the picture on the film and on the oscilloscope screen determined a certain picture/object ratio which had to be kept; third the beam had to fall on the film at a certain angle and therefore it was difficult to achieve adequate sharpness of the beam all over the film.

The final arrangement used for the investigation of the resistive circuit can be seen in Figs. 3.2 and 3.3. The lens (13) mounted on another optical bench was used for focusing the screen of the oscilloscope (12) on the film. For economic reasons, i.e., using both ends of the 100' film, the oscilloscope beam had to be switched on after the first half of the film had run through the camera. This was achieved by means of a magnetic device (14) exerting torsion momentum on the illumination knob of the oscilloscope.

3.5 Trigger pulses

As previously mentioned the shortest possible repetition time of the successive light pulses was about 40 $\mu$s, though most of the time 130 $\mu$s was used.

Further reduction of the repetition time was not feasible for several practical reasons. Firstly the recovery time of the thyratron could not have been reduced much further. Secondly with the given high-speed camera the speed of the film could not have been increased further. The 3200 frame per second top speed gave approximately 1 mm film movement during 40 $\mu$s which meant that the height of the pictures was limited to 1 mm. Hence the growth of the kernel could not have been observed properly after reaching 1 mm diameter which is well under the critical size.

For the firing the thyratron positive going pulses were required of about 400 V amplitude and of 200 V/$\mu$s rise time. As the pulse generators available could not provide this output a pulse amplifier circuit had to be designed. The amplifier had two stages. The EL85 valve was working as an amplifier, whilst the EL360, working as a cathode follower, provided the low-impedance drive for the thyratron via a low-pass filter, designed to prevent high-voltage transients appearing on the grid of the thyratron on initiation of the discharge from causing damage to the low-voltage
trigger circuit.

The input signal required for the trigger circuit was 25 V on 600 ohm, negative-going square pulses of 2 $\mu$s width.

3.6 Synchronisation

The final aim was to record the kernel growth and the relevant voltage diagram of an explosion.

There was no way of ensuring that the explosion definitely would commence during the taking of the photograph, it was only possible to make it likely to happen by choosing the corresponding current and voltage values of the test circuit on the basis of the experimental minimum igniting current versus voltage diagram so as to be above the SIRE curve (see Fig. 4.1).

Basically four events had to be synchronised appropriately.

(a) the firing of the spark-gap,
(b) the recording of the high-speed shadow photograph of the kernel,
(c) discharge taking place between the electrodes,
(d) the recording of the voltage of the discharge.

For the experiments made with the model electrode system imitating the operation of the German breakflash, involving make, slide and break, the timing sequence of the experimental apparatus was as follows:

First the firing circuit was charged up, the chamber was evacuated and filled. Then the motor of the high-speed camera was started. After a preset length of film had run through, a mechanical contact on the camera activated a relay circuit which supplied power to the test circuit and started the motor of the breakflash. The change of voltage across the electrodes triggered the oscilloscope and the firing circuit. The triggering of the firing circuit was executed by a silicon-controlled rectifier (SCR) which at first was in the cathode of the pulse amplifier and made the amplifier act as a gating device. The pulse generator was free-running continuously but the pulses could get through the amplifier only when the SCR was closed. This solution was not satisfactory, because the uncertainty in the appearance of the first pulse was equal to the pulse repetition time.

In order to get the first pulse to coincide with the beginning of the change in the voltage another method was used. The pulse generator was stopped and then triggered from the voltage across the electrodes via another SCR.
The main requirements of the triggering circuit were:
(a) not to load or affect the test circuit,
(b) to provide adequate voltage for triggering with minimum delay.

As the voltage diagram changed to a great extent according to the electrode material and circuit parameters, the triggering circuit had to be redesigned for every particular type of test.

The trigger circuit shown in the circuit diagram (see Fig. 3.1) is the circuitry used for synchronization in connection with the tests of resistive circuits using the model electrodes. In order to achieve high sensitivity a pulse transformer was used and the SCR was supplied with a stabilised d.c. grid bias.

3.7 Specification of the experimental apparatus

Photography: (a) parallel beam shadow photography of the kernel development,
(b) voltage diagram of the test circuit, recorded on the same film as the kernel photographs.

Camera: Eastman Kodak high-speed camera (3200 frames per second).
Film: Ilford Mark V.
Oscilloscope: Telequipment double beam oscilloscope Type D53 with special wide-band amplifier.
Spark-gap: Cylindrical stainless steel electrodes, one flat, the other spherical with 2-mm wide insulator tube between them. Pinhole 0.5 mm diameter, argon flush.
Firing circuit: Discharge capacitor 0.01 - 0.05 μF, 10 kV non inductive.
Storage capacitor: 2 - 4.5 μF, 10 kV non inductive.
HT voltage: 10 kV.
Thyratron: English Electric Type 8503.
Light train: 50 - 80 pictures, with minimum repetition time of 40 μs (see Fig. 3.4).
Energy of the discharge capacitor: 0.5 CV^2 = 5 - 25 J.
Triggering circuit: 2-stage amplifier, input requirement: negative-going square pulse of 2 μs width, 25 V on 600 ohm.
4.1 Experiments with resistive circuits

This investigation was primarily concerned with resistive circuits tested with the German type of breakflash. The reason for this choice was the increasing practical importance and application of circuits of resistive character, due to the application of transistors and different safety devices which can render the inductances effectively resistive. Recent work has shown that the German breakflash has a high sensitivity and it may be adopted as an international standard. Furthermore, experiments at SMRE have shown that the sensitivity of this breakflash can be increased markedly by using curved rather than straight tungsten wires and thus providing a smooth slide. It was of great practical importance therefore to investigate the igniting mechanism of this type of breakflash.

In order to use the high-speed shadow photography system that was developed, a model electrode system was designed which was equivalent to the German breakflash with regard to the sparking process and also enabled photographs to be taken of the kernel which develops into ignition.

The standard German breakflash (VDE 0170/0171:1963) consists of a horizontal rotating grooved cadmium disc across which four vertical tungsten wires of 0.2 mm diameter scrape. The relative velocity of the electrodes during the scraping action varies owing to the fact that the axis of the top wire holder and the axis of the bottom disc electrode are offset by 33 mm. The wire holder turns at 80 rev/min and the disc at 20 rev/min. The relative velocity of the wire reaches a minimum of approximately 25 cm/s when it is midway between the two axes of rotation.

The equivalent model electrode system used for photographing kernel development consisted of a stationary tungsten wire electrode of 0.2 mm diameter and a rotating cadmium segment. The path of the wire on the segment was chosen to be equal to the average path length in the German breakflash and the relative speed of the wire on the segment was about 25 cm/s. The triggering and timing of the system was set to allow photographs to be taken of the complete process, i.e. the make, slide and break between the wire and segment.

The circuit parameters were varied between 20 and 60 V and 1.6 and 4.75 A. The V/I values for each test are shown in Fig. 4.1 in relation to Guenault's results of minimum igniting current against
The position of testing points in relation to Guenault's and SMRE's results.
voltage for non-inductive circuits. As can be seen the experimental V/I values were chosen so as to provide the same maximum power output of \( P_s = V_s \cdot I_s/4 = 20W \).

For comparison the minimum igniting current curve by SMRE (published by Y. Cartwright in 1968) is also marked just to indicate how much the level of minimum igniting current has changed since Guenault. The relevant \( P_s \) curves were calculated from the current values.

It can be seen from Guenault's and from SMRE's curves that the minimum igniting current deviates from the constant power line at lower voltages, i.e. more power is required for ignition at lower voltages. It was felt that this feature should be investigated in more detail.

### 4.2 The electrical power transfer function in a resistive circuit

The resistive circuit during the period of the discharge is represented by Fig. 4.2 where

\[ V_d(t) \] is the discharge voltage
\[ R_d(t) \] is the discharge resistance = \( V_d(t)/I(t) \)
\[ R_i \] is the resistance in series with the discharge
\[ I(t) \] is the current in the circuit
\[ I_s \] is the short-circuit current when \( R_d(t) = 0 \)
\[ V_s \] is the source voltage

In a particular test it may be assumed that \( V = \text{constant} \) and \( R_i = V_s/I_s = \text{constant} \).

It can be shown that

\[ R_d(t) = R_i \cdot V_d(t)/\sqrt{V_s - V_d(t)} \] \hspace{1cm} (4.1)

and the power output from the electrical circuit which is absorbed by the discharge system:

\[ P_o = V_d^2(t)/R_d(t) = \sqrt{V_s V_d(t)} - V_d^2(t)/R_i \] \hspace{1cm} (4.2)

or

\[ P_o = I_s V_d(t) - V_d^2(t)/R_i \] \hspace{1cm} (4.3)

For this type of circuit \( P_o = P_s \) when

\[ dP_o/dV_d = I_s - 2V_d/R_i = 0 \] \hspace{1cm} (4.4)

i.e. when \( V_d = I_s R_i/2 = V_s/2 \) \hspace{1cm} (4.5)

The maximum power absorbed by the discharge, i.e. the maximum power available from the circuit is therefore \( I_s V_s/4 \). Hence it can be said that \( P_s = I_s V_s/4 \) is the characteristic power associated with the source. The power available for the discharge mechanism can be considered in terms of an electrical power transfer function.
Fig. 4.2
Resistive test circuit

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<td>0.96</td>
<td>0.88</td>
<td>0.88</td>
<td>0.75</td>
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</tr>
</tbody>
</table>

Table 4.1

Fig. 4.3
Dependence of the electrical power transfer upon normalised discharge voltage.
where \( V_r(t) = \frac{V_d(t)}{V_s} \) is a normalised voltage function.

\[ T_{pe} = \frac{P_o}{P_s} = 4 \frac{V_d(t)}{V_s} - 4 \frac{V_d(t)}{V_s} \]

or

\[ T_{pe} = 4 \frac{1}{V_r(t)} - \frac{1}{V_r^2(t)} \]

\[ (4.7) \]

4.3 The electrical power transfer function of the model electrode system

From the voltage records with the cadmium segment - tungsten wire arrangement (see the photographs in the appendix) it was found that the discharge voltage followed a form shown in Fig. 4.4. Initially the voltage fell in about 10 - 150 \( \mu \)s from the open-circuit voltage \( V_o \) to a low (9 - 12V) arcing level. The voltage remained constant at this level for as long as the electrodes were sliding on each other, although it might alternate between two or more levels in some cases. Then the voltage rose virtually linearly and finally jumped to the open circuit value. The linear rise which was due to the separation of the electrodes lasted about 1 - 2 ms, and the sliding was about 2 - 10 ms depending on the speed and the length of path.

There were two occasions when the discharge voltage crossed the \( V_o/2 \) value, i.e. the power output was favourably high. The first was during the transient from \( V_o \) to the constant arcing level. This proved not to be important in causing ignition presumably because the time interval during which the energy transfer is favourably high was too short. The second occurred when the electrodes were separating and the voltage was rising linearly, beginning at \( V_o \) and ending at
Fig. 4.4

General pattern of the discharge voltage

Fig. 4.5

Investigation of the power transfer during the linear voltage rise.


The ignition is more likely to take place. The important region for further investigation is therefore the rise when the discharge voltage $V_d(t)$ is moving between $V_b$ and $V_c$ and can be described by

$$V_d(t) = \frac{V_d}{2} + \left(V_e - V_b\right)t/t_d$$

(4.8)

where $t_d$ is the time taken for the voltage to rise from $V_b$ to $V_e$.

The time scale has been chosen such that $t = 0$ when $V_d(t) = V_e/2$.

Using normalised voltage values

$$V_r(t) = 0.5 + \left(V_e - V_{br}\right)t/t_d$$

and substituting in equation (4.7)

$$T_{pe} = 1 - \left(V_e - V_{br}\right)^2 t^2/t_d^2$$

(4.9)

(4.10)

Some characteristic values are

$$t = 0; T_{pe} = 1$$

$$t = \pm \frac{t_d}{2}; T_{pe} = 1 - \left(V_e - V_{br}\right)^2$$

$$t = \pm \frac{t_d}{2}; T_{pe} = 1 - \frac{1}{4} \left(V_e - V_{br}\right)^2$$

At the beginning of the linear rise $t = t_b$

$$V_r(t) = V_{br} = 0.5 + \left(V_e - V_{br}\right)t_b/t_d$$

(4.11)

From this

$$t_b = \left(V_{br} - 0.5\right) t_d/(V_e - V_{br})$$

(4.12)

where $t_b$ is measured from the $V_r(t) = 0.5$ i.e. $T_{pe} = 1$. From equations

$$T_{peb} = 1 - \frac{1}{4} \left(V_{br} - 0.5\right)^2$$

when $V_r(t) = V_{br}$

(4.10), (4.12)

The arc ends at $t = t_b + t_d$

Following the reasoning outlined in section 1, further factors should be introduced to account for power loss from the discharge to the electrodes and from the hot kernel to the electrodes, i.e. discharge and quenching factors respectively. It is impossible to give a simple theoretical analysis of these factors but it should be pointed out that the quenching factor as well as the discharge factor should be rather low in the case of a German type of breakflash compared with other types because of the large cadmium electrode which acts as a heat sink.

4.4 Photographic Records

Several photographic records were taken using the high-speed techniques described in section 3, and some of them are included here in
A detailed examination of the initial fall in voltage from the open circuit value showed no sign of an actual contact or make even with a resolution of 0.1 $\mu$s/cm. As the wire and segment moved together the voltage level dropped exponentially within 10 - 180 $\mu$s or less to a 9 - 12V arcing level. Similar behaviour was observed by Lazarenko (1958). A constant arcing level then followed for about 1 - 2 ms. Generally there was no kernel development during the drop in voltage, although on some occasions for a reason unknown the drop was much slower and 'bubbling' occurred (A.2).
Table 4.2

List of the Photographic Records

<table>
<thead>
<tr>
<th>Fig.</th>
<th>( V_s (V) )</th>
<th>( I_s (A) )</th>
</tr>
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<tr>
<td>A1</td>
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</tr>
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</tr>
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<td>1.6</td>
</tr>
<tr>
<td>A8</td>
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</tr>
<tr>
<td>A9</td>
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<td>1.6</td>
</tr>
<tr>
<td>A10</td>
<td>36</td>
<td>3</td>
</tr>
<tr>
<td>A11</td>
<td>50</td>
<td>2.3</td>
</tr>
<tr>
<td>A12</td>
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</tr>
<tr>
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<td>3.2</td>
</tr>
<tr>
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<td>2</td>
</tr>
<tr>
<td>A15</td>
<td>30</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Voltage scale: 1.6V/mm,
time scale: 130 \( \mu \)s/frame,
linear enlargements (kernel, electrode size): five times.
The voltage during the long stable arc was between 9 - 12 V. In the lower range (9 - 10 V) there was no visible development, but if the was in the 11 - 12 V range some 'bubbling' occurred. It may be assumed that 'bubbling' is due to the release of cadmium vapour from the lower electrode. On the 100 μs/cm resolution range used for these experiments no correlation was found between the fluctuation in the voltage and the appearance of individual 'bubbles' (A4).

After this period there was sometimes another phase when the voltage was jumping between two levels, the lower level being about 2 - 3 V. The time spent at each level may be 10 - 100μs (A9) although in some cases the time was longer (A8).

In the third phase corresponding to the separation of the electrodes the voltage increased nearly linearly with little fluctuation. It is during this time that optimum power transfer occurs for a few hundred microseconds together with interesting developments.

4.4.2 Observed Developments

The developments observed can be divided into three categories:

(a) 'Bubbles' growing in different directions to sizes not greater than about 0.8 mm diameter. Their shape was much less defined than that of the ignition kernels. Typical 'bubble' development can be seen in A1, between frames 7 and 23 or in A2 and A3.

(b) Sometimes a 'bubble' seems to be thrown out from the electrodes as if some sort of particle surrounded by hot gas had been quickly ejected from the discharge. This observation is in agreement with Widginton (1965) who studied kernel development between separating wire electrodes. This type of 'bubble' can be found in Fig. A4, frame 22 or A14, frame 14.

(c) Whilst the life of the 'bubbles' seems to be about 100 - 150 μs and more and more appear one after another, a kernel which may lead to ignition appears as a well defined blob which grows steadily. The shape of such a blob is generally round although irregularities may be present because of quenching effects. A kernel will grow in diameter before it disappears or develops into ignition. The contour of a kernel which will cause ignition appears to be sharper than of a collapsing one suggesting that in the former case the temperature difference between the kernel and the surrounding air is higher. There was no evidence of a correlation...
between the appearance of a kernel and the fluctuation in the voltage level. The time between the appearance of a would-be kernel and a steadily expanding explosion with a sharp boundary about 3 mm diameter varied between 0.5 and 2.5 ms (see Figs. A.1, A.5, A.6, A.7, and A.8).

4.4.3 Light emission

During the kernel development light emission was sometimes observed. This phenomenon does not appear in all cases but examples are shown in Figs. A.4, A.8, and A.9. In these particular cases pictures were taken after the arc had stopped. It can be seen that during the break off period more or less simultaneously with the kernel development the general intensity of the frames, instead of going down, starts increasing, probably due to the reflection of light from the arc. After the end of the arc the frames are dark again. In Fig. A.9 the light intensity is changing but it does not seem to have any correlation with the voltage level. It is unlikely that there is a change in the type of discharge because this should coincide with a change in the voltage, and it cannot be explained in terms of the changing power input to the arc either because the light output should then be more pronounced at $V_d = V_s/2$ and should decrease afterwards. An example worth including is shown in Fig. A.10 in which a cadmium rod electrode was used instead of a segment but voltage record was not made.

The light does not appear at the beginning when arcing must be taking place because there is 'bubble' development, nor has it any obvious relevance to the appearance of the kernel and its development. Perhaps it could be associated with certain chemical reactions taking place but in order to answer such a question satisfactorily further investigation is necessary.

4.4.4 Effect of compounds

It is well known that deposits of different colours appear on the surface of cadmium electrodes during ignition tests. At least 4 different deposits were observed, i.e. white, yellow, blue and black which was the most common. It is felt that the appearance of the different deposits might be associated with changes in arcing behaviour, e.g. varying power, and with the appearance of different types of 'bubble'. Further investigations were necessary to elucidate this question.
4.5. Control experiment with platinum electrodes

In order to obtain some information on the importance of electrode material some photographs were taken under similar circumstances but with a platinum segment instead of a cadmium one. Whilst with cadmium at 50V ignition was observed at 1.6 A (Fig. A.1), with platinum no ignition appeared even at 2.4 A which means 50% more power (Fig. A.11). The minimum arcing level was 15V which is in agreement with the minimum arcing voltage measurements carried out by other authors (Widginton, SIRB Report No.240, 1965 Table 1). This level did not coincide with the optimum power output level therefore there was no chance for ignition during the slide. Surprisingly the usual voltage rise at the end, characteristic for cadmium electrodes did not appear at all with platinum electrodes. The voltage level jumped between the make, arc and open circuit levels with very short transients which could not give rise to kernel development. It would be interesting to see whether a minimum in the power level for kernel development could be obtained at a circuit voltage of 30V when the arcing level and the V/2 level should coincide. Also other materials should be studied to see how they influence the voltage diagrams.

4.5. Cine photographs

There are suggestions in the literature that the pre-discharge period has an effect on the probability of ignition. According to Seki et al. (1964) and others the minimum igniting current shows a slight reduction if there is a current flowing for about 1 - 10 ms. prior to ignition. It was felt that it would be of interest to investigate a complete sliding period to see if there is any significant change in the discharge process. With the high-speed photographic equipment it was not possible to take more than 80 - 100 frames and therefore it was decided to take normal, not shadow, photographs of the model electrode system combined with the recording of the discharge voltage on the same film. On these cinephotographs only 1/5 of the voltage trace per frame applies to the picture taken. The reference level for the time scale was adjusted to be level with the top of the cadmium disc and thus the exposure time of the frame corresponded to ± 1/10 of a frame on either side of this level. For reference the second beam was used to indicate the 0V level. The spacing of the frames is 300/μs.

Four photographs were taken each with a 30V source voltage and a short circuit current of 1.8A. Extracts from one of them are shown in the appendix (Fig. A.15). From these photographs it was found that the
voltage starts at an arcing level of about 10 - 12V again without a make. Later the voltage shows alteration between two arcing levels. At first the lower level was a half of the initial arcing level but it gradually decreased to 1.5 - 3V. A perfect make did not appear at all as there was always about 1 - 1.5V between the electrodes but it should be remembered that the resolution of the system was about 1V. Light was visible from the arc when the voltage was at the higher level and it was found that the discharge took place sometimes at 2 or 3 different sites along the electrodes simultaneously. Towards the end of the photograph a long (1 - 4 ms) arc at the higher level, and following this a linear rise in voltage was observed. This rise was accompanied by very intense light but the intensity of the light showed no correlation with the output power of the electrical circuit. In fact the peak in light intensity came after the peak in output power.

As regards the effect of pre-discharge current duration, apart from the slow (within 10 ms) reduction of the lower level of the voltage which could indicate the reduction of heat loss going into the electrodes, no other obvious indication was found which suggested that the pre-history of the discharge had an effect on ignition. There are certain frames in which, according to the voltage trace, an arc was present, but in spite of this there was no sign of light between the electrodes. The obvious explanation for this is that the discharge occurred on the far side of the top electrode and hence was masked by it. It was felt that without a drastic improvement in the resolution in regard to distance and time, this system could not provide any further information.

4.6 Discussion

From the results it seems that there is no correlation between the voltage and bubble development but it must be borne in mind that the resolution of the present system may not be adequate to register the relevant details. The sudden appearance of bubbles suggests that the energy input fluctuates, probably owing to the microstructure of the electrodes, and variations in the discharge, but the magnitude of this fluctuation seems to be too small for causing ignition.

Unlike Lintin and Wooding's (1959) experiments in which the energy was fed into the gas in a pulse form within 0.5 μs and was used up gradually during the kernel development, the concept of critical time (section 2.1.5) loses its meaning when a continuous discharge takes place. If the energy is fed in pulse form, a kernel will collapse if it does not reach a certain size within a certain time.
but when energy is fed in continuously, it is possible for a kernel to be kept on the edge of turning into ignition for even as long as a millisecond. An example of this is shown in Fig. A5(2) where the last but 5, 6 and 7 frames show the kernel developed to 3 mm diameter, stagnating and nearly disintegrating and then turning into an explosion.

During the experiments ignition did not occur whilst the electrodes were scraping on each other. However, it was noticed that when the electrode system was left running, it had a tendency to settle to the most favourable conditions for ignition. If the pressure between the electrodes was too high the voltage trace showed a make or low-level arc and if the surface of the segment was too rough a high-frequency make low-level arc occurred (A.9). Both types of behaviour make ignition difficult. But after the tungsten wire has crossed the segment a few times the voltage diagram settles to the situation shown in Fig. A.1 or A.10. The harder top electrode cuts its way into the soft cadmium surface and after a few crossings the path is so smooth, that after striking an arc it is maintained at a fixed level during the slide. This suggests that during a slide the electrodes do not in fact touch each other but move parallel at an arc distance. This gives a constant power input during the slide but as losses are higher in this condition compared with a break (the quenching is greater, making $T\text{_{qu}}$ smaller, over the segment than at the edge) the probability of ignition will be low.

According to Widginton's (1965) observations, if the electrode system is altered so that one wire scrapes slowly and continuously around a circle on a flat cadmium surface in a 24V circuit, the minimum igniting current can be reduced by 10%. The phenomena which seemed inexplicable to him can be explained in the light of the system's tendency towards the most favourable arcing condition. One may assume this continuous arcing condition is achieved after a few turns and the $T\text{_{e}}$ factor reaches its maximum simultaneously because in the case of a 24 V circuit the power output is the highest when the arc voltage is 12 V which coincides with the arcing level observed during the 'slide'. As a general conclusion it can be said that ignition is likely to occur during the slide only if the arc voltage is such that energy output is at the optimum level. If a higher voltage is required for maximum power transfer then ignition is likely to occur only when the arc voltage rises, i.e. during break off.

As can be seen from the voltage diagrams and high-speed photographs a kernel generally appears during the rise of the voltage. Sometimes it grows quickly (A.1) and sometimes slowly (A.12). (It should be noted...
that A.12 and A.1 are two successive shots taken under identical circumstances). In spite of this A.1 shows a straightforward explosion, whilst there is virtually no development on A.12. This gives an example of how difficult it is to control the ignition. Eventually the kernel either develops into ignition or collapses even though the arc is maintained (A.12).

In order to elucidate the energy situation of the process, the following considerations should be made. During the linear rise of the voltage commencing at the break, the electrical power transfer will move along a parabola corresponding to eqn. 4.10.

\[ T_{pe} = 1 - 4 \left( V_{cr} - V_{br} \right)^2 t^2/d^2 \]

The form of the parabola is determined by the discharge time. Because the arc is continuous the losses are continuously present as well and could be represented by a \( P_{\text{loss}}(t) \) power function. The power output of the electrical circuit will be

\[ P_o(t) = P_b T_{pe} \]

When \( P_o(t) = P_{\text{loss}}(t) \) there is no energy left for kernel development but as soon as a \( P_o(t) > P_{\text{loss}}(t) \) there is a surplus power available for kernel development. The surplus output energy would be

\[ E_{\text{surp}}(t) = \int_{t_0}^{t} \left( P_o(t) - P_{\text{loss}}(t) \right) dt. \]

The energy required for successful kernel development to ignition is \( \int P_k(t) \) (see section 1). Hence if the power output from the electrical circuit can be maintained above the loss level for a sufficient time then the kernel can reach a self-propagating stage. If at any time \( P_o(t) - P_{\text{loss}}(t) < P_k(t) \) the developing stops.

Supposing that the first appearance of the kernel (not bubbles) in the photographs at the time \( t_b \) indicates that \( P_o(t) \) has just become greater than \( P_{\text{loss}}(t) \). Assuming that the losses remain constant at \( P_{\text{loss}}(t_b) \) for the following \( t \) time then the energy available for ignition would be

\[ E_{\text{surp}} = \int_{t_b}^{t} \left( P_o(t) - P_{\text{loss}}(t) \right) dt. \]

In the co-ordinate system of Fig. 4.5 \( t_b \) must be negative and \( t_s < 2 t_b \) or equal to \( t_d \), i.e. \( P_o(t_b) \) must be less than \( P_s \). For the sake of simplicity it is advisable to use normalized values.

\[ E_{\text{surp}} = \int_{t_b}^{t_s + t_b} \frac{P_o(t) - P_{\text{loss}}(t)}{P_s} dt = \int_{t_b}^{t_s + t_b} \frac{t_s \left[ T_{pe}(t) - T_{pe}(t_b) \right]}{P_s} dt - 55 - \]
from the previous calculations

\[ T_{pe} = 1 - \frac{2}{t_s} \left(V_{sr} - V_{br}\right)^2 \]

Hence

\[ E_{\text{surp.r}} = \frac{4}{t_s} \left[(V_{br} - 0.5)^2 - (V_{sr} - V_{br})^2 \right] \left[t_b + t_s\right]^3 - \frac{1}{3} t_s^2 \]

This approximate calculation was applied to some of the photographs shown in the appendix. First the individual parabolas were plotted taking seven relevant points (\(T_{pe}\) at \(t=0\), \(t=\frac{t_b}{2}\), \(t = \frac{t_s}{2}\) and when \(T_{pe}=0\)), the \(t_b\) point was determined for each parabola and hence the \(t_s\) interval was found. Calculated values are given in Table 4.3 and the curves are plotted in Fig. 4.6. The numbers in Fig. 4.6 correspond to the photographs shown in appendix.

From the photographs it can be seen that the kernel development is clear and straightforward in A.7 and A.1. In the case of A.1 surplus energy for the time \(t_s = 1.7\) ms when \(P_o > P_b = P_{loss}\) is 3.5 mJ, but it can be seen that the kernel reaches the self-propagating stage before the end of the 1.7-ms period. If it is assumed that the kernel became self-propagating when it reached the diameter of 2 mm, then the surplus energy required was 0.48 mJ in 0.39 ms. This value is not far from the 0.3 - 0.4 mJ minimum energy values measured by different authors (see table 2.1). It should be remembered that this calculation is based on simplifying assumptions and on a system with continuous energy input, whilst the 0.3 mJ quoted by Litchfield et al (1967) is a source value derived from a capacitive (energy input probably within 1 \(\mu s\)) discharge system.

If the assumption that the rate of losses \(P_{loss}(t)\) during the times \(t_s\) are constant and equal to \(P_b\) were true, there should be no ignition in the case of A.8 and A.6 as in these cases \(P_b\) is nearly equal to \(P_s\). Although it is true that there was no ignition there is some kernel development in these photographs. This kernel development time corresponds to the descending part of the \(T\) curve. This suggests that the losses are not constant, as was supposed, but in fact decrease as the electrode separation and hence the voltage increases. However the rate of reduction of losses cannot be as high as the rate of decrease of the output power after passing the \(P_s\) value, otherwise ignition would have taken place on the decreasing part of the \(T_{pe}\) curve.

The reduction of losses with increase in voltage suggested by the curves of Fig. 4.1 can be observed when different tests all with \(P_s = 20 W\) are compared. These tests with various source voltages
Fig. 4.6

$T_p$ versus time curves of the photographs taken.
<table>
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<th>Serial No.</th>
<th>$V_s$</th>
<th>$P_s$</th>
<th>$I_s$</th>
<th>$V_b$</th>
<th>$V_{br}$</th>
<th>$V_{er}$</th>
<th>$t_d$</th>
<th>$t_s$</th>
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<th>$t_{pe \text{ at } t=t_d}$</th>
<th>$t_o$</th>
<th>$t_b$</th>
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**Table 4.3**

Calculation of the surplus energy for the different photographs.
between $2y = 30$V tend to prove that the resultant transfer function of $T_d - T_{qu}$ increases at the higher voltage values. This is feasible because when the source voltage is higher the $T_{pe} = 1$ situation will be reached at a higher voltage where the distance between the electrodes is greater.

In the tests reported here quenching will depend on electrode spacing as it is well under the quenching distance and the quenching loss is likely to be a dominating factor. Hence as the voltage increases the quenching loss will decrease, i.e. the power output required for ignition at this higher distance (higher voltage) should be lower.

The considerations regarding the electrical transfer function of the resistive circuit are valid for any resistive circuit, regardless of the discharge or quenching conditions. Supposing that the ignition would take place at the maximum power point or, in other words, supposing that the maximum of the $T_{ign}$ function coincides with the maximum of the $T_e$ function, then from Genault's experimental curve given for the maximum igniting current and circuit voltages, the minimum output power $P_{0\text{ min}} (V)$ as a function of the voltage could be determined. The relevant values of $P_{0\text{ min}} (V)$ which according to previous notation are equal to $P_S = V_s T_{ign}$ are plotted in Fig. 4.1 marked as $P_S$ Genault. This curve would give at the same time the voltage dependency of the $T_d - T_{qu}$ function. Hence it could be said that resistive circuits of a given output power are less efficient in causing ignition when the source voltage is about 10 - 30V. At higher source voltages the danger of ignition increases.

Since Genault's experiments several tests have been made regarding the minimum igniting conditions. The latest publication from SMRE (J. Cartwright 1968) gives the minimum igniting curve as shown in Fig. 4.1. This is the experimental minimum igniting current versus circuit voltage curve which is applicable to all quasi-non inductive circuits containing cadmium, in a methane-air mixture. The relevant $P_S$ curve is marked as $P_{smare}(1968)$. From a comparison of the two power curves it can be seen that due to the research carried out in this field there is a great improvement in the transfer function of the testing methods, i.e. with 10 times less power, ignition can be initiated. However it cannot be concluded that this $P_{smare}$ curve represents the ultimate minimum power required to cause ignition.

From the power and energy values of the present experiments it is clear that the minimum igniting energies cannot be determined accurately with the model electrode system or the German breakflash because the power...
output required is rather high. The 20 W level corresponds to 2mJ/100 μs, and for the sake of a rough comparison, if the time to reach self-propagation (Widginton 1965) were 300 μs/then 6mJ energy would be transferred in this time. This value is 20 times the 0.3 mJ measured by Blanc et al (1947). Furthermore it must be remembered that their value is a source value and includes the T transfer factor as well, though according to Rose and Friede's investigation in that case T_e ~ 1. Consequently the transfer factor for the electrode system investigated must be 20 times greater than that of the capacitive system used by Blanc et al, which means that with a German breakflash more than 95% of the energy is lost and less than 5% is utilized in kernel development. Obviously if the ratio \( P_k/P_o < 0.05 \), it means that a 5% inaccuracy in the measurements or change in transfer factors could cause a 100% change in the energy available for ignition. This may account for the apparent variations in the sensitivity of the test equipment in spite of every effort to keep the parameters and conditions constant. However, the equipment may still appear sensitive, i.e. a small change in the circuit parameters can make a difference between ignition and non-ignition.
5. Summary and conclusions

It is felt that besides the practical approach to intrinsic safety more thought should be given to the theoretical explanation of the problem of ignition. Quite a lot of work has been done in this field, owing to lack of sufficient theoretical thought it does not fit into a common framework. The various tests are not systematically connected parts of a complex problem but rather individually designed experiments, attempts to tackle certain aspects of the question of ignition, and can only be related to each other with difficulty.

In order to clear the situation a theoretical framework is suggested on the basis of which past work could be revaluated and future experiments could be designed. It is suggested that the energy distribution in time is of primary importance in the process of ignition hence it is the energy distribution that should be the subject of further investigations. The process of ignition by electrical discharges is in fact a process of energy transfer from the starting form of electrical energy into heat which triggers and subsidises a chemical reaction until it becomes self-propagating. It is a rather inefficient process involving losses of much greater magnitude than the energy itself used up for ignition. Consequently it is rather difficult to reproduce ignitions at energy levels near to the limit values of a given breakflash apparatus. This uncertainty led to the widespread use of the probability theory for approaching the problem of ignition.

The process of ignition could be conveniently tackled by introducing the electrical $T_e$, discharge $T_d$, and quenching $T_{qu}$ transfer factors, which together represent the efficiency of the igniting system as the ratio of the source energy $E_s(t)$ available in the electric circuit and the energy $E_k(t)$ eventually subsidising the kernel development.

$$\frac{E_k(t)}{E_s(t)} = T_e(t) \cdot T_d(t) \cdot T_{qu}(t) = T_{ignition}(t)$$

These transfer factors are complex functions of several parameters such as electric circuit parameters, electrodes material, shape, rate of separation, type of discharge etc. In a particular case they together predetermine a certain time function for the transfer factor, and ignition will take place when

$$E_s(t) \cdot T_{ignition}(t) > E_k(t)$$

inequality is fulfilled.

The high-voltage capacitive discharges, where the duration of the energy input is negligible compared to the time required for kernel
to this interval and the quenching losses can be made negligible by choosing an appropriate electrode distance - can be regarded as a special case which can be tackled in terms of energy instead of energy distribution.

Bearing in mind the above considerations related to the energies and transfer functions involved the ideal approach to the problem might be the following. First of all the \( E_k(T, m, p, r, t) \) function should be investigated. After determining the influence of the temperature \( T \), mixture, \( m \), pressure \( p \), kernel geometry \( r \), and time \( t \) on the energy distribution required for ignition and simultaneously keeping the transfer factors at minimum value and constant, a reference \( E_{kr} \) value should be assigned and internationally accepted as a reference value for further investigations. In most cases the investigations were carried out at 1 atm, 20°C with 8.3% methane-air mixture, thus these would be the most obvious choice for reference. Having fixed \( E_{kr} \) (which means that the relevant parameters have to be kept constant with great accuracy) attempts could be made to separate the different transfer factors. By maintaining certain features which could be equivalent to keeping two of them constant, the third one could be determined from the \( E_{kr}/E_{source} \) ratio.

Though the principle is simple, the determination of these factors is not so easy. The electrical circuit parameters can be easily controlled, and there are oscillographic methods for recording the current and voltage functions at the electrodes. From these the \( E_{output} \) function could be reconstructed. Therefore no difficulty should be encountered in determining the transfer factor \( T_0 \). For these experiments there is not even a need for the presence of the gas mixture as there is virtually no feedback effect from the kernel development into the electrical system.

The difficulty comes when \( T_d \) and \( T_{qu} \) functions are to be determined because there are so many interacting factors. There is no easy way to measure \( E_d \) as this middle stage of the process is hardly accessible. Therefore the best approach seems to be to measure \( E_o \), keeping \( E_{kr} \) strictly constant and if it is ensured that only one parameter (e.g. electrode material, geometry, speed of separation, type of discharge) is varied, then the \( E_{kr}/E_o \) ratio will be a reflection of the effect of this parameter. Unfortunately the parameters are interacting and in many cases it is not possible to vary one of them without affecting the others. Consequently, it is very easy to attribute a certain change experienced in the output value to the
deliberately varied parameter and not to notice that at the same time, owing to some interim effects, a change has taken place in the value of the other parameters supposed to be constant, and hence the attribution is not justified. Therefore it cannot be emphasized enough that these results cannot be generalised, and conclusions drawn from them have to be treated with extreme caution because they are correct only under given circumstances and within certain limits.

On the basis of the above considerations an attempt was made to review and appreciate the work done in connection with intrinsic safety investigations.

In order to relate the development of the kernel to the electrical energy consumed in the discharge, experimental equipment was set up, which made it possible to record the development of the kernel relative to the electrodes in time and to record the voltage - current functions in order to calculate the output energy distribution of the electric circuit. With this equipment numerous photographs were taken to investigate the different aspects of the problem, one of which 'the investigation of the ignition process initiated by the German breakflash used for testing resistive circuits' is discussed in this thesis in detail. Experiments were made to assess the adaptability of the experimental apparatus for other investigations (connected with different electrode systems, different circuits, and different speed of separations) but as these experiments should be regarded as only a beginning to more detailed investigations, they are not discussed here.

The electrical transfer function of a resistive circuit as a function of source voltage and indirectly as a function of time was theoretically examined and the power versus time functions were calculated from the experimental data. It was found that near the minimum igniting level a kernel appears when the electrical transfer function reaches its maximum. This means that the maximum of the resultant transfer factor \( T_{\text{ignition}} \) seems to coincide with the maximum of \( T_e \).

It can be said that of the three phases, i.e. make, slide and break, in most cases the only really dangerous one is the break period when the output power remains at its peak for a relatively long time, which is sufficient to cause ignition. There is an exceptional situation when the source voltage is twice the arcing voltage, hence the electrical power output is maximum during the slide and ignition can occur during slide. It was noted that the cadmium - tungsten electrode system with a bent top electrode has a tendency to make the conditions favourable for a long arc of constant
In connection with the kernel development the appearance of 'bubbles' and of light emission was observed and thought to be associated with the presence of different compounds. These phenomena would need further investigation. No correlation was found between the bubble development and the fluctuation in the voltage level which indicates the fluctuation of the electrical output power.

It was shown that for resistive circuits, by considering strictly the surplus energy available during the observed development of the kernel to the self-propagating stage, energy values of the order of one tenth of a milliwatt could be calculated, which were very near to the minimum energy values measured by different authors for inductive and capacitive circuits under completely different conditions. The reduction of energy requirement with increase in voltage (25 - 60V) was recorded and is in agreement with the findings of other workers.
6. References

G. K. Adams
A repetitive spark source for shadow and schlieren photography.

The incendivity of electric sparks in relation to the characteristic of the circuit. Third symposium on combustion flame, p. 341 - 353. (1948).

G. Allshop
The ignition of explosive atmospheres by electric sparks.

Intrinsically Safe Electrical Apparatus. The variation of Ignition Probability with Circuit Current.

D. H. Berlow
Intrinsic safety - its growing status in Europe.

A. L. Bartels and H. G. Riddlestone
The ignition of methane-air gas mixtures by pulse discharges.

I. Berz
Inductive breaksparks of high incendive power.

M. V. Blanc, P. G. Guest, G. von Elbe and B. Lewis.
Third Symposium on Combustion and Flame and Explosion Phenomenon
Ignition of explosive gas mixtures by electric sparks.

J. H. Benjaminsen and I. P. H. Van Wiechen
Selecting electrical apparatus for use in hazardous areas.
Electrical Review, 12th January 1968, p. 54 - 56.

J. Cartwright
Application certification and testing of el. equipment for flammable atmospheres.
Electrical Review. 1st March, 1968.

Spark ignition. Effect of molecular structure.
B. M. Furmanov
The unstable character of the ignition of explosive mixtures by electric sparks.
Mekhanizatsiyaiaautomatizatsiya v gornoi promyshlennosti Moscow 1963.
S.K.R.E. Translation No. 5427.

Ignition of gas sparks produced by breaking wires at high speed.

The ignition of methane-air mixture by arc discharges of controlled duration.

Ignition of gas by sparks produced by breaking wires at high speed.

E. M. Guenaught
Intrinsic safety, a resume of recent progress. July 1952.

F. Llewellyn Jones
The physics of electrical contacts.

I. R. King H. F. Calcote.
Effect of initial temperature on min. spark ignition energy.

Industrial Eng. Chem. 44. P. 2656 - 2662. (1952)

V. S. Komarov
The energy of an electric spark - the criterion for the incendivity of an explosive gas mixture.
S.K.R.E. Translation No. 5384.

V. S. Komarov
Factors influencing the incendivity of an explosive gas mixture by electric sparks.

V. S. Kravchenko
New data towards understanding the process of ignition on mine gases by electric sparks.
N.C.B. Translation No. A.1197/SEH.
B. R. Lazarenko
Electriechesaya Obrabotka Tokoprovovyashchikh Materialov, Academizdat (1958)

B. Lewis, G. von Elbe

D. R. Lintin, E. R. Wooding
Investigation of the ignition of a gas by an electric spark.

1960 Symposium on safety for electric instrumentation in hazardous areas.

Minimum ignition energy and quenching distance in gaseous mixtures.

H. Lloyd, E. M. Guenault
The use of breakflash apparatus No. 3 for intrinsic safety testing.

R. G. Norrish, G. Porter, B. A. Thrush
The studies of the explosive combustion of hydrocarbons by kinetic spectroscopy.

B. A. Petrenko
Electrical discharge in intrinsically safe circuits.
Mekhanizatsiya i avtomatizatsiya v gornoi promyshlennosti 300, 317 Moscow 1963.

H. G. Riddlestone
The effect of series resistance on the ignition of methane-air mixtures by capacitive discharges.

H. G. Riddlestone
Ignition of methane-air mixtures.

H. G. Riddlestone, W. Nethercot

B. Roston
A theoretical approach to the problem of determining the relationship between the constants of circuits and their intrinsic safety.

W. Rogulski
Ignition of gas mixtures by electric discharges between a heated and a
cold electrode.

H. E. Rose and T. Priede
An investigation of the characteristics of spark discharge as employed in ignition experiments.
The Combustion Institute, Seventh symposium on comb. 1958.

Serov V.N.
Automatic high speed explosion chamber for testing the intrinsic safety of electric circuits. Skochinskii Institute of Mining Report. Moscow 1960.

K. Seki, T. Emura, H. Aoyagi and T. Ikeda
Ignition of methane-air mixtures by feeble electric sparks.

V. M. Thomas
Design of intrinsically safe apparatus for use in coalmines.
AIME Monograph No. 1. 1964.

G. Vogt
Die Schutzart Eigensicherheit,

F. J. Weinberg
Optics of flames,
Butterworths 1963.

L. Whitlow
The use of spark gaps for high speed photography.

D. W. Widginton
The ignition of methane-air mixtures by electrical discharges.
Proc. of the Third International Mining Congress, Salzburg 1963.

D. W. Widginton
Electrical ignition of gases. The use of controlled discharges for investigating minimum igniting energies.

D. W. Widginton
Ignition of methane by electrical discharges.
A similar key applies to

A2 ~ h\k

bubbling

W electrode (stationery)

Cd electrode (moving left)

disturbing blobs

Start

time: 130 μs/frame

discriminate Tobias

one frame overlap

and

A

1

max. power input area

(b)