

MINIMUM IGNITION ENERGY OF DUST SUSPENSIONS

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The value of the minimum ignition energy of dust clouds is uncertain; the recorded "standard" values are mainly useful for hazard comparison. Ignition energy of dispersions of two dusts, polystyrene and cornstarch, have been measured with a range of series resistances in the discharge circuit. Results confirm that 1mJ may ignite the cloud; the order of minimum rate of energy supply and that of discharge time are 10^4 m J s^{-1} and 1ms respectively. These observations and the need for more information are discussed.

INTRODUCTION

Minimum ignition energy may be defined as the smallest amount of energy that will produce ignition in a flammable system. This quantity usually refers to a measurement undertaken in a standard apparatus using a standardised procedure. This value is usually understood to incorporate some consideration of the probability of ignition which will vary as the minimum ignition energy is varied around a specific value. It has been pointed out by Rose (1) that there is a well-defined value of minimum ignition energy for flammable gas/air mixtures whereas the probability of ignition varies widely with concentration and energy input for suspensions of combustible dust in air. In this context the inhomogeneity of dust clouds as it affects the number of particles in the effective zone of a spark is in contrast to the situation for gas mixtures where both mixing and reaction are at molecular level.

An all-embracing, fundamental theory of the ignition and combustion of dust clouds is not yet available. However, a major effort (2) has been expended in describing the behaviour of combustible dusts in terms of the following:

minimum ignition energy
 minimum explosible concentration
 maximum pressure generated
 maximum rate of pressure rise

These parameters have been used in defining ignition severity and explosion severity the product of which has been designated as the index of explosibility. This attempt to define the degree of hazard of the dust cloud is based upon Hartmann testing in apparatus of the type described by Raftery (3); this, basically, was the type of apparatus used in the work reported here.

Ignition sources for dust clouds are numerous; attention is often drawn to the comparative difficulty in producing ignition by electrical discharges. However, sparks are a definable and reproducible source and method of introducing energy that can be conveniently employed in a standard apparatus. It is desirable to understand the basis of defining limiting conditions and the controlling features of the processes involved. Parameters that influence the explosibility of dust clouds have been listed by Carpenter (4) and include:

nature and energy of source of ignition
 circuit characteristics of an electrical discharge

Both parameters affect the rate of release of energy to the combustion system, and the mode of heat transfer may vary with the nature of the source of ignition.

Previous Investigations of Spark Ignition

Finch et al (5) drew attention to the importance of inductance in spark discharge circuits used for the ignition of flammable gas/air mixtures. They found that increase of inductance which increased the discharge time, increased the ease of ignition at the same energy level. Boyle and Llewellyn (6) worked with ether/air mixtures and showed that the values of minimum ignition energy were often considerably reduced by inclusion of a series resistance (0.25M Ω) in the discharge circuit for high values of capacitance (0.1 μ F) as compared with the behaviour for low values (0.01 μ F and 350pF). Their measurements of the effect of series resistance on ignition energy for aluminium and magnesium dust clouds are shown in Table 1. For the former, the minimum value occurred at 75K Ω and for the latter, at 15K Ω ; this was shown to hold for a tenfold range of capacitance. Line et al (7) using lycopodium under the following conditions:

dust concentration 80g m⁻³
 percent oxygen in "air" 23
 range of capacitance 800-2500pF
 series resistance 0.1M Ω

found that the minimum value for ignition was 0.049J.

TABLE 1 - Variation with Series Resistances of Ignition Energies of Dust Clouds of Aluminium and Magnesium (6)

Resistance (10 ³ Ω)	Ignition Energy (J)	
	Aluminium (90% - 200B.S.mesh)	Magnesium (100% - 200B.S.mesh)
0	>0.49	0.20
5	0.37	
8		0.09
10	0.145	
15		0.025
45		0.028
50	0.055	
75	0.047	
100	0.22	0.043

Further values (6) are given in Table 2 illustrating the variation of minimum ignition energy with series resistance in the discharge circuit. The smallest value of ignition recorded was for sulphur using a 550pF capacitance and a 5,000 Ω resistor; the value was 9mJ.

TABLE 2 - Variation with Series Resistances of Ignition Energies of Dust Clouds of Tetryl, Acaroid Resin, Polymethyl Methacrylate and Sulphur

Resistance (10 ³ Ω)	Ignition Energy (J)			
	Tetryl	Acaroid Resin	Polymethyl Methacrylate	Sulphur
Dust conc. (gm ⁻³)	540	500	370	500
Capacitance (μ F)	0.025	0.002	0.002	0.002
0	0.020	0.06		
10	0.027	0.05		0.05
25		0.03	0.024	>0.036
50	0.015	0.06	0.017	0.027
100	0.015		0.024	0.035
250		0.06	0.026	0.024

Line et al (7) worked with lycopodium dispersions in wall-confined and wall-free columns and studied the effect of the oxygen content of the atmosphere and of the characteristics of the discharge circuit. Their findings may be summarised as follows:

- i) Without added inductance or resistance the probability of ignition varied widely for the two types of dust column. With inductance ignition frequencies were very similar in the two cases.
- ii) Ignition took place at lower oxygen concentrations when series resistance was used up to values of $1M\Omega$; at $10M\Omega$ a considerably oxygen-enriched atmosphere was required. These measurements were taken with a capacitance of $0.025\mu F$, stored energy $1J$ and dust concentration of $80gm^{-3}$.

More recently Eckhoff (8) has measured ignition energies directly and found that about 40% of the energy stored in the discharge circuit ($\frac{1}{2}CV^2$) was delivered to the spark; as $\frac{1}{2}CV^2$ decreased the fraction of energy delivered into the spark increased. Eckhoff determined the frequency of ignition of dust clouds at various energy levels; some of these results are shown in Table 3.

TABLE 3 - Energy of Ignition of Dust Clouds at Two Frequencies of Ignition

Material	Spark Energy (mJ)	
	Frequency of ignition	
	0.2	1
Lycopodium	7	50
Wheat dust	20	300
Sulphur		5
Fine aluminium flake	0.6	90

EXPERIMENTAL

In the work reported here two dusts have been examined in an apparatus similar to that developed by Hartmann (3) and shown diagrammatically in Figure 1.

The volume of the air reservoir was $434cm^3$ and it was pressurised to $70KNm^{-2}$. The spark gap was 6mm wide (7), and the electrodes were made from tungsten wire, 1mm in diameter, ground to a point.

The circuit for the spark generator is shown in Figure 2. Capacitance C was charged to different energy levels using a Brandenburg Model 750 E.H.T. source. This energy was discharged into the spark gap through resistance R the value of which was varied in the course of the work. The discharge was obtained by energising relay RL. During the brief period that it was energised the $0.1\mu F$ capacitance, previously charged via the $1.5K\Omega$ resistor, was discharged and a negative pulse applied to the grid of the thyatron (T), type 5C22. The stored energy ($\frac{1}{2}CV^2$) was calculated from the known values of C and V. Direct measurement of the energy delivered in the spark was made as follows:

- i) Current. Using a Tektronix current probe type 131 model 4 connected into the circuit immediately after the discharge resistance.
- ii) Voltage. Using a Tektronix probe No.P6007 and a 100:1 attenuator to which was added a further 5:1 attenuator.

These signals were measured on and photographed from a Tektronix type 549 storage oscilloscope. The energy dissipated was determined directly from these records by estimating the product of current and voltage for chosen time intervals; total energy was obtained by summing these quantities for the duration of the spark.

The two dusts examined were dried before use and a sized fraction, 75 to 90 μm , was selected for these experiments. The dust concentrations used were approximately stoichiometric, i.e. for polystyrene $87g m^{-3}$
for cornstarch $260g m^{-3}$

The criterion for measuring an ignition energy was that ignition (and flame propagation over the length of the combustion tube) should occur during 10 attempts. If ignition did not occur during 10 attempts the energy supplied was recorded as insufficient i.e. less than the minimum.

RESULTS

Typical plots showing the combination of stored energy and value of series resistance for limiting conditions of ignition of polystyrene are shown in Figure 3; the minimum ignition energy recorded was approximately 20mJ. The minimum energy recorded for cornstarch was 50mJ. In the case of cornstarch there seemed to be some dependence of the minimum value of stored energy required upon the series resistance (see Figure 4).

The variation of limiting values of measured spark energy is shown in Figures 5 and 6 where it will be noted that for both materials there are minimum values for ignition. A summary of these minimum values is given in Table 4.

TABLE 4 - Minimum Values of Measured Ignition Energy for Polystyrene and Cornstarch Dust Clouds using a Range of Capacitances and Series Resistors

Capacitance ($10^{-3}\mu\text{F}$)	Energy		Time of Discharge (10^{-6}s)	Series Resistance ($10^3\Omega$)
	Stored (mJ)	Discharged (mJ)		
<u>Polystyrene</u>				
0.5	12.25	1	1.6	470
1	24.5	0.31	0.12	6.8
2	49	0.5	0.16	5.6
4	98	1.0	0.2	5
6	147	0.5	0.08	1.5
8	196	1.7	0.4	0.92
<u>Cornstarch</u>				
2	64	1.74	0.4	22
4	128	2.36	1	22
6	169	2.18	0.6	10
8	256	4.53	0.6	10

It will be noted from the results in Table 4 that the energy recovered in the discharge is a small fraction of that stored in the capacitors. This is in agreement with the observations of previous workers and with the conclusion of Eckhoff (8) that the energy dissipated is usually less than 10% of the stored energy depending on the value of the series resistance. These results also support Eckhoff's findings and his conclusion (8) that minimum ignition energy should be considered as having under some circumstances a much lower value than has been customarily assumed. Examples of Eckhoff's values are given in Table 3.

DISCUSSIONStored Energy and Discharged Energy

Attention has already been drawn to the fact that the energy discharged into the spark gap may be one or two orders of magnitude less than that stored. This suggests that information of the circuit characteristics of the spark generator is of importance to enable an assessment to be made of quoted values of minimum ignition energy. Of these characteristics several may be of significance

- i) size and rating of the capacitances
- ii) the value of the series resistance and the energy dissipated therein
- iii) rate of discharge of energy in the spark gap
- iv) residual energy remaining in the capacitances

Rate of Energy Release

This aspect is likely to be of particular relevance in considering dust clouds in view of the limited availability of fuel from the particles. As recorded above current and voltage were measured directly; the time of discharge was also directly available. The rise time to peak current was small compared with the total time of discharge and both voltage and current were relatively steady in value for a major proportion of the discharge. There was a low amplitude oscillation on

the current record (approximately 15KHz). The rate of discharge was therefore averaged over its duration; these values were in the range 0.5×10^4 to 20×10^4 mJ s⁻¹. As shown in Figures 7 and 8 these averages have been plotted against values of series resistance for polystyrene and cornstarch respectively. It is noteworthy that as series resistance increases and the time of discharge increases the average rate of energy requirement for ignition appears to approach a limiting value of about 10^4 mJ s⁻¹. This may be expected in that energy release (and therefore ignition) depends upon the product of resistance and capacitance (time constant) as well as on capacitance (energy stored) and resistance (current flowing). Eckhoff and Enstad (8) have examined the difference in effect of "short" sparks (1μs) and "long" sparks (0.1-lms); it may be inferred from their results that "long" sparks are better able to produce ignition at similar energy levels.

Line et al (7) made the observation that dust particles may be removed from the sphere of influence of the spark; they suggested that this arose from expansion of the gas in the neighbourhood of the discharge. The rate of expansion will depend upon the rate of release of energy as will the strength of the compression wave produced. Litchfield (9) has suggested that this accounts for about 5% of the energy of the discharge; its "shock" heating effect is, therefore, likely to be small. The degree of turbulence produced by the release of energy will depend on the rate of release. The turbulence in its turn will affect the rate of heat transfer and the subsequent rate of propagation of combustion. In studying methane/air flames Bartels (10) has observed by Schlieren methods that both the geometry and the rate of propagation of flame kernels depend upon duration and energy level of the discharge.

Energy Balance

Hay (11) has examined the requirements of a simple thermal model of ignition against the energies reported here. Consideration of the rate of production of volatile matter and of the concentration generated in the period during which an active ignition source was present indicate that the energy input and the energy requirement are not incompatible. On a qualitative basis it seems likely that a longer discharge time that allows a longer period for thermal decomposition of dust particles and hence produces volatile matter will favour ignition.

Comparison of Values of "Minimum" Ignition Energy

In the present work the minimum values of ignition energy measured were:

Polystyrene (87g m⁻³) 0.3mJ
Cornstarch (260g m⁻³) 1.7mJ

It is of interest to compare these with results obtained by standard tests carried out on similar materials (2). In making the comparison it must be against the background that the ignition energy of dusts of the same chemical material, but obtained from different sources, may be widely different.

TABLE 5 - Values of Minimum Ignition Energy for Samples of Polystyrene and Cornstarch

Material	Dust Concentration g m ⁻³	Ignition Energy mJ
Polystyrene moulding compound	15	40
Ground polystyrene	20	40
Clear polystyrene	20	15
Cornstarch - commercial product	45	40
Cornstarch - 325 B.S. sieve	40	30

The difference between values of ignition energy for polystyrene and cornstarch dust depends, among other factors, upon their chemical composition. The difference in ignition behaviour that may be inferred from Figures 3 and 4 is consistent with a difference in the mechanism of ignition as suggested by El Aassar and Napier (12).

CONCLUSION

The results reported here indicate that a re-appraisal of values of minimum ignition energy for clouds of combustible dusts is required. Indiscriminate use of $\frac{1}{2}CV^2$ as a measure of energy release may be distinctly misleading. It is suggested that rate of energy release and time of discharge are important parameters in assessing hazard, to which must be added a measure of the probability of ignition that these values will produce. While this value of probability is useful, a low probability does not preclude the event occurring forthwith.

Eckhoff (8) has drawn attention to the importance of the type of discharge. It is well known that static charges may discharge in one of several ways which in their turn describe the rate of discharge and the energy density in the discharge. Thus quantity of charge and mechanism of discharge are likely to control the probability of ignition of dust clouds from static charge. The examination of rate, duration and input of energy from non-electrical sources should further elucidate the basis of the concept of minimum ignition energy. Clearly such fuller understanding is necessary for safe design of equipment intended for use in dusty atmospheres.

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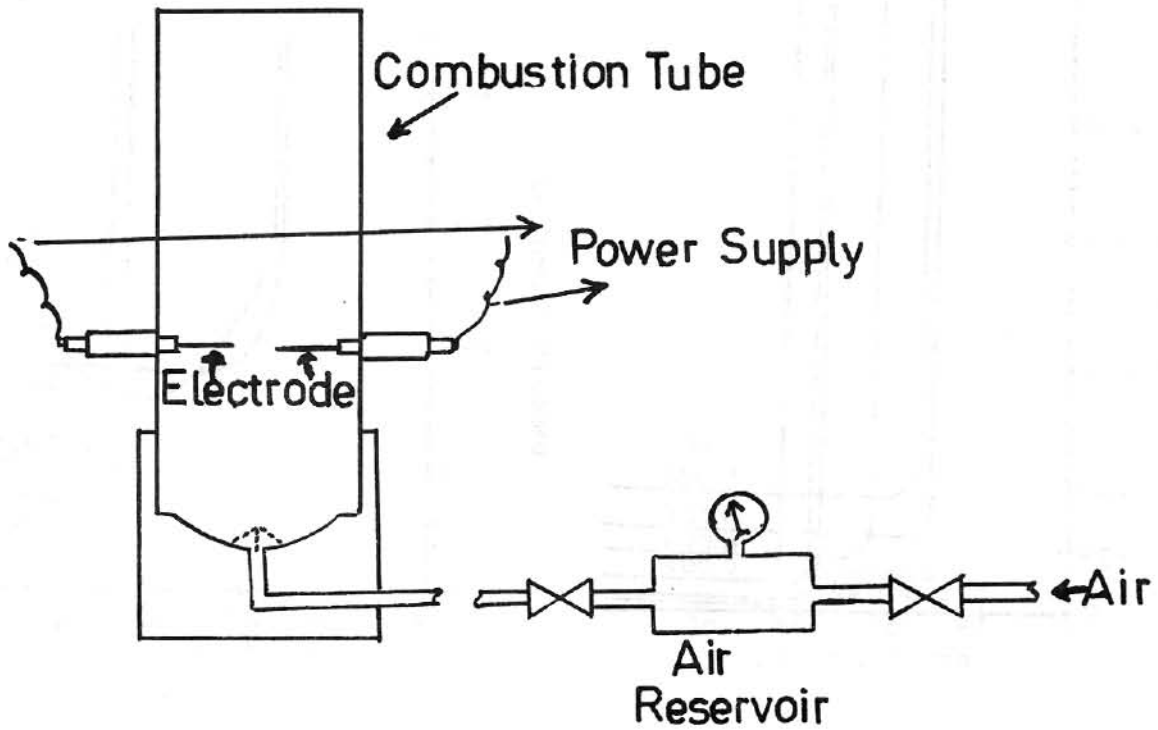


Figure 1 Apparatus for dust cloud ignition

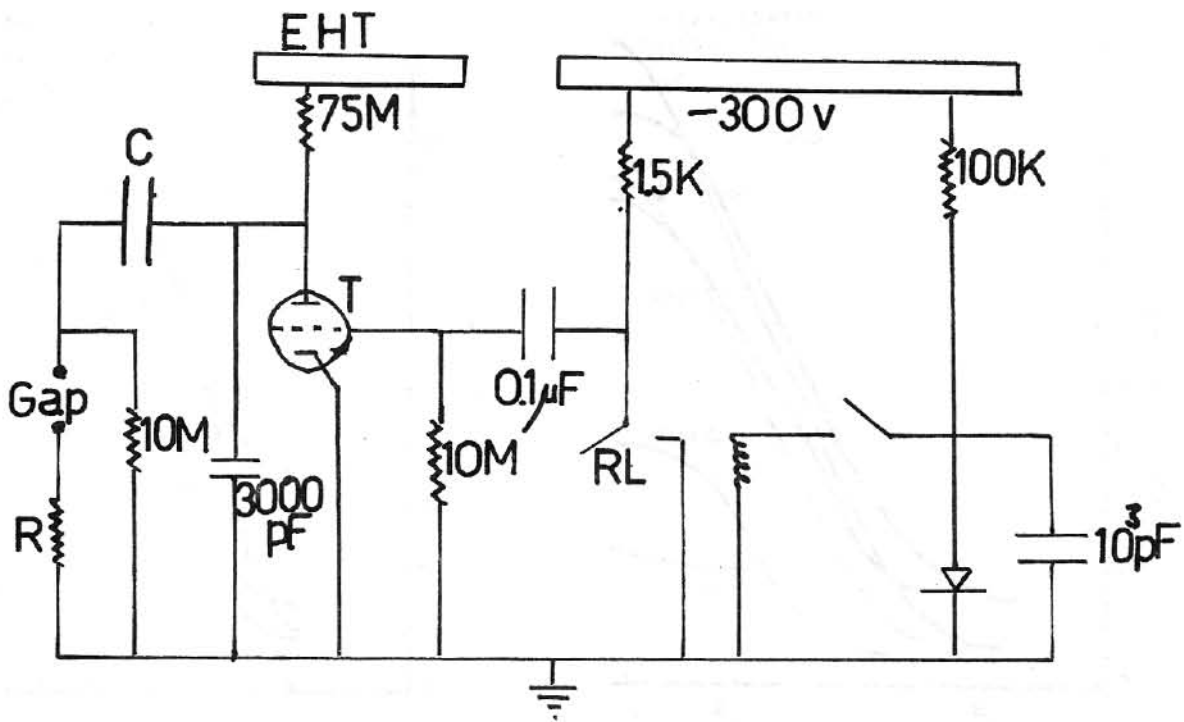


Figure 2 Circuit of spark generator

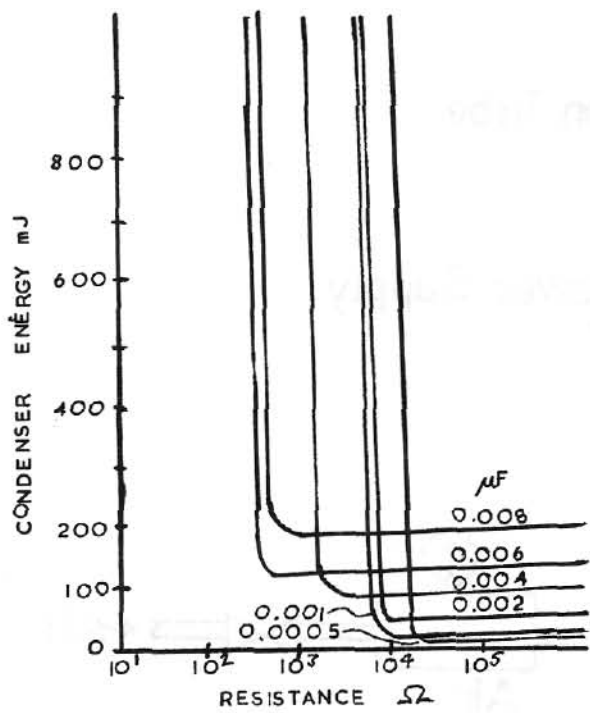


Figure 3 $\frac{1}{2}CV^2$ vs Resistance for ignition of polystyrene dust

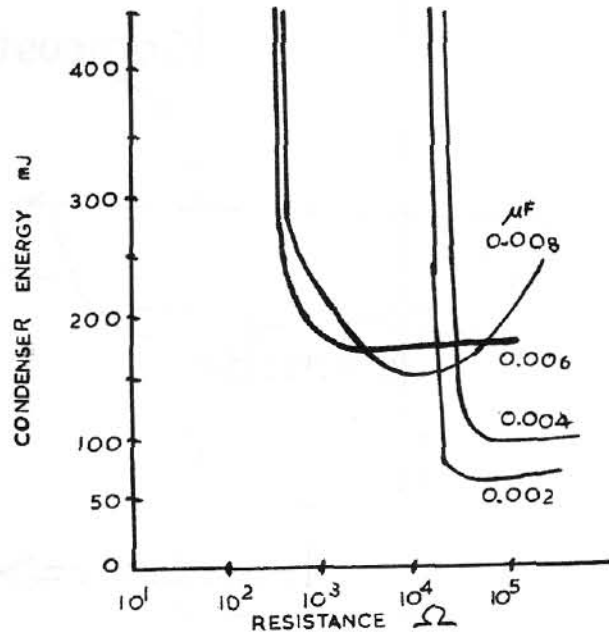


Figure 4 $\frac{1}{2}CV^2$ vs Resistance for ignition of cornstarch dust

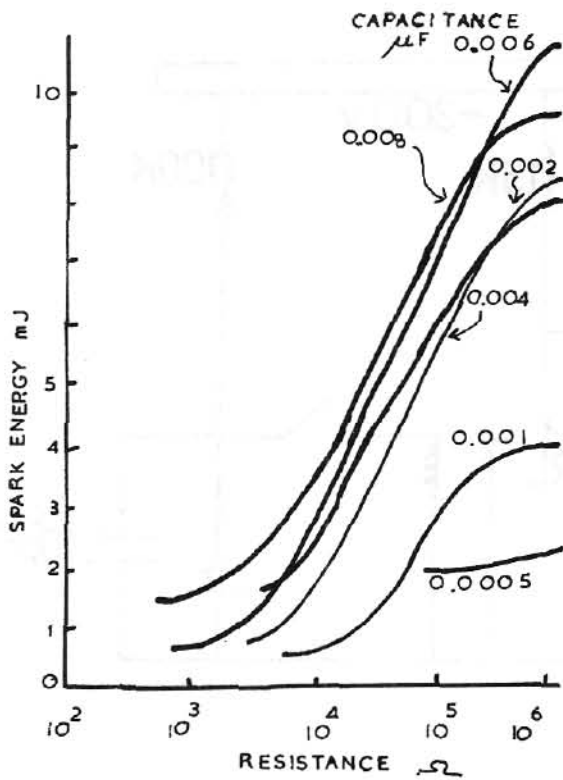


Figure 5 Spark energy vs Resistance for ignition of polystyrene dust

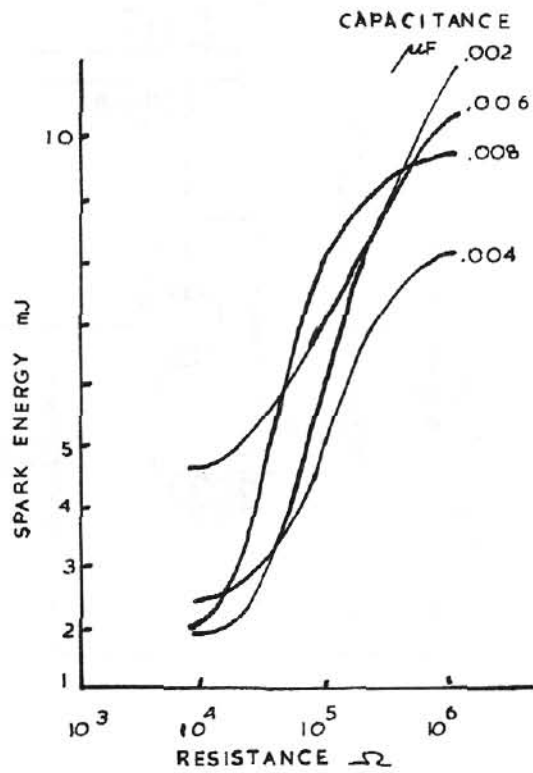


Figure 6 Spark energy vs Resistance for ignition of cornstarch dust

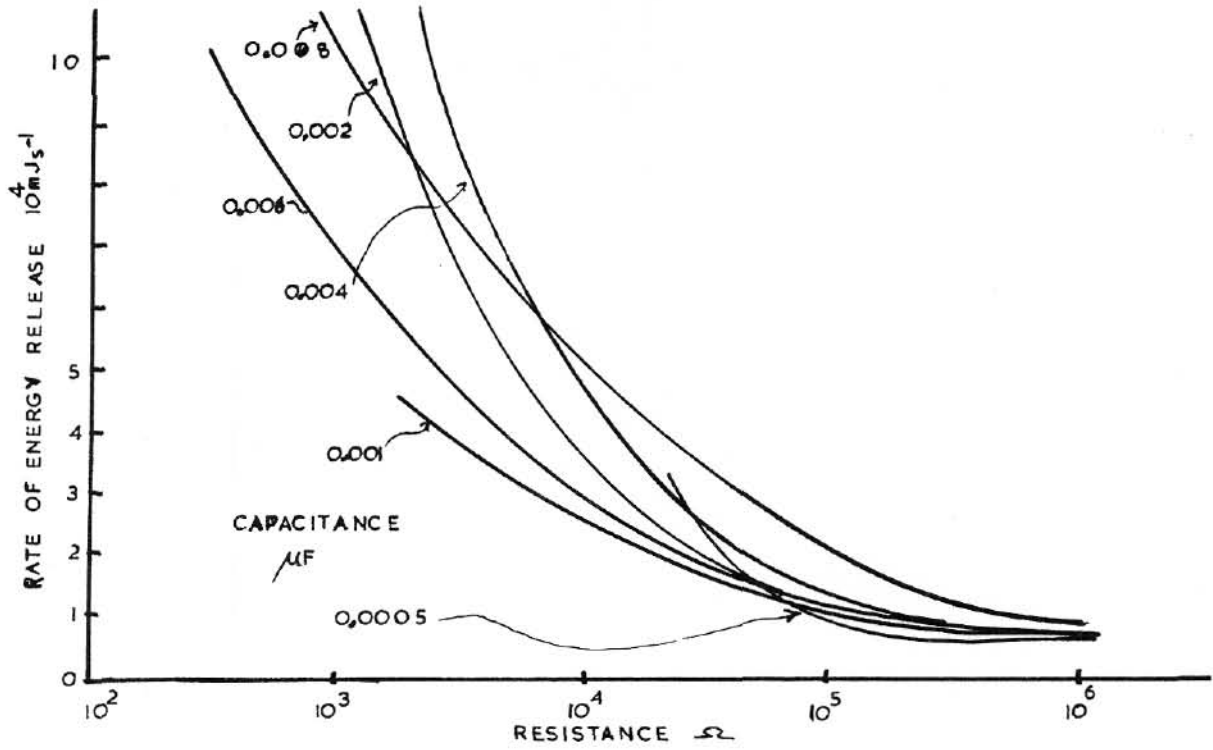


Figure 7 Rate of energy release plotted against resistance for ignition of polystyrene dust

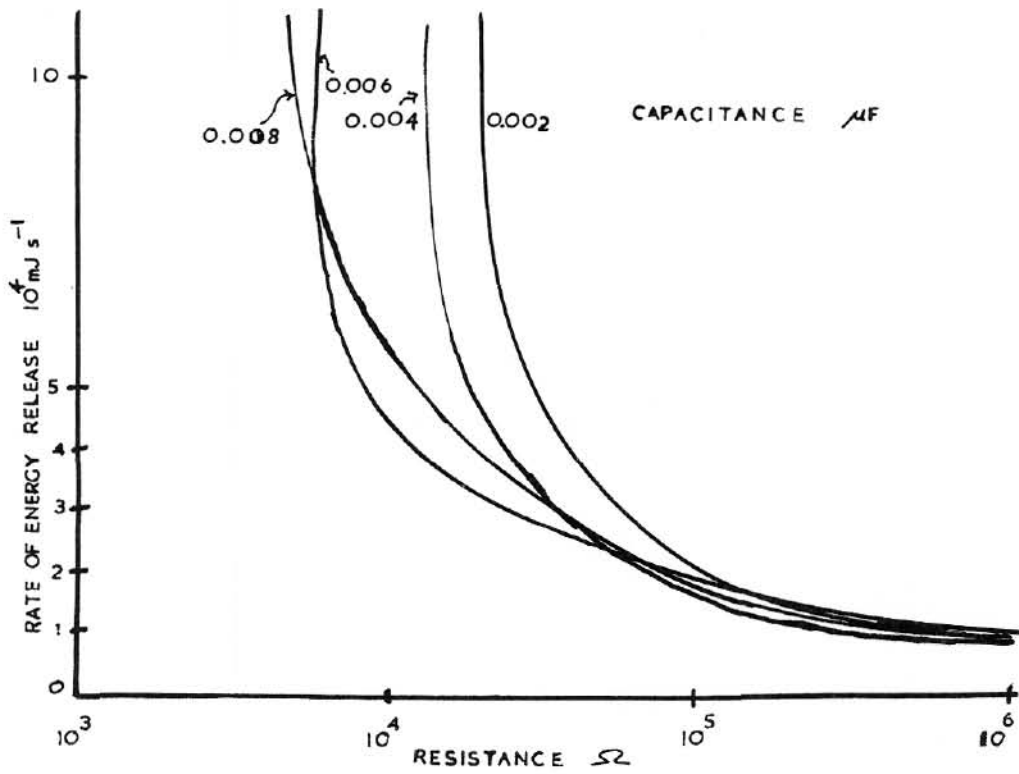


Figure 8 Rate of energy release plotted against resistance for ignition of cornstarch dust