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Ph.D THESIS

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"IGNITION OF A TURBULENT FLOWING GASEOUS MIXTURE"

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SUMMARY

The basic properties of arcs in flowing gases, minimum ignition energy and quenching distances are the focal points of this research. The flow parameters turbulence, pressure, velocities, fuel-air ratio etc. are varied over a wide range to simulate high altitude relight conditions of a gas turbine combustion chamber.

It is found that a constant-power energy release in the spark gap, having an optimum duration of $60 \mu s$, more than halved the minimum ignition energy requirements over most of the flammability range of propane-air mixtures. At large quenching distances, lengthening of discharge path by the flowing stream results in significant reduction in heat losses to the electrodes and improvements in minimum ignition energy. The large scale & intensity of turbulence tends to increase the minimum ignition energy but the quenching distance is significantly affected only by intensity.

In the light of the above experimental research some discussion is presented on the practical aspects of the aircraft relight problem. Finally the various theories on ignition in turbulent flowing gases have been studied and compared with the experimental results of the present work.

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NOTATIONS:

(Unless specifically stated in the text, the following nomenclature is used. All calculations are in Metric units).

A, a	Constants.
B, b	Constant, Bar size of perforated plate (cms.).
C, c	Capacitance (μF), Constant.
C_p, C_v	Specific heat at constant pressure and volume respectively (CHU/kg deg. C).
D, d	Diffusion coefficient, Gap spacing (cms.).
E, e	Energy (electrical or activation), Reaction zone thickness (cms.).
H	Calorific value of fuel. (CHU/Kg).
I	Current (amps)
J	Joule's constant (m Kg/CHU).
L, l	Integral scale of turbulence (mms.) or inductance, Discharge length (cms.).
n	Exponent.
P	Pressure (atm. or mms. Hg abs.).
Q	Thermal energy.
R	Resistance (Ω) or gas constant (mKg/Kg $^{\circ}\text{K}$).
S	Switch or flame speed (cms./sec.).
T, t	Temperature ($^{\circ}\text{K}$), Spark duration (μs).
U, u'	Velocity (m/sec.), Absolute turbulence intensity (cms./sec.).
V	Voltage (volts.)
X, x	Molecular concentration or field strength, Distance downstream of turbulence plates in x direction (cms.).
y	y direction.
Z	Impedence (Ω)

γ	Probability of new electron emission from cathode.
δ	Electrode characteristic length or diameter (cms.).
η	Efficiency (Q_g/Q_s).
λ	Micro (dissipation) scale of turbulence (mms.).
ν	Kinematic viscosity ($m^2/sec.$).
ρ	Density (Kgs/m^3).
ϕ	Equivalence ratio.
Δ	Difference.

Abbreviations:

MIE	Minimum ignition energy (mJ).
FAR	Fuel air ratio.

Superscripts:

—	Mean value.
! or ref.	Reference value (new value).

Subscripts:

c	Cathode, Critical value, Charging (viz. resistance).
d	Discharge.
e	Energy (current) limiting.
f	Flame, Fuel.
g	Spark gap.
i	Instantaneous value, Initial value, Current (viz. Ri).
l	Loss, Laminar
m	Molecular, Minimum, Mixture.
o	Oxygen fraction.
s	Sparkover or breakdown, Storage, Spark.
t	Turbulent, Time, Total.
	Traverse () axis.

1.0 INTRODUCTION:

The need for research on the ignition of gaseous mixtures has been prompted mainly for two basic but opposite reasons. On the one hand a deep understanding of ignition as a means of producing a propagating flame in a combustible mixture is essential to all forms of combustion problems, while on the other, the same knowledge is often required to prevent explosions in a gaseous inflammable mixture. Combustion research is therefore naturally concerned with ignition and the high temperature chemical kinetics associated with it. Ignition energy requirements usually supply the boundary conditions of the time dependant equations governing flames and allow some of the basic theories, viz. Semenov's thermal theory of ignition, theories of detonation or flammability limits etc. to be tested. The study of flame quenching which is a limiting critical case of propagation of non adiabatic flames between two parallel walls, also forms a subdivision of the ignition research.

Practical work on this subject is usually aimed at developing an efficient, reliable and simple system to cover ignition requirements in I.C. engines. Apart from the rocket engine, (where ignition problem is basically different and more related to poorly timed ignition) nowhere are the conditions of ignition as adverse as in a modern aero gas turbine combustion chamber, where it is required to ignite a combination of high velocity, high turbulence-intensity and large eddies of swirling mixture at a very low pressure and temperature. With the advent of supersonic flight and combustion of fuels in a gaseous form, the research into ignition of gaseous flowing mixtures has acquired a new impetus. Laboratory investigations over the years have tended to produce better methods of ignition, Fig. 1a. However comparing these with the generally accepted values of Watson [1] in Fig. 1b shows that there is a considerable room for improvement.

The addition of electrical energy to a combustible mixture by means of spark discharges is one of the most common methods of ignition. However, during the last few years alternative methods are being extensively studied and some of them promise to have certain distinct advantages over the spark ignition system. This therefore warrants a brief survey of the various ignition methods, as listed in Table 1. The recent use of focussed laser beams by Weinberg and Wilson [2] seems to offer the major advantage of a short duration point source of energy without the disadvantage of proximity of electrode surfaces. However most of these new techniques are still to be developed and improvements in the spark ignition method are by no means over. Some of the basic reasons why spark ignition is preferred are:-

- (a) The thermal energy is dissipated in a very efficient manner and in a smaller pocket of gas compared with pilot flames, hot gases or hot surfaces.

- (b) The control and duration of energy input is precise.
- (c) Since the spark ignition system has been developed over many years, it is reliable, light in weight and its performance can be predicted to a high state of accuracy.

A considerable amount of literature is available both on experimental and analytical aspects of the spark ignition of stagnant mixtures. However, there is a scarcity of knowledge on the ignition of turbulent flowing gaseous mixtures. The classic work of Swett [3] and the recent publications of De Soete et. al. [4,5] are the only two systematic studies of the ignition of flowing gases. However, their work has several shortcomings:-

- (a) The effects of quenching distance on minimum ignition energy were not investigated in detail. Hence their ignition energies do not represent minimum values.
- (b) Although an optimum spark duration was found for igniting the mixture, most of the data was obtained with longer durations because of the measurement difficulties.
- (c) A high-voltage, low-current form (Glow discharge) of spark was used for ignition rather than a high-current, low-voltage (arc) type of discharge which is much more efficient.
- (d) The effects of a constant-power arc source on the minimum ignition energy requirements of a flammable mixture, in comparison with the conventional oscillatory or exponentially decreasing power spark source, were not determined.

In the present work it is intended to cover most of these shortcomings. Only the line source of ignition is studied because of the low pressure ambient conditions and resulting large quenching distances. Table II presents the scope of the present research in relation to the work of Swett [3] and DeSoete [4] and also to the approximate conditions that are likely to exist in a modern aero gas turbine combustion chamber.

2.0 ELECTRICAL CIRCUITS USED IN IGNITION RESEARCH:

Broadly speaking three major types of electro-mechanical networks are used in producing a spark. Table III shows also the major subdivisions of these types.

2.1 Networks of Type A:

This type of circuit utilizes the mechanical arrangement of separating the electrodes in a very short time, thus establishing a "stretched" arc discharge across them. It is clear that the circuit is prone to inaccuracies because of the mechanical components involved and the stretching of the arc itself involves a loss of useful stored energy of the circuit and power released in the gap. Therefore over the years the minimum ignition energy (MIE) values have always been much greater than those for the other two types of circuits used. Berz [6] has tried to remedy the situation and shows that if very fine wires carrying current are broken, the minimum ignition energy values approach those obtained in capacitor discharge experiments. The two major disadvantages of this system are:-

- (a) A very rapid electrode wear due to metal transfer.
- (b) A large heat loss to the electrodes of conventional size.

2.2 Networks of Type B:

2.2.1 Inductive Spark:- Usually the basic circuit for obtaining such a spark is given in Fig. 2a. When the switch S is closed, the power supply gradually stores an energy $E_s = \frac{1}{2}LI^2$ in the induction coil. If the switch is now suddenly opened, the current I in the circuit ceases to exist and the electrokinetic energy E_s appears across the spark gap causing an inductive or impulse spark. Burgess and Wheeler [7] and Wheeler [8] were one of the first to use such impulse sparks for the study of flammability limits of different hydrocarbons with air. The method has unfortunately some severe disadvantages.

- (a) There is always a spark of Type A, across the switch.
 - (b) The high inductive field can also cause dielectric breakdown in the inductor.
- and
- (c) Inconsistencies in the results because of the switching surge etc. The method was therefore abandoned as a scientific tool for research.

2.2.2 Capacitive Spark:- This type of spark has been used in most ignition research. The main advantages of a simple capacitive discharge system are:-

- (a) By choosing a variable capacitor, spark discharge of short or longer duration can be achieved, and incorporating a switch allows high voltage to be applied to the gap only at the moment of sparkover.
- (b) The spark characteristics are repetitive since the capacitance values do not change significantly.

Fig. 2b shows one simple example of this type of circuit which is that of Swett [3]. In the position S1 of the switch, the condenser is charged and in S2 position it is discharged across the gap through the series "energy control" resistor R_e . R_t is the time duration control resistor and R_i the current shunt. By using high value of R_e , the discharge system is strongly damped so that the presence of stray inductances etc. does not influence the spark characteristics to a significant degree. The spark discharge is gradual exponential. For short duration sparks, Swett [3] discharged the capacitor directly across the gap and the released energy was taken as $CV^2/2$ in the spark duration range 1 to 2 μ s. Here the current was oscillatory. The electrical systems used by most other workers are very similar to those of Swett [3] or Metzler [9]; the only major differences being:-

- (a) Olson, Gayhart, Edmonson [10], Edmonson, Olson et. al. [11] use type 5C22 hydrogen thyratron as a fast switch.
- (b) Witchell [12] used auxiliary spark gap trigger with a time "jitter" of about 0.1 μ s.
- (c) Over the past few years, Litchfield and coworkers [13] have considerably improved the electrical systems and charging circuits described in (a) and their report represents an up to date version of systems in use for ignition research at the U.S. Bureau of Mines.
- (d) Cheng [14] used a variable plate capacitor which was initially charged at low voltage to eliminate corona losses. At the firing moment the spring increased the capacitor plate distance to 50mm. The charge on the capacitor remained constant until the spark occurred. The mechanical system is, however, fairly inaccurate, and a correct value of energy cannot be calculated because of the loss of mechanical

work in separating the capacitor plates.

- (e) Rose and Priede [15, 16] charge their storage capacitors to a voltage slightly greater than the breakdown voltage of the gap and use the technique of UV irradiation of the gap to cause the breakdown. They obtain spark discharge energies as small as 50 μ Joules. Fig. 2C shows the circuit used by Rose & Priede [15].

In spite of the various modifications and improvements that have occurred in these type of ignition units, some inherent disadvantages remain and these are outlined as under.

- (f) The switch S, if mechanical, introduces undesirable inductance. If a hydrogen thyratron is used, at very low values of ignition energy the capacitance of the thyratron elements etc. become significant in comparison to the discharge capacitors which can be as low as 5pF.
- (g) Small changes in discharge capacitance have pronounced effects on the time duration, and frequency of oscillations of discharge, Rose and Priede [16].
- (h) There is no standardization or control over this type of pulse since any change in capacitance also changes both the circuit time constant and the discharge energy. Simultaneous accurate recordings of such pulses is very difficult.
- (i) Purely capacitive sparks are normally oscillatory (aperiodic with high series resistance) and this is a disadvantage from an ignition point of view since discharge energy is fluctuating and therefore distributed over too many separate channels. Various workers have tried to suppress the oscillatory sparks. On some occasions the principles of overcritically damped discharge have been used, to allow the breakdown voltage at the main electrodes to rise slowly. But in this system less than 1% of stored capacitor energy appears in the gap. Bradford and Finch [17] studied the low frequency (LF) and high frequency (HF) components of the spark and observed that the igniting power of the capacitive (HF) component was less than the inductive (LF) component. Again

it is sometimes possible to use a thyatron or semiconductor device in the spark circuit to obtain nonoscillatory sparks from an undercritically damped circuit.

2.2.3 HYBRID CIRCUITS:- To avoid some of the disadvantages of a purely inductive or capacitive circuit and to have more control and flexibility of operation a hybrid circuit is sometimes used, its important advantage being, that it allows independent variation of spark energy and duration. Carpenter [18], DeSoete [4] use this type of circuit Fig. 2d. The capacitor is discharged through a transformer (ignition coil) by means of a switch, usually a thyatron. The spark thus generated is of the capacitive type since sparkover occurs when dI/dt has a large value i.e. immediately after closing the switch.

Appendix A shows the mathematical analysis of some basic circuits.

2.3 Pulse Forming Techniques:

2.3.1 Hard tube (HT) networks: These networks are designed to give single or repeated constant power pulses across the gap. Wolf and Burkett [19] first employed this technique to deliver arc pulses of 2-13 Amps and 1 to 8 μ s duration across the gap, with a pulse recurrence frequency of 400-1000. These pulses have extremely well-defined time intervals with controlled repeatability and can be observed accurately on the oscilloscope. The values of MIE obtained were 60% lower than those of Lewis and Von Elbe [20]. Unfortunately no attempt was made by these authors to use a single long duration rectangular pulse. This is precisely the technique that has been adopted in the network used in the present work.

2.3.2 Transmission line technique: Although this technique of pulse generation has been known to nuclear physicists and communication engineers, it has only very recently been developed for spark ignition studies. It is likely to be used to test the current concept on ignition which is that the MIE required to enable the spark kernel to grow to its critical size d_c is assumed to be independent of its rate of supply as long as it is available in a time duration $\ll$ mean reaction time of the chemical species. The technique being developed by Johansson, Johnsson and Straid [21] claims several advantages over most of the methods, purely from an electrical aspect.

- (a) Extremely well defined, repeatitive spark (rise time < 2 ns). The spark duration is reduced to ns range (20-50ns) using a coaxial transmission line. This is not possible with a switching device, since even the fastest hydrogen thyatron requires comparable avalanche or streamer build up time.
- (b) Sparks are not influenced by stray capacitance, inductances or energy released in the gap.

Spark energies of up to 10mJ have been obtained.

- (c) The spark streamers have almost perfect axial symmetry, and energy calculation in spark gaps is extremely simple and accurate since it is the difference of incident and reflected pulses.
- (d) The only disadvantage of the technique is probably the risk of multiple reflections in the circuit leading to pulse distortion and instability.

It now remains to be seen how the MIE values obtained by using this technique compare with those of Weinberg and Wilson [2] and the present work.

2.3.3. Simulated transmission line (STL) technique:- It is obvious from the theory of transmission lines that to produce rectangular pulses of long duration would require a very long cable (1μs duration requires 76 m of cable). Hence a capacitor-inductor pulse forming network is used to get single pulses of long fixed duration. Unfortunately the pulse duration cannot be altered without varying the capacitances and inductances in the network which also change the pulse shape. Depending upon its application this technique has advantages and disadvantages compared with the conventional hard tube networks utilizing high vacuum tubes or thyatron switches described in Sec (2.3.1).

- (a) The circuit efficiency, i.e. fraction of total energy delivered to the gap is more for STL networks than for HT networks since they require considerable heating power for the tubes. The circuit complexity of HT networks is greater and hence size and weight is increased.
- (b) The HT network gives a more accurately defined rectangular pulse of fixed or variable duration (within the ratings of the tubes) and repetitive pulses can be obtained without much additional circuitry. The pulse duration changes can be easily accomplished by switching in the low tension side of the circuit.
- (c) The HT network tolerates a wide range of load impedance mismatch (viz. long and short spark gaps).

The above discussion clearly indicates a preference for the HT type of network for research purposes. But once all the unknown variables like optimum spark duration, spark gap impedance characteristics, energy requirements are determined, and some definite

relationships between all these variables established, it should be possible to design a light-weight and efficient STL type of network.

3.0 IGNITION UNIT USED IN PRESENT STUDY.

The basic electrical network used in the design of the pulse generator is shown in Fig.3, along with the block diagram of the complete system. The ignition unit was built at the Instrumentation laboratory of the Institute.

The electrical circuit is fairly simple. A high voltage power supply (HVPS) is used to charge a bank of four storage capacitors C (in parallel) through two charging resistors R_c , to the breakdown voltage of the gap. The 'discharging circuit' consists of four type 715 tubes (with permitted operation up to 15KV and a maximum plate current of 22 Amps) which act as the output switch. The spark duration is accurately controlled by activating this output switch by a well defined rectangular pulse through two driver stages which are type 3E29 tubes. Variable current resistors R_e are incorporated in series with the gap, while a very low impedance current measuring shunt is used on the negative side of the circuit. The individual component specifications are given on the circuit diagram. To reduce any ringing of the current pulse in the 1 to 5 μ s duration range low inductance (carbon elements) current resistors R_e were used. Both the voltage and current pulses on the oscilloscope were triggered directly from the output at the electrode gap. Plate I shows the current and voltage pulse forms obtained. The general specifications of the unit are:

Breakdown voltage available	=	0 to 20 KV.
(Continuously variable)		
Maximum spark current rating	=	22.0 Amps.
Range of energy released at the gap	=	2mJ to 130mJ.
Spark duration	=	0.8 μ s to 100 μ s
(continuously variable)		
% drop in energy with duration	=	See Fig.4

Although the overall circuit efficiency is small, and the unit large and bulky, the network is ideally suited for ignition research because of the wide flexibility of operation it provides which therefore allows the effects of various parameters to be studied.

4.0 MEASUREMENT OF ENERGY.

4.1 Current.

The current flow through the gap is determined by measuring the voltage drop across a very low impedance shunt. The major difficulty experienced, particularly with rectangular pulses, is the high dI/dt at the leading and trailing edges, because of the small value of inductance of the shunt. Repeated calibration and checks are therefore essential.

The design of the shunt used here reduces the induced voltages due to stray fields etc. to an insignificant level and the current path is arranged to minimise inductance of the unit itself. The calibrated values of Witchell [12] were rechecked and are -

$$R_i = 5.30 \text{ m } \Omega, L = 0.01 \text{ mH and } C \approx 200\text{pF } (+ 1\%).$$

4.2 Voltage.

The potential drop across the gap measured directly on the oscilloscope in fact consists of a sum of various components, i.e.

$$V_{osc} = V_g + V_{cable} + L_e \frac{dI_g}{dt} \quad - (1) \text{ where } L_e \text{ is the}$$

inductance of the path from the electrode sparking tip to the oscilloscope input. Witchell [12] for example, has shown that for very short duration sparks (0.5-3 μ s) terms II and III on the right-hand side of this equation can be appreciably higher than the gap voltage drop. Thus the inductance and stray voltage drops are much too significant to be ignored. In order to measure correctly the spark gap voltage (which in the case of an arc can be as low as 15 volts) only two methods seem to be useful.

- (a) In addition to measuring the resultant voltage drop V_{osc} , above, readings of voltage drop are also noted with spark gap shorted out. The difference of these two readings then gives the correct gap voltage. However this method is very tedious.
- (b) A reasonably simple and accurate procedure is to solder two low inductance copper strips near the electrode tips and connect the voltage probe attenuators to the other ends. In addition, use can be made of a compensating network at the oscilloscope and to cancel out the effects of cable and other inductances and their resulting voltage drops. The comparison of results between (a) and (b) shows almost negligible difference and hence

this arrangement was adopted here. It may be mentioned that although the negative side of the circuit is grounded, the cathode tip voltage (at the gap) is slightly different than zero since electrode inductances etc. are involved and hence only the difference of voltage traces on both the electrodes will truly represent the spark gap voltage.

The two voltage attenuator probes used here are the Tektronix P6015 with an attenuation factor of 1000. The probes are supplied with the compensating network. The Tektronix 551 Dual Beam oscilloscope (with Type L unit for current measurement and Type 1A5 Differential amplifier for voltage measurements) is used. The Type 1A5 unit is preferred over the usual Type G because

- (c) Maximum Gain on Type G unit is only 50mV/cm whilst that on 1A5 is down to 1mV/cm and hence small voltage signals of 20-30V (which become 20-30mV after attenuation) can be accurately measured.
- (d) At the Maximum Gain setting of Type G, the overloading voltage is only 4 volts, while for the same setting Type 1A5 overloads at 50 volts. This is important because immediately after the breakdown of the gap, the voltage falls from 10KV to 20 volts (10V to 20mV attenuated) and insufficient overloading capability at this instant causes distortion (or smoothening out) of the leading edge of the pulse.

4.3 Energy.

The author soon hopes to design a Hall effect multiplier to get a direct energy measurement i.e. $E_g = \int_0^{t_s} V_g(t) \cdot I_g(t) dt - (2).$

This technique, if successful, will be far simpler than building an actual multiplier performing the operation

$E_g = \int_0^{t_s} \exp [\ln V_g(t) + \ln I_g(t)] dt - (3).$ In the present work, photographs are taken of the voltage and current traces and the energy released in the spark gap calculated by direct multiplication.

5.0 SPARK ELECTRODE DESIGN:

The design problems discussed here are purely from the research point of view since to obtain trustworthy repetitive minimum ignition energy values, it is necessary to have a good design of spark electrode. The applications and limitations in practical design are discussed later under Sec. 9.2. Ideally one would like an electrodeless spark generation in the combustible mixture since the heat loss to the electrodes would then be zero. However, apart from optical or chemical means, this is unfortunately not possible.

5.1 Electrical Requirements:-

- (a) The impedance of the electrodes must be as small as possible ($c < 1 \text{ pF}$) since in many cases the storage capacitance itself is as low as 5 pF . Electrodes fed through the metal working section can increase this to $7\text{--}8 \text{ pF}$, and distort the input signal.
- (b) It is known from Paschen's law that $V_s = \int_0^\infty X_s \, dx$ where X_s is the field strength. For ratios of $\left(\frac{\delta}{d}\right)$ from 1 to 3 a uniform electrical field exists (within 1%) in the gap and prediction of electrical characteristics is easy. Such gaps must therefore be used, if possible. Insulating surfaces like glass plates which are mounted on the electrodes for quenching distance studies, are excellent static charge carriers and this may affect the experiments.

5.2 Electrode Material:

- (a) It is best to use clean electrodes of pure metals like Al, Zn, Cu, Fe or Pt. Brass and other alloys are often non-homogenous in composition and the electrical properties can change with wear.
- (b) Soft metals like Al, Cu, Pt require repeated cleaning because of oxidation. Hence these surfaces can only be prepared using vacuum evaporation techniques. Also these metals have a high coefficient of thermal expansion which means a tight ceramic insulation around them would not be possible.

- (c) Some metals like Cu, Ni, Fe, Pd are surface catalysts, viz Pt absorbs H on the surface at high temperatures and causes secondary emission.
- (d) Swett [3] has found that the MIE depends upon the type of discharge i.e. arc or glow and therefore indirectly on the material. Decreasing density of electrode material usually makes it easier to achieve thermionic emission at the cathode. Therefore soft materials such as Cd have a very high wear rate in arc discharge conditions, leaving craters on the wall. This is probably worst at high operating temperatures since decreasing density usually accompanies lower melting points.

5.3. Geometric Configuration and Size of the Electrodes:-

- (a) Two similar spherical electrodes facilitate easy discharge. But since the charge is concentrated in the region near the tip, as the potential is raised, corona losses often occur, gradually leading to a glow discharge (consistently for different materials and especially with small diameter spheres).
- (b) As expected, Swett [3] finds the effects of electrode size and shape at the quenching distance negligible because the heat lost to the electrodes is minimum. However, for $d < d_c$, larger electrodes require more ignition energy than smaller ones because of their increased area. For $d > d_c$, the ignition energy is not directly influenced by the electrode size or shape, but by the spark length.
- (c) Smaller diameter electrodes $\left(\frac{\delta}{d}\right) \leq 5$ do not have sharply defined quenching distances as Lewis and Von Elbe [20] have found. Needle electrodes usually lead to unsymmetrical sparks and therefore heat is dissipated in a large volume of mixture which means more ignition energy requirement.
- (d) If the electrodes are of dissimilar shape or size and if unsymmetrical potentials are applied to them, non-uniform interelectrode field results. Although little information

is available on nonuniform fields, the standard books on this subject viz. Loeb [22] Von Engel [23], and Wheatcroft [24] indicate that the two main controlling parameters which determine the spark-over are (i) $P \cdot d$ and (ii) $P \cdot \delta$ where δ is the characteristic dimension of the electrode. When $(\frac{\delta}{d})$ is very

large a uniform field is obtained and breakdown is essentially a function of $(P \cdot d)$. When $(\frac{\delta}{d})$ is

small, the breakdown surface gradient $x_s = f(P \cdot \delta)$. For large nonuniform fields, the break-down potential may be considerably less than the sparkover voltage and significant corona losses may result viz. at sharp needle points where intense ionization fields exist. Fig. 5 provides the sparking potential for various electrode arrangements showing the effects of different nonuniform fields for various electrode configurations.

5.4 Choice of Electrodes for the Present Experiments.

In addition to the general considerations of electrode design discussed above, the choice for the present research work was influenced by additional important factors;

- (a) Of paramount importance was the fact that the insertion of electrodes would alter the intensity and scale of turbulence downstream of the electrodes in the flame propagation zone. This consideration immediately led to a choice of electrode diameter less than the smallest value of the microscale turbulence, i.e. $\delta = 1\text{mm}$. For plane electrodes this meant that the diameter of cylindrical line source was $\leq \lambda$ (Tables IV & VII).
- (b) Plain electrodes were preferred because of their maximum area of contact with gas and therefore well defined quenching distances.
- (c) Heat resistant stainless steel was chosen as the material for the electrodes because, of all the commonly used electrode metals, it has the lowest thermal conductivity. In the present research "heat resistance" is a main criterion rather than maintenance of dimensions and retention of strength at elevated temperatures. Low thermal

conductivity means less conductive heat loss to the electrodes and consequently smaller quenching distances and gaps.

- (d) The melting and boiling points of stainless steel are 1800°K and 3100°K respectively. These values are considerably higher than most other metals. Its coefficient of linear expansion is fairly close to that of Nilo 50. All these properties would give less erosion in an arc discharge compared with other metals.

Summarizing, it may be said that the choice of electrodes for this investigation was mainly governed by turbulent flow and quenching distance considerations. Plate II shows the different electrode sizes and shapes tested.

6.0 DESCRIPTION OF THE EXPERIMENTAL SET UP.

6.1 Flow Apparatus.

Plates III and IV show the experimental set-up. It consists of a Keith-Blackman blower recirculating the mixture in a closed circuit. The fan discharges $0.785\text{ m}^3/\text{sec}$ of air at atm. pressure against a pressure drop of 38 cms. SWG. The working section is $31 \times 9 \times 9$ cms. which gives a maximum velocity of around 100 m/sec . at atm. pressure.) In order to keep the total volume of combustible gas as low as possible, but at the same time maintain realistic conditions of experiments, a 15.2 cms. dia. $\times$ 1.27 cm. thick piping was chosen. With a totally enclosed system like this safety measures are essential. It is estimated that a transient temperature rise of 2000°K and peak pressures in the region of 7-8 atm. could be produced if a stoichmetric fuel air mixture was ignited at atmospheric pressure. A 15.2 cm. dia. plate relief valve is incorporated in the construction and is expected to give a reasonably safe opening. The outlet velocity can be changed from 6-100 m/sec without appreciable deterioration in the working section inlet velocity profile. A vacuum pump and propane supply connection is also provided.

The working section has two 1.27 cms. thick schlieren-free glass windows for photography of the spark kernel development. Holes are drilled at distances of 3.24, 8.30, 10.20, 13.40, 21.0, 31.20 cms. from the bottom flange of the section for turbulence measurements and subsequent electrode insertions.

6.2 Fuel Air Ratio Measurements:

These are based on partial pressure measurements. Considerable efforts were taken to make the rig gas tight since leakages can change the fuel air ratio. The final small leakage rates were measured (at 25.4 mms. Hg. ab. pressure the leakage rate was down to 10.0 mms. Hg. ab. pressure/min) and appropriate allowance made in the quantity of fuel added. Because of this ability to hold the vacuum for a sufficiently long time as many as 5 or 6 ignition trials could be made before rejecting the mixture. The fuel-air mixture was thoroughly mixed by the blower and because of the interposition of the turbulence grid, complete homogeneity and uniformity of fuel-air ratio values were obtained across the working section. Propane gas was used for the ignition studies.

6.3 Generation and Measurement of Turbulence:

The generation and measurement of turbulence in a pipe flow downstream of a perforated plate or grid is a wide field of inquiry. The extensive results obtained in wind tunnels are often contradictory and could not be used here because of the high level of non-isotropic approach turbulence of the pipe flow of fixed large scale. This meant that turbulence studies had to be started from scratch and carried out with considerable care. This topic is covered in detail by the author in two separate publications Ref. [25, 26] and only a summary is given here.

Three perforated plates were designed to promote a wide variation of Reynolds number of turbulence Re_λ between 20-120. This range spans the most useful region of turbulence in combustion chambers and makes it possible to simulate actual ignition conditions. Measurements of the pressure loss (drag coefficient of plates), intensity, integral scale, dissipation scale and energy spectrum were made over this range. Some of these values were further checked with propane-air mixtures flowing in the rig and electrodes in situ. Only some minor changes were observed. The isotropy of the flow was rechecked using a X probe. Since all the measurements of ignition energy were carried out at or below 127 mms. Hg. ab. pressure, only one set of turbulence measurements are presented in Table IV. Reference to this table shows the following important considerations that governed the design of the three perforated plates:-

- (a) The plates should give a wide range of turbulence intensity. This was arranged to vary between 2.5% to 21%. The turbulence field was near-isotropic [26]. This was purely for the convenience of the research. In actual gas turbine combustion chambers, the turbulence is anything but near-isotropic.

- (b) The largest sizes of the integral scale of turbulence generated should be of the order of magnitude of the quenching distances involved. Again in an aircraft combustor, the eddy sizes of the flow are probably considerably larger than those obtained here (particularly at low pressures), but since isotropy (and decay) of the turbulence is difficult to achieve for large eddies, a limitation had to be imposed on their size.
- (c) At the low pressure operation (High altitude conditions) of the combustion chamber the range of eddy sizes in a flow (i.e. the difference between the sizes of integral and dissipation scales) is continuously being narrowed due to the increasing viscosity of the flow (and therefore increasing size of dissipation scale). This has an important effect on diffusion coefficients. The turbulence generating grids design had to simulate this different range of eddy sizes.
- (d) It should be possible to vary turbulence intensity and scale independently of each other by interchanging the grids. This was possible here at only two locations downstream of the grids since only three plates were used.

In concluding, it has been assumed that the spark generated does not affect the whole turbulence field as such, but only the local region, since the diameter of the line source is less than the smallest microscale of turbulence.

7.00 SPARK DISCHARGE IN FLOWING GASES:

It is now generally accepted that thermal effects of the spark are responsible for ignition and subsequent flame propagation rather than electrical ones (Rose and Priede [15], Lewis and Von Elbe [20]) although there is doubt as to the exact form in which the released energy exists during a discharge. It has also been accepted that the measure of ignition energy of the spark is not the stored energy $\frac{1}{2} CV^2$ or $\frac{1}{2} LI^2$, but the actual $(V_g \cdot I_g)$ across the spark gap.

The electrical properties of the crossflow or blown spark are noticeably different from the usual observations under no flow conditions. For example, at higher velocities forced convection completely penetrates the plasma thus considerably altering the local temperature distribution and cross sectional shape of the arc. However, our interest is confined only to those factors which affect (a) the electrical properties of the circuit (b) the MIE determination. The aim therefore was to study the effects of various flow and other parameters on these factors.

Electrical parameters

Flow and other parameters

(1) Breakdown or sparkover voltage	Effects of following flow and other parameters. (a) Pressure (b) Velocity (c) Gap size (d) Nature of discharge (arc or glow discharge, line source or point source of energy). (e) Turbulence.
(2) Spark duration.	
(3) Spark discharge length and shape.	
(4) Current-voltage or gap resistance R_g .	
(5) Energy release in the spark gap.	
(6) Energy distribution in the spark gap.	

7.1 Breakdown Voltage:

The condition for the sparkover in air for a uniform field is the well known Paschen's law [22]

$$V_s = \frac{B(Pd)}{C + \ln(Pd)} \quad \text{where } C = \ln \left[\frac{A}{\ln(1+1/\gamma)} \right] \quad (4)$$

For air the values of the unknowns are $\gamma = 0.01$, $A = 15$, $B = 365$

Von Engel [23] has calculated the breakdown voltage for nonuniform intergap fields for various electrode configurations Fig.5. Paschen's law and even nonuniform field calculations show that the significance of the (Pd) term lies in the number of molecules/cm length of the gap. The number of molecules depends more on gas density ρ , than pressure P since ρ takes into account the temperature term. Table V shows the experimental tests conducted. The following important conclusions were reached from the observations:-

- (a) Figure 5 shows that if the nonuniformity of the gap field is known, it is possible to predict the breakdown voltage for a given electrode configuration. It is clear from this figure that as δ/d approaches unity, this field becomes increasingly uniform and the V_s values lie close to those predicted by Paschen's law.
- (b) Figure 5 shows that the nonuniformity of the field before the breakdown is in no way affected by velocity or turbulence values and the small variation occurring, is probably due to ρ (and this for thin spark streamers may be more significant) since Swett [3] finds no influence of velocity on larger electrodes.

- (c) At very low pressures, the quenching gap distance is likely to be quite high. For such long gaps, Loeb and Meek [27] show that the breakdown is affected by an altogether different process of "streamer formation". In such cases the voltage V_s is likely to diverge slightly from Paschen's law, but the error is almost negligible (At $Pd = 760$, an error of only 2% occurs for a tenfold increase in gap length.) However, all the gap lengths of the present experiments were considerably less and therefore this factor was insignificant.

Summarizing it may be noted that the breakdown voltage here is defined as the lowest voltage that will cause a sparkover, irrespective of any external means used to ionize the gap, viz. UV or radioactive irradiation of the gap.

7.2 Spark Duration:

For a direct capacitor discharge system of the type employed by Swett [3], Rose and Priede [16] where series resistances are neglected, the voltage across the spark gap decreases with time according to the well known equation -

$$V_g = V_s e^{-t/R_g C} \quad \text{or} \quad R_g C \ln V_s - R_g C \ln(I_g \cdot R_g) = t \quad (5)$$

(t = capacitor discharge time). From the above equation (5) we see that as R_g increases, the second term on the left side increases much more than the first term and the result is a reduction in t the discharge duration. Thus R_g directly controls the discharge duration and therefore all the factors that influence R_g (viz. pressure, velocity, gap distance) also influence the discharge time t . With a large series resistance in the circuit the situation is reversed and t increases, Rose and Priede [16].

Now if the switch is closed for a time small enough compared with the time constant $R_g C$, only a fraction of the total energy stored in the capacitor is removed, and the voltage across the gap and the current through the switch are very nearly constant, i.e. R_g is constant. Hence t is not affected. Also, if the steady-state current I_g is high (and therefore the initial value of V_g small as in an arc discharge) a significant rise in R_g still does not increase the magnitude of the second term on the left side of the equation (5) to make it comparable with that of the first term; hence discharge time t is unaffected. In the present work, where the tests were conducted over a spark duration of 25 - 100 μs , the value of t was unaffected. However, when very short duration sparks are generated (ns range) by techniques of the type described in section 2.3.2 the "Time Lag" (i.e. the time required for the current to build up) tends to be large [22].

7.3 Spark Discharge Length and Shape:

The line source of spark is subjected to the crossflow of the turbulent stream and therefore the discharge moves along with the stream. The mechanism is outlined by Swett [3] for long gaps, but considerable rounding of the vertical and horizontal portion of the discharge (Figure 6) occurs. No photographic study of this phenomenon was made here, but the observations of some plasma physics experiments are discussed.

- (a) Benenson and Cenknner [28] recently reported a study on Crossflow, high-density current arcs. The line source was found to be noncircular in cross section with its major axis in the flow direction, Figure 6C. The central core of the arc however was observed to be generally well shielded and as the current increased the arc became stiffer and less sensitive to forced convection.
- (b) Von Engel [23] and others noticed (Figure 6B) that the above constricting effects of arc were less significant at low pressures (or gas densities) and velocities and the line source spread more evenly on both sides of the electrodes, i.e. the diameter of the central positive column considerably increased and current density fell. Although a decrease in gas temperature occurred, as Benenson and Cenknner [28] noted, this temperature was still high enough (temperatures of 7000°K and above were recorded 2 to 3mm. away from the arc centre line) to cause local ignition of the mixture, in the inner as well as the outer layer of the plasma.
- (c) The addition of turbulence to the already complicated forced convection situation makes the less constricted arc wobble near one of the electrodes (Figure 6). This is probably worse when large scale eddies sweep past the electrodes. The observations need however to be substantiated with photographic evidence.

7.4 Current-Voltage or Gap Resistance (R_g):

It is more appropriate to discuss changes in gap resistance (R_g) since this includes both the current and voltage terms. The gap resistance is noticeably affected by mainstream velocity $\bar{U}$, pressure (density) P , gap size d and turbulence field for both glow and arc discharges.

7.4.1 Gap resistance R_g Vs pressure:

Figure 7a shows that as pressure is increased, R_g also increases. This is understandable because of the larger number of molecules that are involved per cm. of gap length in the arc conducting path. However, this increase is gradually reduced with the combination of higher pressure and larger gap sizes (upto $d = 1.27$ cms) until finally at $d = 1.9$ cms. the opposite trend is observed. The interpretation of this result is as follows:-

- (a) The turbulence intensity Vs. ambient pressure characteristics of the grid is such that turbulence intensity and scale increase with falling pressure. This is because below a certain grid Reynolds number, laminar separation occurs and creates a higher pressure drop in the grid which is manifested as higher turbulence intensity, as explained in Ref. [26]. This causes a bigger increase in the spark discharge length with wide gaps than with narrow gaps, since the line source is spread more. As a result, V_g across the gap is considerably increased at low pressures and hence R_g also. At no flow conditions R_g increases because of the reduced current density of the unconstricted arc.
- (b) Since the increase in discharge length ℓ also depends upon spark duration time t_s ($\ell = 2 \bar{U} t_s$ from Swett, Ref.[3]), it is clear that where this increase is significant R_g increases with t_s . This is illustrated in Figure 7b.

7.4.2 Gap resistance Vs Velocity:

Fig. 7b shows the effect of $\bar{U}$ on R_g . It is clear that the effect is one of increasing the discharge length much more for wide gaps than narrow ones. Some guidance is given by Swett's [3] formula, i.e. the resistance at any specific voltage and current conditions is given by

$$\frac{R_g}{R_{g \text{ original}}} = \frac{2 \bar{U} t_s + d}{d} \quad \text{--- (10)}$$

It is however clear from this equation that for sparks in the important μs region, the $2 \bar{U} t_s$ (for $U_{\max} = 30$ m/sec) term hardly affects R_g in comparison to the gap length. In addition, the rounding off at the corners of the discharge reduces the effect of $2 \bar{U} t_s$ still further. This is reflected at higher gap lengths where the influence of velocity is not so prominent. The data of Benenson and Cenkenner [28] are also shown.

7.4.3 Gap Resistance Vs Gap Spacing: Figure 7C shows this effect.

The linear relationship at zero velocity and low pressure may be anticipated because the resistance per unit length of the gap depends upon the molecular structure of the ionized gas and is not affected by other considerations.

7.4.4. Effect of turbulence intensity and scale:

It is clear that for large gap sizes (> 1.2 cms.), higher velocities and lower pressures, a combination of large scale and higher intensity of turbulence slightly increases the gap resistance as shown in Figure 7. It is felt that a more thorough study of this is desirable, using photographic techniques, and therefore no definite conclusions are drawn.

7.4.5 Gap resistance Vs spark duration: All the above observations of R_g were based on its value immediately after the initiation of the discharge. As the discharge proceeds Witchell [12] found that R_g gradually decreased in the first half duration, but increased to its original value at the end. In the present experiments, R_g tended to remain sensibly constant over the whole of the discharge duration. Under the conditions of higher velocity, higher pressures and (most important) wider gaps, (i.e. where the effects of $2 \bar{U} t_s$ term was significant in equation 10) R_g increased with t_s as shown in Figure 7b.

7.4.6 Nature of discharge:- This has an important influence on the R_g value as follows:-

- (a) For a glow discharge it is known that the cathode voltage drop is the most significant single parameter in the total voltage V_g . Since this occurs only in the first few mms. of the cathode, flow parameters do not have any significant influence on R_g . The gap resistance however depends upon the circuit parameters. For oscillatory sparks, Rose and Priede [16] have found that -

$$R_g = K \cdot e^{\alpha Z} \quad \text{where } K \text{ and } \alpha \text{ are spark gap parameters} \\ \text{and } Z = \sqrt{\frac{L}{C}} + R_e \text{ i.e. circuit parameters.}$$

- (b) In contrast, for arc discharges, as used here, since the most important region is the central positive column (Table VI), effects of flow parameters are significant in relation to circuit parameters. In a pulsed circuit of the type employed in the present work, only a very small part of the total stored energy is removed and therefore the capacitor value is very high. Thus as for aperiodic discharges, R_g is solely influenced by the circuit current flow. This accords with the observations of Rose and Priede [16].

7.5 Energy Release in the Spark Gap.

From an ignition point of view, the primary purpose of studying spark discharge in a flowing gas is to increase the energy released in the gap since this determines the circuit efficiency of the ignition equipment. The total energy released in the gap is

$$E_g = \int_0^{t_s} V_g \cdot I_g dt = \int_0^{t_s} I_g^2 R_g dt \quad \text{--- (12)}$$

7.5.1 Effects of electrical parameters on energy release:

These effects were studied by Rose and Priede [16], Watson [1] and others for simple capacitive type discharge systems. Their conclusions include the following:-

- (a) The energy release E_g depends upon the ratio R_g/R_e and hence with any increase in R_g a greater proportion of the stored energy is released in the gap. For stagnant mixtures, R_g can be increased by reducing the storage capacitance C (see equation 11), and thus circuit efficiency is thereby considerably improved. This applies to both oscillatory and aperiodic discharges, but in the latter case, the fraction released during the initial phase of the discharge increases markedly. However, the rate of energy release is reduced because the total discharge time has increased.

It should perhaps be mentioned that considerable confusion exists in the literature on the term "energy release". Sometimes this is expressed in terms of the stored energy when, in fact, the useful energy is very much less. The author contends that the energy release is a function of R_g and I_g only and the influence of all other factors is felt through changes in the value of R_g . This is illustrated below.

7.5.2 Effects of flow parameter on energy release:

- (a) E_g Vs. P :- Figure 8 shows that as the pressure increased, the energy released in the gap also increases. For a constant spark duration this means that the rate of energy release also increases. At higher pressures however, there is a fall in energy release owing to the reduced gap resistance (see Section 7.4.1).
- (b) E_g Vs. $\bar{U}$:- Increase in $\bar{U}$ leads to increase in E_g or dE_g/dt (Figure 8). As the gap distance increases higher velocities and higher pressures force a reduction in the rate of rise of R_g and consequently the energy term $dE_g/d\bar{U}$.

- (c) E_g Vs. d :- Figure 8 shows the effect as anticipated from the variation of R_g with d i.e. increase in gap distance increases energy (or rate of energy release) more steeply than for pressure or velocity (a or b).
- (d) E_g vs. turbulence:- The effect is same as for R_g . Section 7.4.4.

It is clear therefore that the energy release depends essentially on gap resistance R_g , and all other factors viz. breakdown voltage, spark discharge, length and shape influence energy release only through their effect on R_g . Additionally, in the present experiments, controlled capacitor discharge was used (rather than allowing a capacitor to discharge fully as in Swett [3] or Rose and Priede [16]) and therefore the effects of changes of spark duration etc. were eliminated.

(e) Nature of discharge:-

The discussion under Section 7.4.6 highlights the following points:-

- (i) In a glow discharge ignition energy release is influenced mainly by the cathode voltage drop within a few mms. of the cathode. Thus flow parameters affect the energy release much less than with an arc discharge where the positive column length and shape is profoundly affected by the flow. In other words it is much easier to control ignition energy release in a glow discharge since it can be done by modifications to circuitry or electrodes, while for arc discharge the control is to a large extent external.
- (ii) The energy release in oscillatory or aperiodic discharges is discussed by Rose and Pried [16] and their conclusions are plotted in Figure 9 of their paper.

It is useful to consider the form of energy release function at this stage. Photographic evidence (Watson, [1]) of spark ignition in stagnant mixtures, shows that a strong shock wave originates at the first onset of the spark. This can radiate away fifty per cent or more of the electrical energy (Watson [1]). This is probably

the reason why long duration sparks ($100\ \mu\text{s}$ or so) give smaller values of MIE than short duration sparks ($1\text{--}5\ \mu\text{s}$) Swett [3]. One is thus led to the conclusion that a single, constant-power, arc discharge of optimum (around $100\ \mu\text{s}$ or so) duration is the best form of energy release, since this reduces the initial shock front and radiation losses considerably and gives sufficient time for dissipation of the thermal energy in the interelectrode gap. Desoete [4] has recently shown that in theory the fraction of the spark energy that contributes to ignition is higher for a linearly decreasing spark power than the constant power spark, provided the energy is distributed in the form of a line source. For a point source the situation is reversed. However, no allowance was made for heat losses in the first few $\mu\text{seconds}$ of the discharge duration, and no experimental results were obtained to substantiate the argument. Figure 9 shows how the efficient fraction of the linearly decreasing spark power source is likely to be modified if heat losses are taken into account. The present work shows that the constant power spark is as good or even better in terms of its ignition capability. The use of oscillatory or repetitive sparks is not discussed since it is well known that both are inefficient (Swett [3] and present work), although the latter form may sometimes be used in practice (discussed under Section 9.1).

7.6 Energy Distribution in the Spark Gap:

The energy distribution is the last and the most critical factor in the long chain of events leading to ignition. Table VI shows how the total electrical energy released in the spark is distributed. A very conservative estimate would show that only 10% of the total spark energy is utilized in ignition process (Watson [1]). Improvements in the energy distribution pattern is thus directed in two main directions to make more energy available for ignition.

7.6.1 Conversion of electrical energy to thermal energy:

This can be made more efficient by the use of an arc instead of a glow discharge, since in an arc discharge maximum energy is released in the central positive column (rather than near the cathode as in a glow discharge). This gives a small concentrated energy source away from the electrodes, thereby reducing heat losses.

It is not possible to achieve a true point source energy distribution unless some optical means of ignition are employed (those of Weinberg et al Ref. [2]). This is because at low pressures, electrode quenching distances are large and therefore a line source of energy distribution is inevitable. Even for small quenching distances (2 to 3 mm.), Rose and Priede [15] show that the spark is a very narrow cylindrical channel. Thus the energy distribution is no longer in a small volume but spread over a longer path. Desoete [4] shows that with a point source distribution twice as much energy is available for ignition as for a line source. One is then tempted to reconsider the glow discharge where most of the energy is available a few mm. away from the cathode and indeed photographs show that this acts as a point source (Watson Ref [1]). However, this advantage is outweighed by the electrode acting as a powerful heat sink.

7.6.2 Reduction of loss of thermal energy:

- (a) The conductive heat loss can be reduced by a proper choice of low conductivity electrode material as discussed in Section 5.0 as metal conductivity values are almost three or four orders of magnitude higher than the surrounding gases. Again as the density (pressure) of the gas increases, the anode end of the positive column forms a hot spot, filling the region in front of the anode with a quantity of metal vapour depending upon the conductivity and vaporization properties of the electrode metal. Needless to say the use of low conductivity materials with high boiling temperatures can reduce the thermal loss.
- (b) The convection losses from the positive column depend on velocity and turbulence, both of which reduce the available thermal energy for raising the surrounding mixture to its ignition temperature. As Desoete [4] has pointed out, the turbulent diffusivity increases the critical volume of the flammable mixture and causes an increase in heat dissipation, this effect being dependant on spark duration. This emphasises the importance of using optimum spark durations.
- (c) As pointed out in Section 7.5.2, radiation and shock waves in the initial burst of spark energy can be drastically reduced by altering the form of the energy release.

8.0 MINIMUM IGNITION ENERGY REQUIREMENTS OF FLOWING MIXTURE.

Following the usual practice, the minimum ignition energy is defined as the total electrical energy required to cause a steady propagation of a combustion wave when the spark gap is set at the quenching distance. Thus not all of Swett's [3] or Desoete's [4] data represent true minimum ignition energy values, since quenching distance was not investigated. In this work at least thirty repeatable readings were obtained for each combination of E_m and d_c and the average values presented. The repeatability of the values was very good and random checks were made at quenching distances, for different flow parameters. After a few hundred tests, the electrodes were replaced by identical clean electrodes and experiments repeated backwards until no departures from the first set of readings was observed. Because of the very low rate of wear of stainless steel electrodes, only two changes were necessary. Attention must be drawn to the following points discussed in Section 8.2.1 and 8.2.2 later.

- (a) Wherever possible experiments were conducted with the optimum spark duration of $60\mu\text{s}$. (in actual practice $40\text{--}70\mu\text{s}$). The E_m requirements for the given conditions were achieved as far as possible by changing the current limiting series resistance R_e rather than the spark duration t_s .
- (b) Since minimum values of E_m were observed close to the stoichiometric fuel-air ratio ($\phi = 1.04$), all experiments were conducted at that mixture strength.

The quantitative measurements are all given in Table VII. The non-dimensional plotting of results is preferred to avoid inconsistencies in the units. Comparison with data of other authors is given and wherever extrapolation has been made to illustrate a point, it is specifically stated. The maximum scatter of experimental values is (inclusive of fuel-air ratio measurements).

- (i) d_c within $\pm 5\%$.
- (ii) MIE within ± 4 to 7% .
- (c) Glow-arc or arc discharges were used for these experiments; the current values varying from 200mA to 10A and voltage from 500V to 100V . For stainless steel electrodes, it is estimated [24] that the transition to a fully developed arc occurs slightly below a current density of 50 amps/cm^2 (i.e. 400 mA for 1mm . diameter electrodes used here). Thus only the very lowest values of E_m lie in the Glow-arc region.

8.1 Effects of Flow Parameters on Quenching Distances:

8.1.1. Fuel-air ratios vs. d_g : Fig.10 shows the effects of fuel-air ratio on quenching distance for a flowing propane-air mixture. The range of mixture strengths covered was from $\phi = 0.6$ to 1.55 , outside of which the larger gap sizes and very rich mixtures prevented good repeatability of results. The following important conclusions can be drawn.

- (1) The trend of the results is the same as that obtained in the studies of stagnant mixtures. At rich mixture strengths the

concentration of free and active hydrocarbon radicals in the mixture is large. Because of their highly reactive and energetic nature, these radicals initiate reaction in the unburnt mixture. The quenching distance has to increase in order to prevent the electrode walls from absorbing these radicals. This diffusional interpretation of Simon, Belles, Spakowski [29] based on destruction of active particles at the walls seems to be surprisingly accurate even at lean to stoichiometric fuel-air ratios.

- (2) S_t and d_c vary inversely over the whole fuel-air ratio range. This agrees with the predictions of various theories on quenching distance, viz. Friedman [30].

8.1.2 Pressure Vs. d_c : Fig. 11a shows this effect. A comparison with stagnant mixture results is also shown. The wide discrepancy between the two results can be explained as follows.

- (a) At the large gap sizes that are encountered, the flow velocity tends to draw the line source of energy away from the electrodes. This means that heat loss to the electrodes is considerably reduced and so is the rapid rise in quenching distances.
- (b) The large length of the discharge and low pressures both contribute to an increase in the gap resistance R_g (Section 7.4.1) and therefore more energy is released in the gap than previously, thus making the reduction in d_c possible.
- (c) The fact that quenching distance reduces with increase in pressure can easily be explained. A certain value of ignition energy is required to ignite a known mass of propane-air mixture. Now if the pressure is decreased, the volume of this mass increases and hence the gap length has to increase in order to be of sufficient size to ignite the larger volume. In addition, if there is a flow velocity across the electrodes at low pressures, this volume is further increased resulting in a cumulative rise in d_c . That is why some of the results obtained here are as much as fifty per cent higher than the corresponding values for stagnant mixtures, (Ref. [29]) although it is likely that because of the small diameter of the electrodes used, d_c is not as well

defined as in rectangular slit experiments.

8.1.3 Velocity and turbulence vs. d_c : In a turbulent flow, any increase in the mean velocity component $\bar{U}$ also increases the absolute turbulence intensity u' . The data plotting has to be done carefully since there are three velocities involved.

- (a) The instantaneous velocity $U_i \equiv \bar{U} + u'$ affects the overall ignition process. Its effect is plotted in Figure 11b for constant values of $u'/\bar{U}$, the relative turbulence intensity. The scatter of the values is fairly small up to $u'/\bar{U}$ of fifteen per cent. However at higher values of $u'/\bar{U}$ (say 21%) a very large increase in d_c is observed.
- (b) Figure 11c shows the effects of mean velocity $\bar{U}$ which increases the overall transport of thermal energy and active radicals to the electrode walls and surrounding unburnt mixture thus increasing the value of d_c . However, for large values of u' (and already long gap distances) reduction in heat loss to the electrodes (as a result of the spark discharge being drawn away) increases considerably to outweigh the transport effects and quenching distances in fact fall as shown in Fig. 11d.
- (c) The effects of absolute turbulence intensity u' are shown in Figure 11d. The increase in u' increases the local transport of heat and mass. At low values of $\bar{U}$ therefore, increase in d_c follows increase in u' until the line source of energy is blown away from the electrodes. This transition can be clearly observed in this figure as d_c suddenly falls to a very small value. At slightly higher values of $\bar{U}$ (15 m/s) d_c remains fairly constant but any further increase in $\bar{U}$ continuously decreases d_c as u' increases. At low values of $\bar{U}$, the trend observed here is the same as that of Desoete [4].

8.1.4 Integral scale of turbulence Vs. d_c . Figure 11c shows these results. Even a large increase in L_y (with values of u' and $\bar{U}$ held constant) does not noticeably affect the quenching distance d_c . This is perhaps true because the electrode diameter $\delta \ll L_y$.

It needs to be seen whether large values of L_y significantly affect the quenching for large diameter electrodes $\delta = O(L_y)$ as a logical follow up of the above arguments.

To sum up, when a flame propagates between two electrodes, the reaction zone undergoes a thermal and chemical (loss of active radicals) loss to the electrode walls. The turbulence field enhances this loss in many ways -

- (a) The local turbulent diffusivity increases the heterogeneous chain breaking and branching probabilities due to the additional diffusional velocities of radicals at the wall.
- (b) The overall increase in turbulent diffusion increases burning velocity and thermal diffusivity factors because of the increased probability of chain propagation.
- (c) The turbulent diffusion affects heat loss to the walls.

For the specific case of the spark ignition experiments a total heat balance can be set up as shown in Fig.12. Since the central core of the energy containing portion of the positive column of the arc is blown away due to (i) high flow velocity (ii) high turbulence intensity at large gap sizes and high pressures, a major reduction in quenching distance d_c occurred as explained above, and this can be written as proportional to reduction in thermal and chemical loss.

$$\text{i.e. } \left[(d_c/d_c')_{\text{original}} / (d_c/d_c')_{\text{New}} \right] = K \cdot \left[(Q_\ell/Q'_\ell)_{\text{original}} / (Q_\ell/Q'_\ell)_{\text{New}} \right] \quad - - \quad (13)$$

$$\text{or} \quad \Delta d_c = K \cdot \Delta Q_\ell \quad - - \quad (14)$$

The value of the constant K depends upon (i) how far downstream the discharge has been blown away from the electrodes, (ii) the diameter of the electrodes; and (iii) the energy content of the spark in the near electrode region. All these factors are unknown at this stage of the work. Photographic and other evidence will be required to get even simple quantitative results. It is therefore proposed to make only qualitative assessments of the term $K \cdot \Delta Q_\ell$.

8.1.5 Reduction in heat loss to the 1mm. dia. electrodes due to blowing away of the discharge: This is plotted in Figure 13 for different pressures, velocities and turbulence intensity. The figure shows the advantages to be gained from drawing away the arc column from the electrodes. For an optimum spark duration of 60 μ s, Figure 14a shows how many electrode diameters downstream the positive column is blown away due to flow velocity. Figure 14b also shows how the requirements of breakdown voltage increase as the quenching distance widens. This forms a topic for discussion again in Section 9.3.

8.2 Effects of Flow and Other Parameters on Minimum Ignition Energy:

8.2.1 Fuel air ratio Vs. E_m : Figure 15a shows how E_m requirements change with fuel-air ratio. The flammability of propane in air was investigated and shows well defined lower and upper limits. The least value of E_m occurred at stoichiometric fuel air ratio ($\phi = 1.04$). The lean flammability limit extended to $\phi = 0.65$, but on the rich side repetitive ignition data were possible only up to $\phi = 2.0$. At higher values of ϕ either ignition was inconsistent, or energy values exceeded the capabilities of the ignition unit because the quenching distance was too small for this electrode diameter. In addition it is likely that velocity reduced the flammability limits. Figure 15a also shows Swett's data [3] alongside those of the present work. The following observations can be made.

- (a) The advantages of using a constant-power, optimum duration, spark is immediately obvious. The E_m requirements below $\phi < 1.6$ are reduced viz. for stoichiometric mixtures the E_m value is reduced by a factor of 2.3. Given the fact that Swett's [3] results were less accurate because of the measurement difficulties encountered at the time and the inevitable small differences in test conditions (viz. spark duration), the E_m values obtained here are lower by a factor of 2.0, in spite of the fact that the electrode diameter was twice as large (1.0mm). For values of $\phi > 1.6$, a fair comparison cannot be made because Swett [3] used electrode diameters of 0.57mm, and thus was able to reduce the high thermal and diffusional losses described in Section 8.1.1 to both the electrodes by a factor of $2(1/0.57)^2 = 6.0$. If, however, such a comparison were to be made by incorporating a suitable correction, one would find a significant advantage offered by the present approach right upto a value of $\phi = 2.5$. One can thus conclude that the constant power spark is the most efficient form of energy release from the ignition viewpoint.

8.2.2 Spark duration Vs E_m : This is plotted in Figure 15b at and below the quenching distances. The following conclusions can be drawn.

- (a) An optimum spark duration of around 60 μ s was indicated for most of the experiments. The effect of raising the spark duration above this optimum point is to distribute the energy over a larger volume of mixture and increase the minimum ignition energy.
- (b) The above-mentioned flow parameters also increase the gap resistance R_g and hence more ignition energy is released in the gap, resulting in the steep

slopes of some of the curves in Figure 15b. This means that the optimum spark duration is much more critical for lower pressures and higher velocities of the flowing mixture.

- (c) As the discharge duration is reduced below the optimum value, the E_m requirement again increases. This is because (i) the efficiency of the ignition circuit is reduced, (ii) a large fraction of the released energy is radiated away and (iii) short duration arcs give rise to concentrated pockets of energy (particularly the anode and cathode hot spots) which do not heat the mixture uniformly. All these effects combined make short duration discharges much less satisfactory than longer duration sparks.

8.2.3 Pressure Vs E_m : This effect is plotted in Figure 16a. Since the present values of E_m correspond to correct quenching distances the pressure exponent obtained in the present study was around 1.25 compared with the value of 1.75 obtained by Swett [3]. This discrepancy is believed to be due to the fact that whereas the present study is based on true quenching distances, Swett's data was obtained with electrode settings less than the quenching distance and therefore include the variation of heat loss with pressure.

8.2.4 Velocity and Turbulence Vs E_m : As discussed in Section 8.1.3, the three different velocity effects of U_i , $\bar{U}$ and u' are involved.

- (a) Figure 16b shows the effects of increasing U_i at constant values of $u'/\bar{U}$. It will be apparent later that this is a combination of $\bar{U}$ and u' effects. The increase in E_m is very rapid because both the local and overall turbulent diffusion terms have increased the heat losses not only to the electrodes but also to the unburnt mixture surrounding the ignition kernel. Increasing velocity also means that the spark has to heat a continuously flowing fresh mixture throughout its duration. This means that the flame zone is more diluted with cold unburnt mixture, thus requiring more ignition energy to make up for the loss.
- (b) Figure 16c shows the effect of mean velocity $\bar{U}$, for the case of large or small values of Ly . There is not a noticeable difference. This proves that as far as overall transport effects are concerned, eddy size does not have a significant

influence compared with the large mean flow velocities. Again the data of Swett [3] which were obtained with a constant electrode spacing less than d_c , are plotted to show the marked difference between these two sets of results. In the present results two opposing factors are at work. As the velocity increases from zero, the electrode spacing d is increased until $d = d_c$ (where electrode heat loss is minimum) and E_m was recorded at this spacing. A further increase in velocity blows the discharge away from the electrodes and the spacing has now to be reduced to give the least value of ignition energy. In other words, while Swett's [3] results contain a large component of continuously increasing electrode heat loss, the present results are free from this defect, the electrode loss being the lowest possible. The difference between the two results does, in fact, represent the increase in electrode heat loss with increasing $\bar{U}$.

- (c) Figure 16d shows how the absolute turbulence intensity affects the E_m requirement. The two factors controlling the local turbulent diffusion are the intensity and scale of turbulence. In the figure, the effects of scale are separated. The recent values of Desoete [4], some of which were obtained at $d = d_c$ are plotted. The agreement between the results is remarkably good. The increasing value of u' at a particular electrode location is obtained by either increasing the approach mean velocity ($\bar{U}$) to the grid or by moving the electrode nearer to the grid. Both factors unfortunately also tend to reduce the value of scale L_y . Since a definite effect of L_y on MIE is shown to occur in the present experiments, it is necessary to separate at least partially this component from the u' Vs E_m results. The curve (A) thus represents correct results, showing in fact that a homogenous turbulence field with relatively small scale eddies (i.e. most of the energy containing eddies affecting diffusion and mixing) is far better for ignition than when energy is concentrated in the small wave number region. Thus it is possible that measures taken to increase turbulence and thereby improve mixing in gas turbine combustors at sea level conditions may actually result in a considerable deterioration of ignition performance at high altitudes.

8.2.5 Integral scale of turbulence L_y vs. E_m : This effect can be observed in Figure 16e. The variation in scale of turbulence was obtained by using different grids and different locations of the electrodes downstream of the grids so as to keep a constant value of u' . The turbulence energy spectrum obtained at various ambient pressures clearly shows (Ref.26) how a continuous energy transfer is taking place from high to low wave number eddies, thus narrowing the difference between L_y and λ , resulting in this very small range of eddy sizes carrying the bulk of turbulent diffusional energy.

The experiments on E_m show that for a relatively small rise in scale L_y , E_m is only marginally affected; if anything, it is probably reduced slightly. But as L_y continues to increase the E_m requirement increases also. For a three-fold increase in eddy size, E_m rises by 25%. In general, difficulty was experienced in igniting turbulent mixtures containing large eddy sizes. A careful observation of Swett's [3] results also reveals a similar trend as shown in Figure 16e. In comparison to the u' effect, the change of scale L_y does not significantly influence the E_m but this may be important at high altitude conditions where very large eddy sizes exist in the primary combustion zone.

9.00 SIGNIFICANCE AND APPLICATIONS OF IGNITION DATA TO THE AIRCRAFT RELIGHT PROBLEM:

Most of the experimental data obtained and the subsequent conclusions drawn are for homogenous mixtures with simulated flow conditions approaching those occurring in a combustor at high altitudes. The ignition performance is defined in terms of a minimum spark energy required to effect successful flame propagation. The next question is to consider the practical application of this knowledge. The results of experiments on practical combustors are not generally available for security reasons, but at least a qualitative picture of the difficulties encountered can be obtained from References [1, 31, 32]. It is therefore assumed that the inherent difficulties of ignition in practical systems are fairly well known.

9.1 Ignition Circuitry.

With the advent of supersonic flight, the ignition unit is already being subjected to ambient temperatures in excess of 400°K . Fortunately advances in the dielectric material technology has now made it possible to increase the operating voltage of the unit and reduce the weight and size of the capacitor and associated components. Thus 4kv systems are already shown to operate satisfactorily. In the early stages of the ignition unit development, Watson [1] found that in order to increase circuit efficiency, the spark voltage V_g had to be as high as possible while all other voltages must be as nearly as possible 90° out of phase with the current i.e. the system must be oscillatory with V_g providing the only damping term. Research over the years has however already indicated that the unidirectional (linearly decreasing spark power) system is far superior in its

ignitability than the standard oscillatory system, i.e. the adoption of this system leads to almost halving the weight of the electrical components in the high energy box. The results obtained here with a constant power spark source indicate that ignitability can be further improved since the energy requirements have again halved below those using unidirectional system. On the rich fuel-air ratio side the ignition performance is especially improved (Figure 15a and Section 8.2.1). Thus the standard 12 Joule system could be replaced by a 3 Joule pulse generating network, or alternatively with this new system a fourfold reserve of ignition energy is available to meet ignition requirements.

The present work has indicated an optimum spark duration of 60 μs , while other works on practical systems, notably that of Watson [1] have given values around 100 - 150 μs .

The problem of fuel wetting has always tended to cloud the "ignitability" issue. In a series of tests it was found that fuel wetting of electrodes is to be positively encouraged since upto a certain point this increases the value of R_g and allowed more energy release at the gap, whilst beyond this point excess fuel absorbs most of the spark energy in evaporation from the tips. While using the standard oscillatory or unidirectional system, the most efficient fraction of spark power (the initial high amplitude peak) is used up in evaporating the liquid fuel and therefore either more successive attempts are necessary for ignition or an auxiliary leader discharge circuit has to be incorporated in the system. With this arrangement the first leader spark at one energy level is closely followed after controlled time interval (about 1ms) by the main discharge of higher energy level. Thus an additional storage capacitor and time delay circuit has to be incorporated. On a pulse forming circuit however this type of arrangement may not be necessary because of excess storage power that is available at hand.

9.2 Electrode Shape, Size and Material:

The surface discharge plug with a flush gap has been the overwhelming choice of the engine manufacturers over the years. The plug life has been extended by increasing the diameter of the central electrode at the expense of deterioration in ignition energy. This may not be necessary now because of the fourfold decrease in E_m values.

Tests have shown that a fourfold reduction in spark energy can increase the plug life by approximately five times. The practical design of the electrodes is usually a combination of the "longer life" and "best ignitability" requirements. Thus whilst "sunken fire" gives longer life, the "flush fire" gap gives best ignitability.

In a flush fire type of igniter plug, a ceramic insulator extends the full length of the one-piece body and insulates the screening as well as the central electrode which is sealed in the insulator by a fused glass composition. Nilo "K", is an ideal material for the central electrode because -

- (a) The coefficient of expansion of Nilo "K" is very small and almost the same as that of the fused glass insulator surrounding it. So there is no danger of insulation cracking at high temperatures.
- (b) Although the thermal conductivity of Nilo "K" is almost twice that of heat resistant stainless steel, it is still far less than other commonly used metals. At the same time the electrical resistance is lower than that of stainless steel.
- (c) The wear rate of Nilo "K" is quite low because of its high boiling point.

9.3 Electrode Gap Size and Location based on Flow Considerations.

- (a) With a 4Kv system, the maximum gap length that can be broken down at atmospheric pressure (assuming a uniform field) is 0.101 cms. Choice of spark gaps has tended to stay between 0.101 to 0.15 cms. Reference [32]. At atmospheric pressures, very small ignition energy requirements do not necessitate a long length of the discharge, but at higher altitudes an increase in line source length increases R_g and the energy released. With a gap of 0.15 cms successful relight is possible upto altitudes of 6 to 8 x 10³ meters. The deterioration is very rapid after this. This deficiency must therefore be countered by blowing the arc away from the electrodes.
- (b) The flush-fire type of electrode has the advantage of causing the arc to elongate and blow away from the surface of the semiconductor. In addition, with a flush design the low velocity in the boundary layer of the flow not only helps ignition, but clears the liquid off the plug face. Thus it is not at all surprising that the flush-fire surface discharge igniter is widely used.

10.0 THEORETICAL CONSIDERATIONS:

It is of interest to examine some of the theories on ignition and quenching mechanisms in the light of the experimental data obtained.

- (a) Thermal Theories:- These assume that since the rate of spark energy released <<< reaction time of the mixture, practically the entire energy becomes thermal in nature within the short-time. The necessary and sufficient

condition for successful ignition is that heat generation slightly exceeds the heat lost, in accelerating the chemical reactions and as a result a stable flame front is established. Similarly the quenching effect is assumed to occur solely as a result of thermal conduction losses.

- (b) Diffusional theories:- Here importance is given to the diffusion of certain active radicals and atoms (H, O, OH) known to be produced in flames. Because of their highly reactive nature, they initiate the chemical reaction in the unburnt portion of the mixture, thus leading to flame propagation.

At the present time, useful analytical treatments of both the above types of problems are available in the literature together with occasional reviews provided by Wohl [33] Hazard [34] and Potter [35].

10.1: Swett's [3] Theory:

The analytical aspects of ignition in flowing mixtures were first studied by Swett [3] on the assumption that only a portion of the discharge length is important in the ignition process and that in flowing mixtures heat loss by eddy diffusion out-weighs thermal conduction losses. Swett [3] found his data to agree with the derived expression

$$E_m = \frac{8\pi \bar{U} t_s J C_p (T_f - T_i)^3 \exp(2E/RT_f)}{H^2 X_f X_o \rho a^2 \log(1 + 2 \bar{U} t_s / d_c)} f. (u') \quad - - (14)$$

Since then some of the arguments raised against Swett's [3] approach, both in terms of its fundamental concept and the recent experimental observations are:-

- (a) Swett's theory is based on the assumption that heat is generated throughout the entire kernel volume, but lost only at the kernel boundary. This means any flow of heat from the centre, to the surface is opposed by the radially inward flow of burnt products from the flame front, which is difficult to conceive (Reference 36). Ideally the process can be visualised as follows:-

The initiation of any spark causes a local chemical reaction in the unburnt gas surrounding it. Thus the thermal equilibrium equation reads:

At $t = 0$ to t_s . ($t_s \ll \text{reaction time}$).

$$\begin{array}{ccc} \text{Heat generated} & \text{Heat generated by} & \text{Heat lost by the} \\ \text{by spark} & + \text{local reaction zone} & \text{kernel volume} \\ \text{I} & \text{II} & \text{III} \end{array} = \quad - - (15)$$

Now as long as the L.H.S. $>$ R.H.S. successful growth of spark kernel continues. However as $t \rightarrow t_s$, the first term of LHS $\rightarrow 0$, and the second term should, by that time, release sufficient thermal energy to sustain the heat loss of the growing volume. If this does not occur, ignition is unsuccessful.

- (b) Although Swett [3] rightly emphasized the effect of turbulence on minimum ignition energy, this dependence is expressed in a somewhat arbitrary form. Also effects of turbulence scale are shown to be unimportant.
- (c) The effects of rate of energy release are not taken into account. Although an exponentially decaying spark power was used in experiments the average power of discharge was assumed to be constant.
- (d) A correction term $\left(1 - \frac{0.02}{X_f}\right)$ was determined empirically to correlate the variation of ignition energy with fuel air ratio, but no theoretical justification of this term was given. Some of the other limitations of Swett's work have been mentioned by Lefebvre [36].

Since it has already been proved by the present experiments that the minimum ignition energy values are consistently lower than those obtained by Swett [3] and since Swett's theory and experiments are shown to agree with each other, it follows logically that a new theory must be developed to correlate true E_m values.

10.2 DeSoete's Theory [4,5]:

Over the last two years, DeSoete [4] has carried out a more general analysis of minimum ignition energy and quenching distance. A diffusional theory has been used to predict how increase in turbulent diffusivity acts to reduce the efficient fraction of the total spark energy in two ways.

- (a) The additional turbulent diffusivity superimposed on the molecular diffusivity acts to increase the flame front thickness and the critical volume (or quenching distance) that must be heated by the ignition energy.
- (b) The increase in thermal dissipation as a result of (a) above, results in reduction of efficient fraction of spark energy, this effect being dependent on the discharge duration.

Experimental evidence has been put forward to support the analysis. In another publication Desoete and Van Tiggelin [5] analysed the flame quenching phenomenon for non-adiabatic flames as a steady state problem based on the thermal and diffusional theories of transport. The mean values of reaction temperature, radical concentration and probability of heterogenous chain breaking due to diffusion in the reaction zone were obtained. The non adiabatic flame velocity and molecular heat loss to the walls during combustion were expressed in terms of these quantities.

$$S_L = f [T_i, d, T_f, H, N, E, M, M_R, \bar{T}_m] \quad - - - (16)$$

where H is the mean molecular enthalpy of combustion products, N the Avagadros number, E the mean activation energy, M and M_R are molecular weights of molecules and radicals respectively and $\bar{T}_m$ the mean temperature of the flame front. Graphical computation of the above equation yields a value of d_c and the critical values of flame velocities S_L etc. below which the non-adiabatic flame cannot propagate. Effects of turbulence may be taken into account in three ways:-

- (c) Turbulence increases probability of heterogenous chain breaking and therefore by assuming the turbulent and molecular diffusivities as additive, a new expression for probability is obtained.
- (d) The turbulent diffusivity increases the flame velocity and hence values of S_L are related to total diffusion coefficients. Similarly the mean temperature values based on chain branching probabilities are also affected.
- (e) The turbulent diffusion affects the molecular heat loss and hence a new expression for it is derived.

The same procedure is used to calculate increased values of d_c in the homogenous

isotropic turbulence field. No experimental data in support of the theory has been presented.

It was decided to compare experimental results obtained here with the following expressions, i.e.

$$\text{Desoete [4]} \quad E_m = J \pi d \ell C_p (T_f - T_i) e^2 \left[(u'^2 t_s / 2D_m) + 1 \right] = \epsilon \cdot \beta - (17)$$

$$\text{and } \eta = \frac{E_m \text{ turb.}}{E_m \text{ lam.}} = \text{constant} \left[\frac{u'^2 t_s}{2D_m} + 1 \right] = \text{Constant } (\beta) - (18)$$

Desoete and Van Tiggelen [5]

$$d_c = \text{Constant} \left[\frac{D_t + D_m}{D_m} \right] \quad \text{---} \quad (19)$$

Figures 17a and 17b indicate the results of such a comparison. Whilst this theory promises to be a much better alternative to that of Swett's, it unfortunately predicts only one aspect of the E_m Vs. d_c relationship, i.e.

- (f) It does not take into account the reduction in heat loss due to blowing of the line source of energy away from the electrodes.
- (g) Calculations indicate that although the theoretical interpretation is sound the term D_m is very small in comparison with D_t .
- (h) Equation (19) overestimates d_c - Figure (17b).

It would be improper to make further comments because Desoete [4] and Desoete and Van Tiggelen [5], used different gaseous mixtures, electrode sizes, and made their measurements at atmospheric pressure. Also few details of mean velocity, scale of turbulence and quenching distances were mentioned.

10.3 Lefebvre's theory [36] : Here the criterion for successful ignition is that the rate of heat release in the thin reaction zone surrounding the heat kernel must exceed the rate of heat loss from the volume. This assumption is different from that of Swett [3] and a simplified analysis leads to an expression for quenching distance

$$d_c = \frac{21.5 \cdot u^{0.66}}{S_L^{1.66}} \quad - - - (20)$$

The minimum ignition energy requirement is assumed to be equal to the heat required to raise the temperature of this critical volume to burnt gas temperature which gives

$$E_m = \frac{1.2}{10^6} \cdot \frac{u^2 T_i^4 C_p (T_f - T_i)}{S_L^5 P^2} \quad \text{mJ} \quad - - (21)$$

Figures 18(a) to (d) compares theoretical values of quenching distances and minimum ignition energy expressions with experimental data obtained here.

10.3.1 Quenching distances d_c :

- (a) From Figures 18a and b the effects of velocity and pressure are observed to be slightly greater than measured experimentally. The laminar flame velocities used in the calculation of equation (20, 21) above, were those of Kuehl [37] where $S_L \propto \frac{1}{P^{0.1}}$. Thus the major velocity and pressure deviations are those produced by the S_L/S_L Vs Re (The Reynolds number) relationship, which is used in Lefebvre's [36] paper (eq. 7).
- (b) The variation of d_c with ϕ is plotted in Figure 18c. The predictions of the theory are relatively better in correlating the experimental result. The deviation at lower than and rich than stoichiometric fuel-air ratios, is approximately the same.
- (c) The effects of turbulence intensity u' on d_c are plotted in Figure 11d. Again the prediction is much higher (similar to that of Desoete's [4] theory) than the experimental results.

10.3.2 Minimum Ignition Energy:

- (a) From Figures 18d and 16a the effects of mean velocity $\bar{U}$ and pressure on E_m can be observed. The experimental data seems to agree reasonably well with the theory upto a value of $\bar{U}$ of 30m/sec after which the deviation increases markedly.
- (b) The fuel-air ratio effect on E_m is the same as that observed with quenching distance. The agreement with the experiments is again reasonably good.
- (c) Figures 18d shows the effect of turbulence on E_m . The experimental values are considerably lower, in some case almost an order of magnitude less than predicted, although the slope of both the predicted and experimental values are the same.

In conclusion it can be said that wherever the influence of S_t is felt, the E_m and d_c values deviate significantly from experiment. Obviously the weakest relationship is the equation (7) of the theory. This relationship is plotted against recent experimental work of Lefebvre and Reid [38] and the appreciable deviation is clear, Figure 19. It is therefore proposed to modify this equation in future.

It may also be stated here that the effects of scale on E_m and d_c have not featured prominently in many previous theories. However in the last few years, a much more unified approach to this problem in the turbulent flame speed calculations in isotropic turbulent flows has been made, notable recent examples being Williams [39] and Shetnikov et. al. [40]. An approach along these lines is facilitated by the experimental data obtained in the present series of tests.

11.0 CONCLUSIONS:

11.1 Spark Discharge in Flowing Gases:

- (a) Breakdown voltages are substantially lower for nonuniform interelectrode fields and it is possible to predict their value to a reasonable accuracy, since they are not affected by flow parameters and other changes except P and d .
- (b) The line source of spark is blown away from the electrodes by the flow and the subsequent increase in arc resistance R_a cannot be

accurately predicted using Swett's [3] method, since the length and shape of arc is very much different.

- (c) The distribution of energy in an arc is more affected by the flow than in glow discharge, because in the former the central positive column contains most of the energy, while in the latter case the energy is concentrated near the cathode electrode.
- (d) In general the rate of energy release increases with increase in pressure, velocity, turbulence intensity, and gap length.

11.2 Study of Quenching Distance d_c :

- (a) The radical diffusion losses are particularly high at very rich fuel-air ratios and hence the quenching distance increases. Thus the quenching distance varies inversely with turbulent flame speed over the flammability range of the mixture.
- (b) For the large gap sizes encountered at low pressures, drawing of the line source away from the electrodes appreciably reduces heat losses to the electrodes. Hence the quenching distance is either reduced (at very high pressures, velocity and turbulence intensity) or its rate of increase is curtailed.
- (c) For modest increases in velocity, turbulence intensity, pressure the quenching distance increases. The scale of turbulence has no noticeable effect on quenching distance. As stated in (b) above, blowing of the spark away from the electrodes is to be encouraged.

11.3 Study of Minimum Ignition Energy:

- (a) The use of a constant power arc source of optimum duration circa 60 μ s more than halves the minimum ignition energy requirement over most of the flammability range of the gaseous mixture.
- (b) The minimum ignition energy varies inversely with pressure. It increases with mean velocity and absolute turbulence intensity.

- (c) For a constant level of turbulence intensity, slight increase in the scale of turbulence at first decreases MIE, but a substantial increase in scale raises the MIE requirement. Thus a homogenous turbulence field with some optimum size of energy containing eddies is preferable from an ignition viewpoint.

11.4 Theoretical Considerations:

- (a) The theories proposed by Desoete and coworker [4,5] which emphasise the diffusional aspects of thermal and chemical loss, have modest success in the prediction of experimental results only at low flow velocities, low turbulence intensity and high pressures. In other situations the analysis predicts much higher values of d_c and E_m than are obtained here.
- (b) Examination of Lefebvre's [36] theory which emphasizes the mixing aspect of thermal loss also shows similar disagreements. It is observed that the errors lie in the gross simplification of the S_t/S_λ relationship. Therefore further research is needed to improve the understanding and prediction procedures of S_t in high velocity, near-isotropic turbulent flows.

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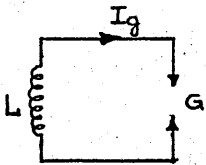
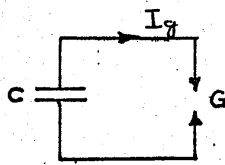
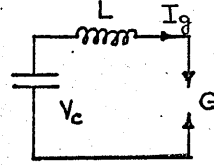
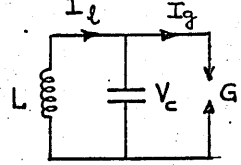
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APPENDIX A

Simple Mathematical Analysis of Electrical Networks Used For Ignition Research



a) Inductive Spark. b) Capacitive Spark C1) $C \gg L$ C2) $L \gg C$

SEC : 2.2.1

2.2.2

Hybrid circuit 2.2.3.

V_s = Capacitor Voltage (at $t = 0$). E_s = stored energy (at $t = 0$)

A = Time constant of discharge. I_s = Steady current in inductor

I_l = Current in L (at $t = 0$). B = Angular frequency of discharge.

For circuits (a) and (b) it can be shown [41]

$$I_g = I_s \exp (-L/R_g)t \quad \text{--- (1)}$$

$$\text{or } I_g = \frac{V_s}{R_g} \exp (-t/R_g C), \quad \text{--- (2)}$$

For circuits of type (c), the energy conservation equation gives

$$E_s = \frac{C V_c^2(t)}{2} + \frac{L I_l^2(t)}{2} + \int_0^t I_g^2 R_g(t') dt' \quad \text{--- (3)}$$

The auxiliary equations are: C1) $I_g = I_l = -C dV_c/dt$

C2) $V_c = R_g I_g = -L dI_l/dt$. Differentiation of (3) and substituting (2) yields:

$$C1) \quad V_c = \begin{cases} V_s e^{-At} e^{-\sqrt{A^2-B^2}t} & A \geq B \\ V_s e^{-At} \cos(\sqrt{B^2-A^2}t) & A \leq B \end{cases} \quad \text{--- (4)}$$

$$C2) \quad I_l = \begin{cases} I_s \text{ (Similar to eq. 4)} & A' \geq B' \\ I_s \text{ (Similar to eq. 4)} & A' \leq B' \end{cases} \quad \text{--- (5)}$$

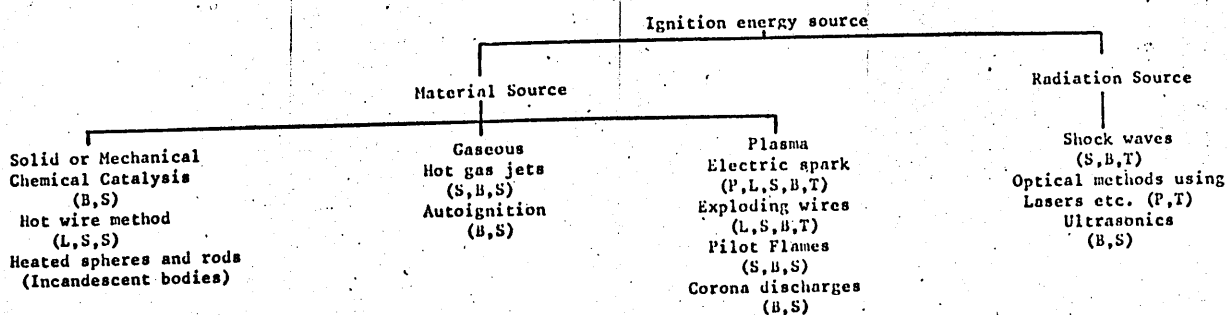
APPENDIX A (Contd.)

In equation (4) we assumed $C \gg L$ ($L \neq 0$) and $V_c(o) = V_s$ while in equation (5) it was assumed that $L \gg C$, ($C \neq 0$), $I_L(0) = I_s$ i.e. electrical energy is wholly stored in the inductance prior to spark over. In these equations we had $A \equiv \frac{R_g}{2L}$, $A' \equiv \frac{1}{2R_g C}$,

$B = B' = \frac{1}{\sqrt{LC}}$. The discharge characteristics are then -

- | | | |
|---|-----------------------------|----------------------------|
| 1) Overcritical (exponential) damping of I_g | C1) $L < \frac{R_g^2 C}{4}$ | C2) $C < \frac{L}{4R_g^2}$ |
| 2) Undercritical (oscillatory) damping of I_g | $L > R_g^2 C/4$ | $C > \frac{L}{4R_g^2}$ |
- 3) Critically damped discharge $L = R_g^2 C/4$ and then

$$I_g = \frac{2V_s}{R_g} \exp(-R_g/2L)t$$



P: Point source, L: Line source, S: Surface source, B: Bulk source.

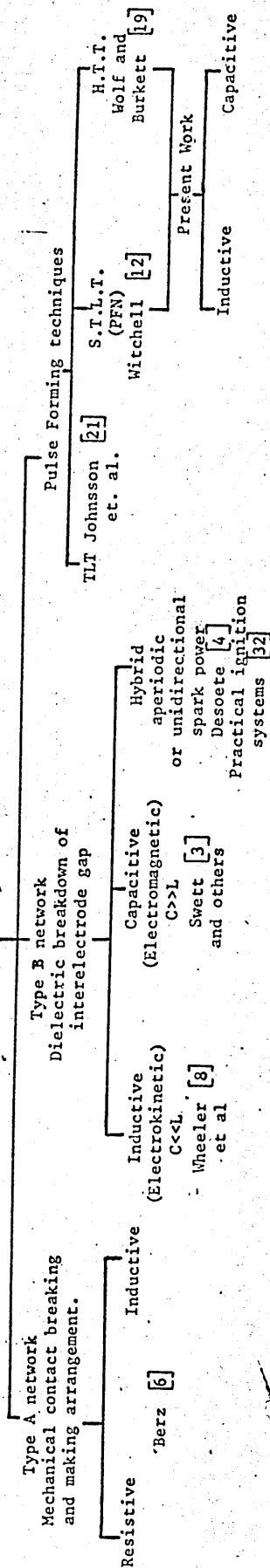
The last letter represents whether the source is transient (T) or Static (S). Further details in NACA RME 54107
APRIL 1955 or Strid K.G (1971) Oxid. Combust. Rev.

Table I: Survey of Different Methods of Ignition.

Ignition characteristics and parameters	Swett [3]	Desoete [4]	Present Work	Gas Turbine Combustor
Spark characteristics etc.	600-800 μ s glow discharge exponential decrease in power (100 μ s opt. duration)	Glow discharge 20-250 μ s, linear decrease in power.	Constant power arc discharge of 60 μ s optimum duration.	Arc discharge 100-250 μ s. oscillatory or unidirectional discharge.
Electrodes	Various materials, Pb, Cu, Al, W, Cd, Brass etc. (0.5mm. dia. plain gap)	Stainless Steel 0.3mm. dia. plain gap.	Heat resistant stainless steel 1mm. dia. plain gap.	Niilo-Tungsten etc. plain gap type.
Equivalence ratio	0.7 to 2.3 for Propane.	Propane as gas Not investigated.	Propane as gas 0.65 to 2.0.	Kerosene, methane 0.8 to 2.5
Ambient Pressure (mm. Hg.ab.)	0.06-0.16 atm. Mostly 0.16 atm.	Atmospheric.	0.03 to 0.16 atm. Mostly 0.16 atm.	0.03-0.32 atm. (24000-8400 m).
Mean Velocity (m/sec)	4.5 to 60	5 to 18	6 to 45	5 to 45
Turbulence intensity	Laminar to 8%. (near isotropic).	Up to 15%.	2 to 21%. (near isotropic)	5 to 30% (non isotropic)
Turbulence scale Variation ratio	1 to 1.5	-	1 to 3.5	1 to 10 (max.)
Quenching dist.	Minor investigation	Minor investigation	Major investigation	Important
Temperature	300°K - 390°K	—	—	250°K - 800°K

Table III: Scope of present research in relation to previous work and gas turbine ignition.

Electrical Circuits



TLT: Transmission Line Technique, SLT: Simulated Transmission Line Technique. PFN: Pulse Forming Network and HTT: Hard Tube Technique.

Table III: Survey of electrical circuits used in ignition studies

Plate	x (cms)	x/b	u/U (z)	Ly (mms)	uLy/U x 10 ² (cms)
C	3.24	21.5	15	1.05	1.59
	8.30	55.0	7.5	2.04	1.52
	10.20	68.0	6.0	2.34	1.4
	13.40	89.0	5.0	2.54	1.27
	21.0	140.0	3.3	3.20	1.05
	31.20	207.0	2.5	4.60	1.15
A	24.0	24.0	13.0	1.10	1.42
	61.4	61.4	7.0	2.24	1.57
	75.5	75.5	5.7	2.54	1.45
	100.0	100.0	4.7	2.84	1.34
	155.0	155.0	3.3	3.25	1.07
	230.0	230.0	2.5	4.50	1.12
A ₁	5.1	5.1	21.0	2.36	5.0
	13.1	13.1	18.0	3.50	6.35
	16.1	16.1	15.0	4.80	7.16
	21.0	21.0	10.0	5.70	5.75
	33.2	33.2	8.0	7.00	5.60

Remarks:

Values of λ can be calculated from the equation

$$\lambda \text{ (mms)} = 24.7 \sqrt{t \text{ (secs)}}$$

where $t = x/U$

Ref: [6]

Table IV: Turbulence measurements downstream of perforated plates (at 127mm. Hg. ab. ambient pressure).

PLATE A (with electrodes 13.4 cm. downstream)

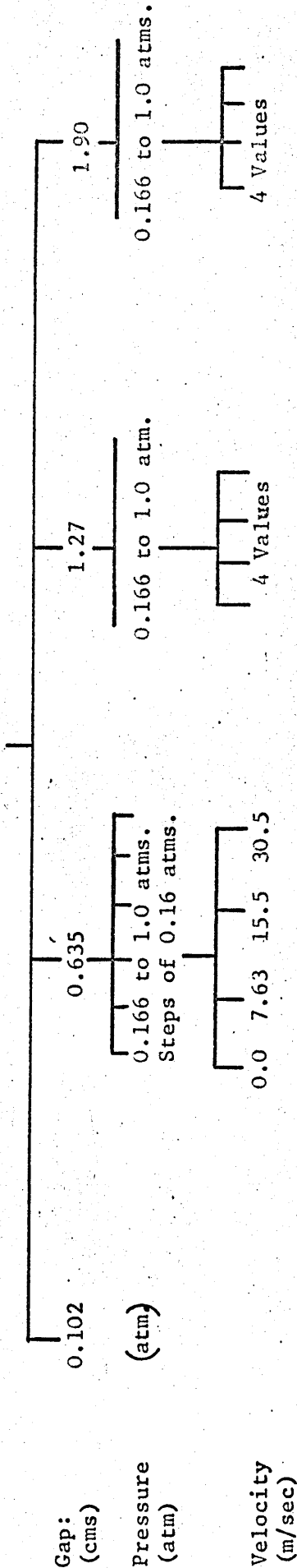
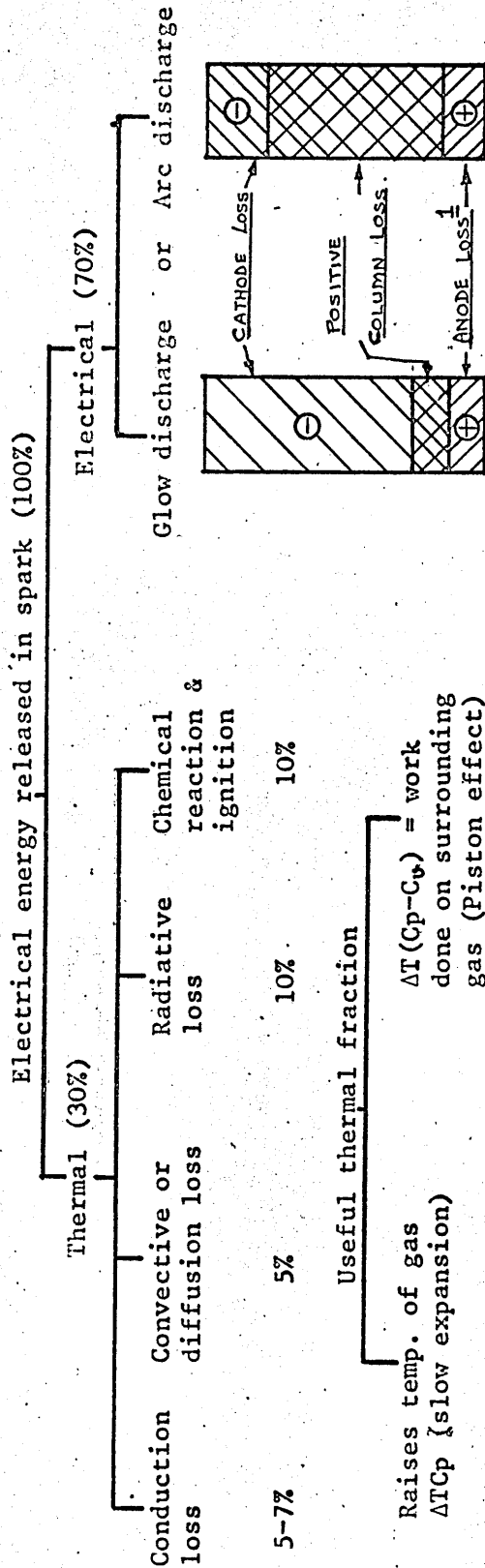


Table V: Experimental investigation of an arc discharge in a flowing gas (discharge duration 80 μ s $V_s = 10$ kV)



Raises temp. of gas ΔT_{Cp} (slow expansion)

Useful thermal fraction

$\Delta T(C_p - C_v) = \text{work done on surrounding gas (Piston effect)}$

Watson [1]

1: For longer gaps, only 10% of anode fall energy goes to anode and is used in heating the electrode mass.

Table VI: Electrical energy distribution in the spark gap. (All % data are approximate. The energy distribution of arc or glow discharges can be found in texts like Loeb [22], Von Engel [23])

Plate C: $\bar{U} = 6.1$ m/sec. $u'/\bar{U} = 2.5\%$

Plate A: $\bar{U} = 15.3$ m/sec
 $u'/\bar{U} = 5\%$

$P = 127 \text{ mmHg. abs.}$				$\phi = 1.04$				$P = 127 \text{ mmHg. abs.}$				$\phi = 1.04$			
FAR	ϕ	NIE (mJ)	dc (cm)	P (mmHg. abs.)	NIE	dc (cm)	ϕ	I.E.	P	I.E.	ϕ	I.E.	P	I.E.	ϕ
0.04	0.625	4.80	2.54	25.4	28.0	2.50	0.625	7.50	25.4	52.0	0.625	7.50	25.4	52.0	0.625
0.052	0.810	4.00	2.10	51.0	10.8	2.36	0.810	6.30	51.0	20.5	0.810	6.30	51.0	20.5	0.810
0.66	1.04	3.50	1.90	76.0	7.0	2.30	1.04	5.80	76.0	13.5	1.04	5.80	76.0	13.5	1.04
0.83	1.30	5.0	2.30	102.0	5.30	2.12	1.30	8.0	102.0	8.10	1.30	8.0	102.0	8.10	1.30
0.096	1.50	10.0	2.80	127.0	3.50	1.90	1.50	40.0	127.0	5.80	1.50	40.0	127.0	5.80	1.50
0.104	1.63	19.0	3.05	-	-	-	-	-	-	-	-	-	-	-	-

Table VIIA: Effects of fuel air ratio and pressure on min. ignition energy and quenching distance.

$\bar{U} = 6.1$ m/sec.

$\bar{U} = 15.3$ m/sec.

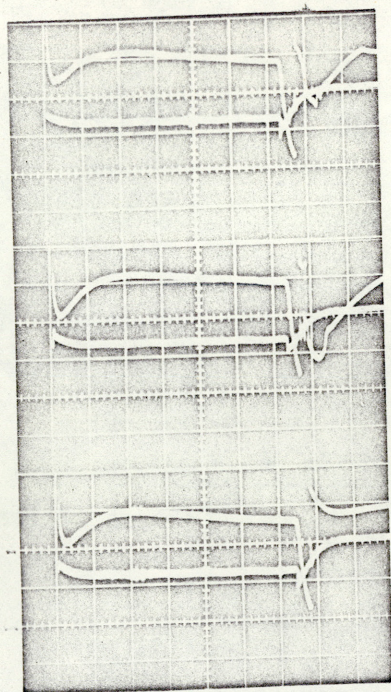
Plate	$u'/U(\%)$	$u'(\text{cm/s})$	$l_y(\text{mm})$	λ (mm.) Extrapolated	MIE (mJ)	Quenching dc (cm)	Plate	$u'/U(\%)$	$u'(\text{cm/s})$	$l_y(\text{mm})$	λ (mm.)	MIE mJ	Quenching dc (cm)
C	2.5	15.3	4.60	3.80	3.50	1.90	C	2.5	38.0	4.60	3.20	4.40	2.18
C	5.0	30.5	2.54	-	5.00	2.03	A	4.7	70.0	2.84	2.0	5.80	2.22
C	7.5	46.0	2.04	1.90	5.50	2.13	C	5.0	76.5	2.54	2.0	6.15	2.25
A ₁	8	48.5	7.00	5.80	6.80	2.20	C	7.5	115.0	2.04	1.73	7.20	2.35
A ₁	15.0	92.0	4.80	3.66	6.50	2.30	A ₁	15.0	230.0	4.80	2.54	8.30	2.55
A ₁	21.0	128.0	2.36	2.10	7.00	0.95	A ₁	21.0	320.0	2.36	2.00	9.00	1.73

$\bar{U} = 21.3$ m/sec.

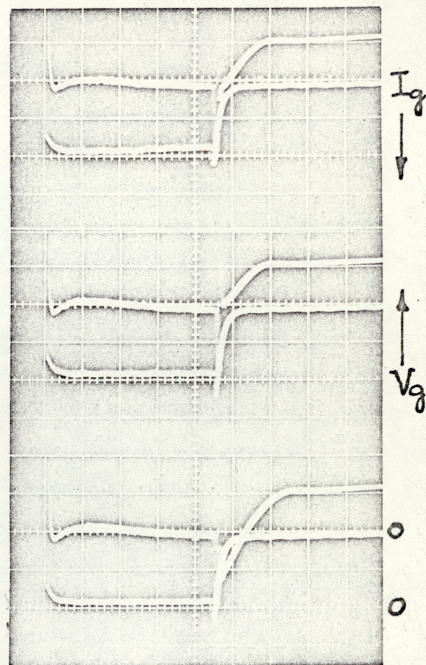
$\bar{U} = 30.5$ m/sec.

C	2.5	53.5	4.60	2.54	6.2	2.47	C	2.5	76.0	4.60	2.42	9.00	2.55
A	4.7	100.0	2.84	1.73	8.2	2.42	A	4.7	144.0	2.84	1.55	12.30	2.46
C	5.0	107.0	2.54	1.93	8.4	2.33	C	7.5	230.0	2.00	1.27	14.50	2.66
C	7.5	160.0	2.00	1.55	10.0	2.56	-	-	-	-	-	-	-

Table VII : Measurement of minimum ignition energy and quenching distance for propane air mixture.
($\phi = 1.04$, Pressure = 127 mm. Hg. abs. Temp. = 288-295°K). Effects of velocity and turbulence.



5 t ($\mu\text{s}/\text{cm}$) 10
 100 V_g (mV/cm) 100
 5 I_g (mV/cm) 5
 35 t_s (μs) 45
 6 E (mJ) 18



$\rightarrow$ 45 μs $\leftarrow$

Plate I: Voltage and current pulses in the spark gap.

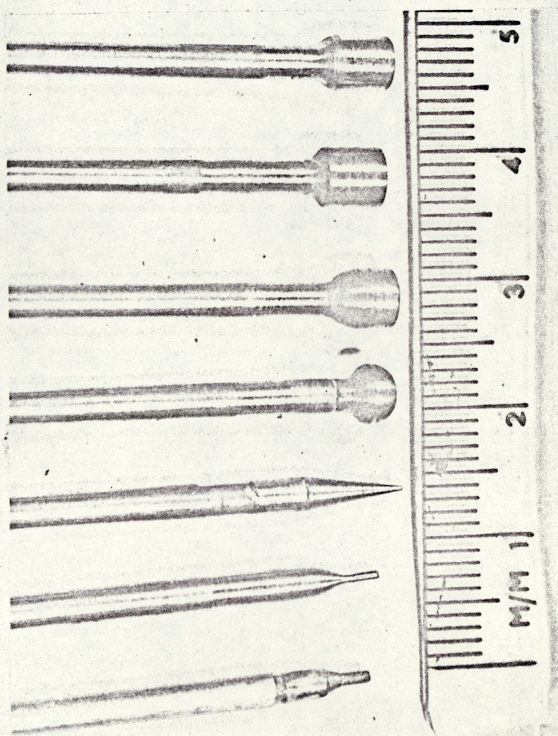
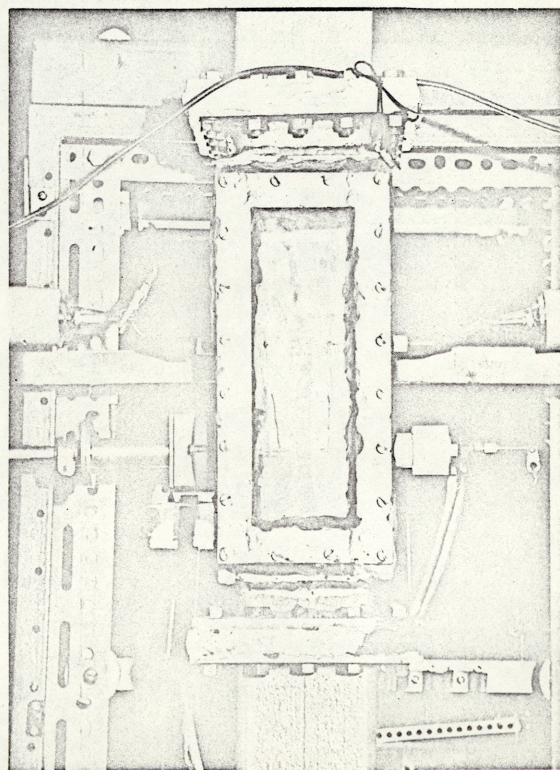


Plate II: Different shapes and sizes of the electrodes.

Plate III: The working section.

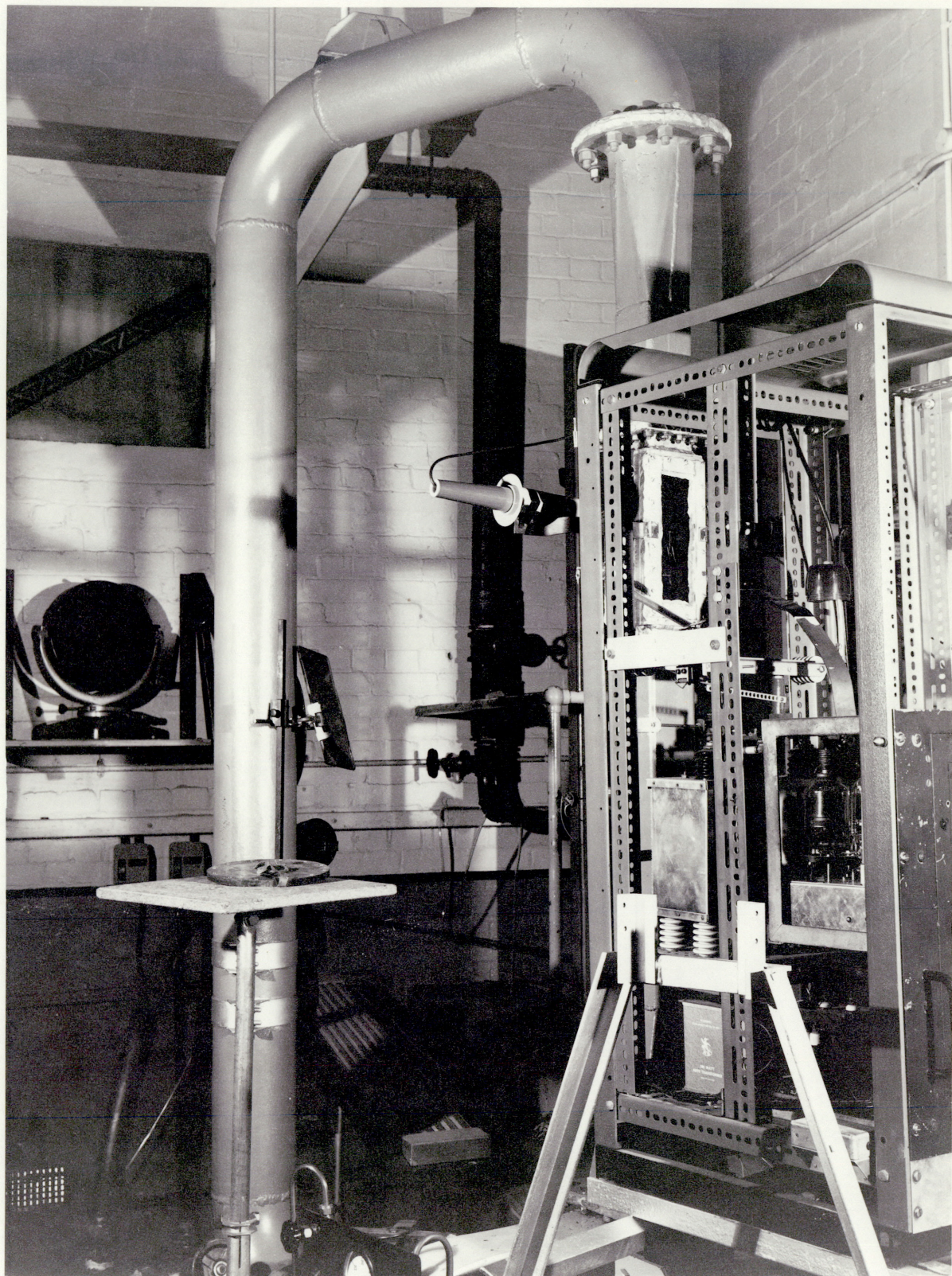
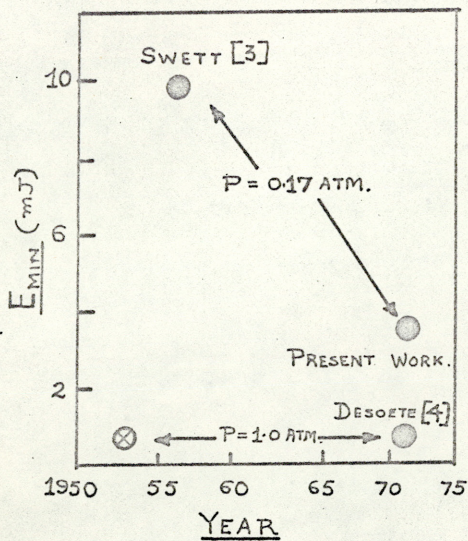
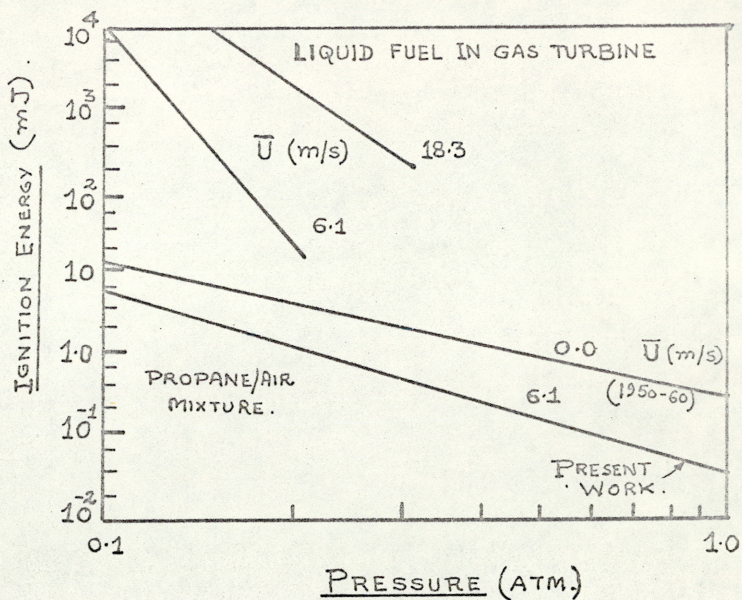


Plate IV : Low Pressure Ignition Rig.

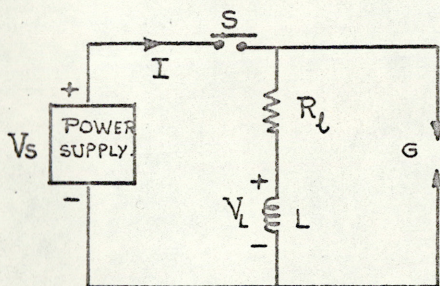


(a) Laboratory research in ignition (⊗ stagnant mixture ● Flowing mixture).

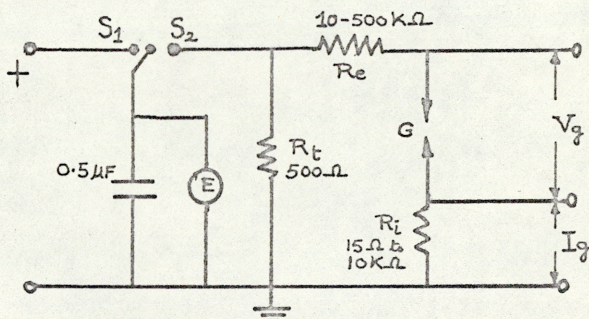


(b) Ignition energy requirements of practical and laboratory systems.

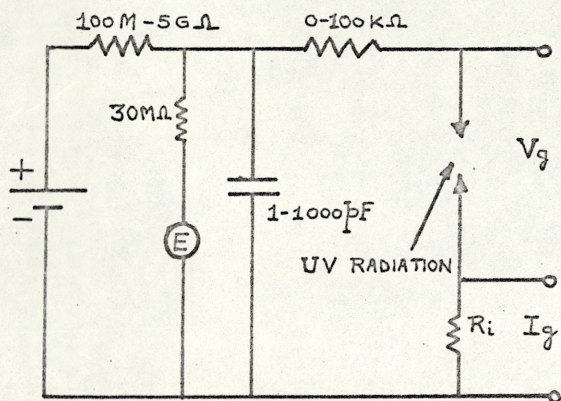
Fig.1: Summary of relevant ignition research.



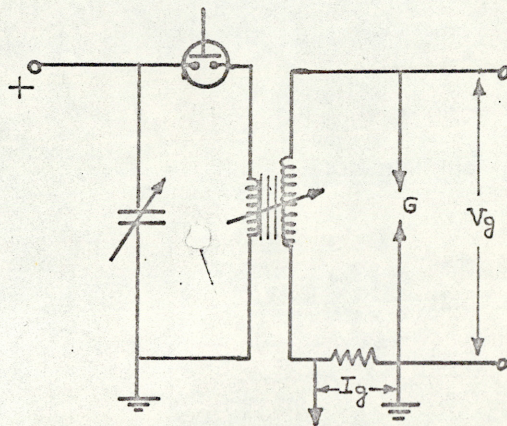
(a) Inductive network of Type B.



(b) Swett's [3] circuit. (E = Electrostatic voltmeter).

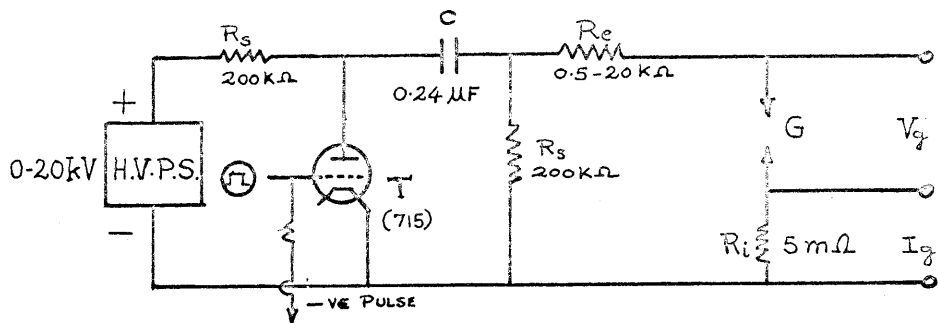


(c) Rose & Priede [15] circuit.

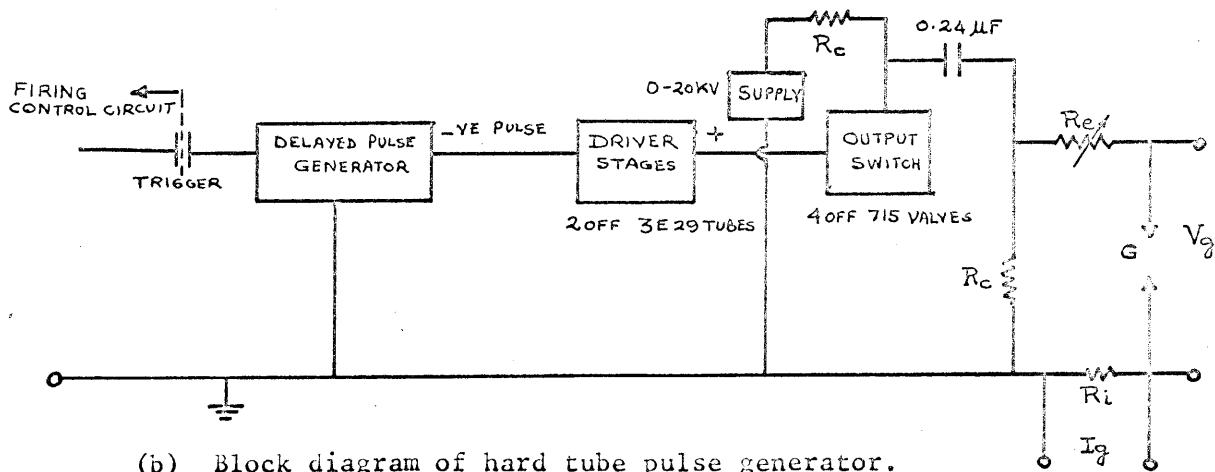


(d) DeSoete's [4] circuit. (T: Hydrogen Thyratron)

Fig.2: Electrical networks used in ignition research.



(a) Basic electrical network of present study.



(b) Block diagram of hard tube pulse generator.

Fig.3: Ignition unit of the present study.

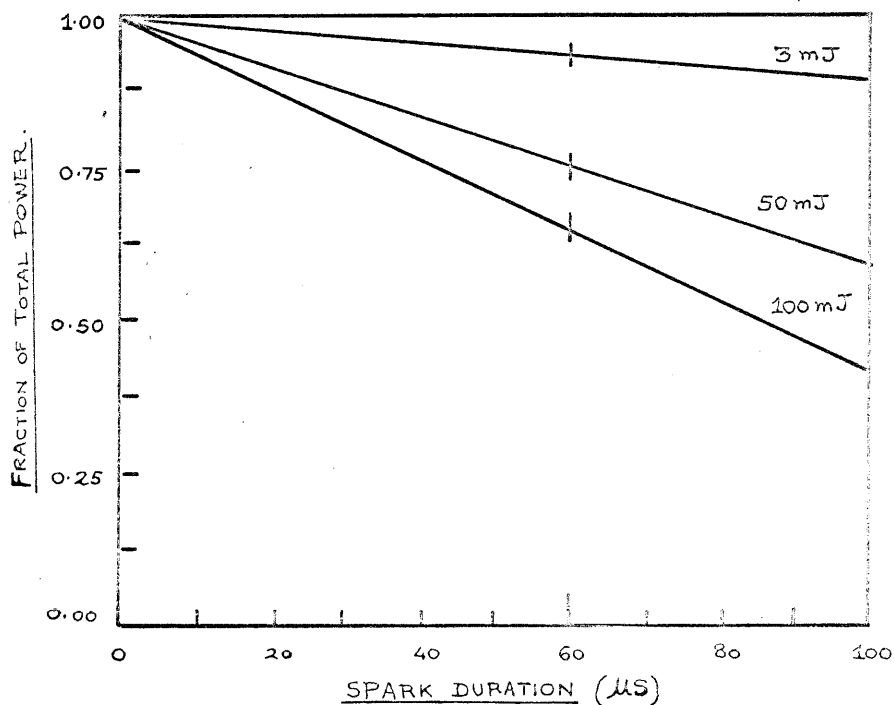


Fig.4: Energy release characteristics at the spark gap.

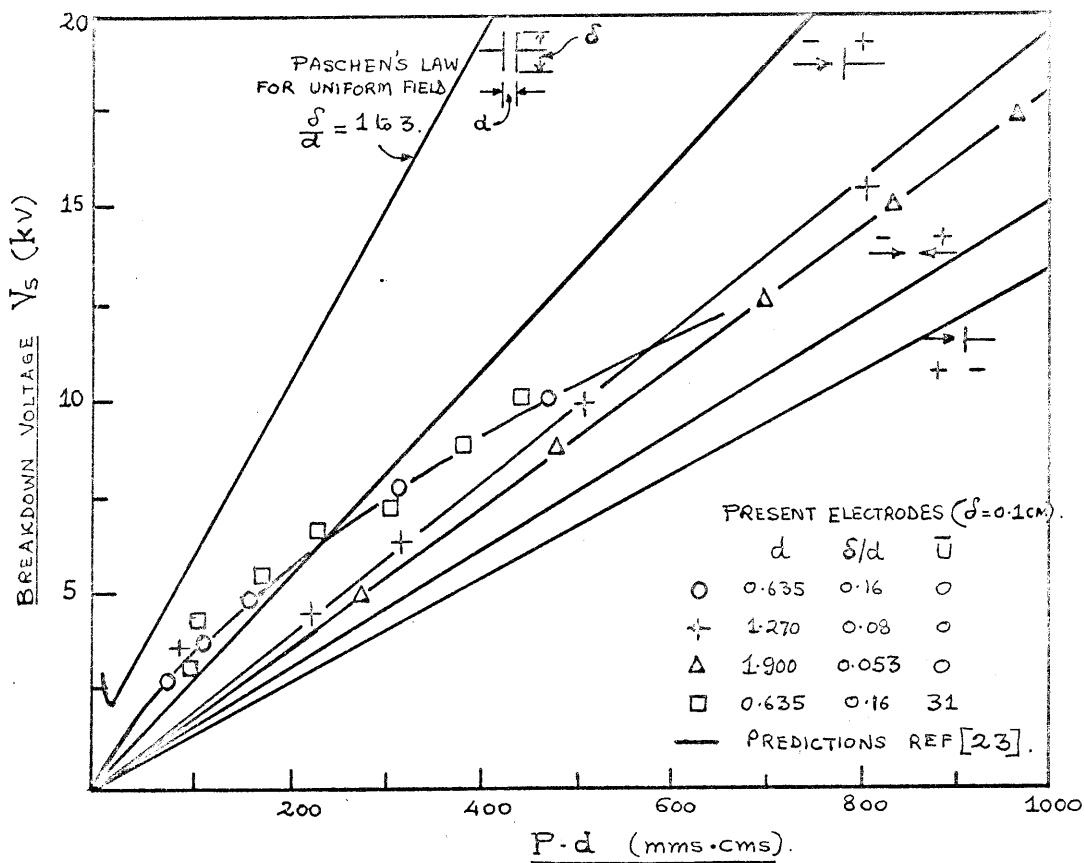


Fig.5: Breakdown potential for various electrode configurations.

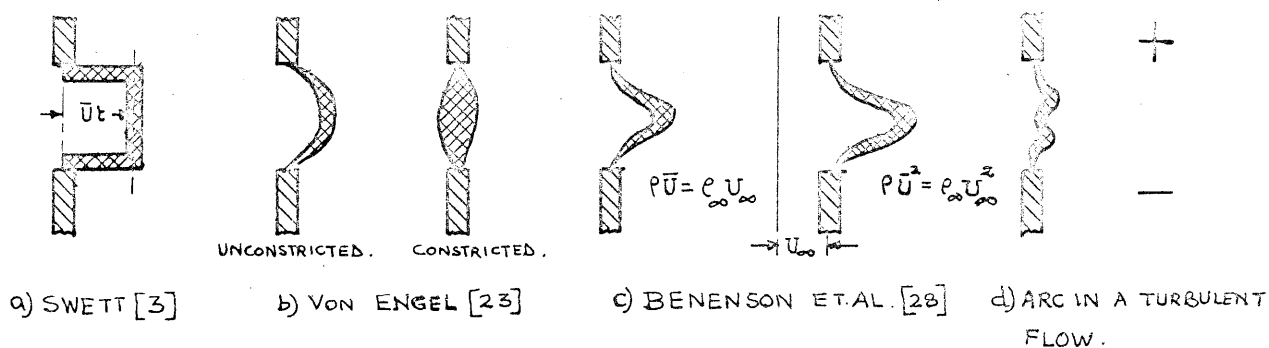
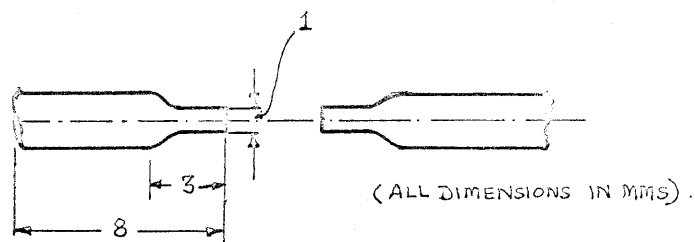
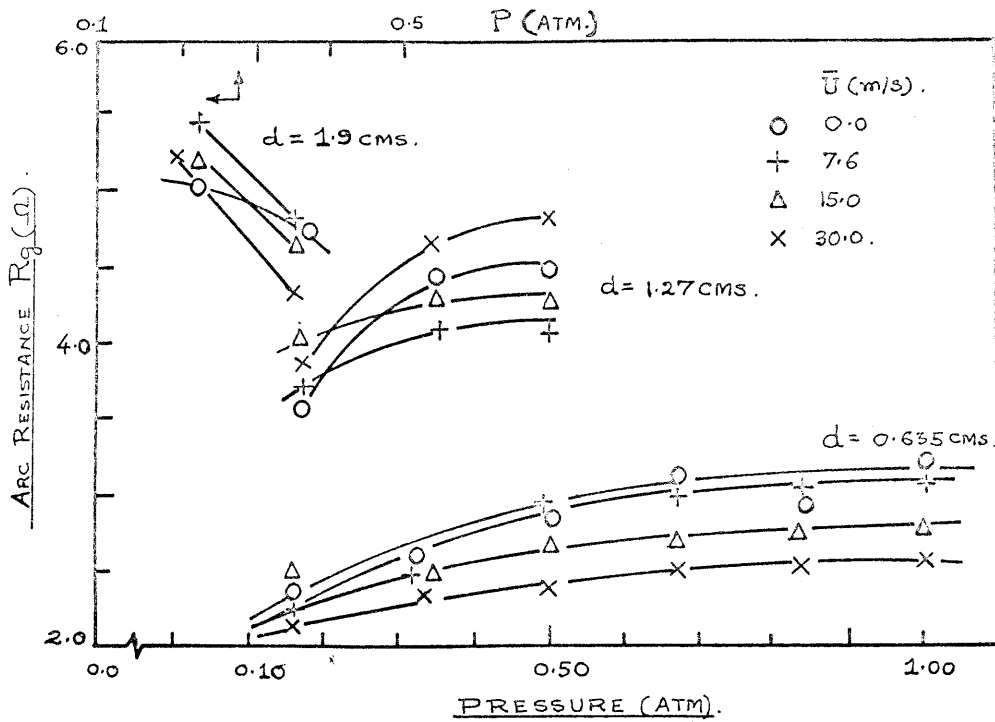


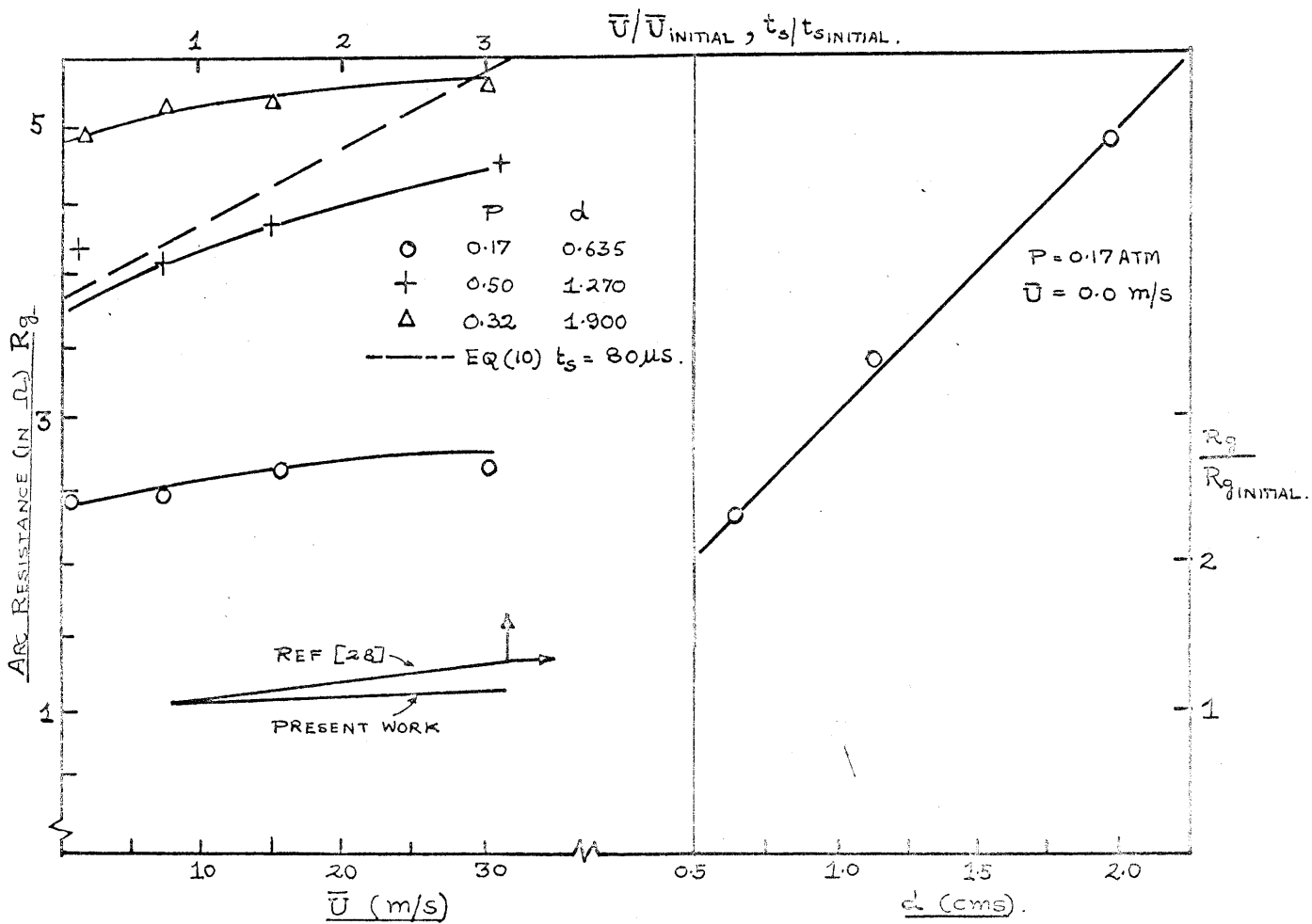
Fig.6: Arc column in forced axial turbulent convection.



(b) Electrodes used in present study (Hardened stainless steel).



(a) Effect of ambient pressure on gap resistance.



(b) Effect of $\bar{U}$ &/or t_s on R_g .

(c) Effect of d on R_g .

Fig.7: Effects of flow parameters on arc resistance R_g ($u'/\bar{U} = 5\%$).

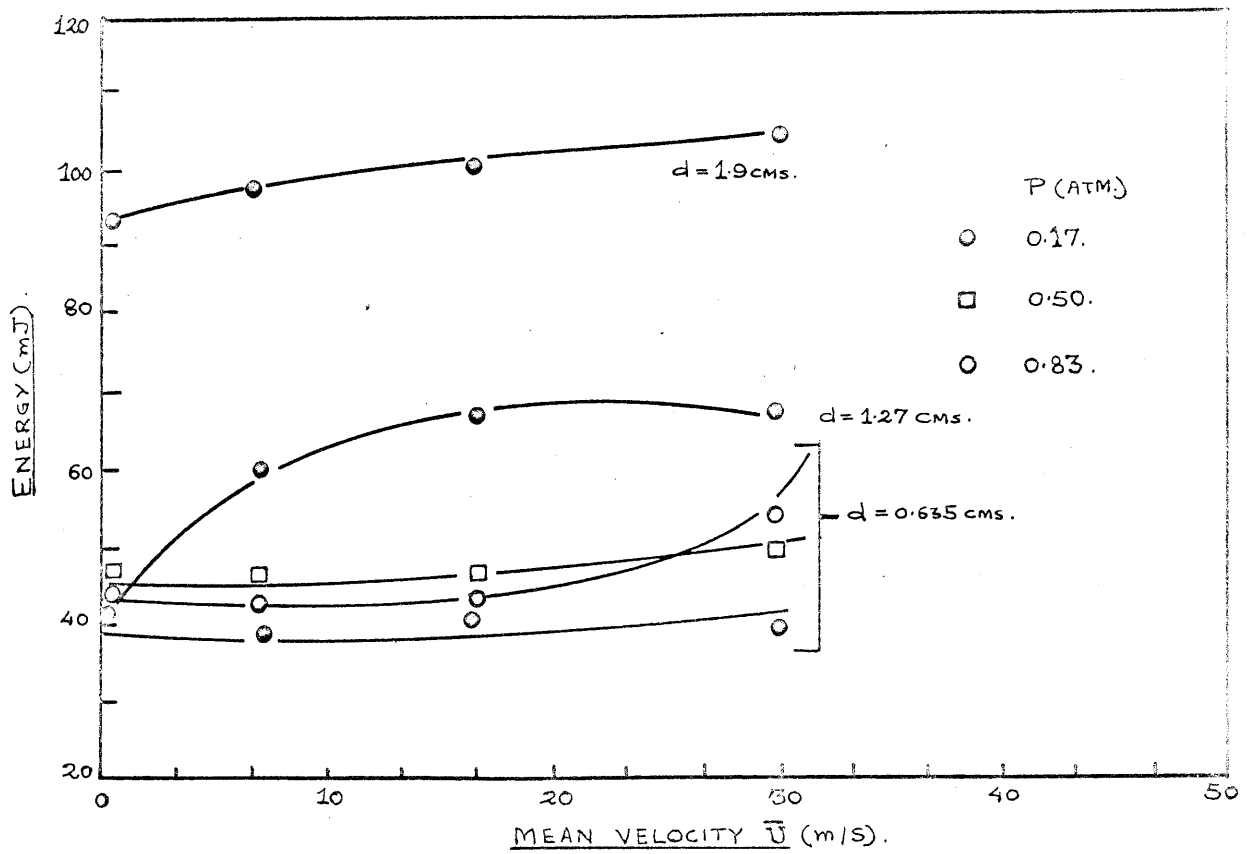


Fig.8: Effects of flow parameters on the energy released in an arc. ($u'/\bar{U} = 5\%$).

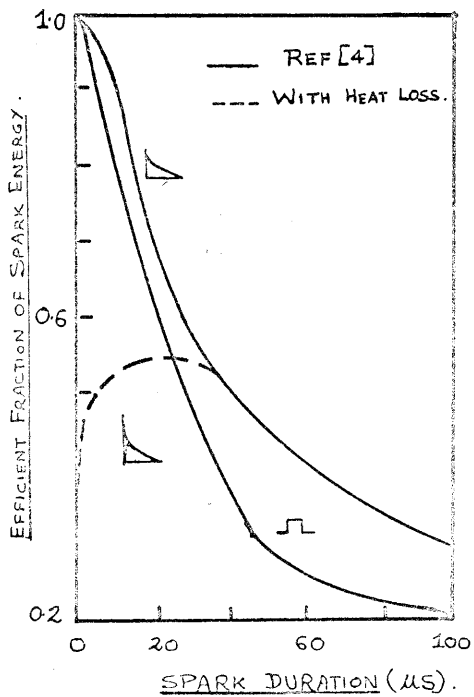


Fig.9: Efficient fraction of spark energy as a function of spark duration.

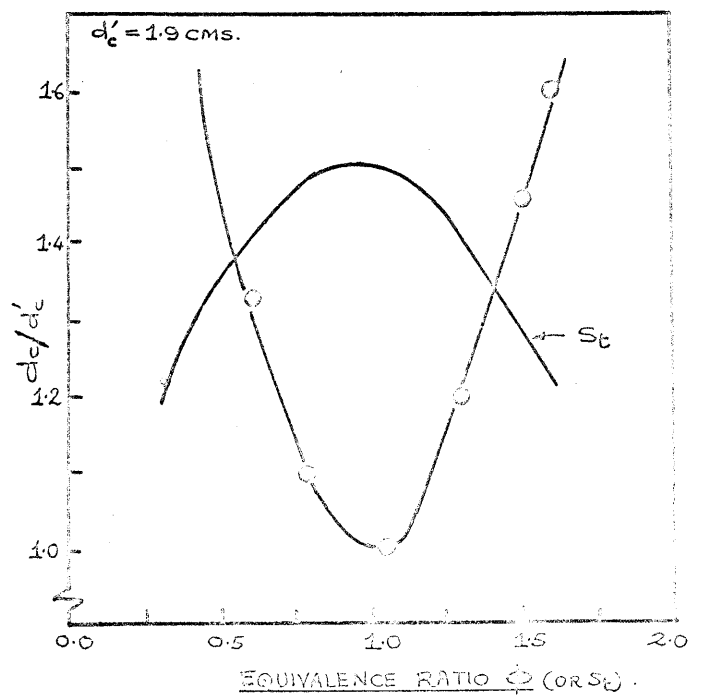
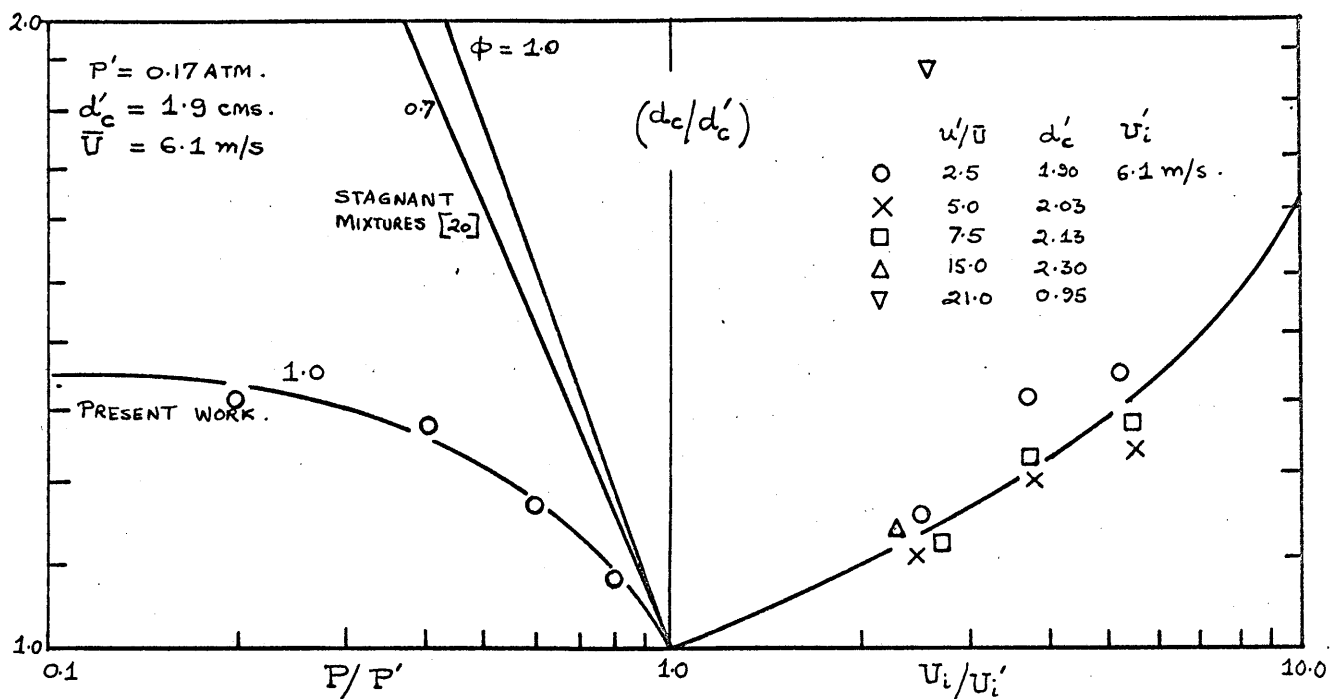
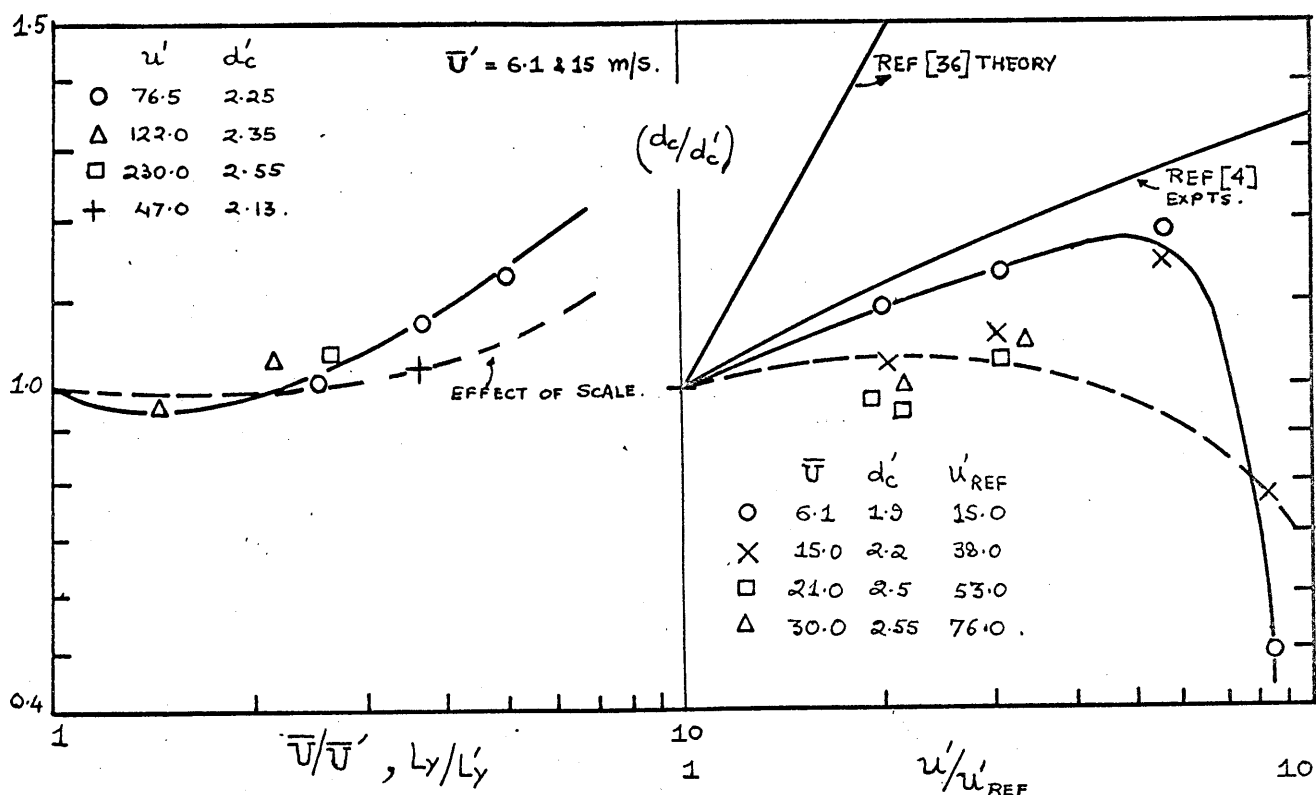


Fig.10: Effect of fuel/air ratio on quenching distance.



(a)

(b)

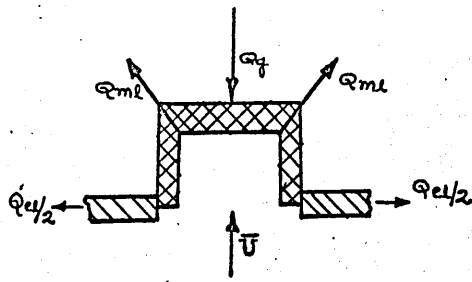


(c)

(d)

Fig.11: The influence of flow parameters on quenching distance.

(P = mm Hg. abs. d_c = cms. U_i & $\bar{U}$ = m/sec. u' = cm/sec.)



(a) Energy balance ($\bar{U}=0$)

$$Q_l = Q_{el} + Q_{ml} \quad \eta = \frac{Q_g}{Q_s}$$

$$Q_g = Q_i + Q_l$$

(b) Energy balance ($\bar{U}>0$ discharge blown away)

$$Q'_l = Q'_{el} + Q'_{ml}, \quad Q'_{el} < Q_{el}, \quad Q'_{ml} > Q_{ml}$$

$$Q'_g = Q'_i + Q'_l, \quad Q'_g > Q_g, \quad Q'_i > Q_i$$

$$\eta' = Q'_g / Q_s \quad Q'_l < Q_l$$

(c) $\eta_k = \eta' / \eta$ and $Q_r = Q'_{el} / Q_{el}$

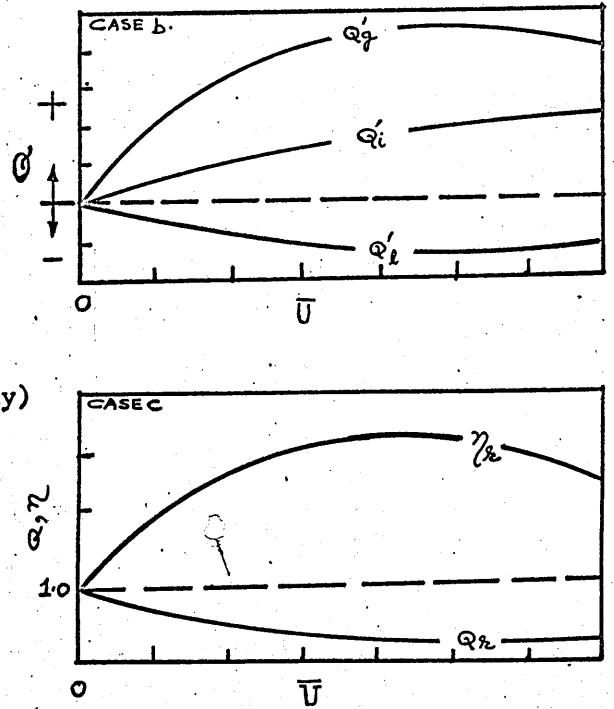


Fig.12: Energy balance of an arc discharge in flowing combustible mixture.

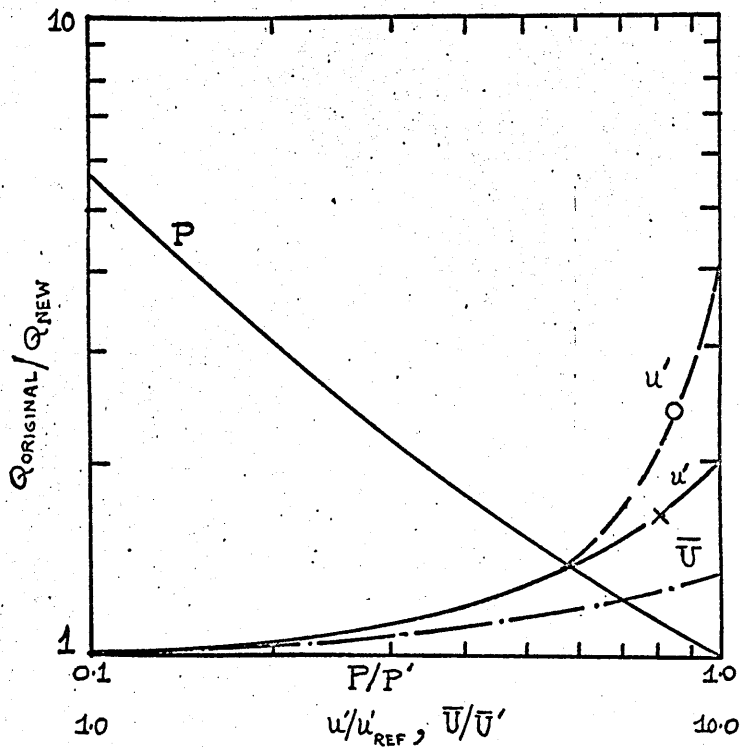
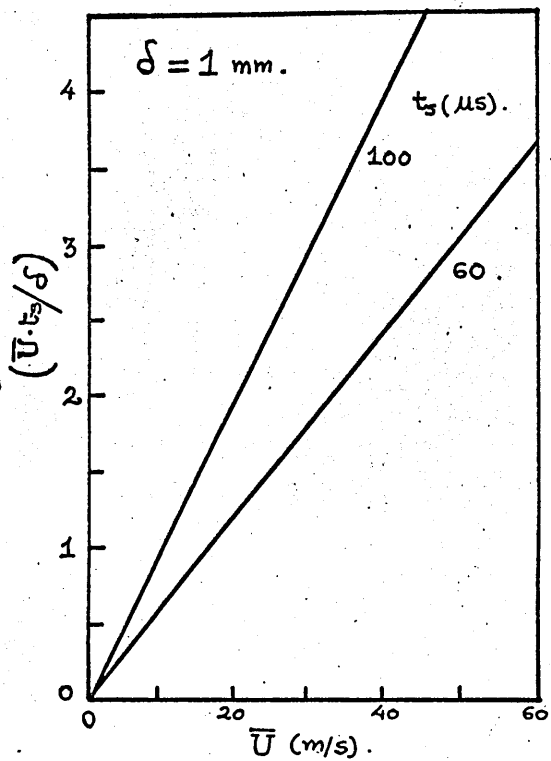
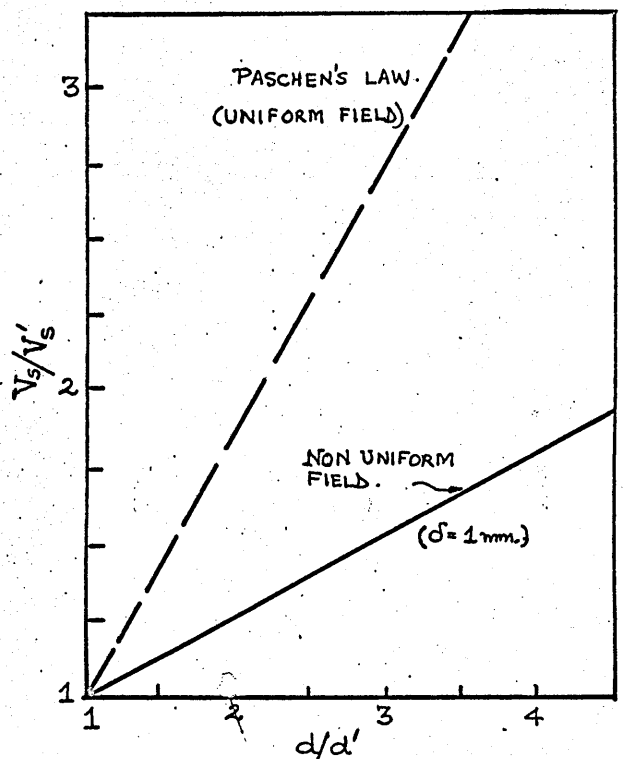


Fig.13: Reduction in heat loss to electrodes due to the arc being blown away.



(a) Air velocity Vs. downstream displacement of an arc.



(b) Breakdown voltage Vs. gap length.

Fig.14: Influence of velocity and gap length on the arc properties.

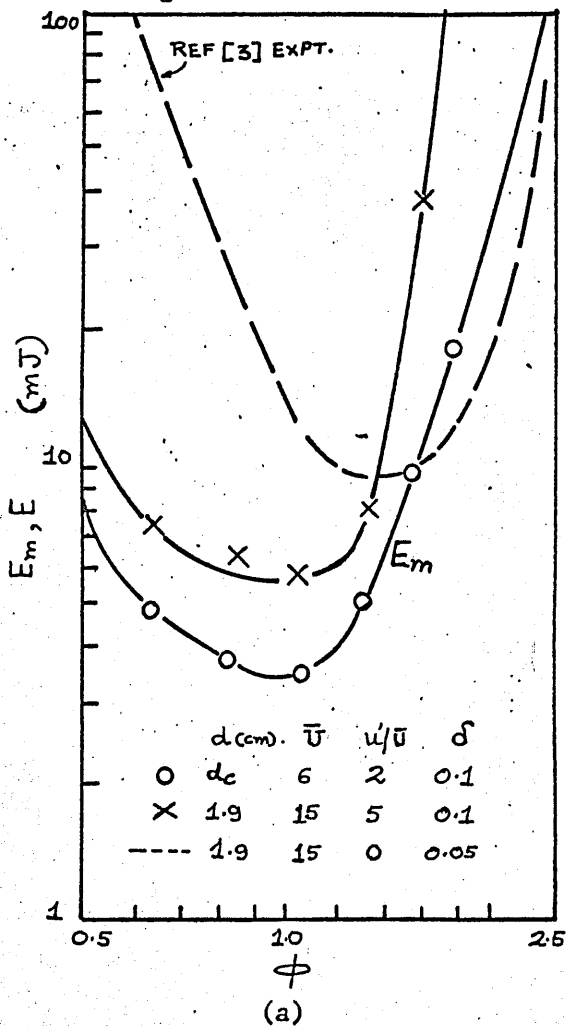
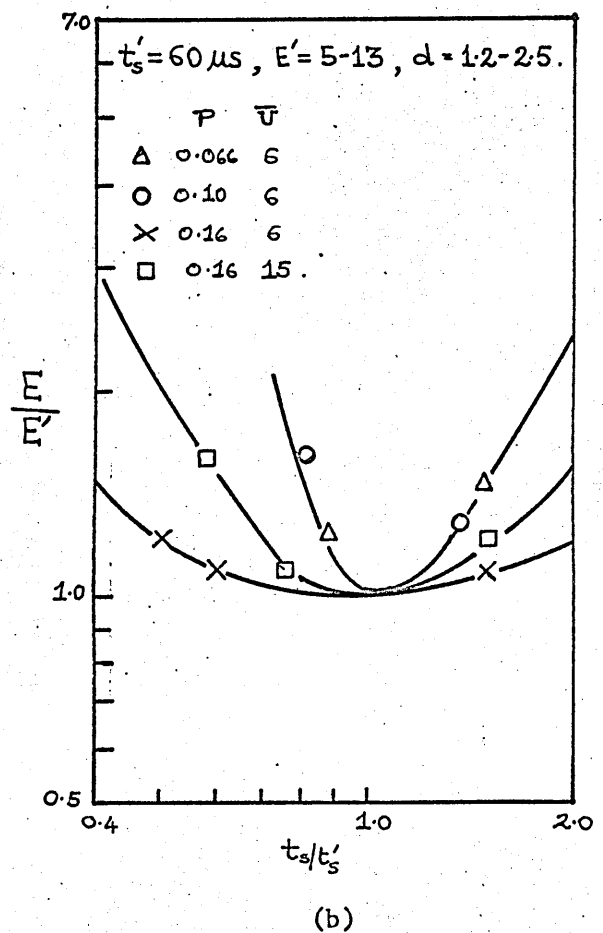


Fig.: 15 The effects of fuel air ratio and spark duration on minimum ignition energy.

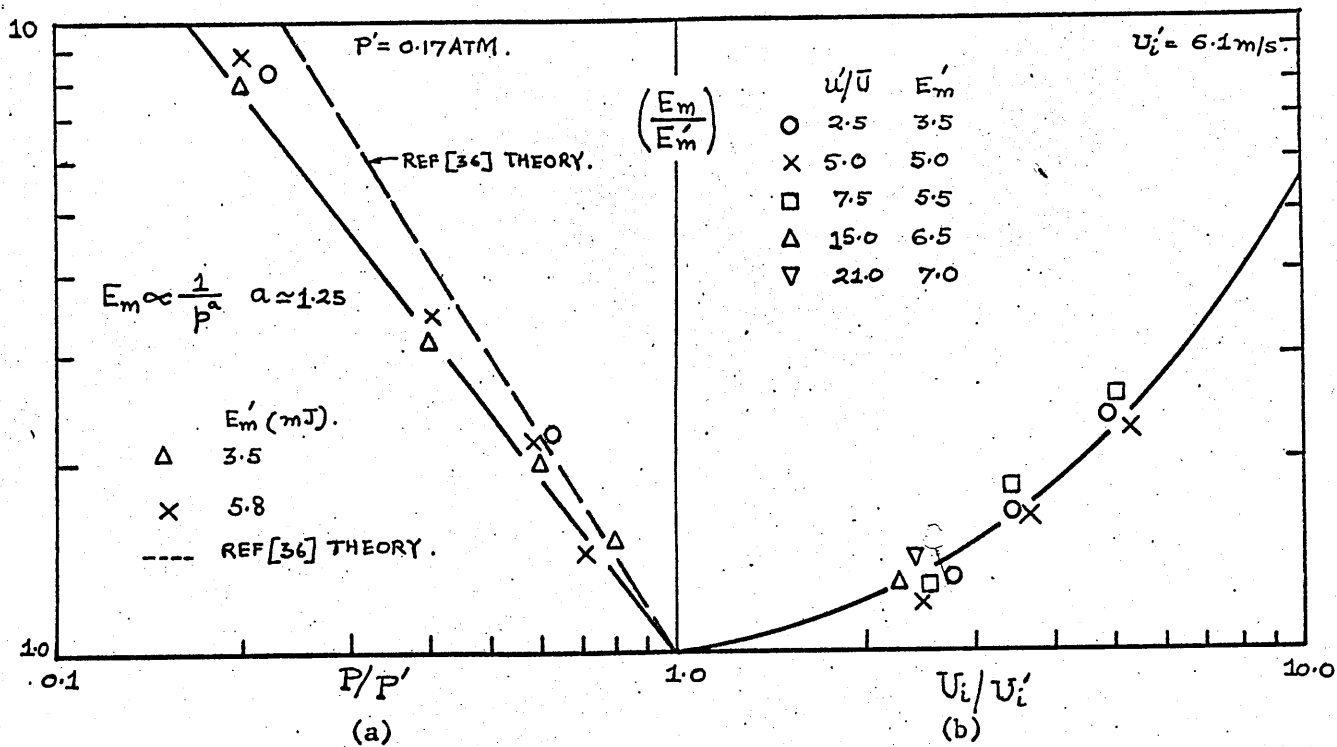
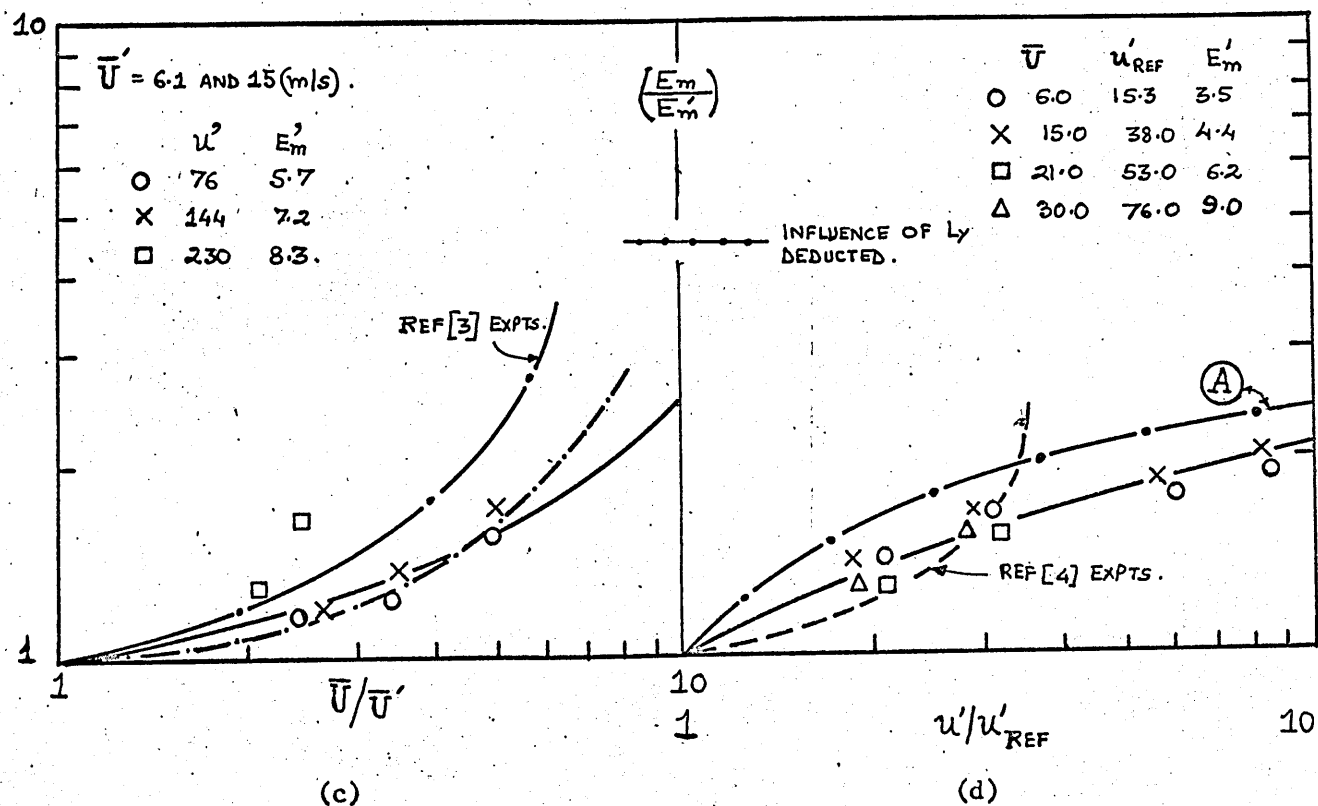


Fig.16: Influence of flow parameters on minimum ignition energy.

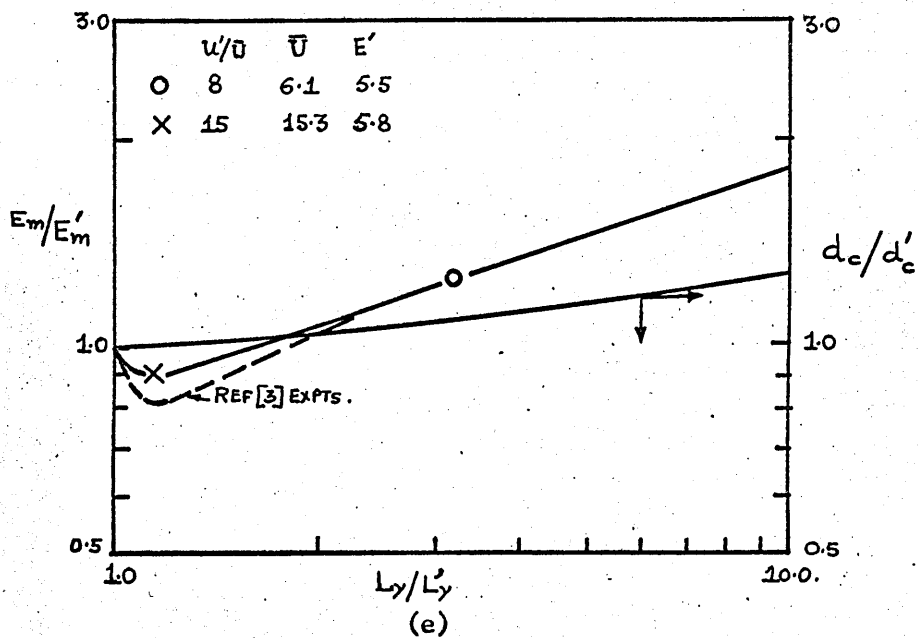


Fig.16: (Contd.) Influence of flow parameters on minimum ignition energy ($E_m = \text{mJ}$)

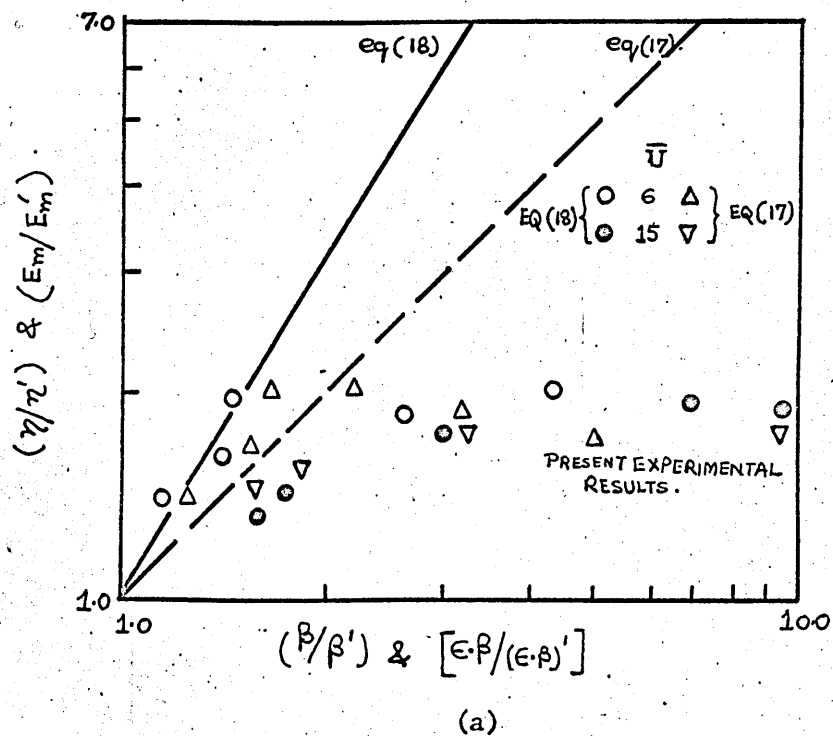


Fig.17: Comparison of present experiments with Desoete's [4] theory.

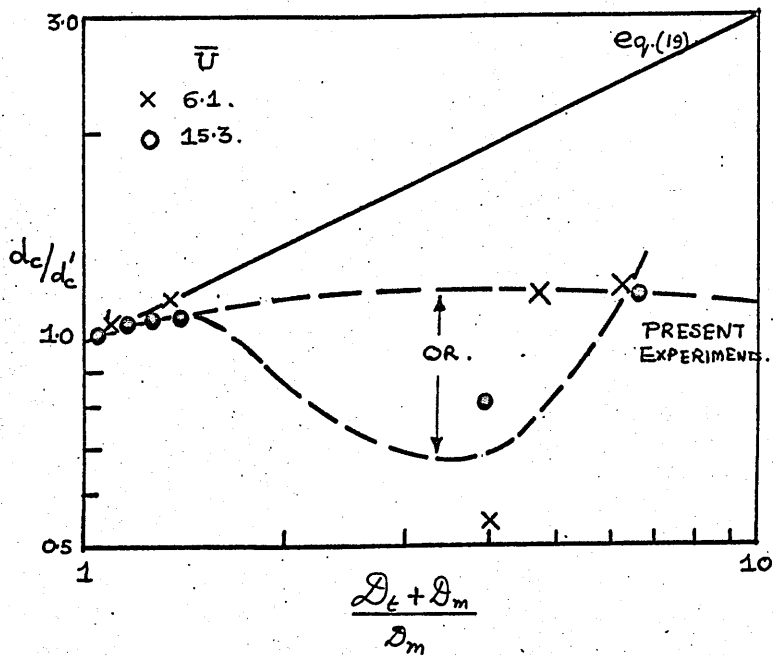


Fig.17 (Contd.): Comparison of present experiments with Desoete's [5] theory.

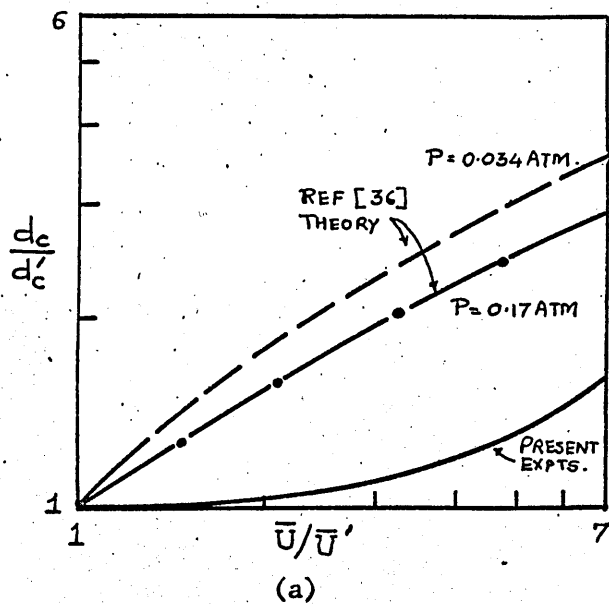
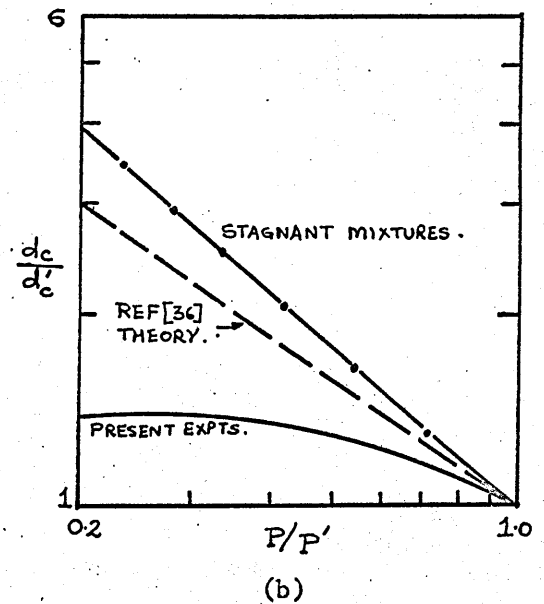
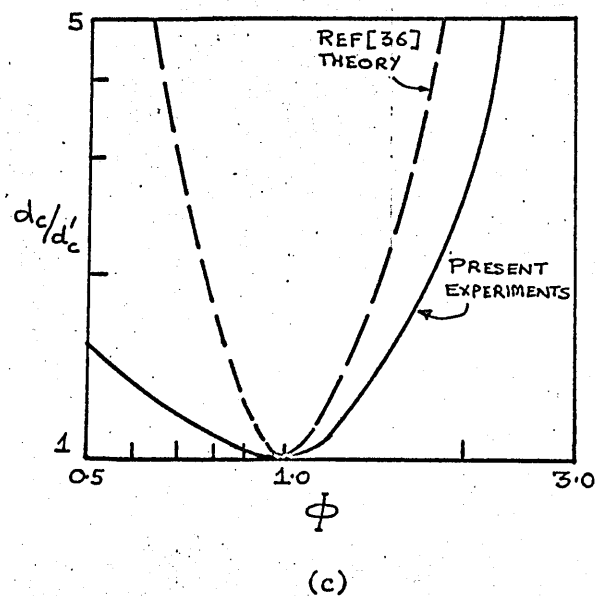


Fig.18: Comparison of present experiments with Lefebvre's [36] theory.

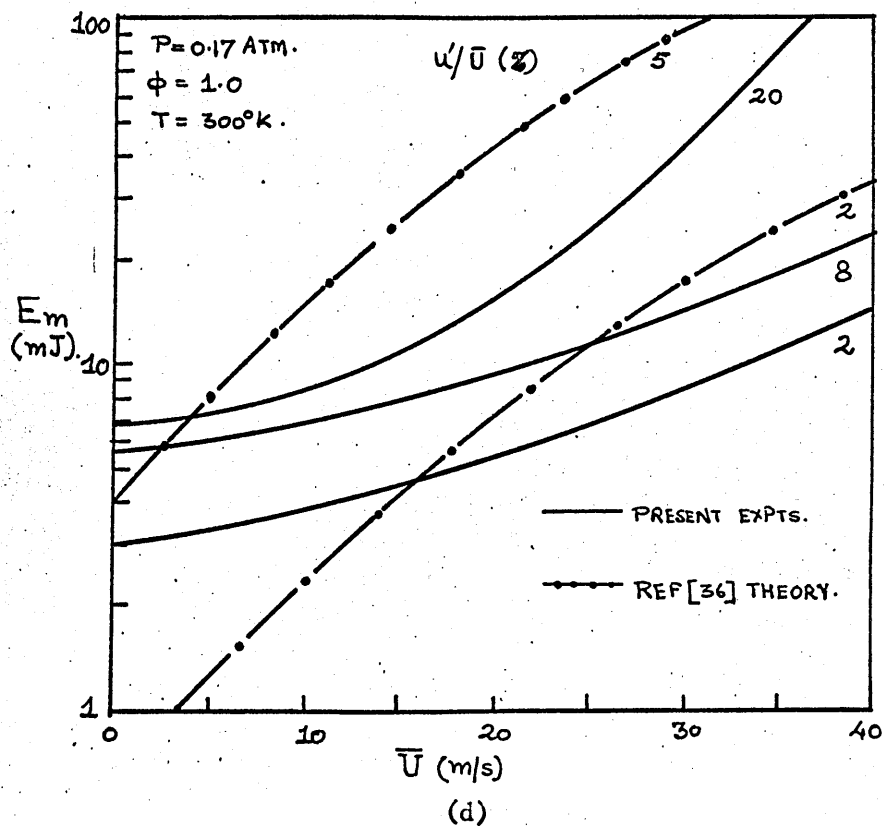


Fig.18 (Contd.): Comparison of present experiments with Lefebvre's [36] theory.

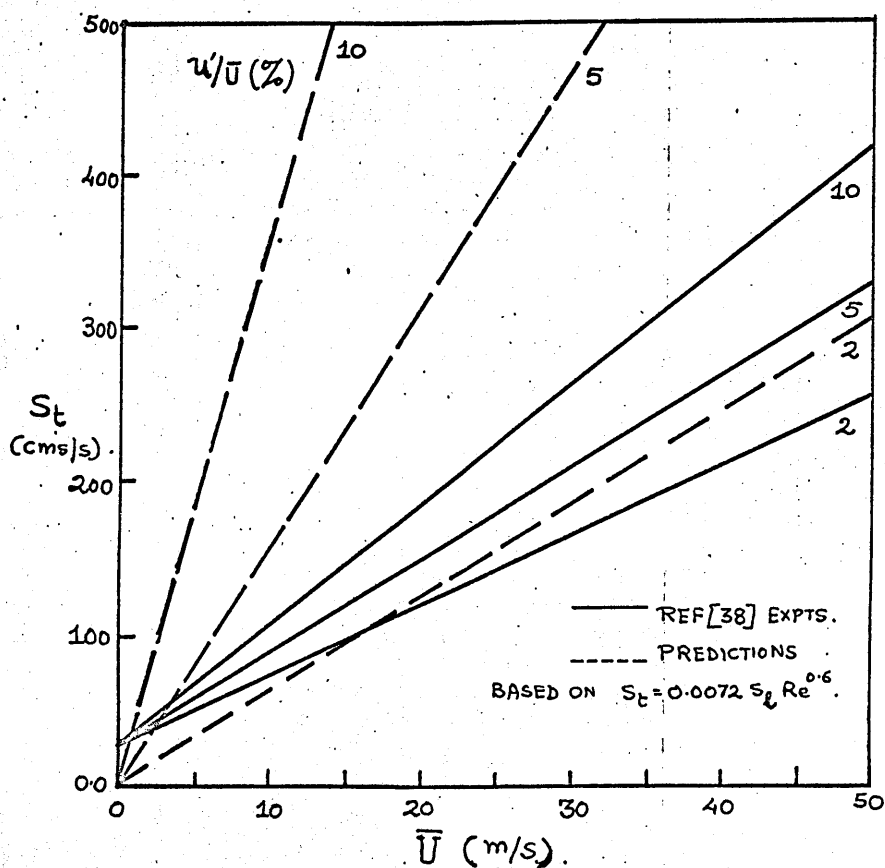


Fig.19: Comparison of experimental and analytical values of S_t .