

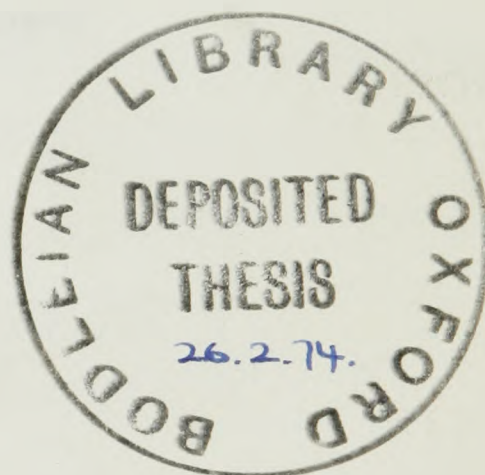
SOME OPERATING CHARACTERISTICS OF NOVEL IGNITION

DEVICES FOR HYDROCARBON/AIR MIXTURES

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Corrigenda

<u>Page</u>	<u>Line</u>	
9	26	"entirely" should read "largely"
10	1	"duel" should read "fuel"
36	15	"8" should read "22" and "7" should read "20"
40	23	"by" should read "from"
50	31	"cermet" should read "cement"
58	9	"laser" should read "spark"
61	21	" V_1 " should read " v_1 "

ABSTRACT

An introduction to the problems of ignition in the petrol and gas turbine engine is given. Two new ignition devices are considered for their suitability to overcome these problems and a series of experiments were performed to evaluate their relative merits.

The use of a laser spark and the development of a plasma plug igniter were compared with sparks of variable energy produced between two electrodes. A simple combustion chamber was used for the experiments and ionisation probes were used to follow the propagation of the flame from the ignition source and through the gaseous mixtures. The conditions of the experiments were as follows:

Pre-mixed methane/air of	1.0, 0.8 and 0.6 stoichiometry
Pressures	101 kN/m ² - 1067 kN/m ²
Laser spark energies	30 mJ - 400 mJ
Plasma plug energies	50 mJ - 1500 mJ
Electrode spark energies	10 mJ - 2500 mJ

Samples of the combustion products were taken and the results for the three mixture ratios are presented. The performances of the three ignition methods are presented by plotting the flame speeds observed from the ignition sources as functions of energy.

Practical considerations eliminate the use of the laser as an ignition method but the plasma plug could be used for automotive applications if some control of the energy was exercised. The gas turbine engine appears to be the most likely application of the plasma plug as it offers greater penetration into the combustion chamber than current surface discharge igniters.

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"When the duties of men coincide with their interests, they are usually performed with alacrity; the progress of civilization ensures the existence of all real improvements; and however high the gratification of possessing the good opinion of society, there is still more exalted pleasure in the consciousness of having laboured to be useful"

Sir Humphry Davy

On the Safety Lamp for Miners with some Researches on Flames. 1818.

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CHAPTER ONE

THE ROLE OF IGNITION

At the beginning of the 19th century, the ignition of gases first became of scientific interest because of the increasing problem created by explosions of 'firedamp' in the deep coal mines of Northumberland. Investigations carried out were concerned with finding methods of preventing the ignition and explosion of these pockets of 'firedamp'. However, with the development of the gas engine, interest was directed at igniting and controlling such explosions to produce mechanical work. The subsequent development of the internal combustion engine required a reliable source of ignition for smooth and consistent operation. The present methods of ignition using either an electric spark or compression ignition originated early in the development, and their reliability at the present day is related to the gradual improvement in the electrical and mechanical components of the systems. With the increasing awareness of the problems of pollution, greater interest has been shown in controlling the combustion process in order to minimise the quantity of pollutants produced. This can largely be met by careful design of combustion chamber and correct distribution of the fuel/air mixture to the chambers; but, without a reliable source of ignition over the entire range of operating conditions, these two are ineffective.

CHAPTER TWO

THE IGNITION OF GASES

2.1 INVESTIGATIONS OF THE PARAMETERS AFFECTING THE IGNITION OF GASES

It was in 1816 that the serious problem of explosions of pockets of firedamp in the deep coal mines of Northumberland was brought to the attention of Sir Humphry Davy. He investigated the inflammability of mixtures of collected samples of firedamp and air when they were exposed to a flame (ref. 1). His subsequent investigations into the propagation of flames through tubes and wire meshes in the explosive mixtures, led him to the invention of the safety lamp, which, with its widespread adoption, largely solved the problem of explosions in mines.

These experiments were repeated by Coquillon (ref. 2) in 1876 using an electric spark for ignition and were extended by LeChatelier in conjunction with Mallard (ref. 3) in 1883 and Boudouard (ref. 4) in 1898 to pure gases and vapours. Investigations of the inflammability limits of gases with air continued to be made and the paraffin hydrocarbons were covered by Burgess and Wheeler in 1911 (ref. 5). They reported that no effect on the lower limit of inflammability was observed when the ignition source was increased in size, but the rate of propagation of the flame did increase.

Subsequent investigations were concerned with the problem of whether the effect of an electric spark was purely thermal or whether the ionization produced by the spark had a dominating role to play in producing active species. In 1914 Coward, Cooper and Jacobs (ref. 6) performed a series of experiments in which different quantities of inert diluent gases were added to the combustible mixture and a correlation of their thermal conductivity and limiting pressure, below which ignition was impossible, was found. This suggested that a thermal theory would account for their observations.

Thornton (ref. 7), in a series of experiments reported in 1914-15, was the first to recognise that an induction spark had two

distinct components, one due to the capacitance and the other due to the inductance of the discharge circuit. Fig. 1 shows a typical voltage record of the breakdown of a spark gap when the output from an induction coil is applied. When the spark gap breaks down, the first pulse is due to the discharge of the capacitance associated with the leads and electrodes which has been charged by the build up of high tension voltage prior to discharge. This is the capacitive component which is immediately followed by the inductive component if sufficient energy is available from the induction coil. Thornton controlled the relative amounts of energy released in each component and, using the criterion of minimum energy required to ignite the gas, he found that the capacitive component of the discharge was a more effective ignition source than the inductive component. He concluded that the active species produced by the ionization from the capacitive component was more effective than the heating effect of the inductive component. These conclusions were contested by Morgan (ref. 8) and Wheeler (ref.9), who maintained that his results were an indication of the validity of the thermal theory of ignition postulated by Morgan, Wheeler and Taylor-Jones (ref. 10). This was based on the temperature distribution around localised heat sources, which predicted that, for a given amount of energy an instantaneous point source was better than a temporally extended source, and that a volume source was better than a point source. Morgan and Wheeler concluded that these predictions were sufficient to account for the effect of the different methods of energy dissipation in Taylor's experiments.

The part that activated species play in the combustion of gaseous mixtures was investigated by Finch and Thompson (ref. 11). They examined the reaction occurring in the cathode zone of a discharge tube containing combustible mixtures at low pressures. From this they postulated that a necessary condition for the ignition of an explosive mixture was a sufficient concentration of suitably

activated molecules, and not the complete degradation of the electrical energy to thermal energy. In order to test this further, Finch and Thompson studied the effect of frequency of oscillation of a spark discharge on the minimum igniting pressures of carbon monoxide/air mixtures. They found that the igniting power, defined as the reciprocal of the minimum igniting pressure, increased with decreasing frequency. This was contrary to the thermal theory presented by Morgan, Wheeler and Taylor-Jones, because a reduction in the rate at which the energy was dissipated gave an increased igniting power, and was also contrary to the observations of Thornton. Finch and Thompson pointed out that the high rate of dissipation in a high frequency spark would produce greater ionization of the gases than the low rate of dissipation in a low frequency discharge, the latter producing a greater proportion of active molecules. They considered that these results established the importance of active molecules and marked the collapse of the purely thermal theory of ignition.

The conclusions which Finch and Thompson reached were thrown into considerable doubt, however, by an extensive study of the ignition of gases made by Blanc, Guest, vonElbe and Lewis (ref. 12). Their experiments were conducted using purely capacitive sparks and observing the minimum energy which would ignite hydrocarbon/oxygen mixtures, diluted with various quantities of nitrogen and other gases, at pressures at and below atmospheric. Using special electrodes with glass discs attached at the end (Fig. 2) they were also able to measure accurately the quenching distances for the mixtures investigated. This was done by progressively reducing the distance between the electrodes until a sudden increase in the minimum energy for ignition was observed. The gap width at which this occurred was taken as the minimum distance below which the presence of the electrode had a significant effect on the development of the incipient flame kernel. The purpose of the glass discs was to provide a heat sink for the

expanding flame front and quench the flame by removing thermal energy. A comparison with the results of Finch and Thompson showed that Blanc et al were able to ignite similar mixtures with energies two orders of magnitude lower than those used by Finch and Thompson and that the reason for this discrepancy was the quenching effect of the electrodes.

Stiener and Mirsky (ref. 13) have investigated the effect of the rate of energy dissipation on the minimum ignition energy. The electrode configuration they used was similar to that used by Blanc et al, and care was taken to ensure that the gap width was greater than the quenching distance for the lean propane/air mixtures used. The relative magnitudes of the capacitive and inductive components of an induction coil spark were adjusted to vary the rate of dissipation of energy. They showed that the minimum energy decreased by 40% as the rate of energy release was increased by approximately 100%, and that extrapolation of their results to a purely capacitive spark discharge agreed with the minimum energies recorded by Blanc et al.

The development of the 'Q' switched solid state laser has made it possible to create electrical breakdown of gases when the beam is focused with a short focal length lens. The 'spark' so produced has several advantages as an ignition source. It is an almost perfect point source of instantaneous energy since the beam has a peak power in excess of 10 MW lasting for 40-50 nanoseconds. Because the spark is at the focal point of the lens used, it is entirely free from contaminating electrode material and no quenching of the flame kernel can occur by heat conduction along the electrodes. This method of ignition will be examined in more detail in a later chapter.

2.2 The effect of gas flow on the ignition energy.

A study of the effect of flowing gas on the energy required for ignition has been carried out by Kimuna and Kumagai (ref. 14). No exact measurements of the energy required were given for city gas/air mixtures, but the relative magnitudes of their results showed

that less energy was required as the laminar stream velocity was increased. When turbulence occurred at higher stream velocities, the ignition energy required increased. They postulated that the reason for these observations was the removal of the flame kernel from the quenching effect of the electrodes as the stream velocity was increased, but when turbulence occurred the kernel required more energy for ignition because of increased losses due to eddy diffusion.

2.3 Ignition by other methods.

Prior to the use of the laser spark, the electric spark was considered to be the most efficient method of ignition because of the direct deposition of the majority of the energy into the gas. Other methods have been investigated and these include electrically heated wires and plates, and hot jets of gas or flame.

Stout and Jones (ref. 15) have investigated the energy needed to ignite a gas using heated nichrome wires and found that, for a 50% probability of ignition, the energy required increases with the time interval of heating and the diameter of the wire. Measurements of the surface temperature of electrically heated metal strips needed to ignite natural gas/air mixtures were made by Coward and Guest (ref. 16). They found that catalytic effects at the surface of the metal had an important effect on the ignition temperature. In particular, platinum induced an entirely surface catalytic reaction and required a temperature of 1420°C for ignition, whereas nickel promoted a gas-phase chain reaction creating formaldehyde and required a temperature of only 1080°C for ignition at stoichiometric mixtures. The effect of the convection of the gas over the surface was also investigated by Guest (ref. 17) who found that both natural and forced convection increased the surface temperature required for ignition. This has been confirmed by Mullen, Fenn and Irby (ref. 18) using heated metal rods. The graphs of surface temperature/free stream velocity have an increasing positive slope in the region of 80 - 200 ft/sec and, with increased levels of turbulence, the surface temperature

required was further increased for a given stream velocity. They concluded that this was due to an increased transfer of gas into and out of the wake region of the flow downstream of the rod, necessitating an increased heat transfer rate.

Flames and hot jets of gas have features which make them particularly suitable as ignition sources. They ensure a large surface area of contact between the hot gases and the reactants and, in the case of flames, are also a source of active species for promoting a chain propagating reaction. These advantages probably account for the observations of Rodgers (ref. 19) and Dysart and Freeman (ref. 20), who found that it was possible to ignite weaker mixtures using flames or hot jets of gas than was possible using electrical sparks. Their experiments were performed on stratified charge petrol engines and successful operation was possible down to an equivalence ratio of 0.3, whereas a conventional spark ignition engine is limited to 0.8 equivalence ratio before misfiring occurs. Wolfhard and Vanpee (ref. 21) reported that turbulence in a jet necessitated a higher temperature for ignition to take place and suggested that the eddies produced were less effective ignition agents than large volumes of hot gas in laminar flow. It is equally possible, however, that a small amount of turbulence in the jet or flame would promote better mixing of the igniting source and reactants and thereby assist ignition.

CHAPTER THREE

IGNITION IN THE INTERNAL COMBUSTION ENGINE

3.1 Development of ignition methods

The provision of a reliable ignition source for the internal combustion engine proved to be a difficult problem to solve. Until the present day there have been four basic methods used successfully for ignition:-

- i) Flames
- ii) Heated surfaces
- iii) Pilot fuel injection
- iv) Electrical sparks.

3.1 (i) Flames

This ignition source was widely used until the 1890's and a comprehensive account of its development, as well as other methods, is presented in Sir Dugald Clark's book of 1911 (ref. 22). The earliest gas engine working in Britain was made by Samuel Brown in 1823 (ref. 23) and used a pilot flame to ignite the gas which was at, or just below, atmospheric pressure. Street in a patent of 1794 suggested, and Wright in 1833 (ref 24) used a touch hole, uncovered by the piston at the beginning of its working stroke, through which an external flame was sucked into the fresh charge, causing it to explode. The most developed form of flame ignition was patented by Earnet in 1838 (ref. 25) and is illustrated in fig. 3. A continuously burning pilot flame (1) ignites a secondary flame (2) inside a rotating plug (3), driven by the engine. When the secondary flame communicates with the combustible mixture through the aperture (4), ignition occurred and the secondary flame was extinguished. It is re-ignited when exposed to the pilot flame ready for the next cycle. A modified form of this ignition device was developed for working at pressures of 300 kN/m^2 at the end of the compression stroke in the Otto gas engines.

3.1 (ii) Heated surfaces

This method found application in gas, petrol and oil engines and the basic unit is illustrated in fig. 4. A tube was permanently connected to the combustion chamber and heated to red heat by an external flame. The device relied on the time taken for the combustible gases to reach the heated portion of the tube before ignition took place and adjustments of timing could be made by altering the position of the external flame. Daimler successfully used this open tube method of ignition on his petrol engine of 1885 which found wide application in early automobiles and motor bicycles. With the increase in output to 20-25 HP the necessity of accurate timing became evident because of the danger of early ignition. Timing valves were introduced at the entrance to the heated tubes to allow the gas to be ignited at a regular point in the cycle of operation. Although the heated tubes were easy to replace when they became oxidised or cracked, the timing valves gave considerable trouble and the method has not survived.

Oil or paraffin engines were able to use a hot bulb which was kept separate from the main chamber of the engine. The oil was sprayed into the bulb and it vaporized on contact with the hot surface. This vapour was confined mainly to the hot bulb while the air was compressed in the cylinder. The air, forced into the hot bulb through a small aperture, mixed with the vapour and ignited when a combustible mixture was attained. The heat generated was sufficient to maintain the temperature of the hot bulb and an external heater was needed only for starting. This system has been entirely superseded by the compression ignition or Diesel engine.

3.1 (iii) Pilot fuel injection

Ignition in some modern natural gas engines is achieved by injecting a small quantity of heavy oil into the compressed natural gas/air mixture. The hot gas vaporizes the fuel spray which acts as a multiple ignition source for the main mixture. The injected fuel

usually amounts to only 3-5% of the total fuel used.

3.1 (iv) Electrical sparks

The first operating engine to use electrical ignition was Lenoir's gas engine built in Paris in 1860. This resembled very closely the modern method of coil ignition, in that it employed a battery, an induction coil, a high voltage distributor and sparking plug. The high voltage spark was produced between fixed electrodes, set in insulating porcelain inside the combustion chamber. Without careful maintenance this method was very unreliable because of the inadequate design of the electrical components, particularly the spark plug. Nevertheless, electrical ignition systems found use on the early automobile engines, notably those of Karl Benz in 1885 and Messrs. de Dion in 1896.

Various methods were used to produce a spark, the commonest, other than the high voltage spark, being the jump spark. This occurred when electrical contacts inside the chamber were mechanically separated, whilst a current was flowing either from a battery or a magneto. As a source of electrical energy, the magneto developed in both high voltage and low voltage forms, because of the poor performance of accumulator batteries. However, with the improvement of accumulators and increasing use of electric starting motors and accessories, the magneto disappeared from use in the motor car, but still finds application in small engines where an accumulator is not wanted. The low voltage magneto survived until 1930 in large, slow speed gas engines but high voltage is now universally adopted for spark ignition.

Until the late 1940's the majority of petrol engines had low compression ratios, side valves, and were of low specific output. The ignition systems for these engines were adequately developed to perform satisfactorily under these conditions. Since then, there has been a steady trend towards higher specific output engines, using compression ratios greater than 7:1, overhead valves and higher maximum speeds. These have put severe demands on the ignition system

and have resulted in considerable improvements in both spark plug design and methods of producing the sparks.

J.V. Robson (ref. 26) has reviewed the evolution of the spark plug in relation to the modern automobile engine and has also discussed special spark plugs developed for high performance two stroke engines. The modern automobile has to be capable of operating at widely differing conditions, from prolonged periods of idling and slow speed running in city traffic to high speed motorway driving. Under low power output conditions the spark plug nose must remain hot enough to burn off any deposits that might form on it from the combustion process. The formation of deposits, if continued, would lead to a reduction in the insulation resistance and cause misfiring of the plug and, eventually, complete failure to ignite the mixture. Under high power output conditions, the central electrode must not be allowed to reach a temperature at which rapid chemical erosion of the metal will occur, as this will lead to an unacceptable increase in the spark gap width. A very hot electrode may also become a source of pre-ignition in an engine and could cause serious damage to the engine if it occurred frequently or for prolonged periods of time. There is, then, a range of temperature from approximately 350°C to 900°C in which a spark plug is required to operate, if it is to perform satisfactorily and have a reasonable working life. The controlling factor, which maintains the temperature, is the length of the heat flow path from the spark plug nose to the body of the cylinder head in which it is inserted. There are many grades of plug available according to their heat flow characteristics and two of these are shown in fig. 5 (a) and (b). Fig. 5 (a) shows a plug with a short heat flow path which is a colder grade of plug than that shown in fig. 5 (b) which has a relatively long heat flow path. Fig. 5 (c) shows a projected nose type plug which has found increasing application in modern automobile engines. Not only is the temperature controlled by the heat flow path, but extra cooling can be achieved by the motion of the fresh

incoming charge past the nose of the plug, particularly at high power outputs. At low power outputs the projection of the nose into the combustion chamber helps to keep its temperature above the fouling temperature, since it is always exposed to the hot combustion gases. An added advantage of this type of plug is the good scavenging of the spark gap by the incoming charge, ensuring that a combustible mixture is present between the electrodes.

The thermal loading of high performance two-stroke engines is considerably more severe than that of similar performance four-stroke engines. This is a direct result of there being a power stroke for every revolution of the engine and, consequently, very little cooling of the plug is possible by the incoming charge. Preignition using a conventional spark plug was difficult to avoid at high power outputs and a surface discharge spark plug similar to that shown in fig. 6 was developed to overcome this particular problem. Because it was designed to work at temperatures similar to the rest of the combustion chamber walls, it was particularly prone to fouling and required an external gap in the central electrode. This allowed the high voltage to be attained at the external gap and when that broke down, the sudden rise of voltage at the internal gap was sufficient to cause breakdown. This type of plug has also been tried in the Wankel rotary engine which has similar severe thermal loading conditions at the spark plug. In this case there are three firing cycles for every revolution of the rotor and no opportunity for cooling by the fresh fuel/air mixture. Platinum tipped electrodes have also been tried but the life of either of these types of plug is not as good as the conventional plug in piston engines.

In post war years, the improvements in specific power output of piston engines has been achieved mainly by raising the compression ratio and increasing the speed at which maximum power is developed. Raising the compression ratio has led to an increase in the voltage

required to fire a spark plug by virtue of the higher compression pressures reached and the higher speeds has made the mechanical switching of the current in the primary of the ignition coil unreliable. A further stimulus for development came from the desire of motor manufacturers to increase the maintenance free periods of their products and the contact breaker is one of the parts of the ignition system which requires frequent attention if optimum performance of the system is to be maintained.

A typical output voltage at the spark plug from a conventional contact breaker and ignition coil system is shown plotted against engine speed in fig. 7. The drop in the voltage available at high speeds is due to the reduced time in which the contact breaker is closed thus allowing a smaller current to be reached before it is interrupted by the opening of the contact breaker again. Several forms of ignition system have been developed to overcome this problem, all of them relying to a greater or lesser extent on solid state devices. There are three basic innovations which have been added to the conventional ignition system. The first to be successfully applied is illustrated in fig. 8 and involved the transference of the main switching operation to a heavy duty transistor. This still requires a signal to trigger the switching of the current in the ignition coil and this can be provided by the contact breaker system carrying relatively small currents in a non-inductive circuit, or by a further innovation replacing the contact breaker. Fig. 9 shows a magnetic triggering method in which a magnet mounted on a rotating shaft induces a pulse in a detection coil and either triggers the main transistor directly or through a pulse shaping network. An alternative to this is shown in fig. 10. The light from a source is interrupted by a rotating disc and is received by a photodiode which again either triggers the transistor directly or through a shaping network. The third innovation is the introduction of the capacitor discharge system shown schematically

in fig. 11. This involves using an ignition coil as in the conventional system, but rather than switching large currents off, a capacitor charged to 200-300 volts is discharged through the coil inducing the high tension voltage at the spark plug. The discharge is usually initiated by a thyristor triggered by one of the methods outlined above. All of these systems are capable of sustaining the high voltage output at the high speeds attainable with modern petrol engines. The effect that these recently developed ignition systems have on the performance of engines will be reviewed in the following chapter.

CHAPTER FOUR

THE INFLUENCE OF IGNITION CHARACTERISTICS ON THE PERFORMANCE OF THE SPARK IGNITED INTERNAL COMBUSTION ENGINE

4.1 Ignition timing.

The necessity of having variable ignition timing in petrol engines arises from two sources, a third usually being automatically catered for by the engine itself. All arise from the combustion process which requires a finite time for completion. A typical plot of the pressure against crankangle in a combustion chamber is shown in fig. 12. The two time intervals marked correspond with the time taken from the occurrence of the spark to the time at which the pressure has risen by 5% of its total rise (τ_1), and the time taken for the pressure to rise from 5% to 95% of its total rise (τ_2). τ_1 is usually referred to as the induction period for combustion and is associated with the development of the flame kernel from the spark and τ_2 is the main combustion time. τ_1 is almost independent of engine speed and consequently the number of degrees of crankangle required for this period increases as engine speed increases. τ_2 , however, usually requires the same number of degrees of crankangle as the engine speed is varied. This is because increased engine speed leads to an increased mixture motion in the combustion chamber and more rapid combustion, in terms of real time rather than degrees of crankangle, takes place. In order to ensure that the maximum power is produced by the engine, the maximum pressure must be reached at, or very soon after, top dead centre and consequently as engine speed increases, the number of crankangle degrees required for complete combustion increases. The spark has, therefore, to be advanced to accommodate this increase. Similarly, at part load, the pressures reached during compression are lower because of the partly closed throttle. This has the effect of increasing the real time required for combustion affecting both τ_1 and τ_2 , and an advance of the ignition timing is again necessary. At any engine speed and

throttle opening there is, then, an optimum value for the ignition timing but, depending on engine design, the sensitivity of the engine performance to the timing may be relatively low. This is shown in Teasel and Miller's paper (ref. 27) in which a variation of ± 5 degrees from the optimum can result in a loss of performance of less than 5%. Modern engines have automatic centrifugal and vacuum advance mechanisms incorporated in the distributor of the ignition system and these are designed to give as near optimum performance of the engine as possible over its entire operating range.

During the last ten years intensive efforts have been made to reduce the quantity of toxic products exhausted by the petrol engine. The products causing the most offence are carbon monoxide, oxides of nitrogen and unburnt hydrocarbons. Issler (ref. 28) has shown that of these unburned hydrocarbons and oxides of nitrogen are susceptible to a limited amount of control by optimising the ignition timing for minimum output of these products particularly at idling and overrun conditions. Some of his results are reproduced in figs. 13 a & b. By retarding the spark towards, and even after top dead centre, a useful reduction in the unburnt hydrocarbons is produced at idling (fig. 13_b) and similarly by limiting the ignition timing to the shaded area in fig. 13_a, the unburned hydrocarbon produced on overrun can be minimised. Retardation of the spark timing also reduces the quantities of oxides of nitrogen exhausted. However, these controls can only be applied at idling and on overrun, as retardation of the spark under part load or full load would cause an unacceptable loss of economy or power.

4.2 Spark energy and duration.

Several authors (including refs. 29 & 30) have quoted evidence to show that, under normal operating conditions encountered with petrol engines, and provided the energy in the spark is sufficient to cause ignition, it has no effect on the establishment of combustion.

Support for this claim is given by the fact that the energies available in a normal spark generated by a contact breaker and ignition coil system is in the region 10-100 millijoules and typically will be 20 millijoules. These values are at least an order of magnitude greater than the energies required to ignite similar hydrocarbon/air mixtures under quiescent conditions and at atmospheric pressure as found by Blanc et al (ref 12). Their experiments also showed that as the pressure is increased the energy required for ignition decreased. In compressed mixtures used in the petrol engine, therefore, the energy required should be considerably less. The width of the spark gap normally used (0.62 - 1.00mm) is also considerably greater than the quenching distances that would correspond to the temperature and pressure at the time of ignition in an engine and so quenching of the flame kernel by the electrodes is unlikely. Soltau (ref 30) has, in fact, reported successful operation of a single cylinder, variable compression ratio engine using a spark of energy 0.2 millijoules, provided the spark gap was greater than the quenching distance. Conditions encountered in a multi-cylinder engine are, however, far from ideal, particularly when idling and on overrun. Under these conditions, there is considerable dilution of the fresh charge by residual exhaust gases retained in the chamber, and the pressures reached on compression are reduced because of the throttling of the intake. Higher energies are essential for reliable operation under these conditions.

It has proved very difficult to measure the energy released in a spark discharge accurately, particularly on an engine, although Steiner and Mirsky (ref 13) seem to have developed a suitable system for measuring such energies. This difficulty has led to more attention being paid to the effect the duration has on the performance of the engine. Teasel and Miller (ref. 27) have reported the effect

of various ignition systems on the operation of a V-8, 5.2 lt engine in some detail. The systems gave spark durations varying from 12-3000 micro secs, and the effects that these had are shown in figs. 14 a & b. The conditions of the tests were operation at 1200 rpm. and a load of 7.5kW at the specified spark advance and fuel setting. It can be seen that at 0.072 fuel/air ratio the ignition system used has no effect on the performance at the specified spark advance and when retarded. When advanced, however, the long duration discharge shows much less sensitivity to spark advance than the shorter discharges. At 0.061 fuel/air ratio and the same throttle opening, the difference is even more noticeable. The 12 microsec. spark showed considerably less power output than any other system as well as a shift to retarded ignition for optimum output. Once again the longer the spark duration the less sensitive was the engine to the exact spark timing. It must be pointed out that at a speed of 1200 rpm. the spark of 3 millisec. duration occupies 21.6° of crankangle, and the exact timing of the instant of ignition is undetermined particularly if the tail of the spark is important in the initiating process. The effect of a long duration discharge is further supported by some work reported by Ball (ref 31). The engine used was of single cylinder, variable compression design and was operated at 2000 rpm. and light load. Again it was reported that it was possible to operate the engine satisfactorily at weak mixtures without misfire by using a longer discharge spark. As the compression ratio was raised from 7:1 to 11:1 however, the engine became more tolerant to a very short duration spark, even at 16:1 air/fuel ratios. The effect of short duration sparks could be made to approach the performance of a full discharge, however, by connecting a large capacitor (1000 picofarads) in parallel with the plug, but maintaining the duration of the discharge at 2 microsec. This would suggest that some caution is required in stressing the importance of the tail of a spark and that

if sufficient energy is supplied in the short duration sparks the ignition can be just as reliable.

Kugami and Saki (ref 32) have performed some experiments in quiescent propane/air mixtures using very high energy sparks (up to 8 joules) and different electrode configurations. They were interested in reducing the time taken for the flame to accelerate to its normal flame speed because in ultra high speed engines (20,000 rpm.) the time available is very short and the period τ_i , as defined in fig. 12 must be made as short as possible. The most effective way of doing this was to use a very high energy spark which produced a large volume of hot gas extending far beyond the spark gap.

4.3 Location and number of spark gaps.

In modern overhead valve engines, the location of the spark plug invariably takes second place to the location of the valves. Ideally, ignition should be as near to the centre of the combustion chamber as possible, thus ensuring the minimum distance for the flame to travel. With a conventional spark plug, however, the ignition point is always close to the wall of the chamber, and the actual location is usually a compromise between the minimum distance for flame travel and a position which allows good scavenging of the spark gap by the fresh incoming mixture. This has been improved slightly by the use of a projected nose plug, which locates the ignition point approximately 5.0mm away from the wall of the chamber. The effect that this has on the fuel consumption and unburnt hydrocarbons has been reported by Teasel and Miller (ref. 27). In comparing the performance of a retracted gap plug and a projected gap plug they found an improvement of up to 9% in the fuel consumption at 30mph with the latter plug fitted, but at higher speeds the consumption was only improved by 2%. A possible explanation for this improvement is the reduced time required for combustion, which would lead to reduced

heat loss from the process, particularly at the slower speeds. A small reduction in the unburned hydrocarbon was also noted from 300ppm. to 277ppm. on one car and from 269ppm. to 245ppm. on another.

Multiple spark ignition has found application in special circumstances where extra reliability or reduced flame travel time are of more importance than the extra cost and weight. Teasel (ref.33) has expressed the opinion that dual ignition is only suitable for chambers specially designed to operate in that mode and that addition of extra ignition sources to an existing design makes an insignificant difference to its performance. An investigation by G. de Castelet (ref. 34) on the effect of dual ignition on hydrocarbon emissions from a single cylinder engine showed that at some speeds they could be increased above those recorded from the same engine under the same operating conditions, but using a single ignition source. He concluded that this was not necessarily true for other designs of combustion chamber.

4.4 Spark gap width and electrode diameter

The effect that the spark gap and centre electrode dimension have on the performance of a petrol engine has also been reported in Teasel and Miller's paper. Again using a 5.2 lt V.8 engine operating at light load they observed that with a 0.75 mm gap the brake specific fuel consumption increased linearly by 7% as the electrode diameter was doubled but at 0.89 and 1.00 mm the b.s.f.c. was less sensitive to electrode diameter, increasing only when the electrode diameter approached three times the gap spacing. Since the energies dissipated in the spark and the gap widths themselves are very much larger than the energies and gaps used in Lewis and vonElbe's classical work (ref. 35) on the quenching of flame kernels, it would appear that quenching of the flame kernel itself, under ideal conditions is unlikely. However, under the

conditions of light load, it is possible that with a 0.030 ins. gap there is insufficient penetration of the new fuel/air charge into the gap spacing and a large centre electrode would tend to shield the gap area as well, the result being occasional misfires and an increased fuel consumption. Under light load conditions, therefore, it appears to be advantageous to have as large a gap as possible, although this unfortunately imposes a greater stress on the ignition system under conditions of maximum power output.

4.5 Cyclic Dispersion and Ignition

A phenomenon which has received considerable attention recently is that of cyclic dispersion in automotive engines. This is characterised by variations in the pressure/crank angle diagram from one cycle to the next under what are nominally the same conditions. Various parameters may be chosen to represent these variations from cycle to cycle, including the maximum pressure reached, the pressure reached at a specific crank angle, the time taken for the flame to pass between ionisation gaps and the rate of pressure rise. For a large number of cycles all of these parameters show a spread of values around a mean value, but the last two parameters are the most useful as they are directly related to the rate of flame propagation across the chamber. Patterson (ref. 36) has pointed out that for a given spread of, say, 138 kN/m^2 per degree of crank angle in the rate of pressure rise, the percentage variation in pressure and indicated mean effective pressures (imep) are considerably less for a fast burning mixture (mean pressure rise rate approximately 345 kN/m^2 per degree of crank angle) than for a slow burning mixture (mean pressure rise rate approximately 172 kN/m^2 per degree of crank angle).

Any change, therefore, which increases the mean pressure rise rate would appear to reduce the problem of cyclic dispersion, even though the basic combustion problem remains. Thus, the

introduction of multiple spark ignition or a controlled amount of turbulence, by using shrouded valves, would appear to reduce the percentage cyclic dispersion, as reported by Soltau (ref. 30), without necessarily reducing the absolute amount of dispersion in terms of the rate of pressure rise variation.

The desirability of reducing the amount of dispersion in both percentage and absolute terms arises not so much from any increase in the maximum performance of the engine but from a need to improve the smoothness of operation of the engine and make it less demanding on the quality of the fuel it requires. The fastest burning cycles impose a limit on the minimum octane rating of the fuel that can be used to provide knock free operation of the engine: this is because the fastest burning cycles will impose more rapid compression of the end gases in the chamber, which will consequently reach a higher temperature and will be more susceptible to spontaneous or knocking combustion. The overall effect of the variations is to make the engine appear rough in operation because of the variations in torque output.

A further stimulus for the reduction of the effects of cyclic dispersion has come from the desire to operate engines on weak mixtures over at least part of their range in order to reduce unburned hydrocarbon and carbon monoxide emissions to comply with legislation against air pollution by vehicle exhaust products. All investigations have shown that the problem of percentage cyclic dispersion becomes worse as the mixture is weakened, mainly because the flame speed and, therefore, the rate of flame propagation is reduced. However, Patterson (ref. 36) reported that by fitting shrouded valves to a production engine, the road load rate of pressure rise was doubled and allowed a reduction of one air/fuel ratio before the engine became objectionably rough. Nevertheless, these valves had no effect on the absolute amount of dispersion.

After careful elimination of variations in mixture ratio and ignition timing both Soltau and Patterson reported that altering the ignition characteristics had no effect on the absolute amount of dispersion. Soltau varied the ignition energy from 0.2 to 200 millijoules and Patterson from 41 to 140 millijoules, both using conventional spark plugs. In his summary, however, Patterson concludes that "the major cause of cyclic combustion rate variation is the mixture velocity variation that exists within the cylinder near the spark plug at ignition".

His justification for this conclusion arises from the negligible effect that increased swirl, or gross turbulence, has on the absolute dispersion.

A possible velocity distribution within a combustion chamber is shown in (fig. 15(a) where a swirling air motion induced by the inlet valve has a small scale random velocity distribution superimposed on it. This could be induced by vortex shedding from the inlet valve. At the chamber walls the velocity is of necessity zero and there is a considerable velocity gradient close to the walls. A flame kernel spreading from the ignition point close to the wall is subjected to a shearing force as the velocity of the gases increases away from the wall (fig. 15(b)). This has the effect of distending the flame kernel in the direction of motion of the gases and increases the area of contact the flame has with the unburnt gases ahead of it. The effect of local gas velocity variations would be to wrinkle the flame surface and this, combined with the shape caused by swirl, would increase the total flame front area. This increases the area over which the combustion reactions occur and accelerates the burning of the charge. The propagation of a flame from an ignition source close to the wall of the chamber will be subjected, therefore, to a very random process. In the initial stages of flame propagation the random

component is likely to be proportionally greater than in subsequent stages when the swirl component has increased due to the velocity gradient and consequently the disturbance to the flame front is of more significance in determining its speed of propagation during the initial stages.

In a paper by Land (ref. 37) an interesting qualitative comparison of the performance of three types of engine is given, with particular reference to the cyclic dispersion of each. He compares the diesel engine with the spark ignited gas engine and the diesel fuel ignited gas engine. Undoubtedly the worst offender as regards dispersion is the spark ignited gas engine, with the diesel engine being the most consistent and the diesel ignited gas engine falling between the two. Of course, the combustion processes in a diesel and a gas engine are very different: the diesel fuel spray is induced to ignite at a very large number of points simultaneously, whereas the spark ignited engine has only one or two points from which combustion propagates throughout the chamber. The intermediate case of a pilot fuel spray of 3-5% of the total fuel being injected into the gaseous reactant causes ignition over a much larger volume of gas than is possible with conventional spark ignition and overcomes the critical period of kernel development when the flame is most susceptible to the random variations in local flow velocity. A direct comparison of the same engine, operating in both spark ignition and pilot fuel injection modes, showed that the latter produced the same degree of cyclic dispersion when working on mixtures as weak as 0.56 of stoichiometric as the former did when using stoichiometric mixtures and produced only half the dispersion of the spark ignition engine at the same fuel/air ratio.

From these investigations it appears that the problem of dispersion can be reduced by two possible means, or a combination

of them both. It has been shown that increasing the mean rate of pressure rise by introducing swirl into the chamber will reduce the proportion of cyclic dispersion. This does not necessarily reduce the absolute amount of dispersion. A possible way of reducing this is by altering the ignition process from a single point source to a much larger volume of hot gas, as in the oil ignited gas engine. The pressure rise rate is then controlled by the motion of the main fuel/air mixture but the combustion process is started over a larger volume so that the flame kernel development is relatively unaffected by the small variations in local turbulence close to the ignition source.

4.6 Spark Characteristics and Exhaust Emissions

The pressure of legislation to reduce the pollution caused by the petrol engine has led to investigations into the effect that spark characteristics have on the proportions of hydro-carbons and oxides of nitrogen that are present in exhaust gases under various operating conditions. A comprehensive study of these aspects has been reported by Lentz, Miller and Cadmus (ref. 38): they studied the effect of discharges lasting from $20\ \mu\text{s}$ to $1000\ \mu\text{s}$ and gap width from 0.635 mm (0.025") to 1.14 mm (0.045"). Their conclusions stated that "Reduced emission and fuel consumption can be realised with wide gap spacings and longer spark durations up to a certain minimum level (of emissions and fuel consumption) required for consistent ignition". The reason for the improved performance of the longer spark in both space and time is attributed primarily to the increased chance of having a combustible mixture between the electrodes. This is particularly important as the fuel/air ratio is made weaker. However, long duration sparks have the disadvantage of lending some uncertainty to the actual time of ignition. A spark of 1 ms duration at 3000 rpm would correspond to 18 degrees of crank angle. The actual time of ignition would consequently be in some doubt and would depend on the degree of mixing and purging that

takes place between the electrode gap. This would add further to absolute cyclic dispersion observed in the engine.

However, a shorter duration spark, with a larger volume and area of contact with the combustible mixture would overcome both the above problems. The uncertainty of the timing of ignition would be reduced and chances of encountering a suitable mixture of fuel and air would be increased considerably.

4.7 Ignition in the Jet Engine

The open cycle gas turbine has considerably different ignition problems than does the reciprocating spark ignition engine. Further problems are imposed in the application of the gas turbine as a jet engine for aircraft, where minimum weight and volume are important criteria applied to the design of combustion chambers. Of course, combustion is a continuous process which should require initiating only once but, for safety reasons, the igniter has to be capable of re-igniting the fuel/air mixture should a flame-out occur. For this reason the igniter is used in a continuous pulsed mode on take-off and landing and when encountering climatic conditions that might cause a flame-out.

The positioning of the igniter in the combustion chamber has to be a compromise of several conflicting requirements. Because of the continuous combustion process the fuel spray into the chamber must be prevented from approaching the walls of the chamber to avoid overheating them. Usually the main combustion can be provided with secondary air cooling to prevent it from overheating and the igniter needs to be similarly cooled. It is not possible to project the face of the igniter into the chamber significantly and, consequently, some method of projecting the igniting spark into the chamber has to be used. This is currently achieved by a very high energy discharge, typically 8-12 joules, of stored energy. This produces a large surface area discharge over the end of the igniter but penetration of the discharge into the chamber is still

not very great for the energy used.

4.8 Summary

There appears to be a need in both the petrol and the jet engines for an igniter which can satisfy the requirement of the respective engines. The petrol engine requires a short duration discharge ($<1000\mu s$) which has a large area of contact with the combustible fuel/air mixture. The jet engine requires a discharge which can be projected into the combustion chamber from a position flush with the wall so that the igniter can be cooled while the discharge can reach the fuel/air mixture nearer the centre of the chamber. The work described in the following sections relates to the development and testing of ignition devices to achieve these aims.

CHAPTER FIVE

IGNITION DEVICES FOR INVESTIGATION

Two ignition devices were devised which would satisfy the desired requirements. These were a laser generated spark and a plasma jet igniter. For comparison purposes a third method of ignition was investigated using a variable energy electrical spark between a pair of pointed electrodes.

5.1 The Laser Generated Spark

The first reported observation of the breakdown of a gas using a focused laser beam was by Meyenard and Haught (ref. 39). They used a 30 MW 'Q' switched ruby laser, producing a single pulse with an energy of approximately 1 joule. The focused spot had a diameter of 2×10^{-4} m and breakdowns in both helium and argon were recorded using a photomultiplier. Since then, many investigations have been made of the properties of the ionised plasma produced. Pashinin et al (ref. 40) took high speed photographs of the developing plasma from a 50 MW peak power ruby laser using 30, 75 and 210 mm lenses.

The plasma developed in the first $3-5 \mu$ s to lengths of 10-15 mm and a diameter of 5 mm, collapsing in size and brightness in a further $30-40 \mu$ s. Using a calorimeter they also observed that 60% of the energy was absorbed by the growing plasma, the rest being transmitted or scattered. More recent investigations by Basov et al (ref. 41), Evans and Morgan (ref. 42) and Weinberg and Wilson (ref. 43) have shown that it is possible to have multiple breakdown centres occurring with one laser pulse. These can be contained within the overall plasma developed when short focal length lenses are used forming a cylindrical rather than spherical discharge. When peak powers of approximately 1GW are used, however, it is possible to produce a number of discrete sparks by using a 2.5 m focal length over a distance of 0.25 m

on either side of the focus (ref. 41). Streak photographs showed that after the initial spark at the focus the discharges spread both towards and away from the lens.

A typical pulse from a 'Q' switched laser has the power/time curve shown in Fig.16. As the power in the beam builds up, the gas through which it is passing is initially transparent. When a certain energy level is reached, typically $10^{12} - 10^{13} \text{ W/mm}^2$ (ref. 44), the gas begins to absorb the energy and the plasma forms and expands. In the absence of any free electrons in the gas, the initial step in the formation of the plasma is one of multiphoton absorption by the atoms which are raised to an excited state and may release an electron. The presence of free electrons then leads to a cascade process as the electrons are accelerated in the intense electro-magnetic field of the laser beam and the plasma continues to absorb the laser beam, expanding as it does so. There is then a minimum energy density threshold, below which a spark cannot be produced if no free electrons are present.

Mink (ref. 45) has shown that as the pressure is increased from 1 to 100 atmospheres the minimum energy required to produce a spark decreases by a factor of 5.

The energy densities that can be achieved are determined by the divergence (θ) of the laser beam and the focal length (f) of the lens. The focal spot diameter (d) is given by:

$$d = f \theta$$

The mean energy density at the focal spot E_f is given by:

$$E_f = 4E_0 / \pi f^2 \theta^2$$

where E_0 is energy in the laser beam.

For high energy densities at modest laser energies a short focal length lens is required.

5.2 The Laser Spark as an Ignition Source

The intense plasma produced by a focussed laser beam offers several advantages as an ignition source. The deposition of energy is very rapid and takes place in a small volume which rapidly expands to a cylindrical plasma, having a high surface area/unit volume, thus giving good thermal contact with the combustible gases. Because the laser spark is produced at the focus of a lens, there are no electrodes in the vicinity of the expanding flame kernel (fig. 18). Electrodes can conduct away a considerable quantity of the heat generated in the flame kernel and under adverse conditions of weak mixture cause complete quenching of the flame.

Lee and Knystautas (ref. 46) and Weinberg and Wilson (ref. 43) have made use of some of these advantages in their work on ignition. Weinberg and Wilson were interested in the minimum energies required for igniting mixtures of methane/air at pressures below atmospheric, whereas Lee and Knystautas investigated the initiation of spherical detonation waves and the coupling and decoupling of shock wave and flame front according to the energy of the ignition source. Weinberg and Wilson also observed detonation waves in methane/air mixtures at energies of about 100 millijoules and at pressures of 53.2 kN/m^2 absolute and greater. This could be a severe limitation on the use of the laser spark as an ignition source because detonation waves can be very destructive and under most circumstances should be avoided.

As a practical method of ignition the main disadvantage of the laser spark is the high peak powers required for the reliable production of a spark. The only lasers which are capable of producing high enough peak powers are 'Q' switched solid state lasers with optical pumping. These are very inefficient devices, giving at best only a 0.5% transfer of stored electrical energy to light

energy developed in the laser beam. This limits the repetition rate of the laser as any increase in temperature of the laser rod increases the threshold level for lasing action. Repetition rates in excess of ten per hour will require a deionised water cooling system, whereas above that air cooling can be effective in keeping the laser rod sufficiently cool for repeatable operation. Nevertheless, the development of the laser is still going on and it is not inconceivable that the efficiency can be improved and high peak powers achieved using other techniques. The laser spark in many ways approaches an ideal ignition source and an investigation of its ability to ignite combustible mixtures is appropriate, if only to compare it with more practicable methods that can be used at present.

5.3 The Plasma Jet Igniter

The initial idea for the plasma jet igniter arose from development work carried out by F.J. Atkins on plasma spraying (ref. 47). This technique employs the energy released in an electric arc to heat a gas in a confined space and expand the plasma through an orifice as a jet. Powders introduced into the plasma are melted and can be sprayed by the jet on to an object, giving it a coating of the powder material. The plasma spray gun operates with a small flow of gas, usually argon or argon plus hydrogen, introduced into the electrode gap. This determines the temperature and energy content of the plasma jet and provides suitable conditions for spraying. The plasma is hot enough to be able to spray ceramics and other very high melting point materials.

Normally the plasma spray operates continuously but, for adaptation to an ignition device, it would need to be operated in a pulsed mode. The gas flow would be an unnecessary complication for an ignition device and largely irrelevant as it is only used to get the correct spraying conditions for the particular material involved.

The plasma jet igniter, as conceived, is shown in Fig.17 and is covered by British Patent Application No. 53,252/71. Two main electrodes have an applied voltage across them, which is supplied by an external power supply and the energy associated with the voltage is stored in a bank of capacitors. A trigger electrode is introduced behind the two main electrodes and is connected by a spark gap to a conventional car ignition coil operated by a contact breaker system. The production of a low energy spark from the trigger electrode to either of the main electrodes causes breakdown of the main gap. The arc produced heats the gas in the confined space between the main electrodes and trigger electrode and causes it to expand through the orifice of the igniter as a jet of hot ionised gas. This comes into contact with combustible mixture over the whole trajectory of the jet and thereby acts as a large surface area igniter.

As a crude analysis, consider a quantity of energy, E , released into a volume, V , of gas: the expansion of the gas, ΔV , at constant pressure will be related to the temperature rise, ΔT , according to:

$$\frac{\Delta V}{V} = \frac{\Delta T}{T}$$

where T is the absolute temperature of the gas.

The temperature rise of the gas is given by:

$$\Delta T = \frac{E}{p V C_p}$$

where p is the initial density of the gas and C_p is the mean specific heat of the gas over the temperature rise involved.

Thus, eliminating ΔT from the above equations:

$$\Delta V = \frac{E}{p C_p T}$$

Ignoring heat losses, the expansion of the gas is therefore independent of the volume of chamber into which the energy is

released. However, the heating effect of an arc is very localised and a chamber volume that was large compared with that of the plasma would have the effect of expanding a relatively cold portion of gas out of the chamber. The chamber must, therefore, be of such a volume that the plasma can heat the gas that is enclosed, thereby expanding the plasma and hot gas out of the orifice of the chamber.

5.4 The Electrode Spark

For comparison purposes a conventional electrode spark was also used as an ignition source. This type of spark has been investigated as an ignition source since the beginning of the century and its operating characteristics are well documented (ref. 35). However, as the laser spark and the plasma jet were used at several energies, the opportunity was taken to use several spark energies released between the points of the electrodes. This gave a further basis for comparison of the effectiveness of the energy release of the three ignition methods.

CHAPTER SIX

DESIGN OF EXPERIMENTS AND EQUIPMENT

The two methods of ignition proposed were undeveloped as ignition devices. Consequently, it was necessary to have a relatively simple combustion system which was flexible enough to accommodate both methods. The novelty of these devices also required that some standard ignition method be used so that the new devices could be compared with a standard method under as near identical conditions as possible. A spark between a pair of pointed electrodes was chosen to represent the standard ignition source.

The purpose of the ignition devices was to provide a large surface area of contact between the source and combustible mixture, thereby creating a large expanding flame kernel in as short a time as possible. The most suitable technique for evaluating the relative merits of the ignition methods was to record the movement of the flame front from the ignition source. This was to be supplemented by an analysis of combustion products to see the effect on the efficiency of combustion. In order to enable a relatively simple gas analysis to be performed, methane/air mixtures were used as the combustible gases at mixture ratios from stoichiometric to the weak limit for combustion. This would simulate the effect of weakening mixtures for maximum economy and reduced exhaust pollution in the spark ignition engine and the uncertain conditions of mixture ratio in the vicinity of the igniter during the starting sequence of a jet engine. The pressures involved in both these applications would be considerably greater than atmospheric pressure and a range of pressures for the investigation of 101 kN/m^2 to 1067 kN/m^2 (1 to 10 atmospheres approximately) was chosen to simulate the operating conditions that would be normally encountered.

6.1 Mixture Preparation Equipment

The combustible mixture was pre-mixed and stored in a steel

pressure vessel for subsequent use in one series of experiments. The mixing equipment and vessel are shown in Fig. 21 and diagrammatically in Fig. 19. The gases used were 99% purity methane and a dry air mixture of 79% nitrogen and 21% oxygen. These were mixed by the method of partial pressures to a final pressure of 1480 kN/m^2 at ambient temperature.

For the measurement of the partial pressure of the methane a 1.6 m mercury manometer was used and the final pressure was measured on a 0-2070 kN/m^2 standard test gauge, calibrated to an accuracy of 1% of full scale deflection. By this method, the accuracy of the mixture preparation was limited by the accuracy of the methane and nitrogen/oxygen mixtures. However, for one series of experiments the same preparation could be used throughout and the repeatability of the mixture preparation for subsequent series was possible to $\pm 1.5\%$ of the desired mixture. Good mixing was assured by having rotating vanes inside the pressure vessel and also by having a small heater underneath the vessel which would provide a constant convection current in the gas to keep it stirred without increasing the bulk temperature of the gas significantly. From the mixture vessel the gases were piped to the combustion chamber through a stainless steel valve. The pressure in the chamber was measured on a standard test gauge. A rotary vacuum pump was used to evacuate the mixture storage vessel and lines prior to mixing and also to evacuate the combustion chamber before admission of the mixture. The pressure was always reduced to less than 0.133 kN/m^2 (1 mm Hg) before any mixing or filling operations were undertaken.

6.2 Combustion Chamber

The combustion chamber was designed for operation at peak pressures of $10,440 \text{ kN/m}^2$. Its main components were a stainless steel cylinder of 63.5 mm internal diameter and 63.5 mm long and

a pair of circular end plates of stainless steel, sealed to the cylinder by Klingerit asbestos gasket material. Eight bolts were used to clamp the whole chamber together. One end plate has a stainless steel throttling valve screwed into it and connected to the inside of the chamber by a 0.79 mm diameter hole. The valve itself has an insert pressed into its outlet which also has a 0.79 mm hole drilled into it. This made the dead volume of gas in the valve as small as was practical, allowing a reasonable time for filling and evacuating through a small aperture. At the centre of the other end plate there is a 12.7 mm diameter aperture which can take either a 12 mm thick quartz disc and plano-convex lens for laser ignition experiments or the plasma jet igniter. Both these devices could be inserted so that their end faces were only 1.6 mm recessed from the internal face of the end plate. The assembled chamber is shown in Fig. 8²² and diagrammatically in Fig. 7.²⁰

In order to study the movement of the flame front in the combustion chamber, ionisation probes (see fig.23) were introduced through the cylindrical part of the chamber. These were constructed from two 0.25 mm diameter tungsten wires sealed into a ceramic bead, which was cemented into a stainless steel holder using Fortafix ceramic adhesive. The gap between the wires was approximately 1 mm and they extended to the centre line of the combustion chamber, as shown in Fig.20. There were facilities for introducing up to six of these probes, but normally only four were used in an experiment, the other two holes being blanked off with an undrilled stainless steel holder.

Copper washers were used to seal the probe holders and blanks into the chamber and care was taken to fill any gaps between the body and holder with ceramic cement to avoid trapped pockets of combustible gas.

The circuit for operation of these ionisation probes is shown

in Fig. 24. A 10 M Ω resistor was placed in series with the probe and 120 V applied across them from a stabilised D.C. power supply. The output from the probes was taken across the resistor and displayed on a Tektronix 541A or 551 oscilloscope. When four probes were used a four trace plug-in unit was used to simultaneously display the outputs. The output from the probes varied according to the fuel/air mixture used but was usually displayed on 2V/cm or 5V/cm scale, dropping to 0.5V/cm when very weak mixtures were used. This gave a rapidly rising voltage trace for accurate timing of the arrival of the flame front.

In the planes at 45° and 135° to that of the ionisation probes, pairs of electrodes could be introduced from opposite sides of the chamber in the positions shown in Fig.20. This facility was required for testing the performance of electrode sparks for comparison with the other ignition methods. When using laser or plasma jet ignition these could be blanked off with 10 mm spark plugs having a stainless steel cap welded on to the electrode end. Copper washers were again used for sealing and any gaps between the body and plugs were filled with ceramic cement.

6.3 Gas Analysis Equipment

The analysis required was for carbon dioxide, carbon monoxide, oxygen and methane in a dry sample. The most suitable technique for the small samples that would be available was gas chromatography. A Pye-Unicam unit was used (Series 104) for this purpose, with both katharometer and flame ionisation detectors in use simultaneously. The katharometer detector would record all four gases required but the sensitivity of methane detection was not sufficient to record down to the 100 v.p.m. that would be required. The flame ionisation detector was capable of recording this with 5 v.p.m. accuracy. The gas chromatography equipment is shown in Fig.26 and a flow diagram for the gases is shown in Fig.27.

A helium flow of 60 ml/min was used in two columns, one 0.3 m of 80-100 mesh silica gel and the other 2.7 m of 80-100 mesh No.5A molecular sieve. Both columns were enclosed in an oven at a regulated temperature of 353 K and the katharometer maintained at a temperature of 423 K.

The silica gel column separated the carbon dioxide from the other components and the molecular sieve gave separation of oxygen, nitrogen, methane and carbon monoxide in that order. The carbon dioxide had to be prevented from entering the molecular sieve column because it would be permanently retained at the operating temperature of 353 K. Consequently, when the carbon dioxide had been retarded on the silica gel column and the others had reached the molecular sieve column, the latter was isolated and the helium carrier gas passed directly to the detectors. When the carbon dioxide had been recorded, the molecular sieve was reintroduced into the helium line and the other components were recorded. The optimum timing of the isolation of the molecular sieve column was found to be 50 s after the initial sample injection.

Calibration of the chromatograph was performed by the injection of premixed samples of gas mixture of known composition, supplied by B.O.C. Ltd. The range of experimental samples was fully covered by the standards and intermediate calibration points were obtained by diluting the master standard with oxygen-free nitrogen to the desired proportion using the gas mixing equipment used for preparing combustion gases. High proportions of oxygen in experimental samples were standardised by diluting the 79% nitrogen 21% oxygen mixture using the same technique.

CHAPTER SEVEN

LASER IGNITION EXPERIMENTS

7.1 Laser Equipment

The laser system used was designed and built by S.H. Khan and is fully described in Ref.48, from which Fig.28 is extracted. It used a ruby crystal, 9.5 mm diameter and 152 mm long, mounted at one focus of a polished aluminium elliptical cavity. Optical pumping was by a xenon flash tube mounted at the other focus. The energy for the flash tube was stored in a bank of capacitors of $1700\ \mu\text{F}$ at voltages up to 2.5 kV. The 'Q' switching to give a single pulse was performed by a cryptocyanine cell and the maximum power output was a 12 MW pulse with a 20 ns half width. Control of the power output was best achieved by 'stopping' the laser beam with removable apertures. The power output from the beam was not reproduceable to better than 20% and consequently measurements of the power and energy were necessary for each pulse. Khan developed an absolute measurement of laser power and energy using an aligned ammonium dihydrogen phosphate (ADP) crystal. This gives a power/time trace which can be displayed on a Tektronix 551 oscilloscope and recorded using 10,000 ASA Type 410 Polaroid film. Checks made by Khan against a carbon cone calorimeter and a proprietary instrument indicated an accuracy of 10% for the meter; unfortunately, this power meter could not be used simultaneously with combustion experiment because the ADP crystal absorbed some of the laser energy and also had a frequency doubling effect on the transmitted light.

It was necessary, therefore, to use an E G & G integrating photodiode (Lite Mike) to monitor the energy and a fast response photodiode for the power. These were calibrated against the ADP meter. They were operated in fixed positions relative to a diffusing screen on to which approximately 8% of the laser beam energy was directed using a beam splitter.

The combustion chamber was mounted on a tripod table, shown in Fig.31. This enabled the chamber to be aligned accurately in vertical and horizontal planes with the laser beam and by using the telescope for aligning the mirrors of the laser, it was possible to get the quartz disc faces in the combustion chamber aligned parallel to the laser mirrors. This ensured that the laser spark was generated along the axis of the chamber.

A 25 mm focal length plano-convex lens was used for all the experiments. Initially the intention was that the lens should be mounted outside the chamber and the 12 mm thick quartz pressure disc should act as a window to the chamber. However, at the maximum output of the laser beam, damage occurred inside the lens and appeared in the form of localised shattering. This was caused by an internal reflection from the inside face of the quartz disc being focussed within the lens and causing the damage at the focus (fig. 29). This was remedied by mounting the lens on the inside of the quartz disc, as shown in Fig.30. This subjected it to the force of the combustion pressure but a support was made for the lens so that only the aperture required for the laser beam was left. The quartz disc was still used as a window but would only be subjected to combustion pressure if the lens failed.

7.2 Laser Spark Energy

In order to measure the energy that was absorbed by the laser beam when a spark occurred, a perspex chamber and another end plate were made for use at pressures up to 1067 kN/m^2 (fig. 31). The brass end plate had another lens mounted in it which could be adjusted axially so that the emerging laser beam was parallel and could be monitored for energy output using either the ADP meter, the Lite Mike or a photodiode. The arrangement is shown in Fig. 32. Because of the losses associated with reflections at each interface between gas and glass, it was also necessary to do some measurements of the energies transmitted without the formation of a spark.

Identical lenses were used in each end plate of the chamber and it was assumed that the losses would be identical.

Consider the energy transmission after each component shown in Fig.32. If the initial energy in the laser beam is E_0 and the subsequent energies after the quartz disc, first and second lens are E_1 , E_2 and E_3 respectively when no spark occurs, then the overall energy loss ratio is:

$$e_3 = \frac{E_3}{E_0} = \frac{E_3}{E_2} \cdot \frac{E_2}{E_1} \cdot \frac{E_1}{E_0} \quad (1)$$

$$\text{If } \frac{E_3}{E_2} = \frac{E_2}{E_1} = e_{21} \text{ and } \frac{E_1}{E_0} = e_1$$

$$\text{then } e_3 = e_{21}^2 e_1$$

$$\text{and } e_{21} = \left(\frac{e_3}{e_1} \right)^{\frac{1}{2}} \quad (2)$$

The following experiments were performed to establish values for e_3 and e_1 , using the Lite Mike to measure E_0 and an integrating photodiode to measure E_1 and E_3 :

- (i) No lenses or quartz disc present: this calibrated the photodiode against the Lite Mike, both measuring E_0 .
- (ii) Only the quartz disc present, mounted in an end plate: this measured the energy ratio e_1 .
- (iii) Complete unit with quartz disc and lenses inserted; the chamber was evacuated so that no spark would occur: this measured the energy ratio e_3 .

The results of these measurements are shown in Fig. 33, plotted as Lite Mike voltage against photodiode voltage. From this graph, $e_1 = 0.835$ and $e_3 = 0.715$.

$$\text{From equation (2) } e_{21} = \left[\frac{0.715}{0.835} \right]^{\frac{1}{2}} = 0.926$$

$$\begin{aligned} \text{The laser beam energy in chamber } E_2 &= e_{21} e_1 E_0 \\ &= 0.773 E_0 \end{aligned}$$

For a recorded transmitted energy, E_3' , when a spark occurs, the energy transmitted before the spark forms:

$$E_2' = \frac{E_3'}{0.21} = 1.08 E_3'$$

The energy deposited in the spark is given by:

$$E_s = E_2 - E_2'$$

or

$$E_s = 0.773 E_0 - 1.08 E_3' \quad (3)$$

Measurements were made of beam energy before the chamber E_0 and at exit from the chamber E_3' when laser sparks were produced in air at pressures of 101, 239, 515, 790 and 1067 kN/m². Fig. 34 shows the relationship between laser beam energy E_0 and the spark energy E_s for the above pressures and it can be seen that the relationship is linear with no effect from the pressures used.

A least square fit for the data gives the following relationship:

$$E_s = 0.744 E_0 - 53.7 \text{ mJ} \quad (4)$$

with a standard deviation of 25.3.

7.3 Experiments

Mixtures of 1.0, 0.8 and 0.6 of stoichiometric methane/dry air mixture were investigated at pressures of 101 to 1067 kN/m² in steps of 138 kN/m². The laser beam energy varied from 100 to 750 mJ and was monitored for each experiment. The output from the Lite Mike was recorded on a storage oscilloscope, while the outputs from three ionisation probes were recorded on a Tektronix 551 oscilloscope and photographed using a Telford camera and Polaroid Type 47 film.

The combustion chamber was first evacuated to a pressure less than 0.13 kN/m² and then filled with the combustible mixture to the desired pressure. In order to allow the motion of the gas to die down, it was left for 5 minutes before firing the laser.

Immediately after combustion had taken place the valve on the chamber was rapidly opened and closed to the evacuated lines in order to dispose of any unburnt gases in the small volume before the valve seat. Five minutes after combustion had taken place a sample of the products was passed through a calcium sulphate drying tube and admitted to a 250 ml glass sampling tube which had been previously evacuated. After taking the sample, the rest of the products were removed from the chamber and it was re-evacuated. This also removed the water that condensed on the walls of the chamber.

For experiments conducted at pressures of 377 kN/m^2 and greater, the pressure in the chamber was always sufficient to fill the sampling tube to pressures above atmospheric. However, at 239 kN/m^2 and below, the pressures in the chamber and sampling tube equalised at a pressure below atmospheric. Oxygen-free nitrogen was introduced into the sampling tube to bring the pressure above atmospheric. The proportion of dilution was recorded by noting the pressures before and after dilution. The samples were then taken for sampling to the gas chromatograph.

After each series of experiments the position of the tips of the ionisation gaps were measured using a travelling microscope. The point midway between the two probe wires was taken as the position of the ionisation probe and this could be measured to within 0.10 mm. The focal point of the lens was also known by measurement to within 0.2 mm relative to the positions of the ionisation probes.

7.4 Results

The actual position of the ionisation probes could not be maintained from one series of experiments to the next and, consequently, a normalisation procedure was required to assess the effect that the laser had on the flame propagation. A typical

photographic record of the pulses from the ionisation gaps is shown in Fig. 35. The time taken for the flame to arrive at each ionisation probe was found by projecting the leading edge of the pulse to intersect the base line and measuring from the trigger pulse to this intersection. Graphs of time taken for the flame to reach the ionisation probe against position of the probe could then be plotted and the time taken for the flame to travel 10 mm and 20 mm from the ignition point were read from the graphs. The mean flame speed in the intervals 0-10 mm and 10-20 mm could be calculated; these values are plotted against laser spark energy in Figs. 36-41 for the mixtures and pressures investigated.

There is some scatter on the results obtained but the general trends can be observed in the relationship between spark energy, pressure and flame speed.

All the curves show a characteristic of methane/air mixtures in that the flame speed decreases as the mixture pressure increases under stagnant conditions. In the first ten millimetres of flame travel from the focus of the lens the flame speed shows an increase as the spark energy is increased, particularly at 1.0 and 0.6 stoichiometric mixtures, the effect being less marked at 0.8 stoichiometric mixtures. There are two noticeable exceptions to this - at 1.0 stoichiometric, 239 kN/m^2 (fig. 36) and at 0.8 stoichiometric, 101 kN/m^2 (fig. 38) - which show a decrease in flame speed as the energy is increased. The scatter on the points in Fig. 24 at 0.8 stoichiometric make it difficult to be sure of the effect that is being observed. If the lowest energy point at 101 kN/m^2 is regarded as a rogue then the other points show the same trend as all the other points in that figure. The same is not true of the 1.0 stoichiometric mixture at 239 kN/m^2 . This appears to be a very positive trend which is contrary to all the other observations at that mixture ratio. There is no obvious reason why this should be so and no explanation has been found

for this departure from the trend observed at all other pressures investigated. From the 0.6 stoichiometric mixture graph (fig. 40) it can be seen that ignition and combustion was achieved at all the pressures used, although at the high pressures the maximum spark energy that could be achieved from the laser was required. Between 10 mm and 20 mm from the focus of the lens the flame speed shows even less overall dependence on spark energy, although the largest increase in flame speed of 75% for a 60% increase in spark energy was observed in 0.6 stoichiometric mixtures at 101 kN/m^2 (fig. 41). This was the same as the increase observed in the flame speed in the first 10 mm of flame travel at the same mixture ratio and pressure. It appears that the effect of increasing spark energy on the flame speed in the first 10 mm of travel is greatest at pressures below 515 kN/m^2 and that the flame speed is relatively unaffected by the increasing spark energy in the second 10 mm of travel.

The results of the gas analysis were calculated as a percentage of the dry sample taken. A check was made on the accuracy of the analysis by a technique outlined in Appendix 1. From the proportions of CO_2 , CO , CH_4 and O_2 it was possible to calculate the initial mixture ratio of the products by two methods. If the mean values for one series of mixture ratios agreed with the known mixture to within 10%, the analysis was considered to be acceptable: this check proved useful in identifying errors in analysis caused by deteriorating columns and wrong switching times for the isolation of the molecular sieve columns.

The main components of interest as far as exhaust emission are concerned are unburnt methane and carbon monoxide. These are the components which indicate incomplete combustion. The carbon monoxide is formed as an intermediate component in the series of reactions leading to complete combustion but as the oxygen becomes depleted, the oxidation of the carbon monoxide cannot take place.

There was no carbon monoxide detectable in the 0.8 and 0.6 stoichiometric mixture products but in the 1.0 stoichiometric mixture there was a consistent quantity present which was independent of the laser energy used. The proportion increased from 0.86% at 101 kN/m^2 to 1.15% at 1067 kN/m^2 . The unburnt methane is associated with a quenching layer in contact with the chamber walls. Because of the large temperature difference between the flame and the chamber walls, the heat loss to the walls of the chamber is very large when the flame front approaches the wall. This loss of energy from the flame front to the walls causes quenching of the reactions and a layer of gas remains unburnt. On cooling, this layer of unburnt gas mixes with the other products of combustion. The convection currents set up as the gases cool rapidly in contact with the chamber walls assist the process considerably and a sample taken five minutes after combustion has taken place should be a representative of the mixture.

A graph of proportion of methane in combustion products against pressure is shown in Fig. 42 for the three mixture ratios investigated. At 1.0 and 0.8 stoichiometry the proportion of methane in the product was independent of the laser energy and showed little variation with pressure. The minimum proportion of methane for 1.0 stoichiometric mixtures was 150 v.p.m. at 653 kN/m^2 and it rose to a maximum of 290 v.p.m. at 101 kN/m^2 . There was more scatter on the results for 0.8 stoichiometric mixtures but there was a slight increase from 82 v.p.m. at 101 kN/m^2 to 102 v.p.m. at 1067 kN/m^2 . At 0.6 stoichiometry, however, the laser energy used has a large effect on the percentage of methane in the combustion products. This mixture is very close to the inflammability limit of methane/air and as the pressure of the mixture increases, the inflammability limit is passed through in the region $240\text{--}500 \text{ kN/m}^2$.

The percentage of methane rises from less than 0.1% at 240 kN/m² to 2.0% at 550 kN/m², indicating that the flame fails to propagate throughout the chamber at higher pressures. If the laser energy is increased, however, the flame is able to propagate further across the chamber before being extinguished. Thus, by increasing the laser spark energy to 150-200 mJ, the unburnt methane is kept below 0.1% up to a pressure of 500 kN/m² and only reaches 2.0% at pressures of 1050 kN/m². As the laser energy cannot be accurately controlled from one experiment to the next, the laser energy is shown in brackets against each point on the graph. The dashed lines indicate the effects of high and low energies.

CHAPTER EIGHT

PLASMA PLUG IGNITION DEVELOPMENT AND EXPERIMENTS

8.1 Initial Development

From the initial conception of the plasma jet igniter there was obviously a considerable amount of initial work required to prove that it would produce the expected jet of plasma. The first igniters made are shown in Fig. 43 and sectioned in Figs. 44 and 45. These were designed to ensure a compromise between the conflicting requirements of a minimum volume enclosed between the electrodes and the orifice and the provision of adequate insulation to avoid excessive tracking and breakdown between the electrodes. The problem of breakdown also dictated the voltage that could be applied to the main electrodes and it was found that 500 volts was the limit before tracking became a problem. The detailed design was adjusted as experience was gained in the operation of the first igniter. They were made to fit into the combustion chamber in the same position as the quartz disc and lens in the laser experiment. This enabled them to be tested under pressure without any additional equipment being made.

The main body of both these igniters was made from tufnol insulating material and the main electrodes were made from elkonite, a copper/tungsten sintered composite. This was expected to have good erosion resistance as the tungsten would act as a root for the arc to sit on and the copper would conduct away the heat generated at the electrode faces. The first electrodes were constructed as 90° sectors with a main electrode gap of approximately 0.80 mm. These were soldered to copper wires passed through the Tufnol. The electrodes were potted in epoxy resin (Araldite) to insulate them and seal them into the body. The Araldite also acted as insulation between the electrodes and a stainless steel disc placed across the end of the igniter. This had a 0.79 mm diameter hole at its centre

which acted as the orifice for the expanding plasma. The trigger electrode was a 1.6 mm diameter tungsten rod, machined to a point and introduced behind the main electrodes.

The electrical circuit used to supply the igniter is shown in Fig. 46. This consisted of a bank of 600 V paper capacitors which could be varied from $1\mu\text{F}$ to $21\mu\text{F}$ by making suitable connections. These were connected to the main electrodes by heavy copper braiding and supplied via a charging resistor from a 500 V, 500 mA D.C. power pack. The trigger electrode was connected to the high tension terminal of a car ignition coil operated from a 12 V accumulator and switch.

The first igniter operated successfully in air at atmospheric pressure and produced a jet of plasma 10 mm long and 2 mm in diameter at its tip when the maximum energy was supplied to it. The energy supplied to the electrodes had a significant effect, however, and at the minimum energy with $1\mu\text{F}$ capacity, the jet was hardly visible. Operating the igniter under pressure in the perspex chamber was more difficult. However, by adjustment of the trigger electrode gap and placing an external spark gap in series with the trigger electrode, it was possible to operate the igniter at pressures of 1067 kN/m^2 . At this pressure the consistency of operation was poor, mainly because it was not possible to adjust and maintain the gap setting of the trigger electrode. In testing this igniter the tufnol and araldite soon charred and eventually shorted out the main electrodes. The elkonite electrodes also showed erosion because of the small area over which the arc could operate.

The second igniter made was of a similar design (fig. 45) but with several modifications designed to overcome the failings of the previous system. Tufnol was still used as the main insulator but around the main electrodes and the trigger electrode a

machinable ceramic insulator (Ceramtec) was inserted. The electrodes were formed into small rectangular blocks, having a face area of 2.5 mm x 1.6 mm and again sealed into the body using Araldite. The Araldite was machined away until the faces of the electrodes and ceramic were exposed so that there was none in the vicinity of the arc. The orifice was also drilled in a 1.6 mm thick Ceramtec disc which fitted flush with the electrodes. The same trigger electrode was used but it was possible to hold it in position and adjust it using a threaded nylon bush.

This igniter operated successfully at pressures up to 1067 kN/m^2 after suitable adjustment of the trigger electrode gap and external gap. This was constructed from a perspex block with pointed tungsten electrodes mounted within it so that the spark gap was 10 mm. It has the effect of applying a very fast rise time voltage to the trigger electrode which helped the breakdown of the main gap. The plasma jet produced was similar to that produced by the first igniter and the variation of the jet size with pressure was not noticeable. The Ceramtec disc showed signs of cracking after some use but this was easy to replace.

With the successful operation of this igniter it was decided to make one which could be used for combustion experiments in the existing chamber. Some hot pressed silicon bar was obtained and an igniter body was machined from it (figs. 47 and 48). The electrodes were of the same size and configuration as used in the previous plug, except that the main gap was reduced to 0.38 mm to make positioning of the trigger electrode and size of external gap less critical. The orifice was maintained at 0.79 mm and was machined in a silicon disc. All the silicon pieces were nitrided and finally assembled. Sealing the main electrode wires was achieved by using a ceramic ^{cement} cermet and this also helped to retain both the electrodes and the silicon nitride segments on either side of the electrodes.

The disc was not permanently attached as inspection of the electrodes would be subsequently required. The trigger electrode was sealed into the body using an 'O' ring and was adjustable by a threaded nylon bush similar to that used in the previous igniter. This igniter was tested at pressures up to 1067 kN/m^2 and after suitable adjustment to the trigger electrode gap it operated successfully over the whole range of pressures without further adjustment.

8.2 Spark Energy Measurement

Although it was known what energy was stored in the capacitors from voltage measurements, it was necessary to make some measurements of the energy delivered at the electrodes for the purposes of comparison with other ignition sources. The method employed was to record simultaneously current and voltage traces and compute the energy released from integration of their product. The voltage across the main electrodes was measured using a Tektronix 600 V, 10x probe. The current was measured using a coaxial low inductance probe (figs. 49 and 50) of similar design to that used in Ref. 49. The resistance element was a 4.76 mm diameter stainless steel tube of 0.25 mm wall thickness and approximately 60 mm long. The ends were soldered to brass collars and the connection made to a B.N.C. socket soldered into one collar, using copper wire passed axially through the stainless steel tube and soldered into the opposite collar. The coaxial current return path was a 9.5 mm diameter brass tube, 0.4 mm wall thickness, spaced from the input end by a perspex collar. The resistance of the probe was measured using the circuit shown in Fig. 51. Currents of up to 2 A were passed through the probe and monitored using a 5 digit voltmeter across a standard 0.010Ω resistance box. The voltage generated across the probe was also measured on the same voltmeter. The mean D.C. resistance of the probe was $18.73 \text{ m}\Omega$.

The circuit used for measuring the voltage and current pulses when the igniter was operated is shown in Fig. 52 and typical recordings are shown in Fig. 53. The inductance of the probe was measured on a 'Q' meter as being $0.03 \mu\text{H}$ and from the traces it was apparent that the component of induced voltage due to the rapidly changing current was small compared with that from the resistance. The maximum rate of change of current occurs when the current is zero and is crossing the zero axis. Any error due to inductance would manifest itself as a displacement of the current trace away from the zero axis when the voltage trace crossed the zero axis. The photographs show no indication of this effect. From these traces corresponding readings of voltage and current were taken at set times and the energy computed by numerical integration of the product with time.

The measurements of spark energy were performed at four air pressures as well as at the four stored energies and the results are shown graphically in Fig. 54. The length of the discharge also varied with the stored energy and this is indicated on the same graph.

8.3 Experimental Procedure

The same conditions for experiment were used in testing the performance of the igniter as were used for the laser ignition experiments. Similarly, the same procedure was adopted for charging, firing and taking gas samples from the chamber. Because there was no need to monitor the energy of the igniter simultaneously, it was possible to use four ionisation probes and record them on a four trace plug-in unit for each combustion experiment. Again, the positions of the gaps were measured after each series of experiments and their positions calculated relative to the front face of the igniter.

8.4 Results

Normalisation of the results was necessary to take account of

the variation in position of the ionisation gaps. Unfortunately, at the highest and some intermediate energies used, there was no recognisable flame front recorded at the first ionisation probe. This was about 10 mm from the face of the igniter and consequently was very close to the igniting plasma jet. The time of arrival of the high density plasma at the ionisation probe was beyond the resolution of the oscilloscope, the trace being sent off-scale. Consequently, it was not possible to calculate the mean flame speed in the first 10 mm of flame travel but only in the first 20 mm of flame travel. The flame speed in the next 10 mm could also be calculated and both these have been plotted against ignition energy for the mixtures and pressures used (see figs. 55, 56 and 57).

Figs. 55 and 56 cover the 1.0 stoichiometric mixtures of methane and air and show a marked dependence of flame speed on spark energy. The expansion of the plasma through the plug orifice was increased by the energy released due to reaction of the gases between the plug electrodes. At pressures of 101 kN/m^2 and 239 kN/m^2 the flame speed increased by a factor of 7.5 for a 2.6 times increase in spark energy in the first 20 mm of flame travel and this was continued in the interval from 20-30 mm from the plug face when an increase in flame speed by a factor of 2 was observed. At high pressures the increases in flame speed due to increased spark energy were not so large but still showed a five-fold increase in flame speed for a ten-fold increase in the spark energy. At pressures of 515 kN/m^2 and below it was not possible to ignite the mixtures with the spark energies of 50-60 mJ and ignition was never achieved by the trigger spark alone. This is probably due to the large quenching effect that the electrodes and orifice would have on the development of the flame from within the plasma plug.

A similar situation was observed at 0.8 stoichiometric mixture (fig. 57) in that it was not possible to ignite the mixture with

energies of 50-60 mJ, but it was always possible with 200 mJ. The greatest increase in flame speed was from 4.6 m/s to 100 m/s for an increase in spark energy from 200 mJ to 1500 mJ at 791 kN/m² during the first 20 mm of flame travel. In the interval from 20-30 mm it appears to be necessary for the spark energy to exceed 600 mJ in order to ensure that the flame speed increases with increasing spark energy.

Ignition of the 0.6 stoichiometric mixtures was difficult, even with the maximum energy available. This mixture was very close to the inflammability limit of the methane/air (0.56 stoichiometric, ref. 50) and any quenching effect of surfaces would inhibit the propagation of the flame from the ignition source. This could be the case with the plasma plug igniter since it is surface mounted and even though it projects the spark into the chamber, the expanding flame front will eventually reach the cold chamber surface which could quench the flame completely. Ignition was achieved at 101 kN/m² and 239 kN/m² using the maximum energy of 1300 mJ but the recordings of flame speed were unreliable as the propagation was very slow, giving ill-defined pulses from the ionisation probes. The gas analysis, however, revealed that 97.7% and 98.5% of the methane had been consumed at 101 kN/m² and 239 kN/m² respectively. At 1.0 stoichiometric the proportions of methane in the combustion products were found to rise from a mean value of 121 v.p.m. at 1067 kN/m² to 167 v.p.m. at 101 kN/m²: there was no correlation between the proportion of methane and the energy of the plasma plug spark. At 0.8 stoichiometric there was a minimum mean methane content of 60 v.p.m. at 515 kN/m² rising to 84 v.p.m. at 1067 kN/m² and 78 v.p.m. at 101 kN/m². Again, there was no correlation between spark energy and methane content of the products of combustion.

CHAPTER NINE

ELECTRODE SPARK

9.1 Experimental Equipment

The electrodes used were 1.6 mm diameter tungsten rods, brazed into 4 B.A. threaded rods (fig. 58). The tungsten rod was insulated by a machinable ceramic boss from the brass body of the electrode holder. Further insulation was provided by using Araldite, which also acted as a seal for the ceramic boss. The electrodes were ground to a point with a cone angle of approximately 30° . They could be positioned so that the gap between the electrode was at the centre of the combustion chamber and the gap adjusted to between 0.30 mm and 0.60 mm by the selection of a suitable thickness of copper washer for sealing the body to the chamber. Fig. 59 shows the electrical circuit used for producing a spark. The main components are a bank of paper capacitors rated at a nominal $20\ \mu\text{F}$, 600 V, which are connected in series with an inductance of $140\ \mu\text{H}$ to the main electrode spark gap. Breakdown of the main gap is achieved by the application of an E.H.T. pulse from a car ignition coil connected via a switch to a 12 V accumulator. The E.H.T. pulse is first applied to an external spark gap so that the capacitors are not electrically connected to the ignition coil. When the external gap breaks down the E.H.T. voltage is applied across the main electrode gap with a very fast rise time. The inductance in series with the capacitors presents a high impedance path and the main electrode breaks down, allowing the capacitors to discharge across the main gap. The discharge is a damped oscillation with the gap conducting first in one direction and then in the opposite direction until there is insufficient residual voltage on the capacitors to maintain conduction of the gap. The energy discharged was controllable by varying the voltage applied to the capacitors and with no voltage applied there was only the energy

associated with the trigger spark.

The energy released at the electrodes was measured using a similar technique to that used for the plasma plug energy measurement. The voltage probe used to measure the voltage across the gap, however, had to be capable of withstanding the E.H.T. voltage used for the trigger spark. A Tektronix 1000x probe of 12 kV rating was found to be suitable for this purpose and gave a response sufficient to monitor the main discharge but resolution of the trigger spark was not possible. The same current probe was used to monitor the current of the discharge as was used in the plasma plug experiments. Typical traces of voltage and current are shown in Fig. 60 for several voltages on the capacitor bank. Energy measurements were taken from these traces by multiplication of voltage and current ordinates and numerical integration over the duration of the discharge. These measurements were repeated for each series of experiments as the size of the spark gap had a marked effect on the energy dissipated for a given stored energy. The effect of pressure on the energy dissipated at the electrodes was negligible compared with the effect of varying spark gaps used in successive series of experiments.

9.2 Experimental Procedure

Three ionisation probes were used to trace the flame front travelling across the combustion chamber and their positions relative to the electrodes were measured using a travelling microscope after each series of experiments. The position of the electrodes at the centre of the combustion chamber necessitated the positioning of the ionisation probes on opposite sides of the electrode, as shown in Fig. 61.

The first and third gaps were along the axis on one side of the electrodes and the second gap was on the axis on the opposite side of the electrodes. The symmetry of the chamber and

the stagnant conditions of the combustible gases ensured that the flame front would expand symmetrically from the point of ignition.

Time measurements of flame front travel were recorded on an oscilloscope using the trigger spark to trigger the time base. The same conditions of mixture stoichiometry and pressure were investigated as in the previous experiments and the same procedure used for filling the chamber, igniting the gases and sampling the gaseous products as were used in the plasma plug experiments.

9.3 Results

It was again necessary to normalise the results to eliminate the effect of the variation of the positions of the ionisation gaps. The results are plotted in Figs. 62-67, showing the variation of flame speed in the first and second 10 mm of travel as a function of spark energy.

The most noticeable feature of these graphs (figs. 62 and 64) is the very small effect that increases in spark energy has on flame speed, particularly at pressures in excess of 377 kN/m^2 . At 1.0 stoichiometric, the largest increase in flame speed in the interval 0-10 mm from the electrodes was at 101 kN/m^2 and this was also the case in the next 10 mm of flame travel. At all pressures greater than 101 kN/m^2 there was an initial decrease in the flame speed as the energy was increased but above 800 mJ the flame speed showed an increase in the second 10 mm of travel. Only at 515 kN/m^2 did the flame speed reach the same value it had when the trigger spark was used. At 0.8 stoichiometric (figs. 63 and 65) the flame speed was doubled in the first 10 mm of travel by increasing the energy from 100 mJ to 2500 mJ at 101 kN/m^2 mixture pressure. In the second 10 mm of flame travel the increase in speed under the same conditions was only 25%. At higher pressures the increase in flame speed was less than this and in the second

10 mm, a decrease was observed in every case.

Mixtures of 0.6 stoichiometry were difficult to ignite and above 515 kN/m^2 propagation of the flame through the whole chamber was impossible (figs. 66 and 67), although the mixture ignited when the maximum energy was used for ignition. Recordings from the ionisation probes were unreliable but the partial combustion was best observed from the proportion of methane in the combustion products and will be discussed later. Below 515 kN/m^2 the flame propagated with increased speed as the ^{spark} laser energy was increased in both the first and second 10 mm of flame travel.

The large increase in flame speed to over 7 m/s at 101 kN/m^2 in Fig. 66 may not be a real increase but probably was recorded by a late trigger of the oscilloscope and is therefore shown by a dashed line to connect it with the other points at 101 kN/m^2 .

Fig. 68 shows the proportion of methane in the combustion products of 1.0, 0.8 and 0.6 stoichiometric mixtures. At 1.0 and 0.8 the variation of methane against pressure is not very great and no variation with the energy of the spark was observed. At 0.6 stoichiometric mixtures, however, the proportion of methane rose from 300 v.p.m. to 3% as the pressure increased from 101 kN/m^2 to 515 kN/m^2 . Increasing the energy of the spark from 112 mJ to 2180 mJ made it possible to reduce the proportion of methane by one-third at 515 kN/m^2 . The ionisation probes did not register any flame propagation above 515 kN/m^2 and, consequently, only one set of gas samples was taken at 112 mJ spark energy. At higher energies a similar reduction of methane content may be expected as that observed at 515 kN/m^2 . This mixture is very close to the inflammability limit for methane/air mixtures and the large increase in methane proportion as the pressure is increased shows that the limit of inflammability has been crossed. The flame cannot propagate throughout the mixture, but the more energy there is supplied to the ignition source, the more methane there

CHAPTER TEN

CONCLUSIONS

10.1 Comparison of Three Systems

All three methods of ignition which were tested could be used at high energies of the order of 1 J released at the spark. The characteristics of the systems are, however, very different.

The laser spark is produced within the pulse of the laser which is approximately 40-60 ns long although, once formed, the spark itself will be subject to the normal decay processes of an intense plasma. This very rapid deposition of energy takes place at the focal point of a lens and need have no surfaces near it which may remove some of the energy released as well as retarding the propagation of the flame across the chamber. The choice of the position of the ignition source is limited only by the focal length of the lens and the ability to place the lens in the desired position. The production of the laser spark is limited by the energy density achieved at the focal point and the larger the focal length for a given laser beam deviation, the higher the laser beam energy required to achieve the necessary energy density for breakdown. The phenomenon of a detonation reported in Refs. 43 and 46 was not observed under any of the test conditions and combustion was completed normally.

The plasma plug can be readily operated at spark energies in excess of 1 J but the erosion of the electrodes and the orifice plate would be increased considerably. The energy can be deposited in approximately 60 μ s and the very rapid heating and ionisation of the gas between the electrodes produces a jet of plasma extending 10 mm from the face of the plug into the combustion chamber. Fig.69 shows a plasma plug operating in air at atmospheric pressure. When operating with a combustible mixture in the chamber, the addition of the energy release due to reaction of the mixture increases the

penetration of the plasma jet considerably. However, the quenching effect of the electrodes and orifice plate makes the operation of the plug at energies less than 200 mJ unreliable. As can be seen from Fig. 69, the jet of plasma is cylindrical in shape and has a very turbulent surface. This provides a large surface area of contact between the jet and the combustible mixture and, consequently, a large volume of mixture is ignited by the spark. This would overcome the critical time of flame propagation from a conventional low energy spark to the establishment of a flame which is unaffected by small scale turbulence within the mixture.

The rates of deposition of energy for the electrode experiments were similar to those used in the plasma plug experiments. These electrodes had a much smaller quenching effect than the plasma plug and ignition could be achieved at all the energies investigated, including the trigger discharge. Because the electrodes were pointed the spark produced expanded symmetrically and, at the high energies, would take up a spherical form. However, for the same contained volume, a sphere has less surface area than a cylinder of large aspect ratio and, consequently, the area of contact between ignition source and mixture is greater for the plasma plug than for the pointed electrode case.

10.2 Comparative Performances of the Three Igniters

For comparative purposes Figs. 70-74 show the flame speed of the three igniters for the three mixture ratios used and at 1067 kN/m² and 101 kN/m². It was not possible to compare the igniters directly as the plasma plug flame speed measurements were made in the interval 0-20 mm and 20-30 mm whereas for laser and electrode ignition the intervals are 0-10 mm and 10-20mm. Despite the difference, the plasma plug showed a considerably greater flame speed at all pressures and mixtures and also a greater dependence on spark energy than the other two igniters. At 1.0

and 0.8 stoichiometric mixtures the flame speed observed from the plasma plug in the interval 20-30 mm from the plug face was greater than the flame speed in the first 10 mm of travel for either laser or electrode ignition. Comparison of the laser and electrode ignition shows that the laser produced flame speeds approximately 50% greater at 1.0 stoichiometric and up to 25% greater at 0.8 stoichiometric. The plasma plug would not produce ignition at the 0.6 stoichiometric mixtures used and the comparison between the laser and electrode ignition is limited to 101 kN/m². In the first 10 mm of travel the flame speeds for the two systems were approximately the same but the laser system showed double the flame speed of the electrode ignition in the second 10 mm of flame travel.

To appreciate the significance of these results, consider the ignition and idealised combustion process in a petrol or gas engine. Let combustion take place in a constant volume V with a fixed mass M of gas and products in the chamber and initial pressure p . The time T_1 , as defined in Fig. 12 is the time taken from ignition to achieve a 5% rise in pressure in the chamber based on the overall pressure rise achieved. If this pressure is p_1 and it corresponds with volume of burnt gases V_1 at temperature T_1 then these properties are related according to:

$$p_1 v_1 = m_1 R_1 T_1 \quad (5)$$

where m_1 is the mass and R_1 is the gas constant for the combustion products.

If the unburnt can be represented by the remaining volume of gas at the same pressure p , but at a temperature T_2 then the gas law gives the following:

$$p_1 (V - v_1) = m_2 R T_2 \quad (6)$$

where m_2 is the mass and R is the gas constant for the unburnt gas.

$$\text{Initially, however, } p V = M R T \quad (7)$$

and for conservation of mass

$$m_1 + m_2 = M \quad (8)$$

Substitutions for m_1 and m_2 from equation 5 and 6 gives

$$\frac{p_1 v_1}{R_1 T_1} + \frac{p_1 (V - v_1)}{R T_2} = \frac{p V}{R T} \quad (9)$$

At the completion of combustion the final pressure and temperature are p_3 and T_3 respectively and are related by

$$p_3 V = M R_1 T_3$$

Eliminating M using equation 7 and rearranging

$$\frac{p_3}{p} \cdot \frac{T}{T_3} = \frac{R_1}{R} \quad (10)$$

Rearranging equation 9 and substituting for $\frac{R_1}{R}$ gives

$$\frac{p_1}{p_3} \cdot \frac{v_1}{V} \cdot \frac{T}{T_1} + \frac{p_1}{p} \cdot \frac{V - v_1}{V} \cdot \frac{T}{T_2} = 1$$

$$\text{or } \frac{v_1}{V} = \left[\frac{p_1 T}{p T_1} - 1 \right] / \left[\frac{p_1 T}{p T_2} - \frac{p_1 T_3}{p_3 T_1} \right] \quad (11)$$

To estimate the proportion by volume of gases consumed in the first 5% of the pressure rise values must be given to the parameters in equation 11. A typical pressure diagram for an engine is shown in Fig. 12 and from this we have $p = 900 \text{ kN/m}^2$ $p_1 = 1025 \text{ kN/m}^2$ and $p_3 = 3400 \text{ kN/m}^2$. For the case of a very small pressure rise due to combustion, the temperature rise of the combustible mixture due to compression will be small and T/T_2 will be just less than unity. If it is assumed to be unity then equation 11 will produce an underestimate of the volume ratios. The ratio T_3/T_1 will be greater than unity, because the final combustion temperature reached

will be greater than that achieved when combustion started because of the higher initial temperature of the gases due to compression to higher pressures. Again the assumption that $T_3 = T_1$ will produce an underestimate of the actual volume ratio. Substituting the values for pressure and the assumption of temperature ratios gives

$$\frac{v_1}{V} = 0.169$$

Therefore the volume of combustible gas consumed for a 5% pressure rise is in excess of 17%.

Consider further a simple combustion chamber within a cylinder of 500 ml swept volume and 9:1 compression ratio. The volume of the combustion chamber would be 62.5 ml. For a 5% increase in pressure in the chamber due to combustion 17% of this volume would have to be consumed, or 10.6 ml. If combustion was from the surface of the combustion chamber this would be the volume occupied by a hemisphere of 17 mm radius.

The large increases in flame speed which have been achieved by using the plasma plug and laser ignition methods over the more conventional electrode sparks have therefore been in the region where the expanding flame front is most susceptible to disturbance, i.e. during T_1 . A significant reduction in the period T_1 achieved by either of the ignition methods used may result in a decrease in the absolute amount of cyclic dispersion observed in a petrol or gas engine.

The products of combustion of all three methods used were very similar at 1.0 and 0.8 stoichiometric mixtures. Direct comparison of Figs. 42 and 68 shows the proportion of methane in the combustion products at all three mixture ratios investigated for laser and electrode ignition respectively. The major difference can be seen at 0.6 stoichiometric mixture ratios. The laser spark causes the flame to propagate much further across the chamber, so

much so that at 515 kN/m^2 , at the lowest electrode energy of 112 mJ, the proportion of methane is 3.0%, whereas at the lower laser energies (approximately 100 mJ) the proportion is reduced to 0.5%. At the highest electrode spark energy of 2180 mJ the proportion is 0.9%, whereas at the higher laser energies (approximately 220 mJ) the proportion is reduced to 0.1%. No comparison can be made with the plasma plug because no combustion was observed from the ionisation probes, although it is possible that partial combustion of the mixture occurred.

10.3 Practical Considerations

The applications envisaged for the laser spark and plasma plug were the conventional spark ignition and jet engines. At the present state of development of solid state lasers, it would be impractical to use a laser for ignition in a conventional petrol or gas engine. The low efficiency of the conversion from electrical energy to light energy is a major drawback of the system which means that large quantities of electricity have to be stored and the heat produced on discharge has to be dissipated. This requires large capacitors, charging circuits and a heat transfer medium, usually deionised water, in order to achieve repetition rates of the order of six a minute or above. This precludes the use of the laser in anything but stationary conditions. The semiconductor and gas laser have not been developed to produce sufficient peak powers to achieve breakdown of gases. The major drawback is the cost of any laser system compared with conventional methods of ignition which are at least two orders of magnitude cheaper in terms of materials alone. These same factors apply to an ignition system for a gas turbine engine, whether it is a jet engine or a stationary engine. The advantages offered by the laser spark of high energy deposited away from the walls of the combustion chamber are completely overshadowed by the cost and equipment required to achieve the desired objective.

The plasma plug follows very closely the technology presently used for the production of sparking plugs for petrol engines and igniters in gas turbines. However, the energies required for reliable operation of the device are much larger than a normal automotive ignition system. For a 4-cylinder, 4-stroke engine there are two sparks per revolution of the engine. If the plasma plug were operated at 1000 mJ energy level, then the power dissipated in the spark would be 33 W per 1000 r.p.m. of the engine. Allowing for a conversion efficiency of 33%, this would mean the consumption of 100 W per 1000 r.p.m. of the engine. For European engines this would be a major proportion of the electrical output of the generator and would be intolerably high at high engine speeds. It can be envisaged that a control system could be devised which supplied a much lower energy under steady state conditions and that the high energies need only be supplied to the plug when the mixture may be poorly mixed or weakened as on overrun. This would also have the effect of extending the life of the plug at the expense of a control system that would be able to detect conditions requiring high energy plasma plug ignition.

The application of the plasma plug to gas turbines appears to be the most promising for further development. Currently, surface discharge igniters work at stored energies of 8-20 J, which may mean from 2-10 J released at the plug face. This is the energy level at which the plasma plug has been tested. The experimental work indicates a much greater effect from the plasma plug than for the same energy released between two pointed electrodes. This is attributed to the projection of the high intensity plasma away from the face of the plug and chamber wall where any quenching effect would retard and possibly extinguish a flame in a weak mixture. As a comparison, a high energy surface discharge igniter was obtained with its firing equipment and was tested in the combustion chamber.

This is outlined in Appendix 11. The plasma plug showed greater penetration into the chamber than the high energy igniter for the same energy release. This is what is required for a gas turbine igniter as the mixture is confined to the centre of the chamber in order to avoid overheating of the chamber walls. The high energies used in present surface discharge systems is a reflection of the necessity to produce a large ignition source extending well into the chamber without physically having the igniter extending into the chamber. The plasma plug can achieve this with a lower release of energy and, consequently, lower stored and transmitted energy.

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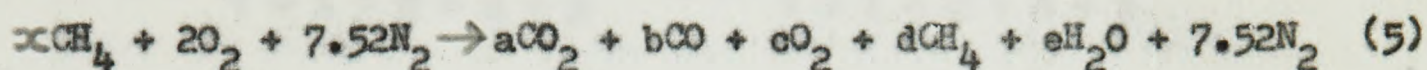
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APPENDIX 1

CHECK MADE FOR CONSISTENCY OF ANALYSIS OF COMBUSTION PRODUCTS

For the combustion of methane in a 79% nitrogen, 21% oxygen mixture, the following equation applies:



where x = No. of molecules of methane in initial mixture

a	=	"	"	"	"	CO ₂	"	combustion products
b	=	"	"	"	"	CO	"	"
c	=	"	"	"	"	O ₂	"	"
d	=	"	"	"	"	CH ₄	"	"
e	=	"	"	"	"	H ₂ O	"	"

For stoichiometric mixtures, x = 1 and at 0.8 and 0.6 stoichimetry, x = 0.8 and 0.6 respectively.

From equation (5):

Carbon balance gives:

$$x = a + b + d \quad (6)$$

Oxygen balance gives:

$$2 = 2a + b + 2c + e \quad (7)$$

Hydrogen balance gives:

$$4x = 4d + 2e \quad (8)$$

Eliminating e between equations (7) and (8) gives:

$$x = \frac{4 + 2d - 2a - b - 2c}{2} \quad (9)$$

Let l, m, n and p be the proportions of CO₂, CO, O₂ and CH₄ in dry combustion products as found by analysis.

from equation (5), with water vapour removed, then:

$$\left. \begin{aligned} l &= \frac{a}{a + b + c + d + 7.52}, m = \frac{b}{a + b + c + d + 7.52} \\ n &= \frac{c}{a + b + c + d + 7.52}, p = \frac{d}{a + b + c + d + 7.52} \end{aligned} \right\} \quad (10)$$

From equation (10) the following can be derived:

$$a = \frac{7.52}{1 - l - m - n - p} \quad b = \frac{7.52 m}{1 - l - m - n - p}$$

$$c = \frac{7.52}{1 - l - m - n - p} \quad d = \frac{7.52 p}{1 - l - m - n - p}$$

and substitution in Equations (6) and (9) gives:

$$x = \frac{7.52 (1 + m + p)}{(1 - l - m - n - p)}$$

$$\text{and } x = \frac{2 - 7.52 (1 + \frac{m}{2} + n - p)}{(1 - l - m - n - p)}$$

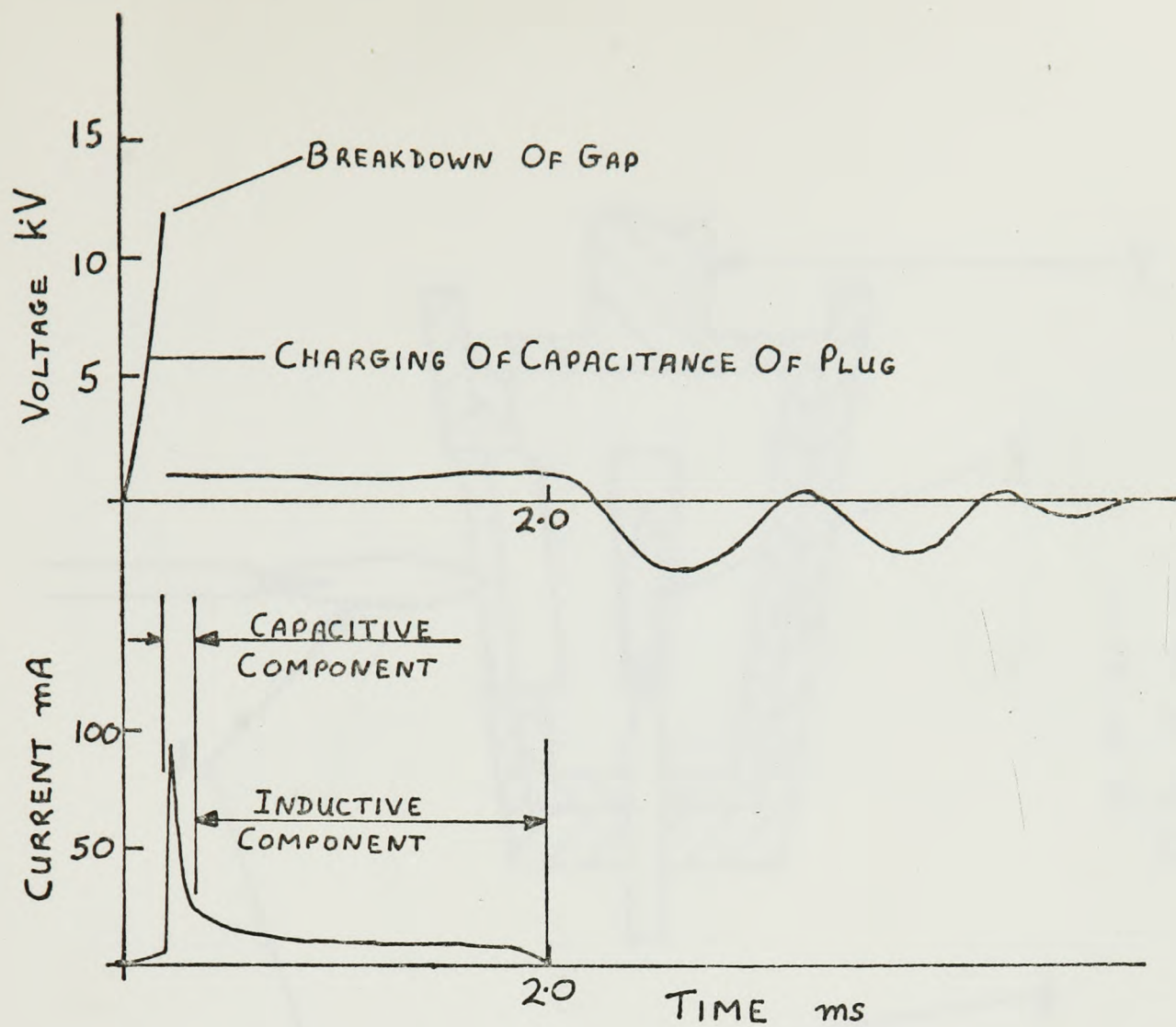
Knowing the values of l , m , n and p from analysis, these two values of x could be calculated and if they were within 10% of the original stoichiometric value of the mixture, the analysis was accepted. This gave a check on the validity of the analysis and ensured that the columns of the gas chromatograph were performing satisfactorily and that switching of the molecular sieve column was timed correctly.

APPENDIX II

FLAME SPEED MEASUREMENTS FROM A SURFACE DISCHARGE IGNITER

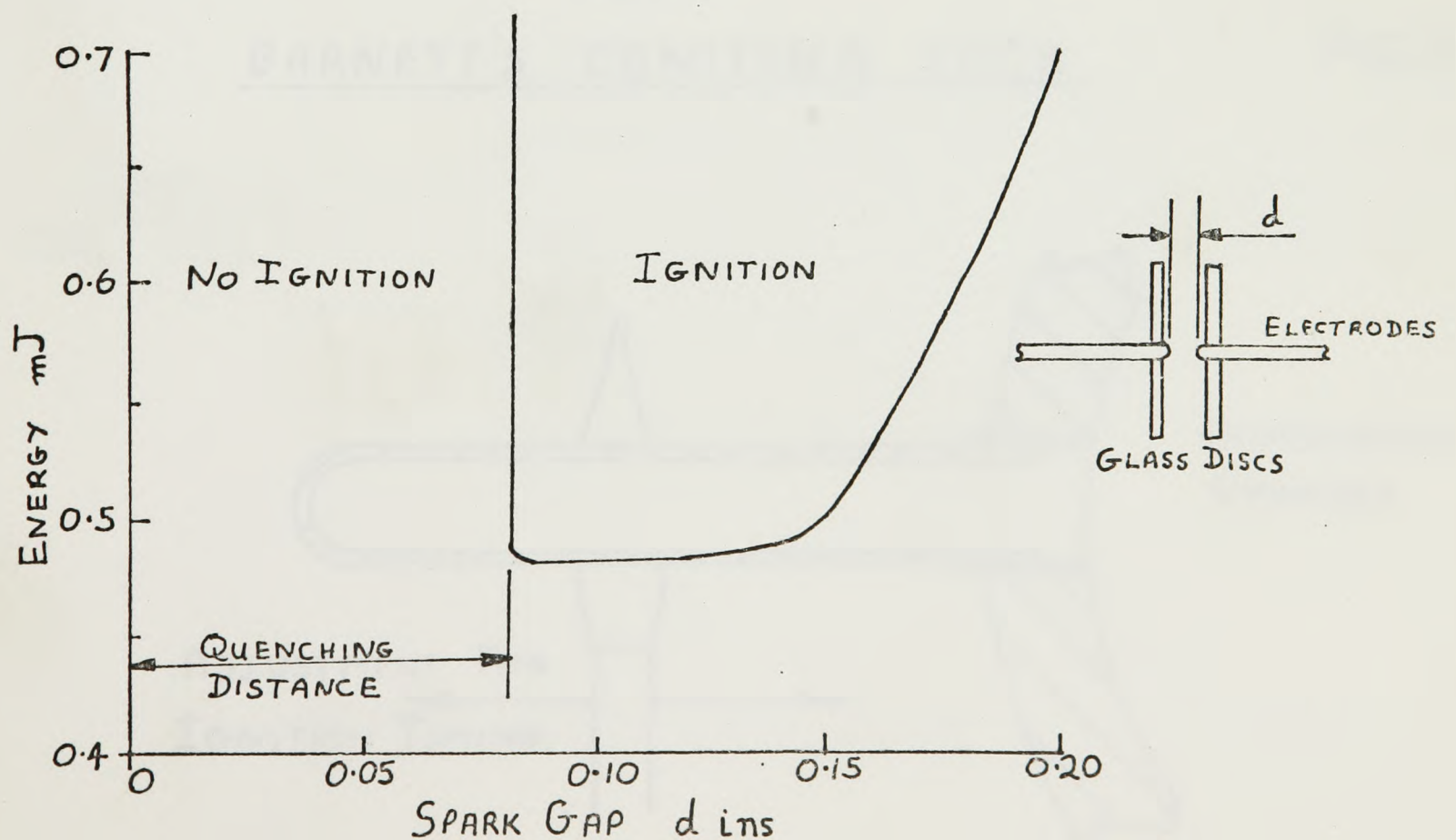
A high energy surface discharge igniter and firing equipment were obtained and tests performed using the igniter in the combustion chamber with stoichiometric methane/air mixtures at 1067 kN/m^2 . It was possible to compare its performance directly with that of the plasma plug igniter and this is shown in Fig. 75. The igniter was operated at four energy storage levels of 1.5, 3.0, 6.0 and 12.0 J and information was supplied giving the energy released at the igniter for these energy levels. These direct energy releases have been used in Fig. 75

The procedure used for the experiments was the same as that used for the experiments using the plasma plug, except that no gas samples were taken. Fig. 75 shows that the plasma plug produces an initial flame speed along the axis of the chamber of up to 20 times that of the surface discharge igniter. This is an indication of the effectiveness of the plasma plug in projecting the ignition source away from the surface of the combustion chamber. Even at a distance of 20-30 mm from the igniter the plasma plug showed a flame speed five times that produced by the high energy surface discharge plug.



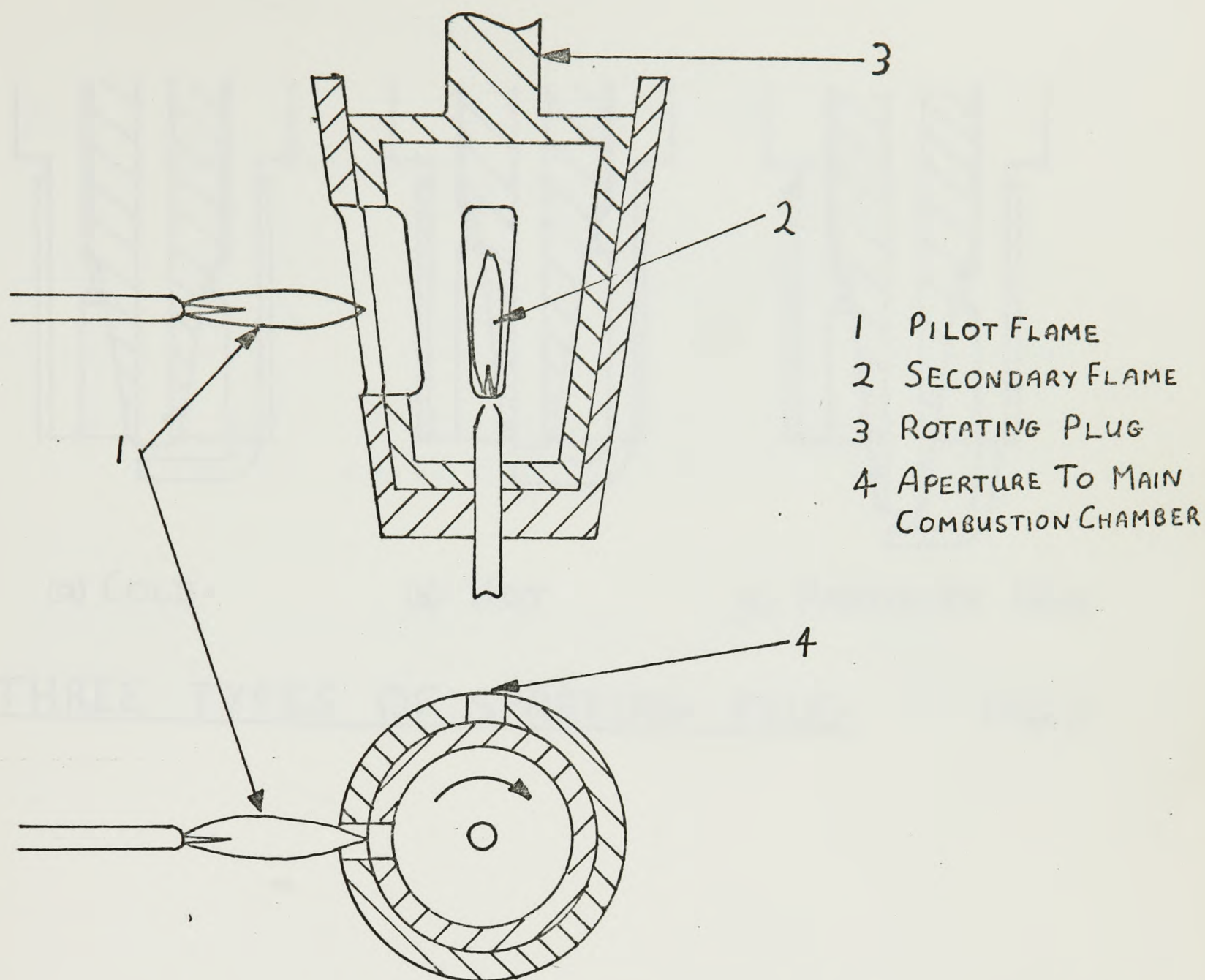
VOLTAGE AND CURRENT TRACES OF SPARK
BREAKDOWN USING IGNITION COIL

FIG. 1



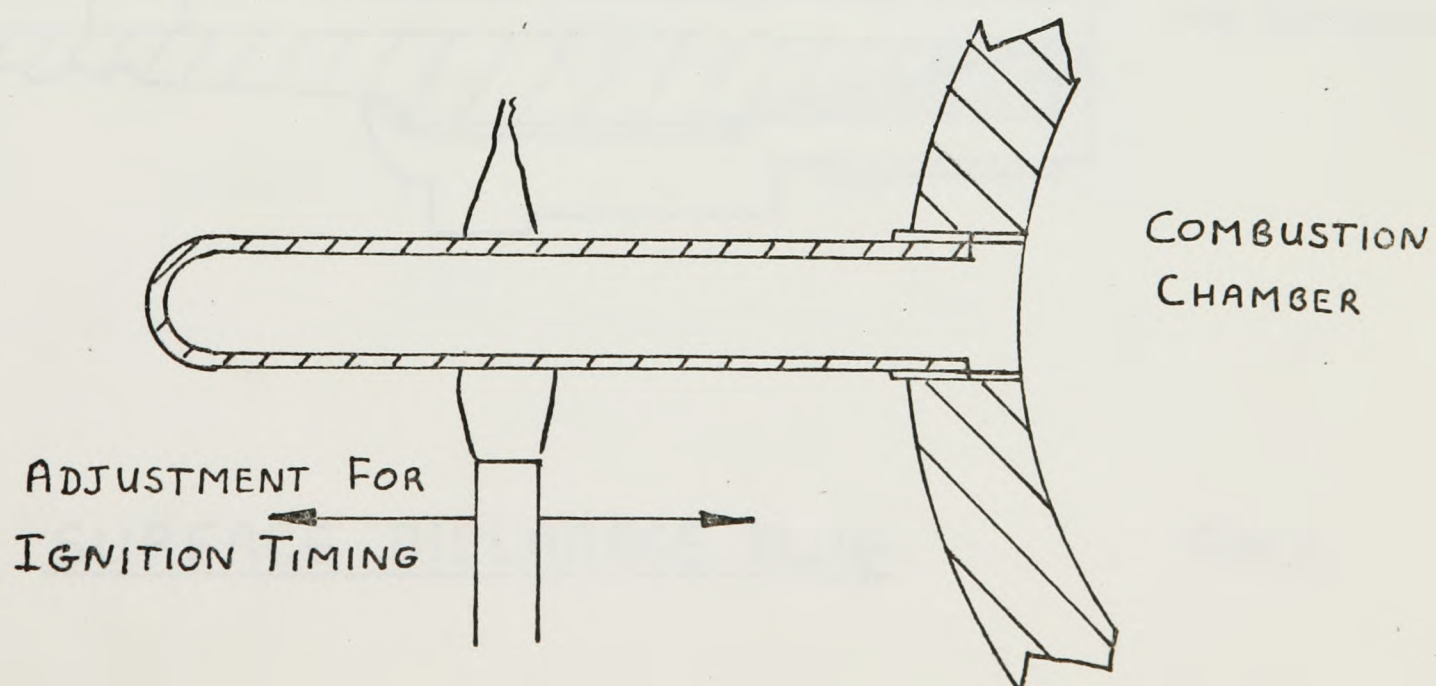
MINIMUM IGNITION ENERGY AND QUENCHING
DISTANCES FOR ELECTRODES WITH GLASS DISCS
(REF. 12)

FIG. 2



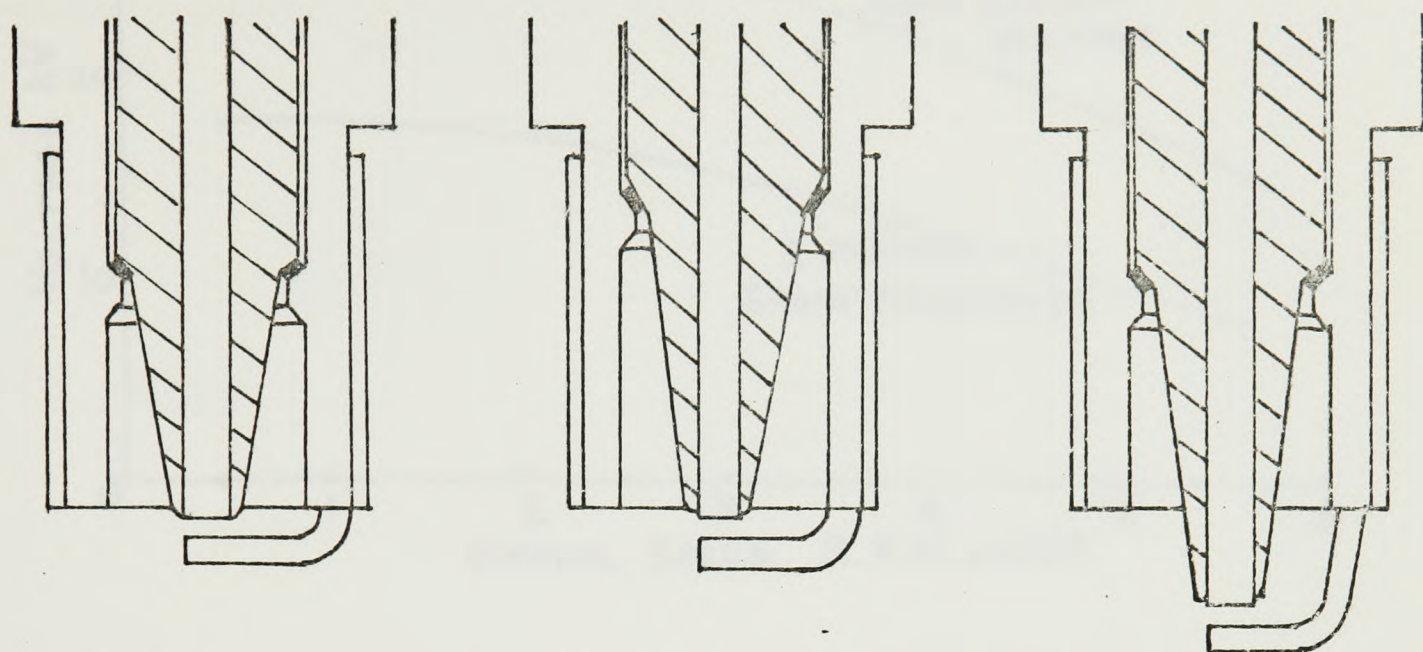
BARNETT'S IGNITING COCK

FIG.3



HOT TUBE IGNITION

FIG.4



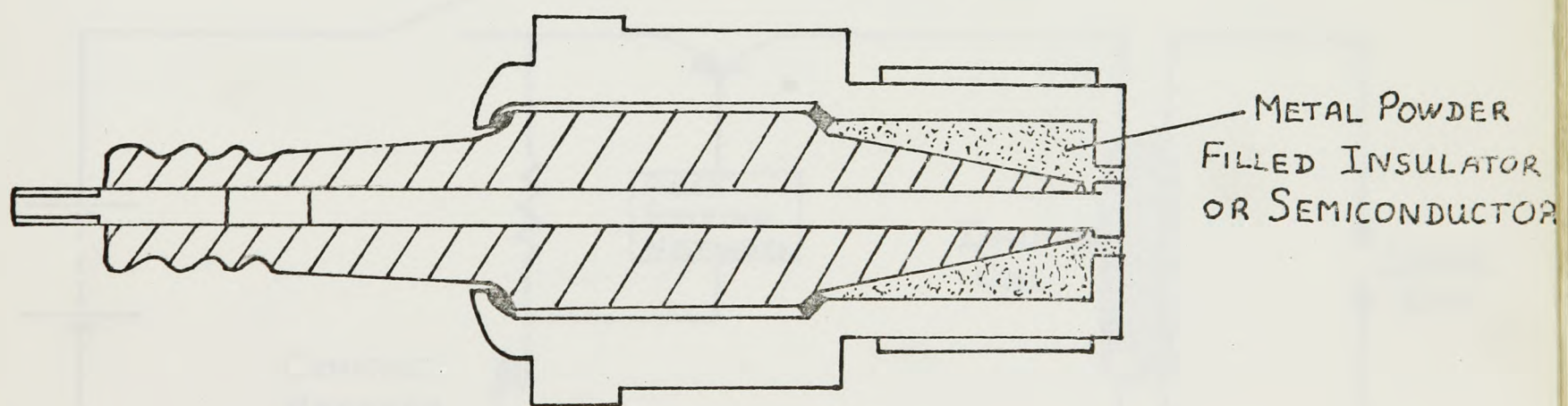
(a) COLD

(b) HOT

(c) PROTECTED NOSE

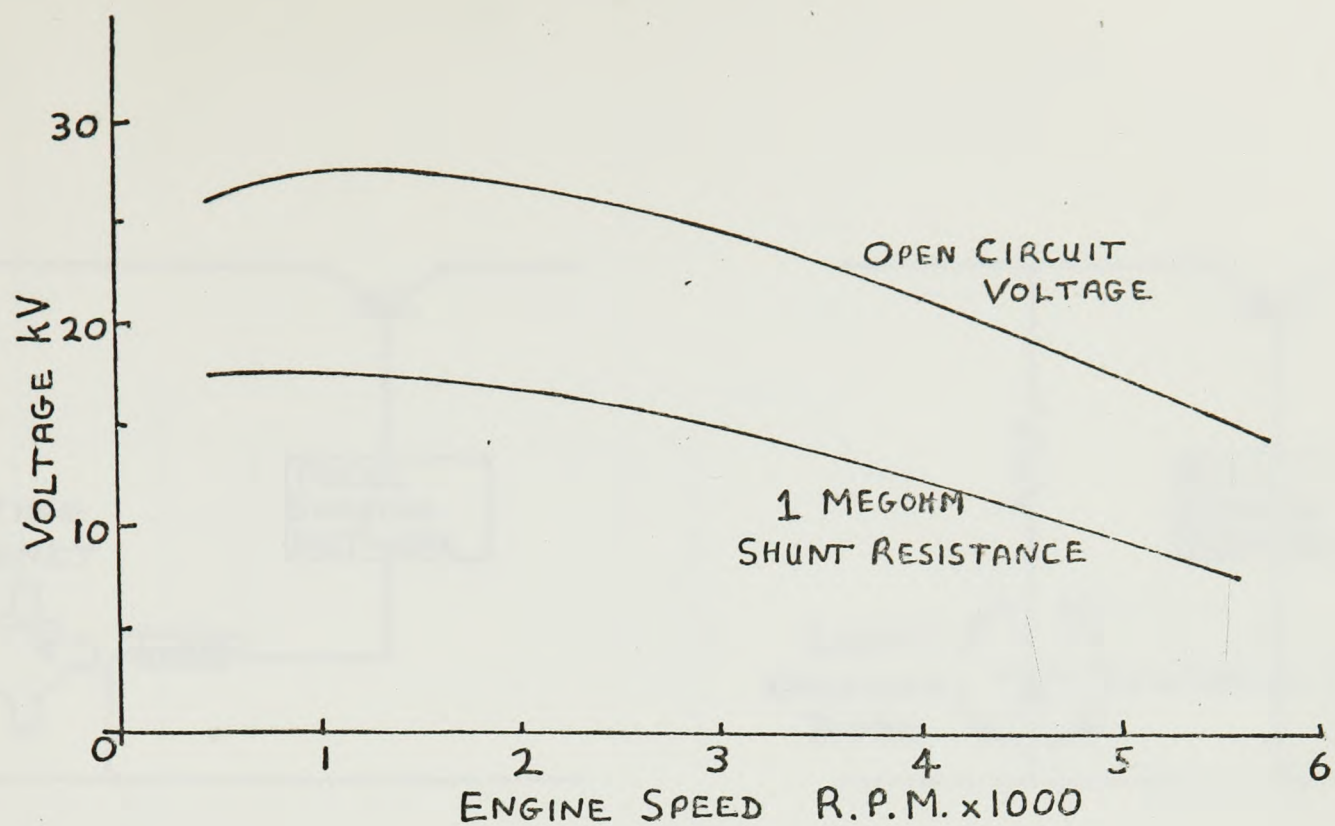
THREE TYPES OF SPARKING PLUG

FIG.5



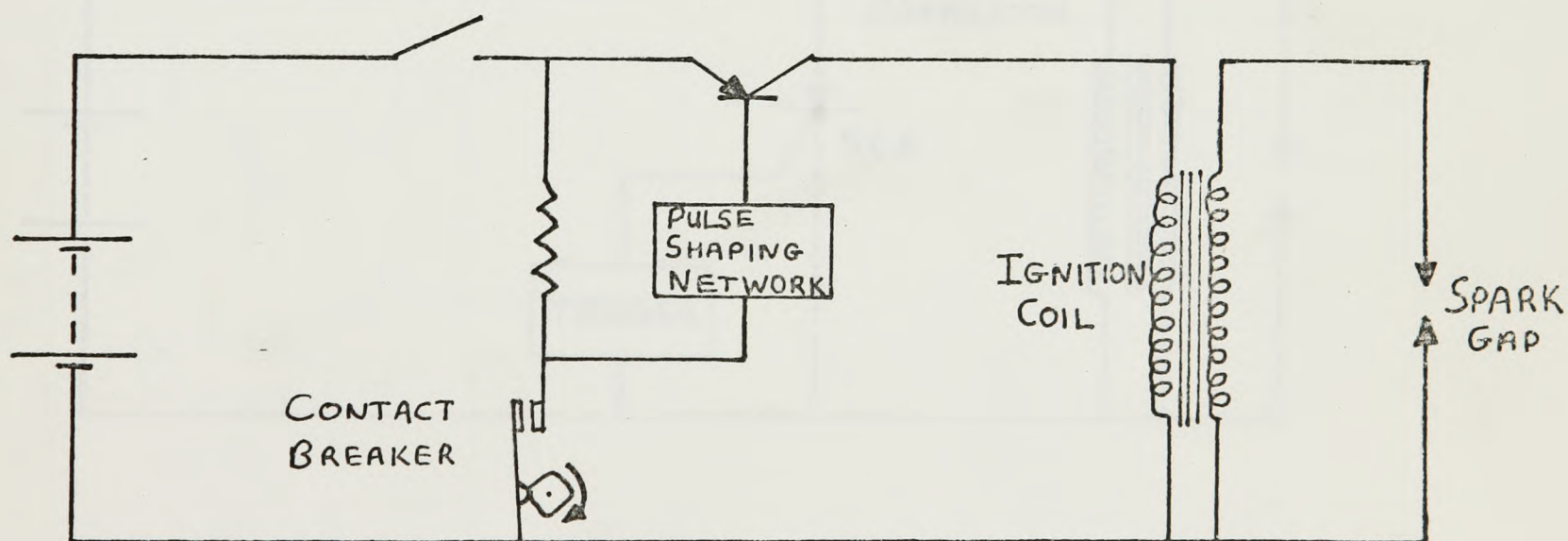
SURFACE DISCHARGE PLUG

FIG.6



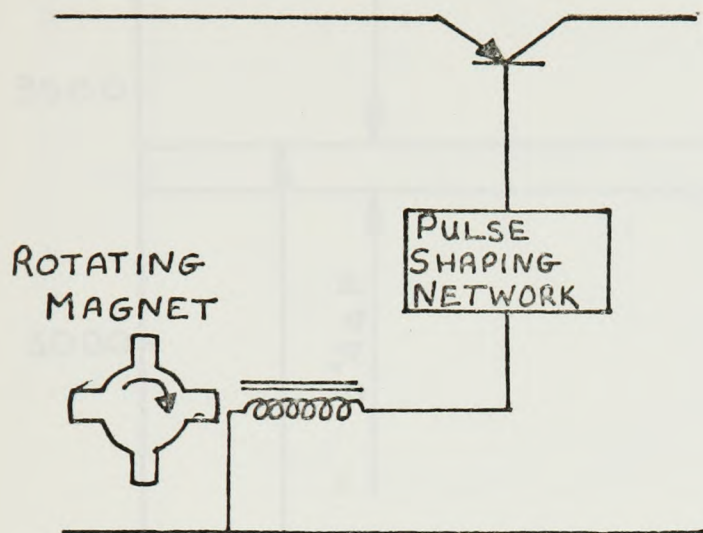
OUTPUT VOLTAGE / ENGINE SPEED FOR CONTACT BREAKER IGNITION COIL SYSTEM

FIG. 7

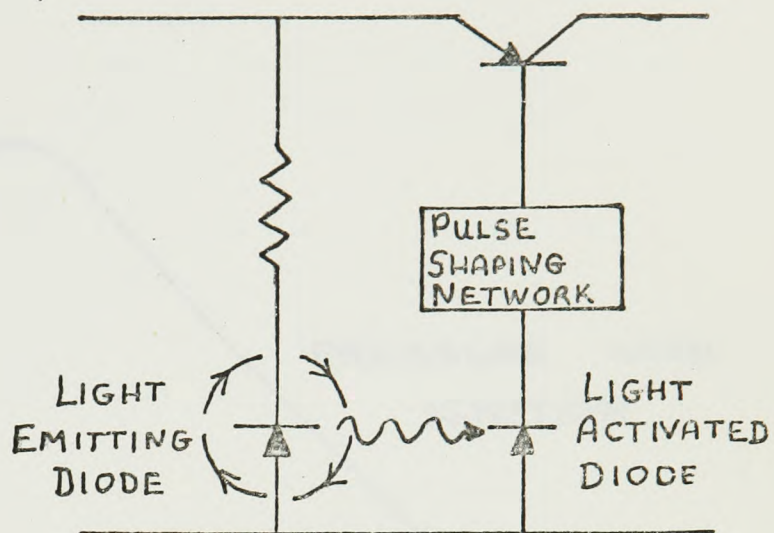


TRANSISTOR SWITCHING OF COIL CURRENT

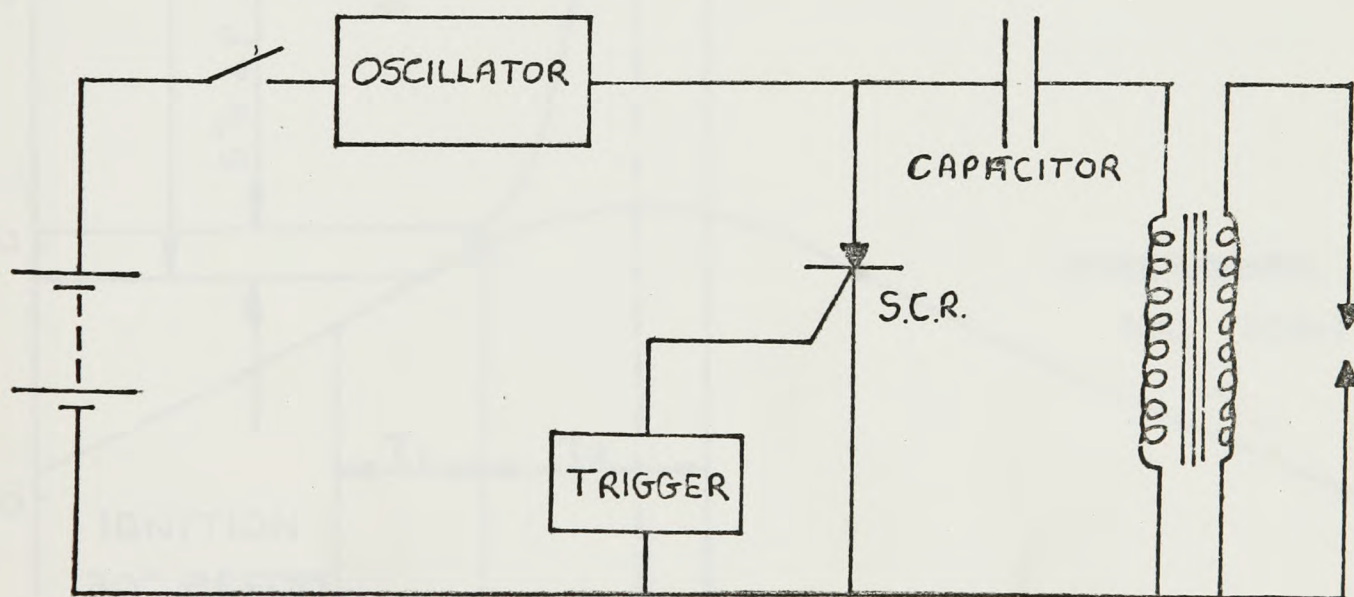
FIG. 8



MAGNETIC TRIGGER
CIRCUIT FIG. 9

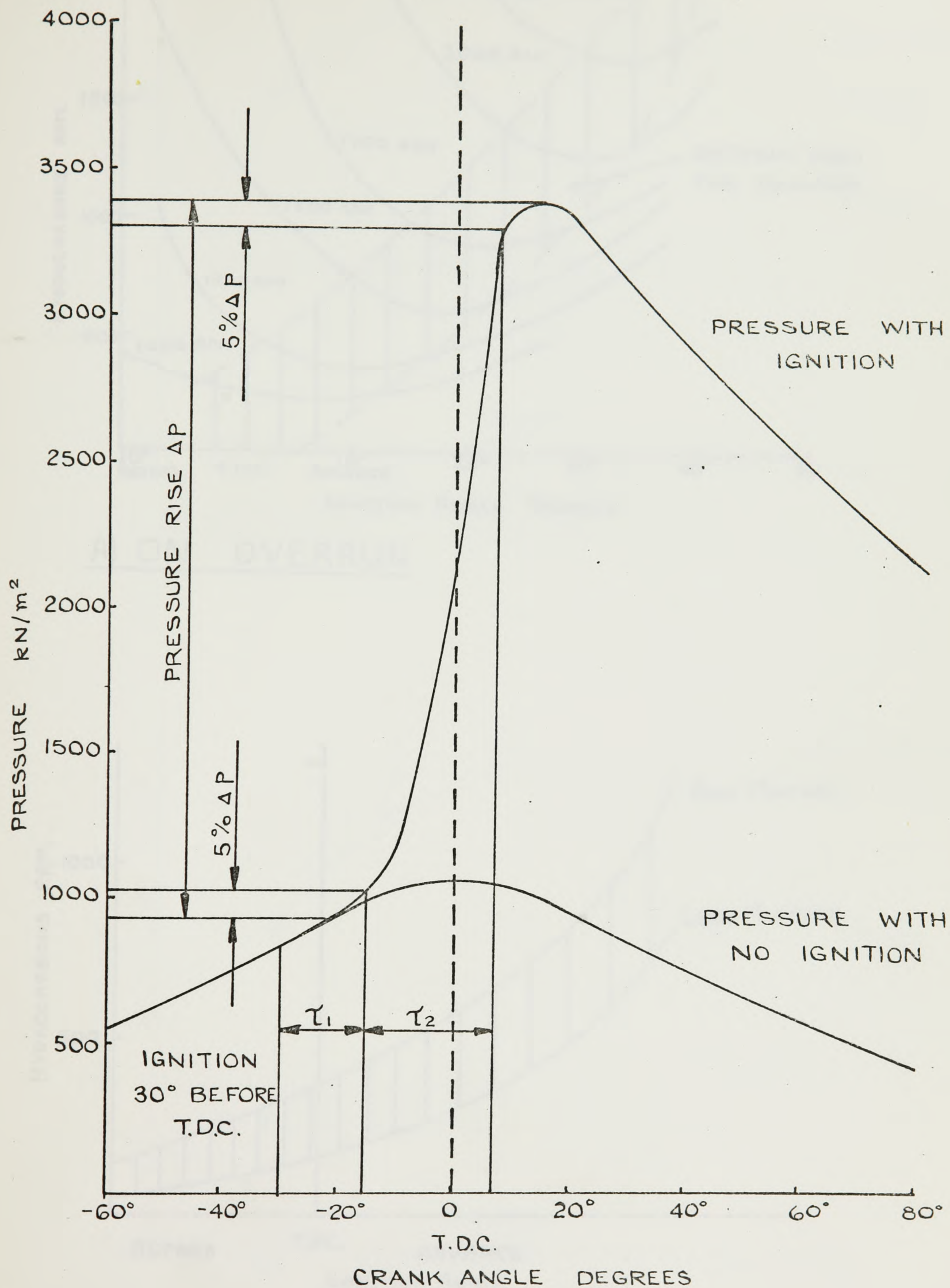


LIGHT ACTIVATED
SWITCH FIG. 10

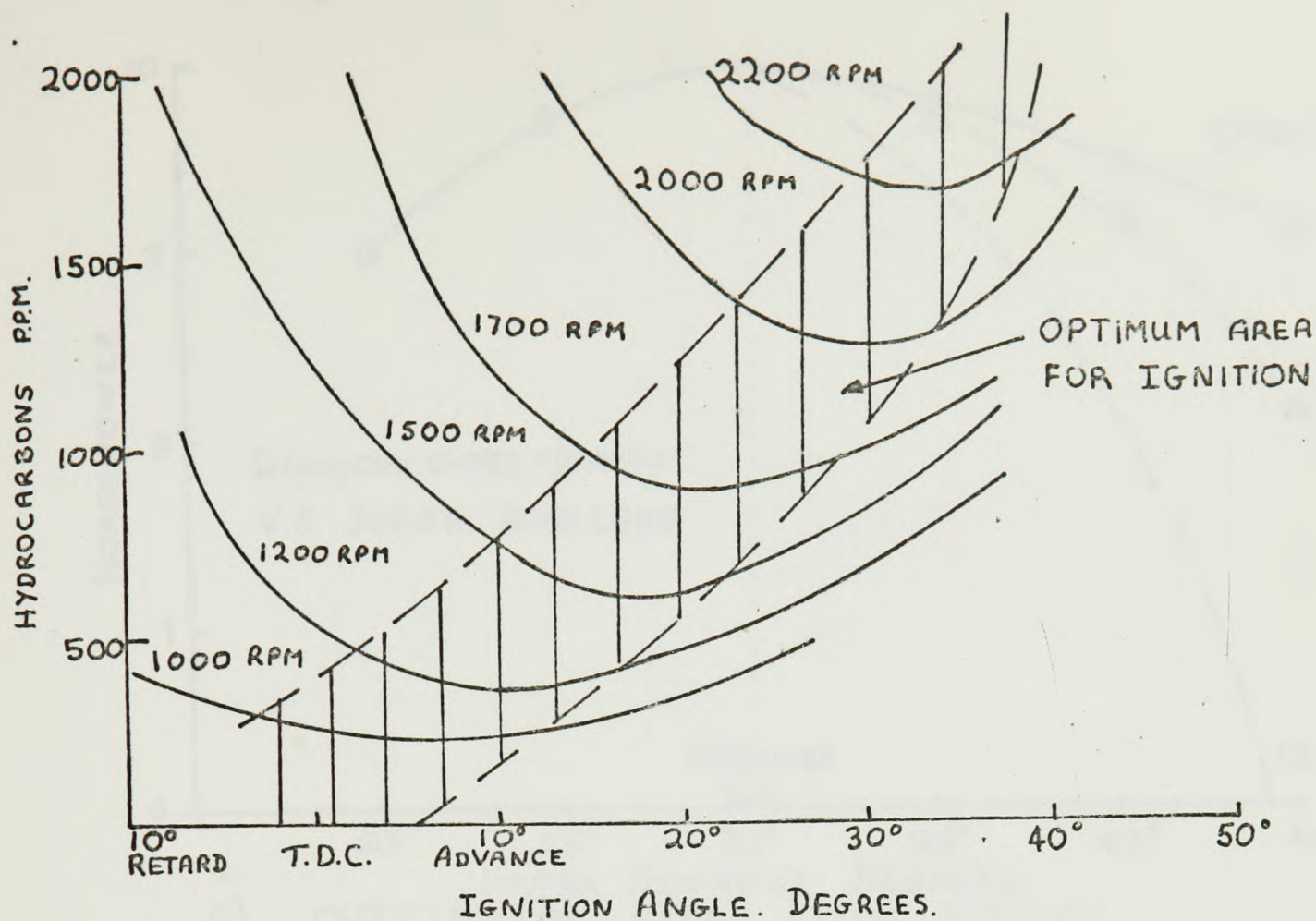


CAPACITOR DISCHARGE SYSTEM

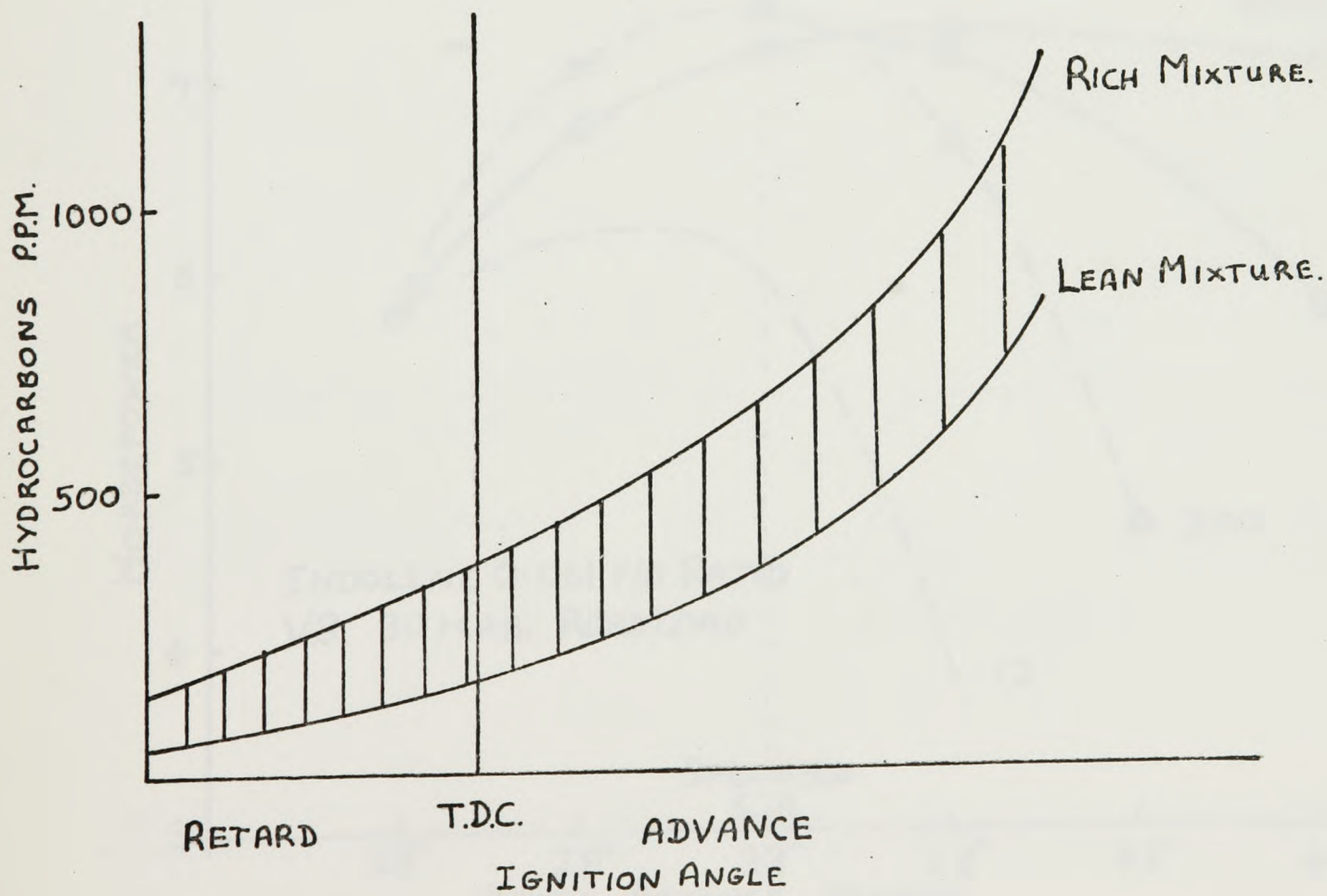
FIG. 11



PRESSURE / CRANK ANGLE DIAGRAM FOR
IGNITION IN A PETROL OR GAS ENGINE

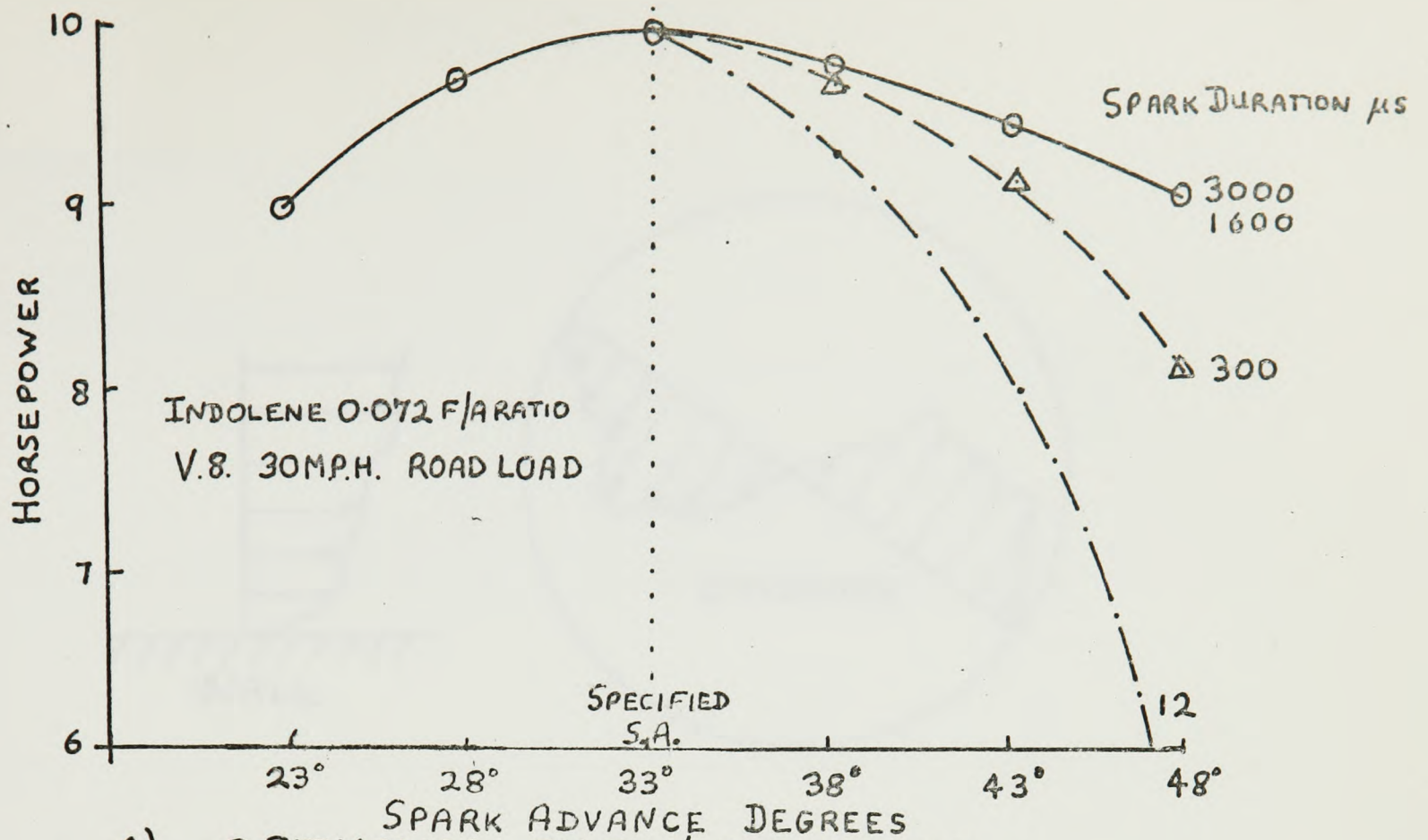


A) ON OVERRUN

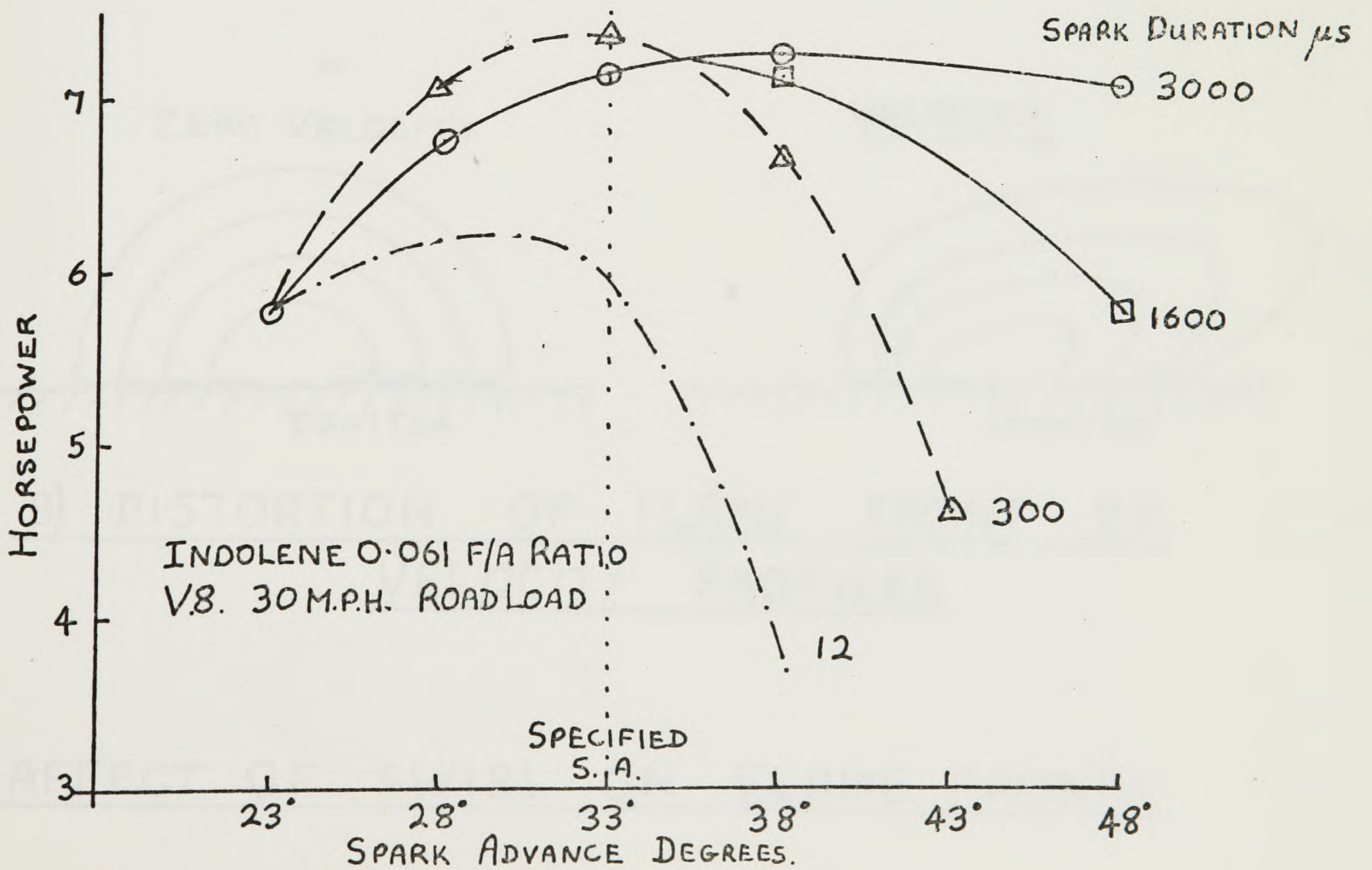


B) AT IDLE

VARIATIONS IN EXHAUST HYDROCARBONS/
IGNITION ANGLE (REF 28)



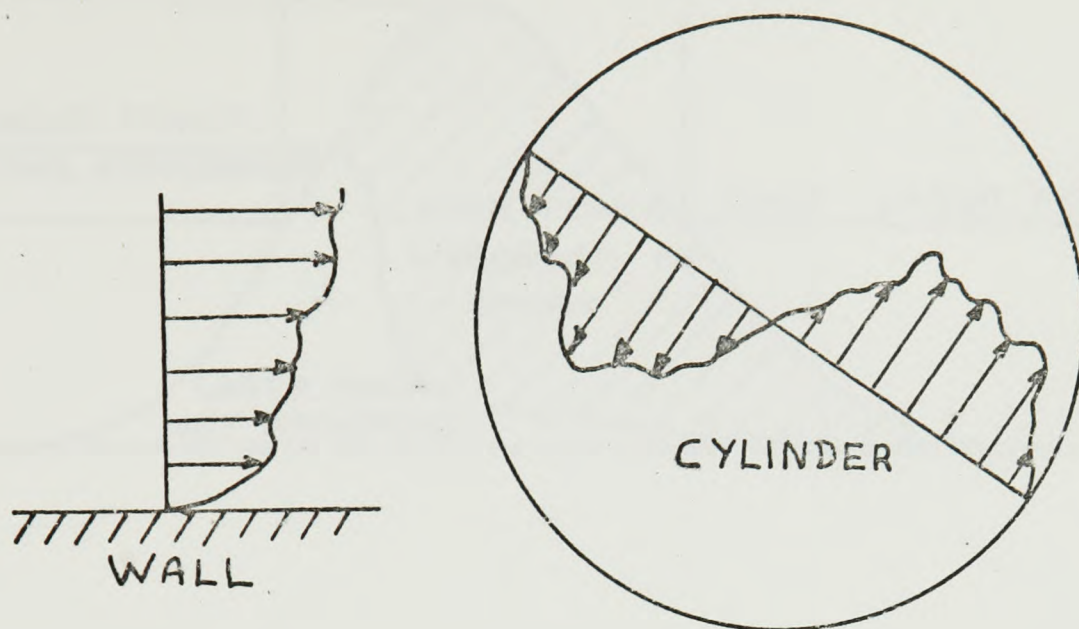
A) OPTIMUM FUEL/AIR RATIO



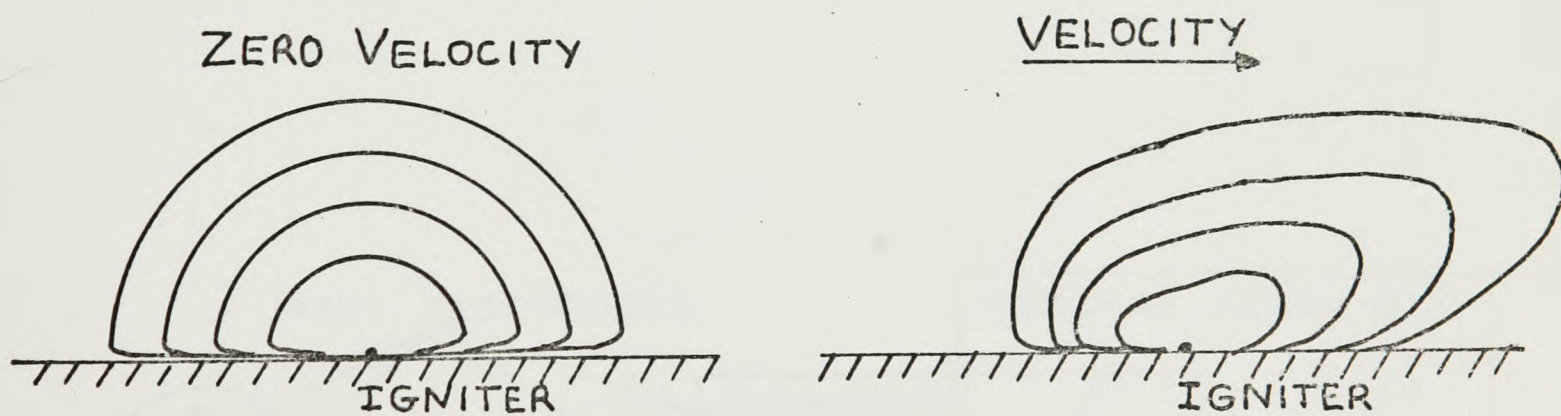
B) WEAK FUEL/AIR RATIO

HORSEPOWER / SPARK ADVANCE FOR FOUR
SPARK DURATIONS (REF. 27)

FIG. 14



A) INSTANTANEOUS VELOCITY PROFILES

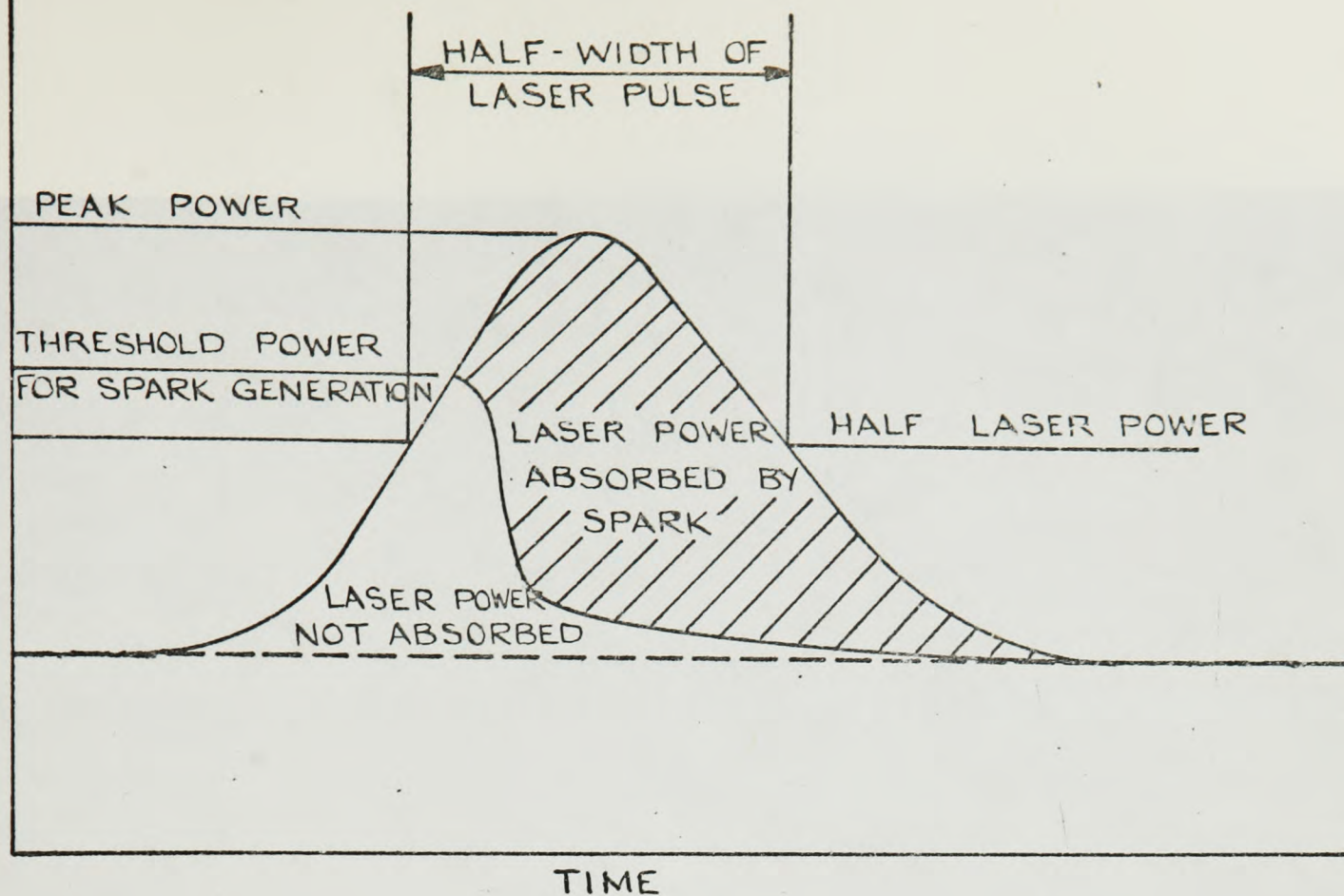


B) DISTORTION OF FLAME FRONT BY VELOCITY PROFILES

AFFECT OF SWIRL ON FLAME FRONTS

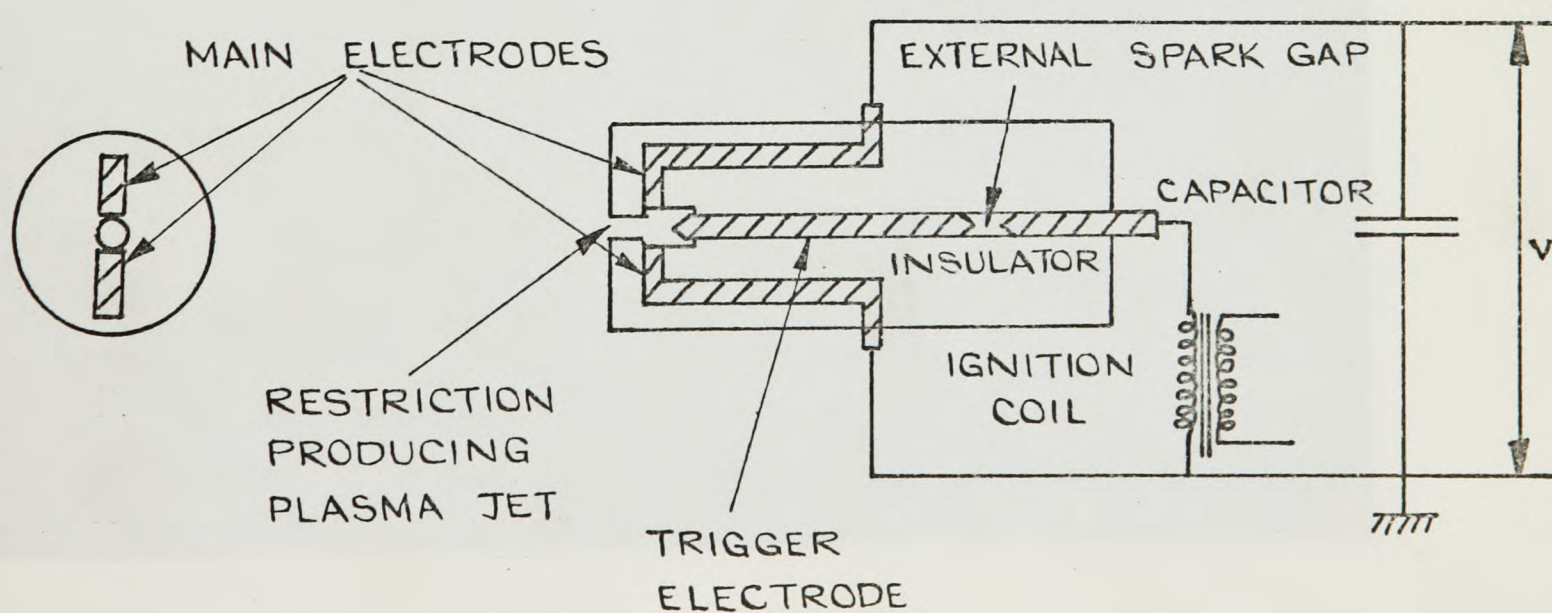
FIG.15

LASER
POWER



LASER POWER / TIME AT FOCUS OF LASER BEAM

FIG. 16



DIAGRAMMATIC SKETCH OF PLASMA PLUG

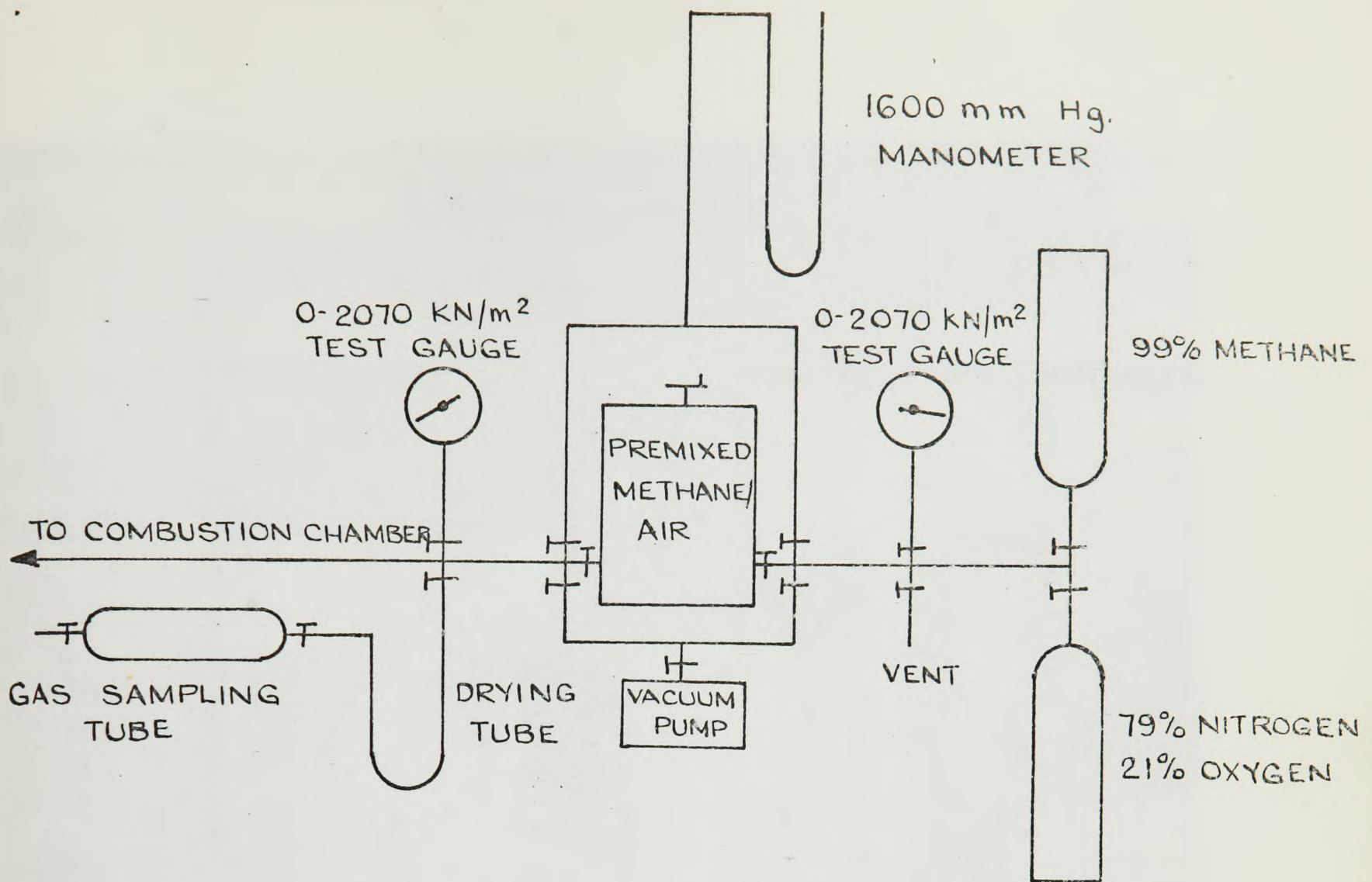
FIG. 17



FIG. 18 LASER SPARK IGNITION OF METHANE/AIR MIXTURES IN SOAP BUBBLE

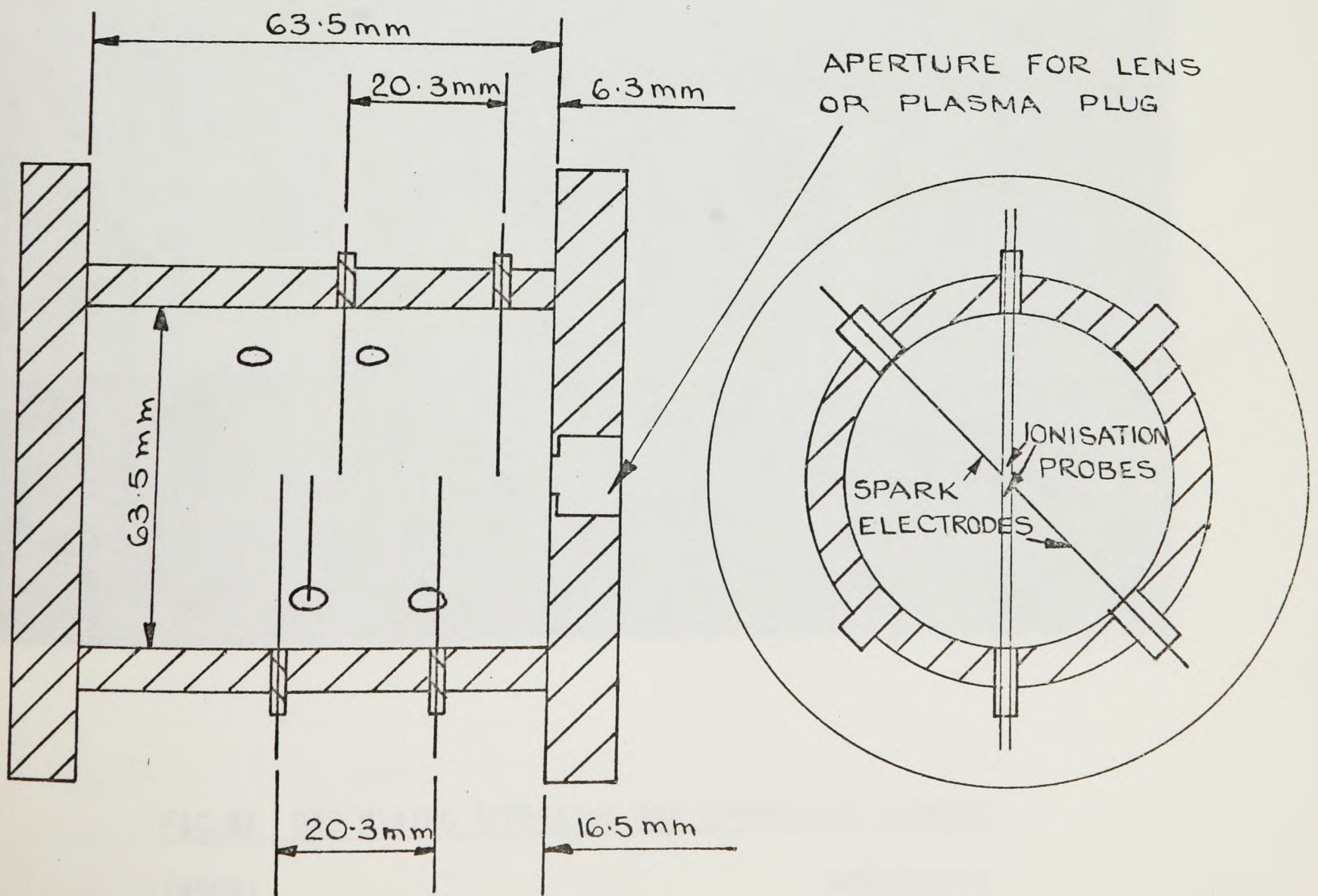
(2161)

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FLOW DIAGRAM OF MIXING APPARATUS

FIG. 19



COMBUSTION CHAMBER WITH IONISATION
PROBES & SPARK ELECTRODES

FIG. 20

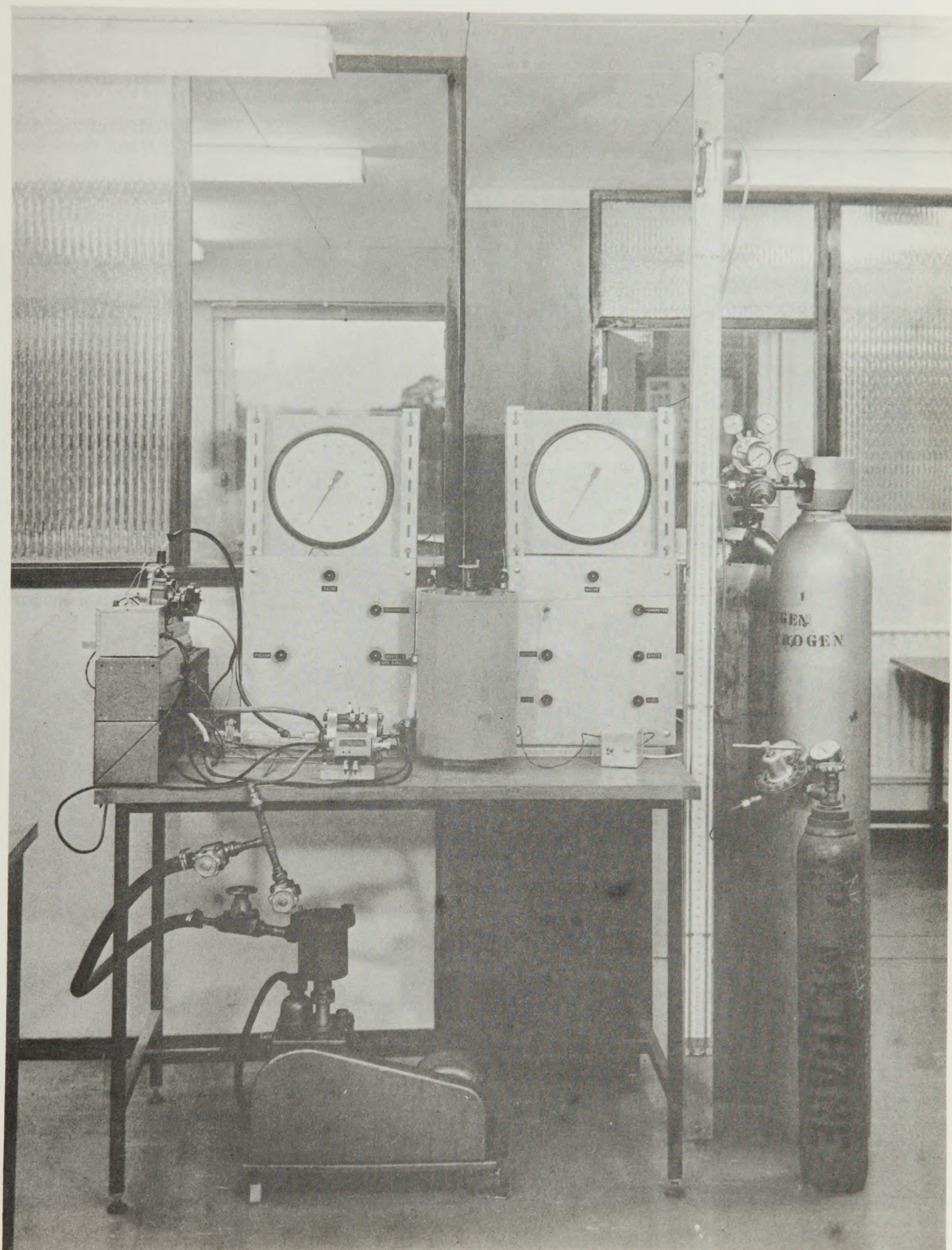


FIG. 21 GAS MIXING APPARATUS AND COMBUSTION CHAMBER

(4504)

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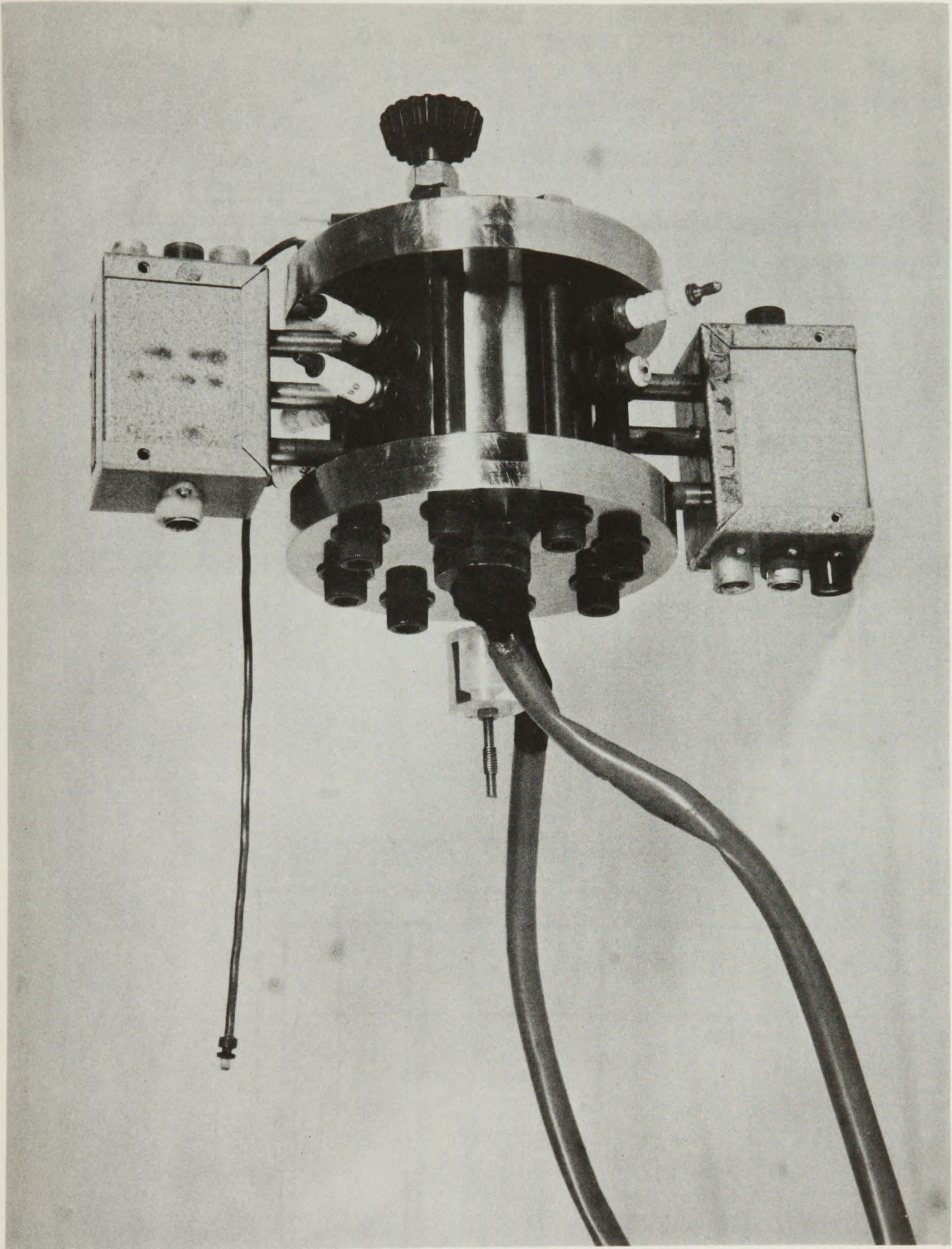
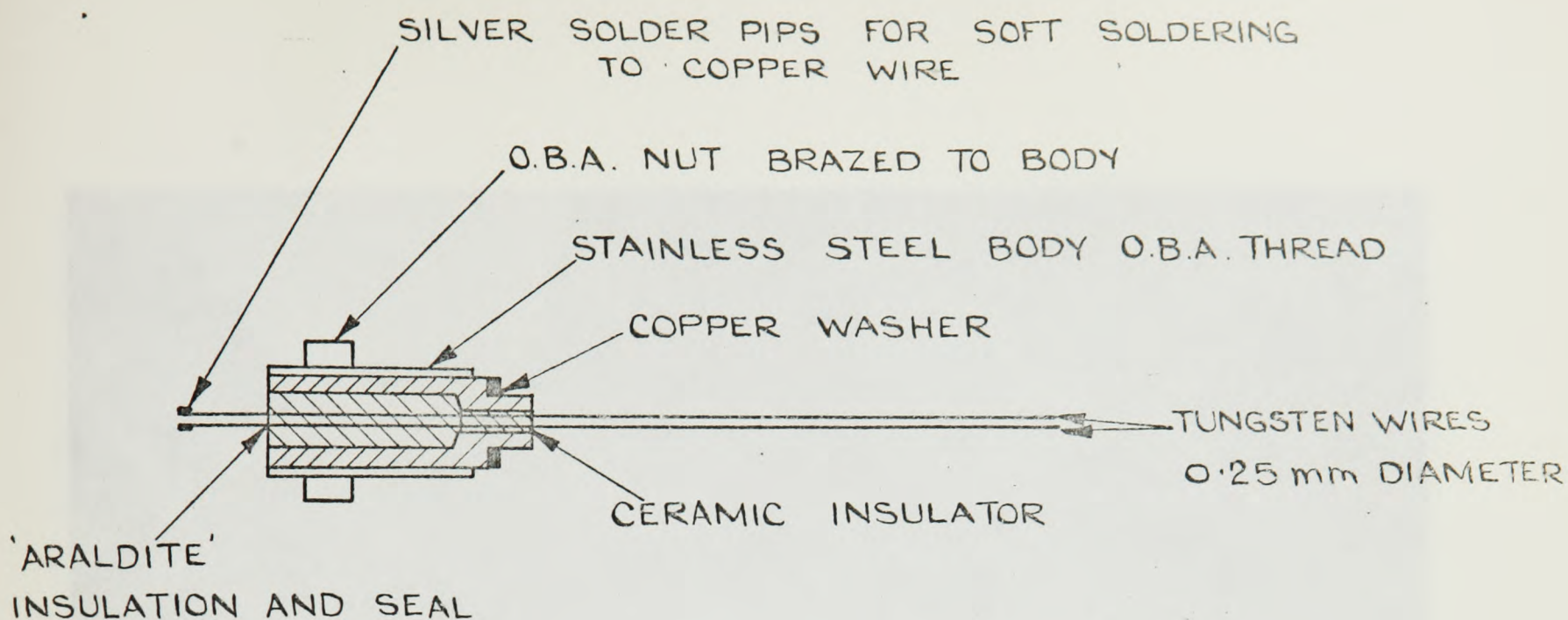


FIG. 22 ASSEMBLED COMBUSTION CHAMBER WITH PLASMA PLUG FITTED

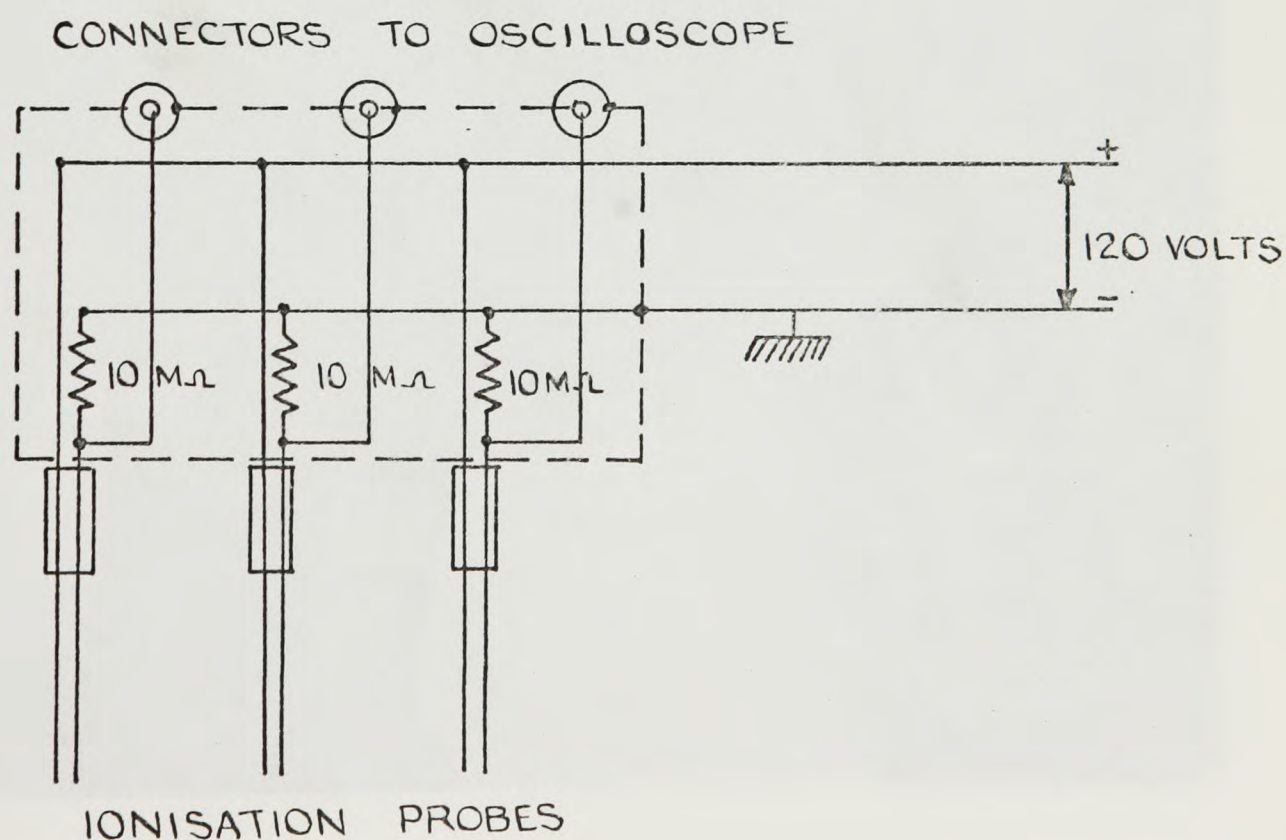
(4501)

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IONISATION PROBE

FIG. 23



CIRCUIT FOR IONISATION PROBES

FIG. 24

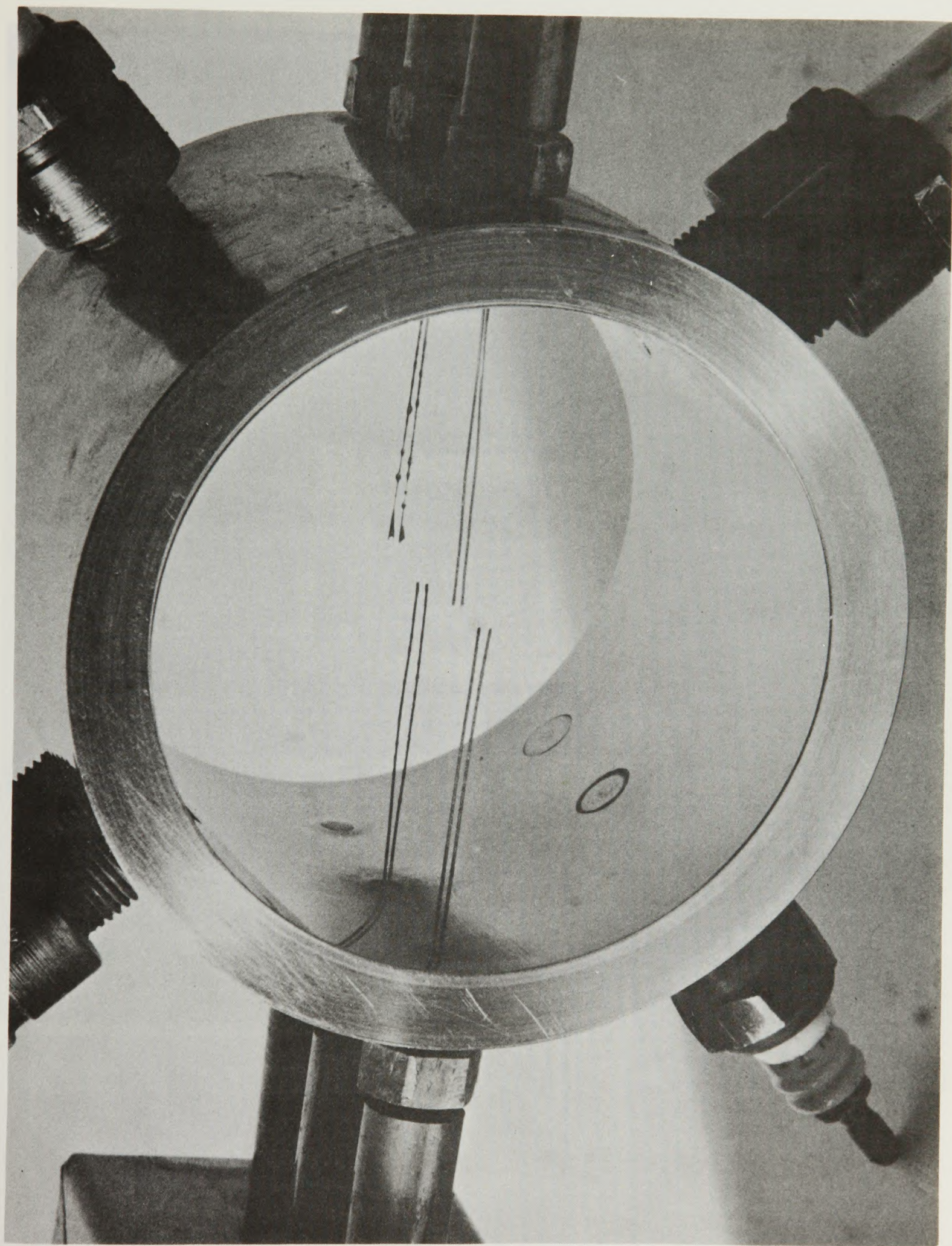


FIG. 25 COMBUSTION CHAMBER WITH IONISATION GAPS FITTED

(4502)

620/003/73

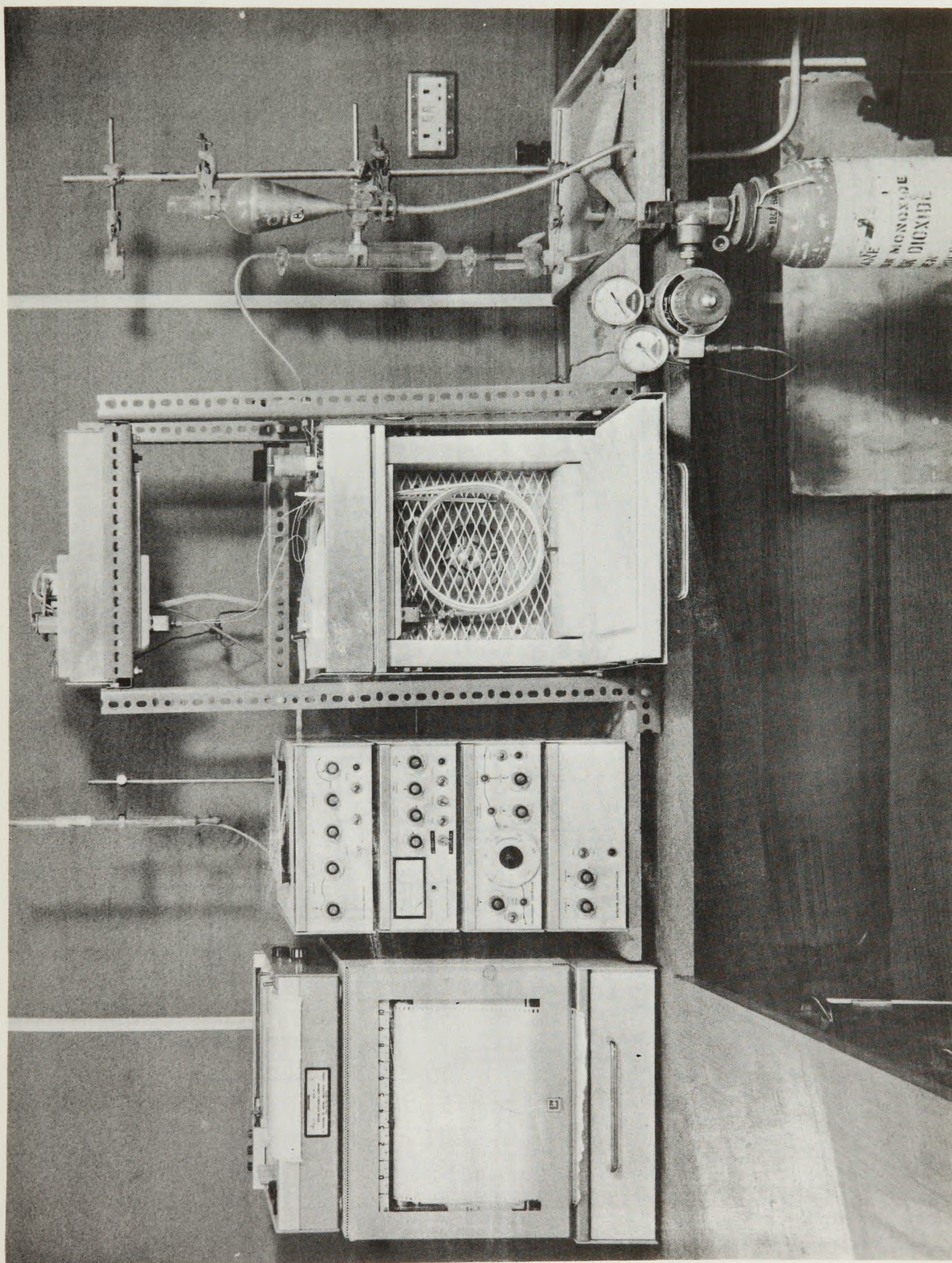
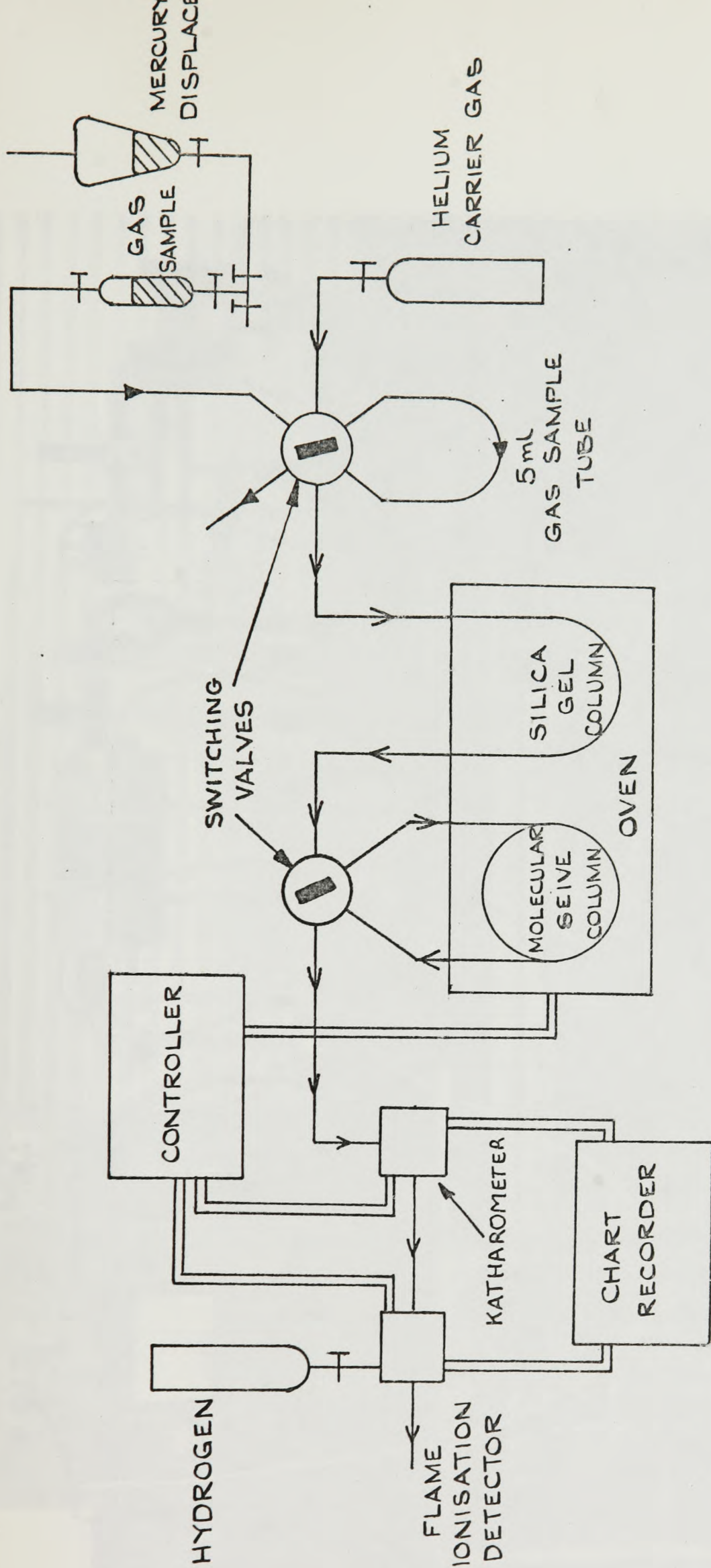


FIG. 26 GAS CHROMATOGRAPH



FLOW DIAGRAM FOR GAS CHROMATOGRAPHY

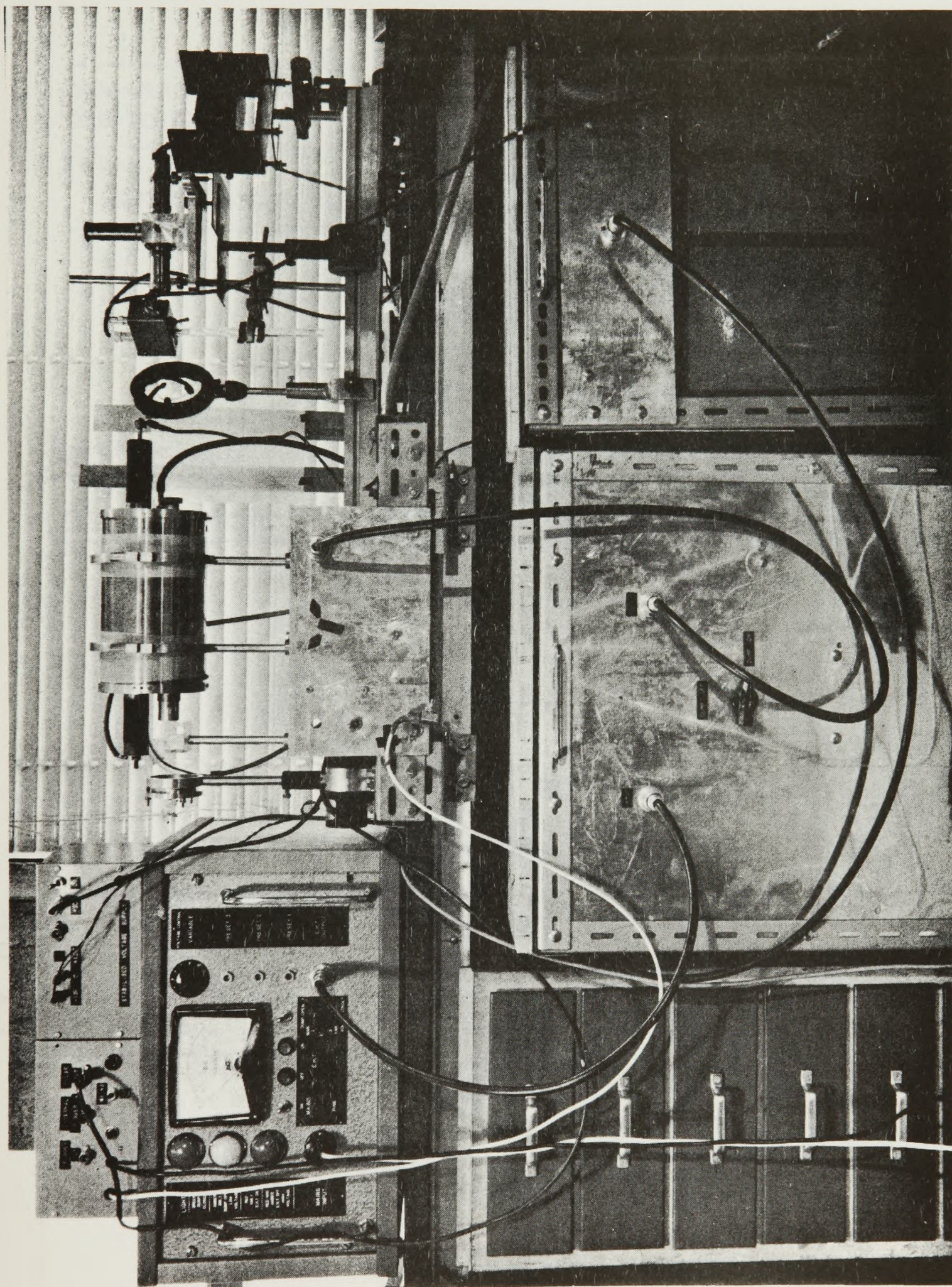
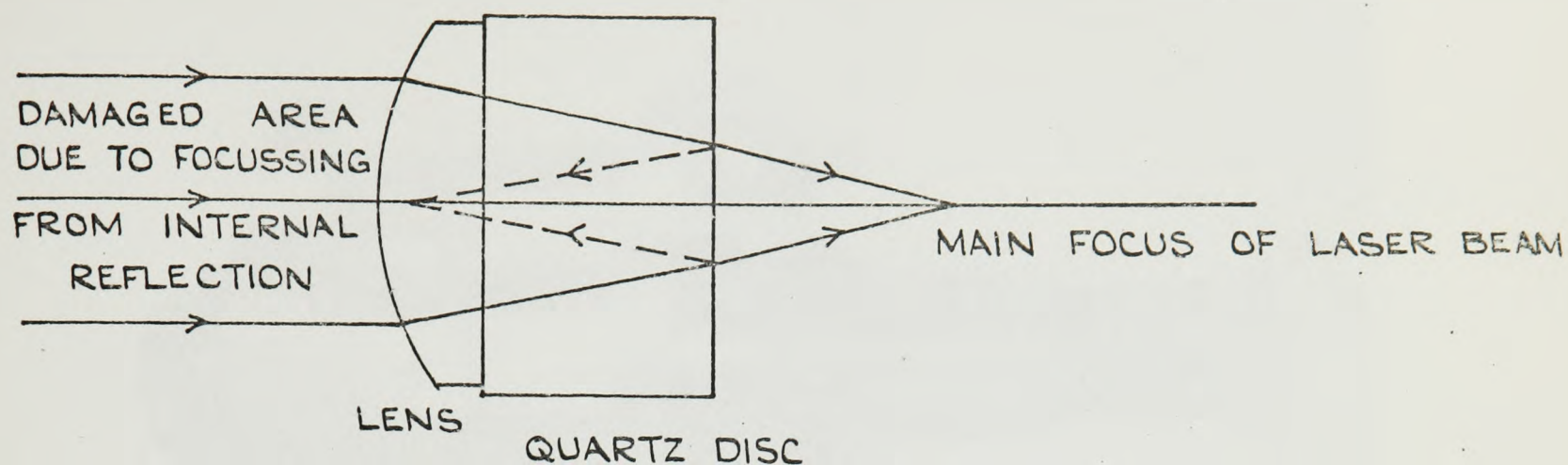


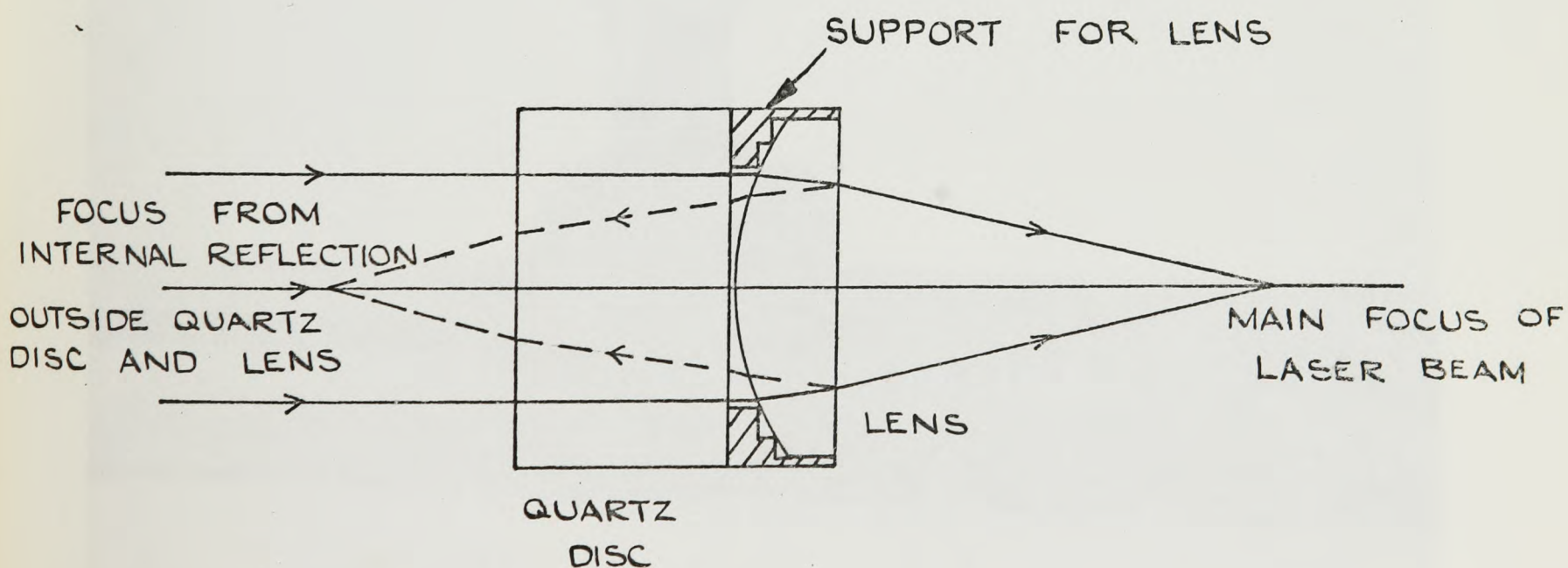
FIG.28 LASER SYSTEM

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FOCUSSING WITHIN LENS DUE TO INTERNAL REFLECTION OF LASER BEAM FROM QUARTZ DISC.

FIG. 29



FOCUSSING OUTSIDE LENS AND QUARTZ DISC AND ADDITIONAL SUPPORT FOR LENS.

FIG. 30

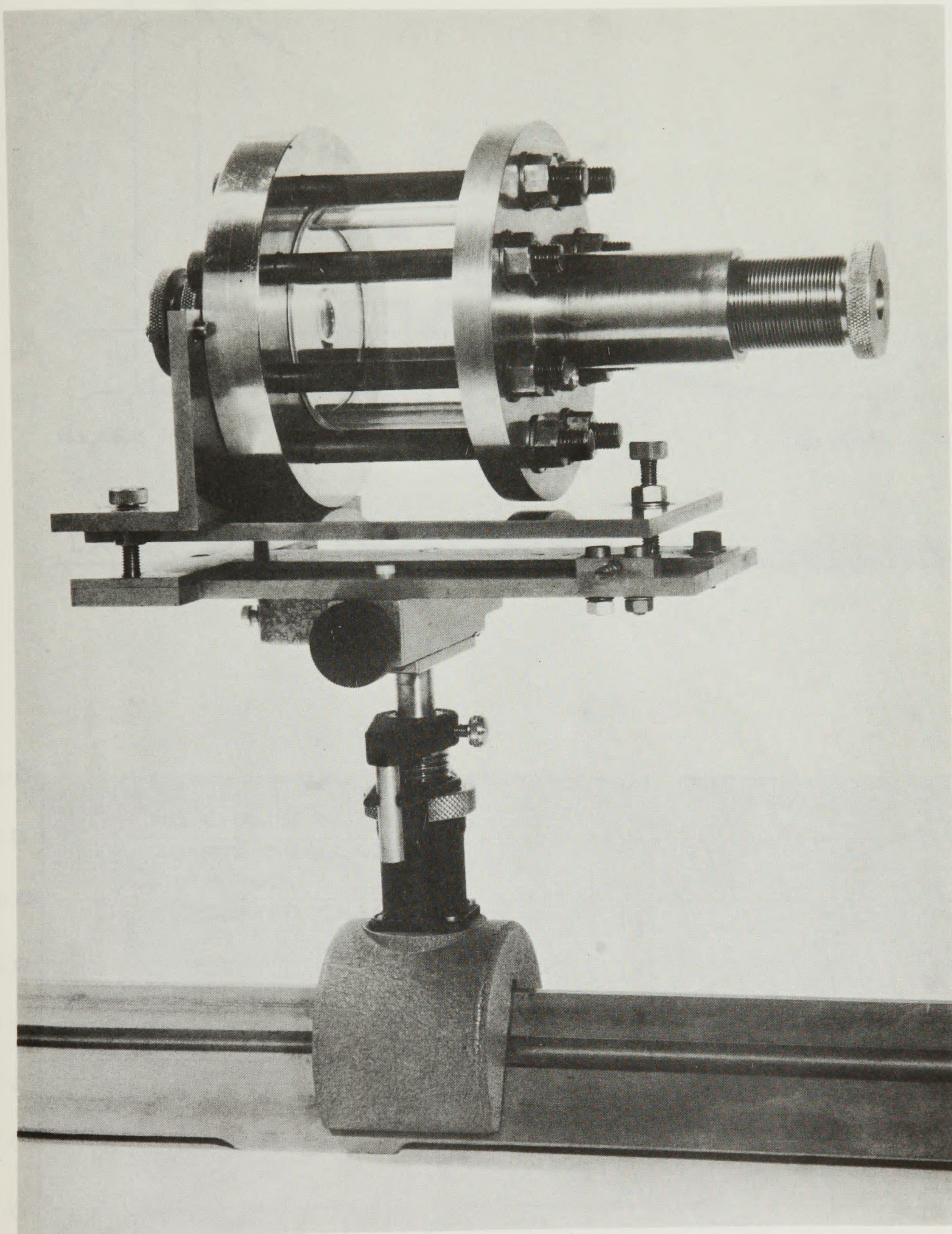
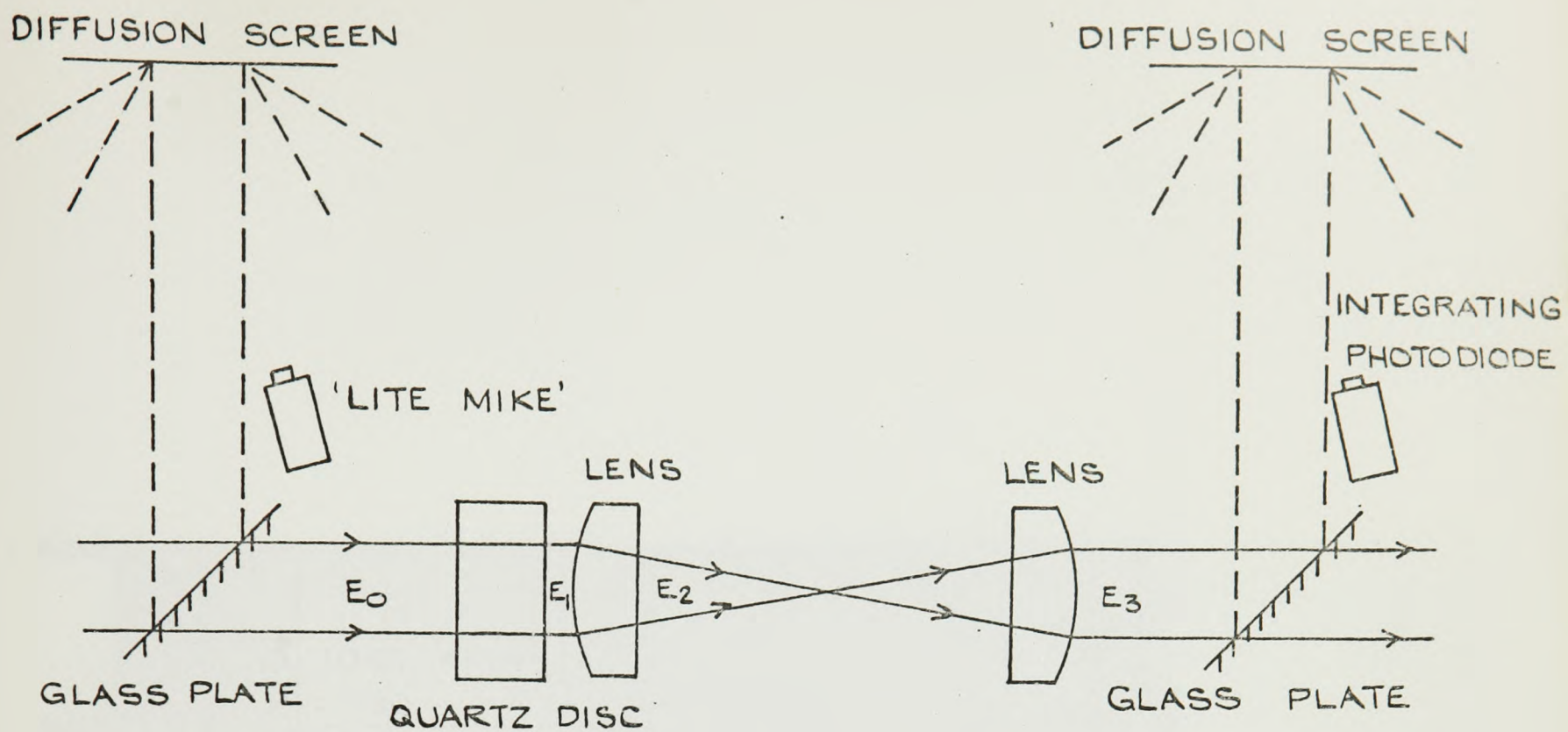


FIG. 31 CHAMBER AND END PLATE FOR ENERGY MEASUREMENT ON ADJUSTABLE TABLE

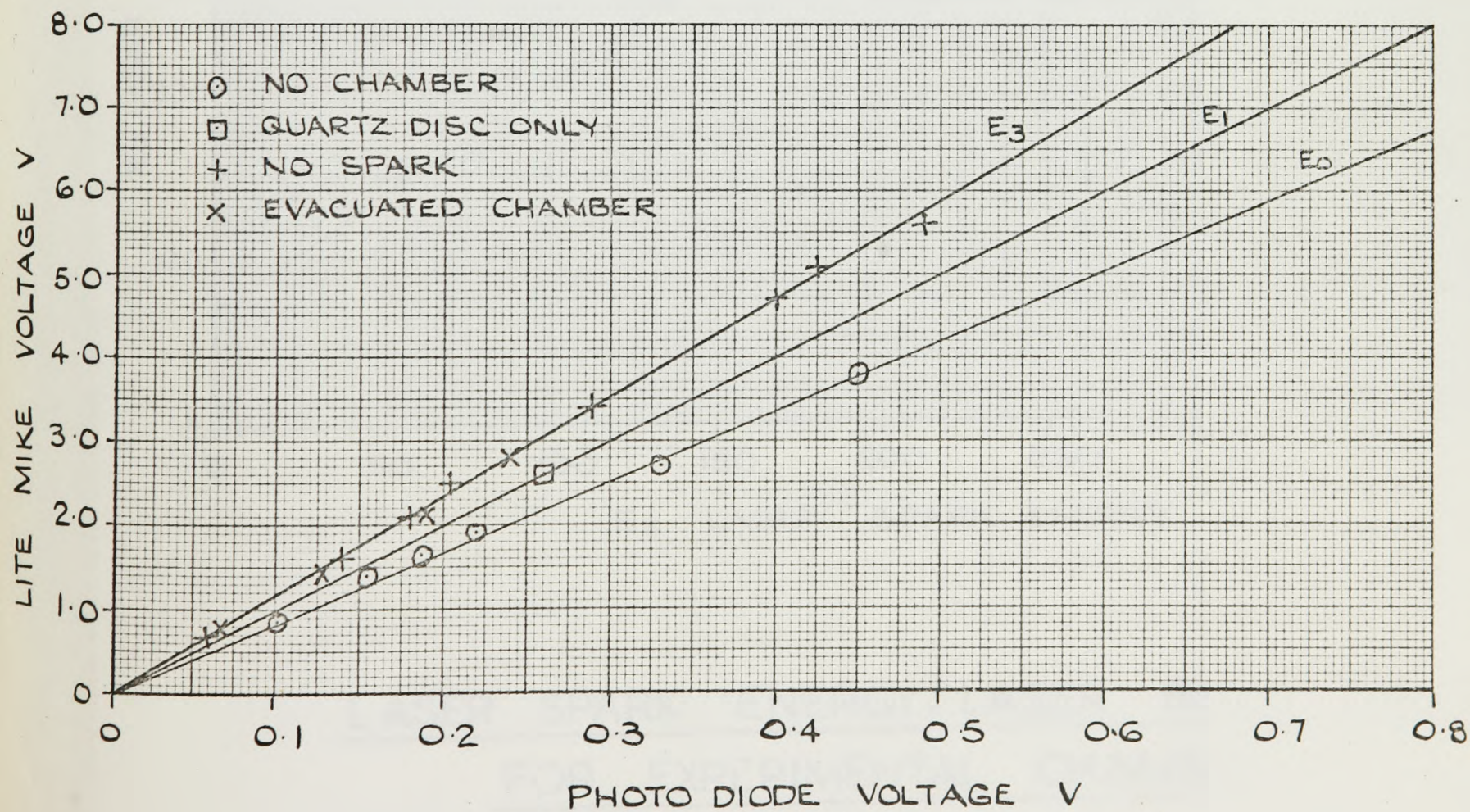
(4503)

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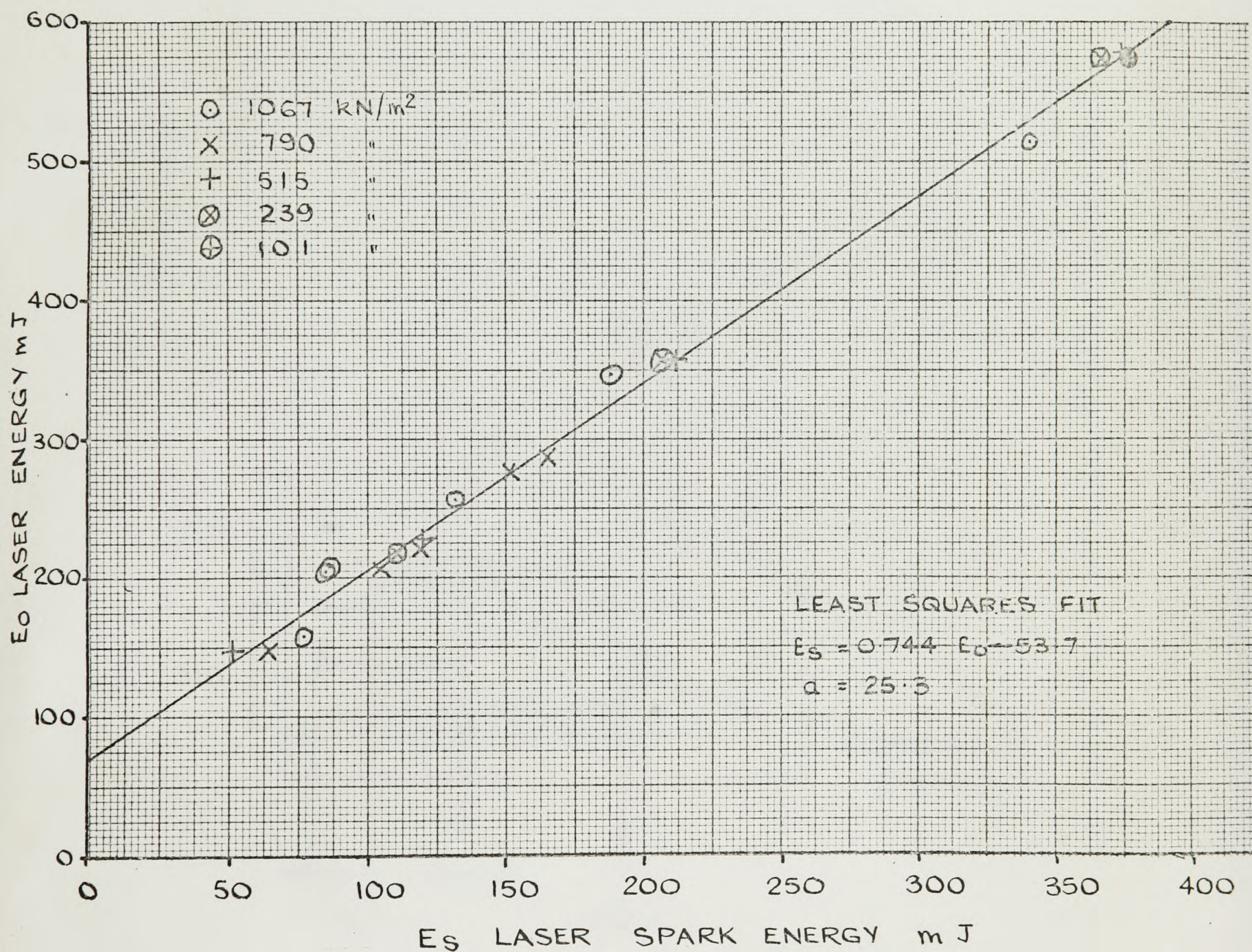
LASER SPARK ENERGY MEASUREMENT EQUIPMENT

FIG. 32

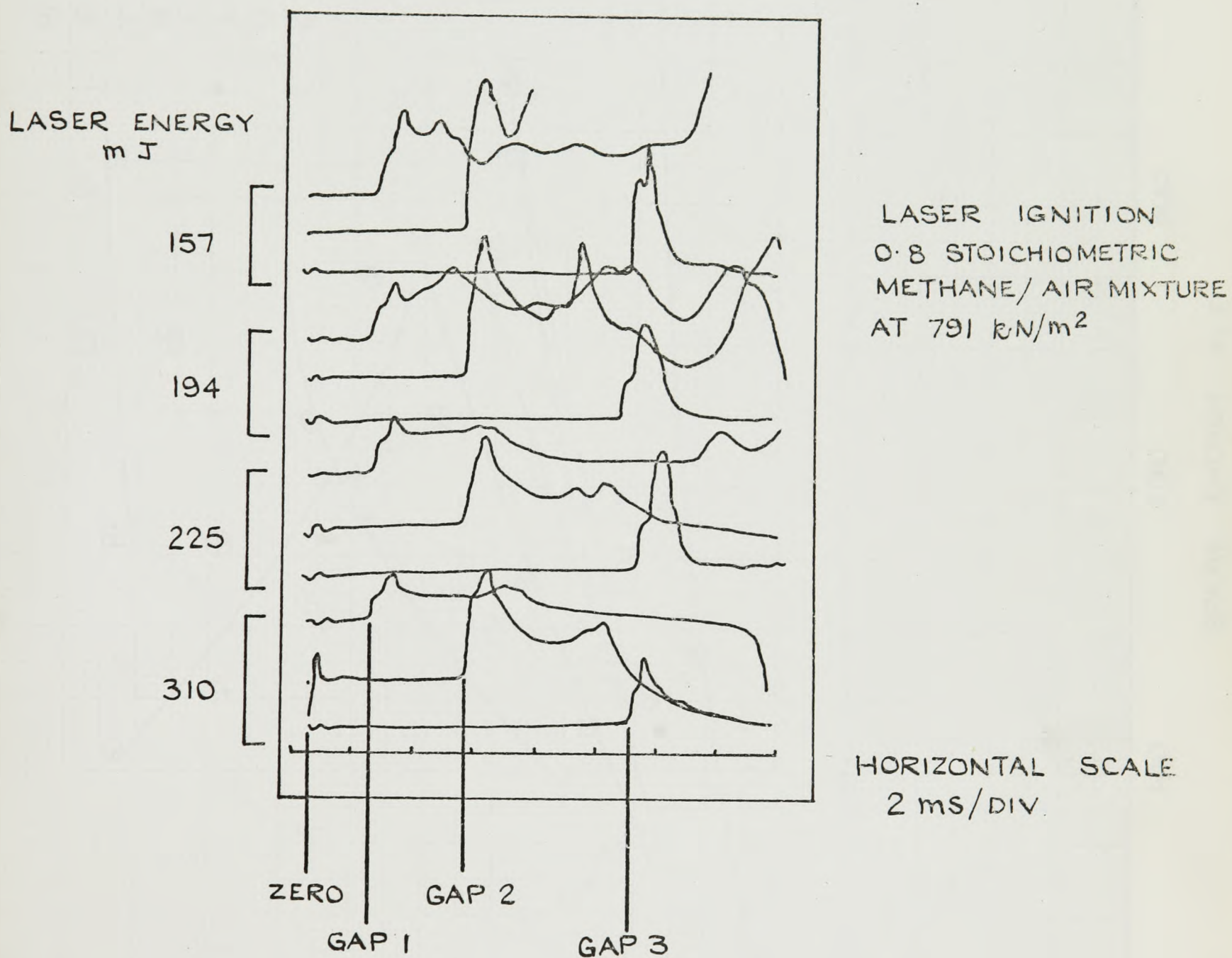


LASER SPARK ENERGY MEASUREMENT CALIBRATION OF EQUIPMENT

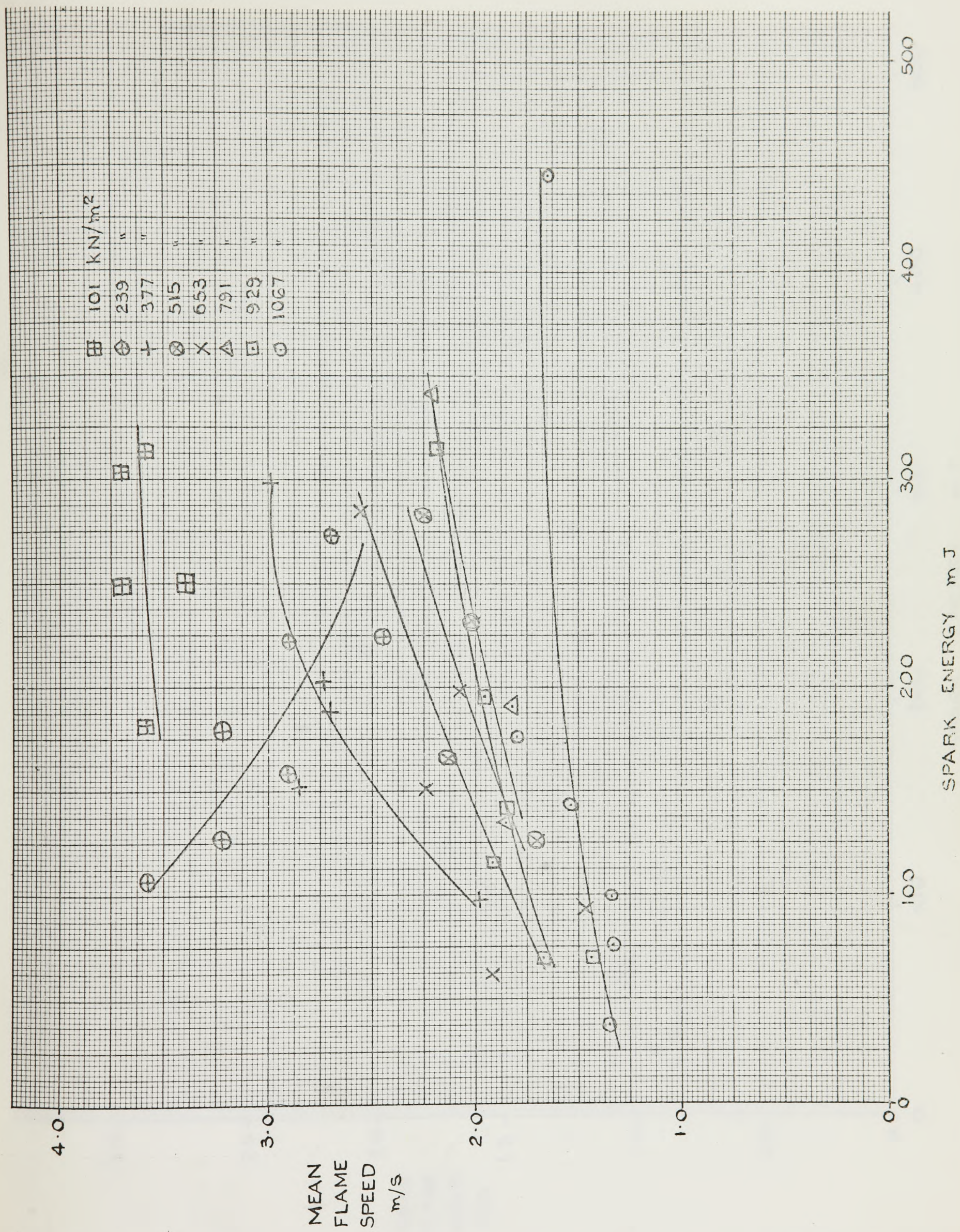
FIG. 33



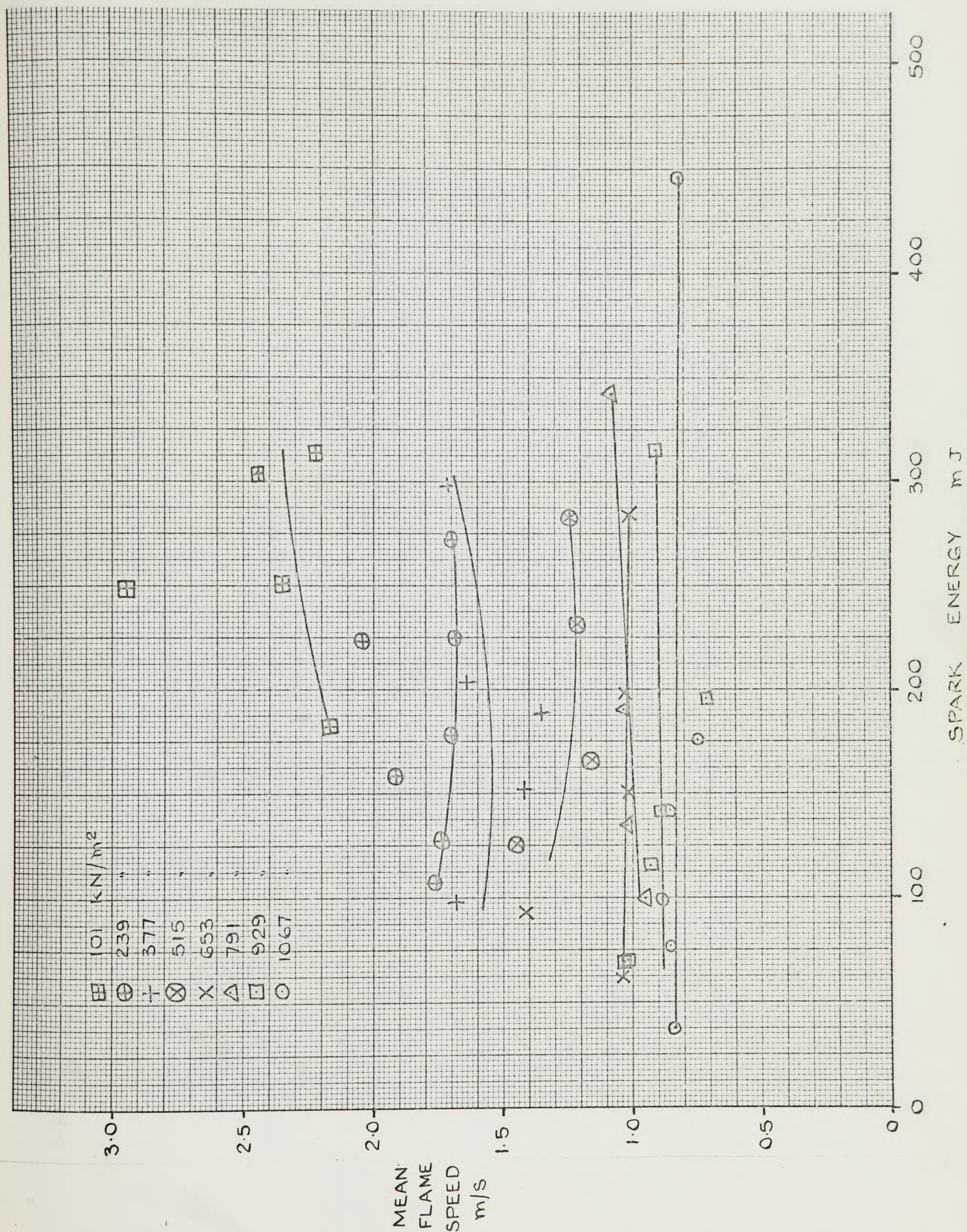
LASER SPARK ENERGY/LASER BEAM ENERGY
FOR EXPERIMENTAL CHAMBER



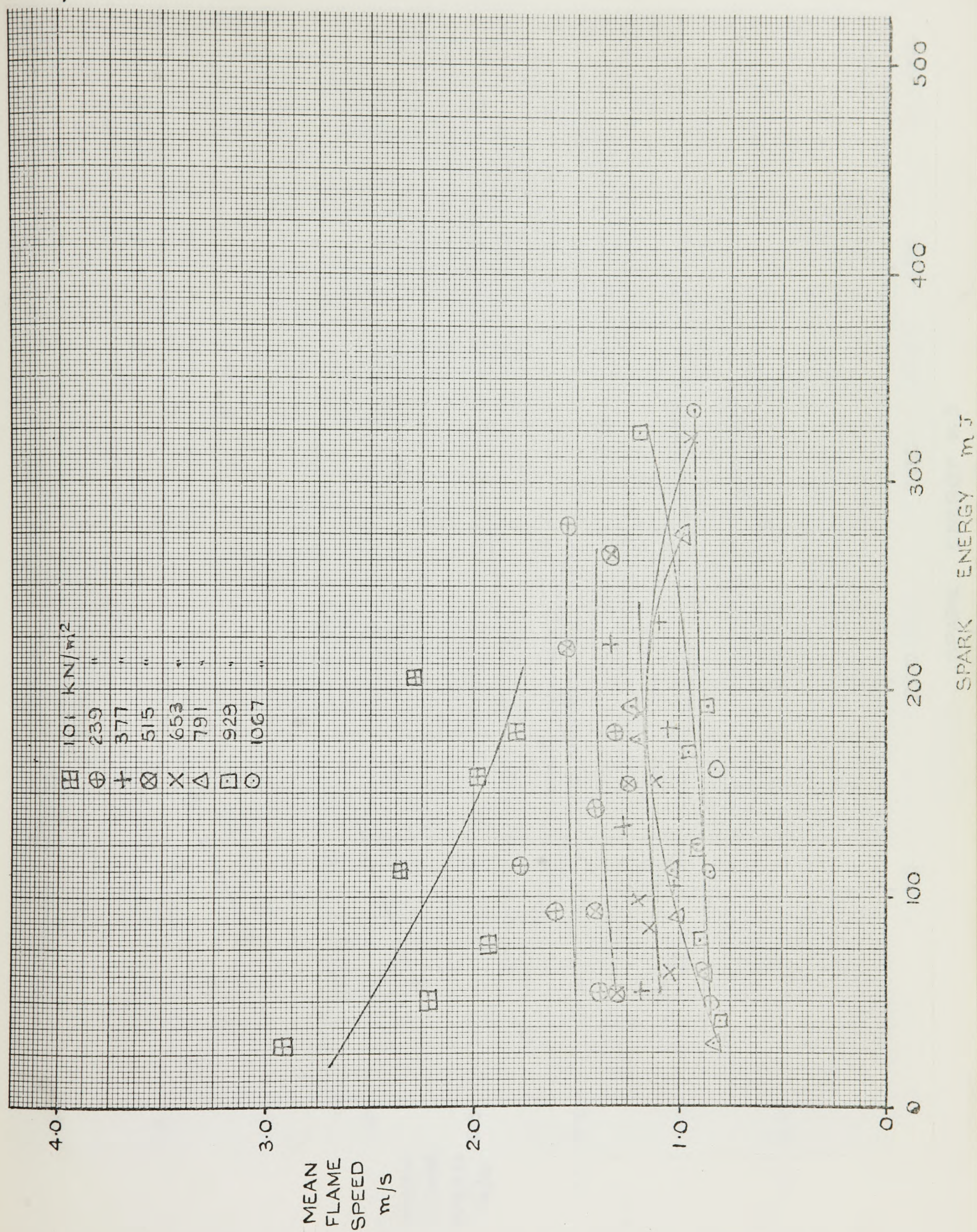
TYPICAL IONISATION PROBE OUTPUT IN
0.8 STOICHIOMETRIC METHANE / AIR MIXTURE
AT 791 kN/m²



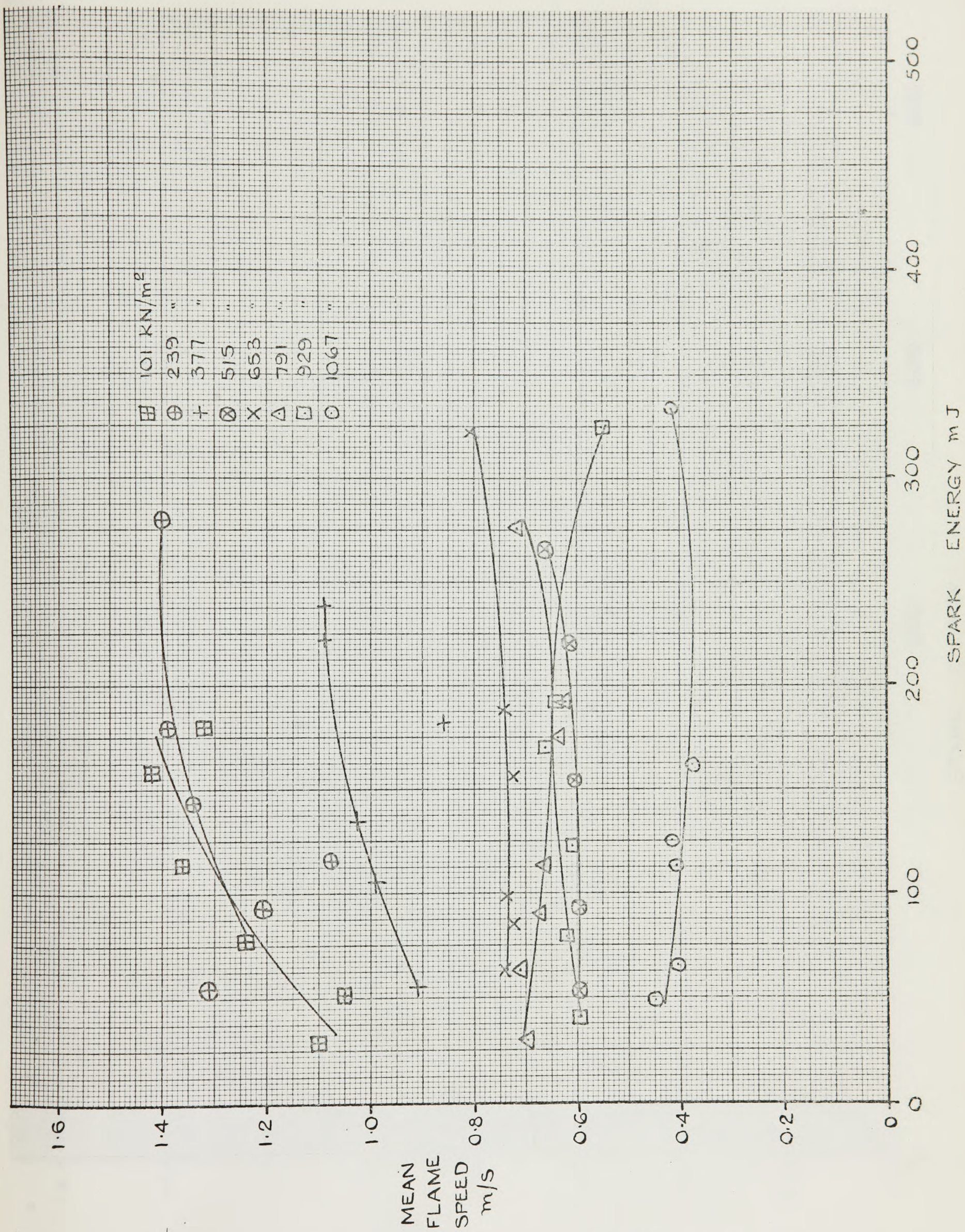
MEAN FLAME SPEED/SPARK ENERGY FOR LASER
SPARK IGNITION OF 1.0 STOICHIOMETRIC METHANE/
AIR MIXTURE 0-10 mm FROM FOCUS



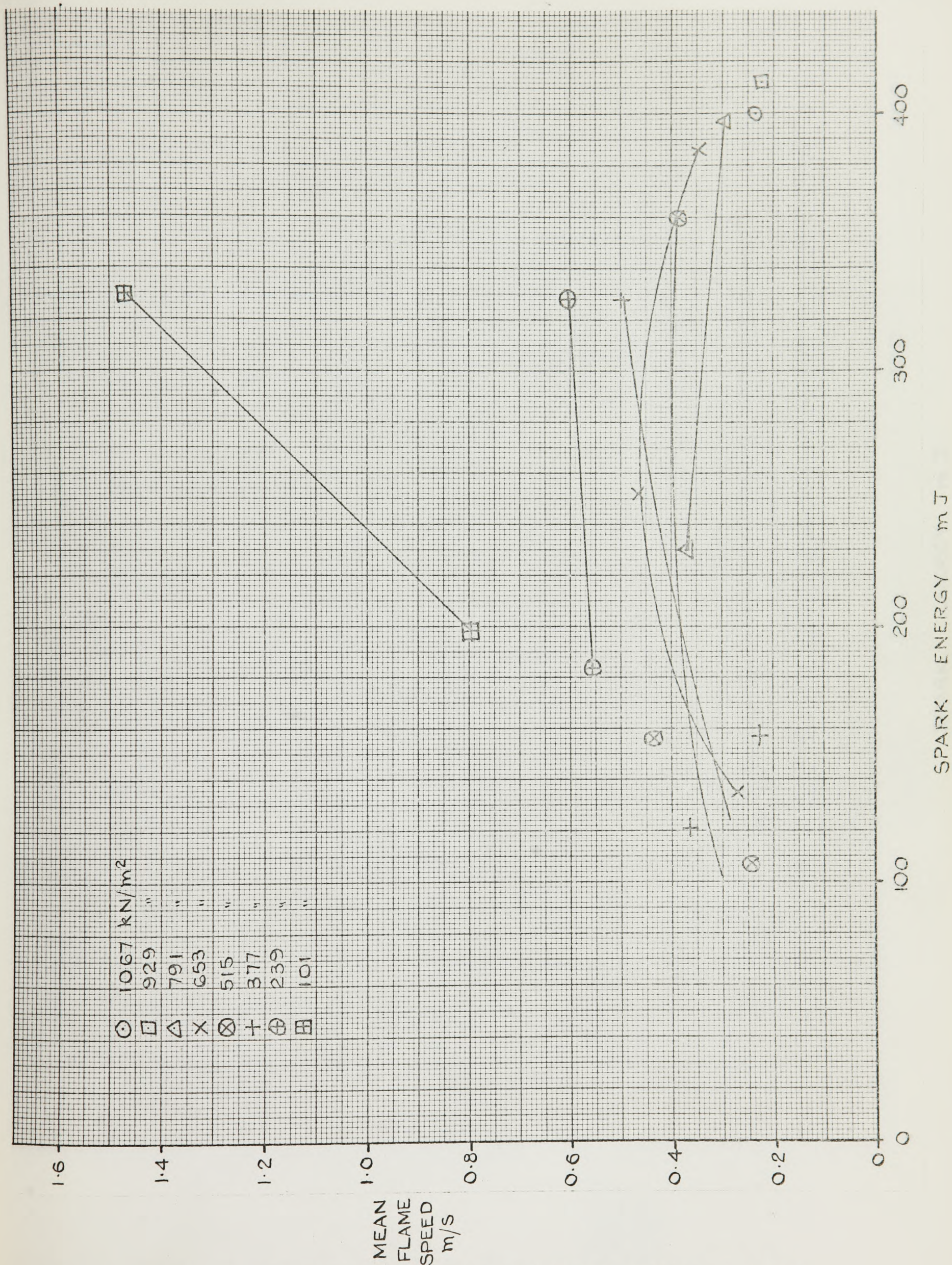
MEAN FLAME SPEED/ SPARK ENERGY FOR LASER SPARK IGNITION OF 1.0 STOICHIOMETRIC METHANE/ AIR MIXTURES, 10-20 mm FROM FOCUS



MEAN FLAME SPEED/ SPARK ENERGY FOR LASER
SPARK IGNITION OF 0.8 STOICHIOMETRIC METHANE/
AIR MIXTURE, 0-10 mm FROM FOCUS

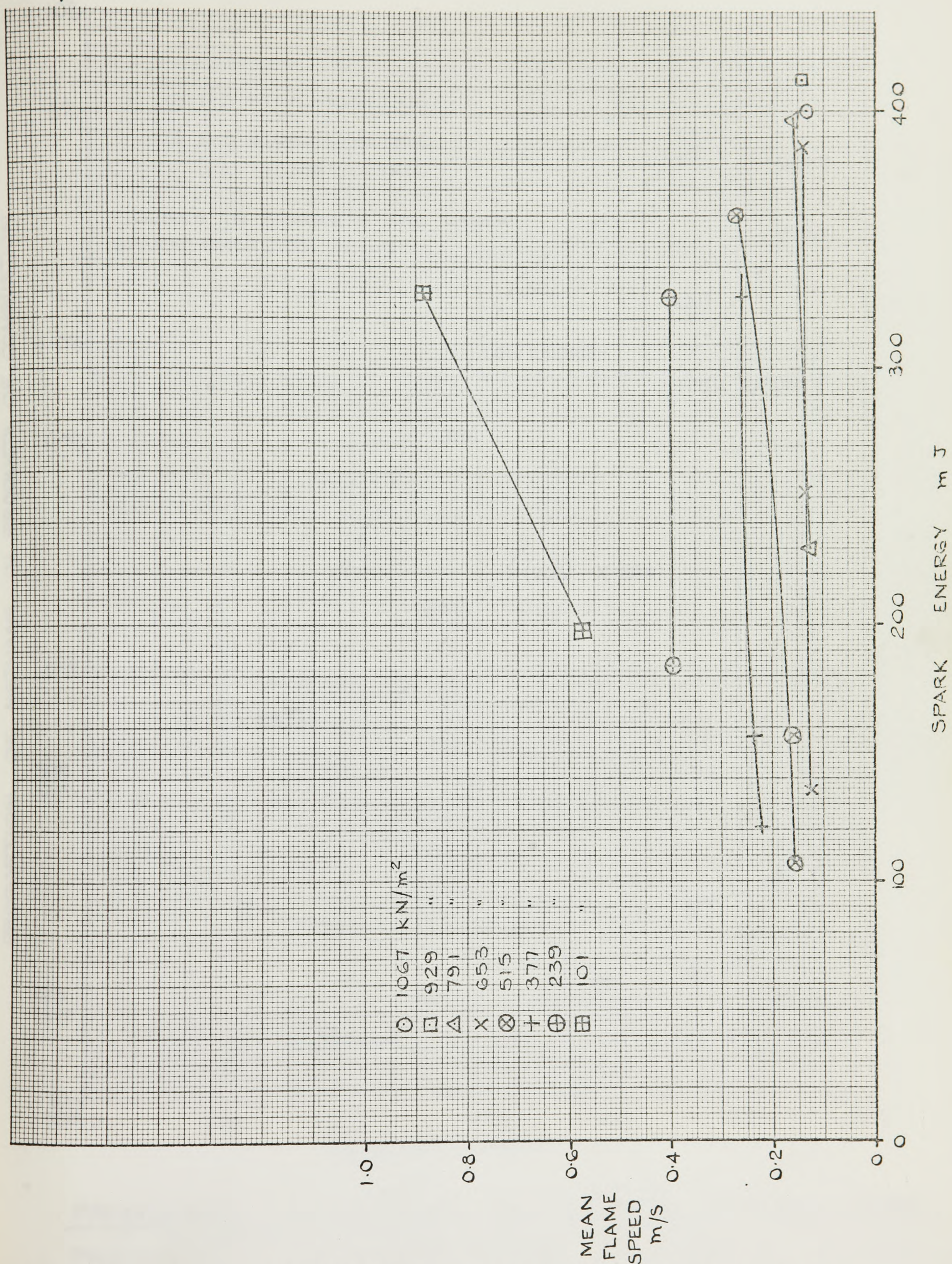


MEAN FLAME SPEED/ SPARK ENERGY FOR LASER
 SPARK IGNITION OF 0.8 STOICHIOMETRIC METHANE /
 AIR MIXTURE, 10-20 mm FROM FOCUS

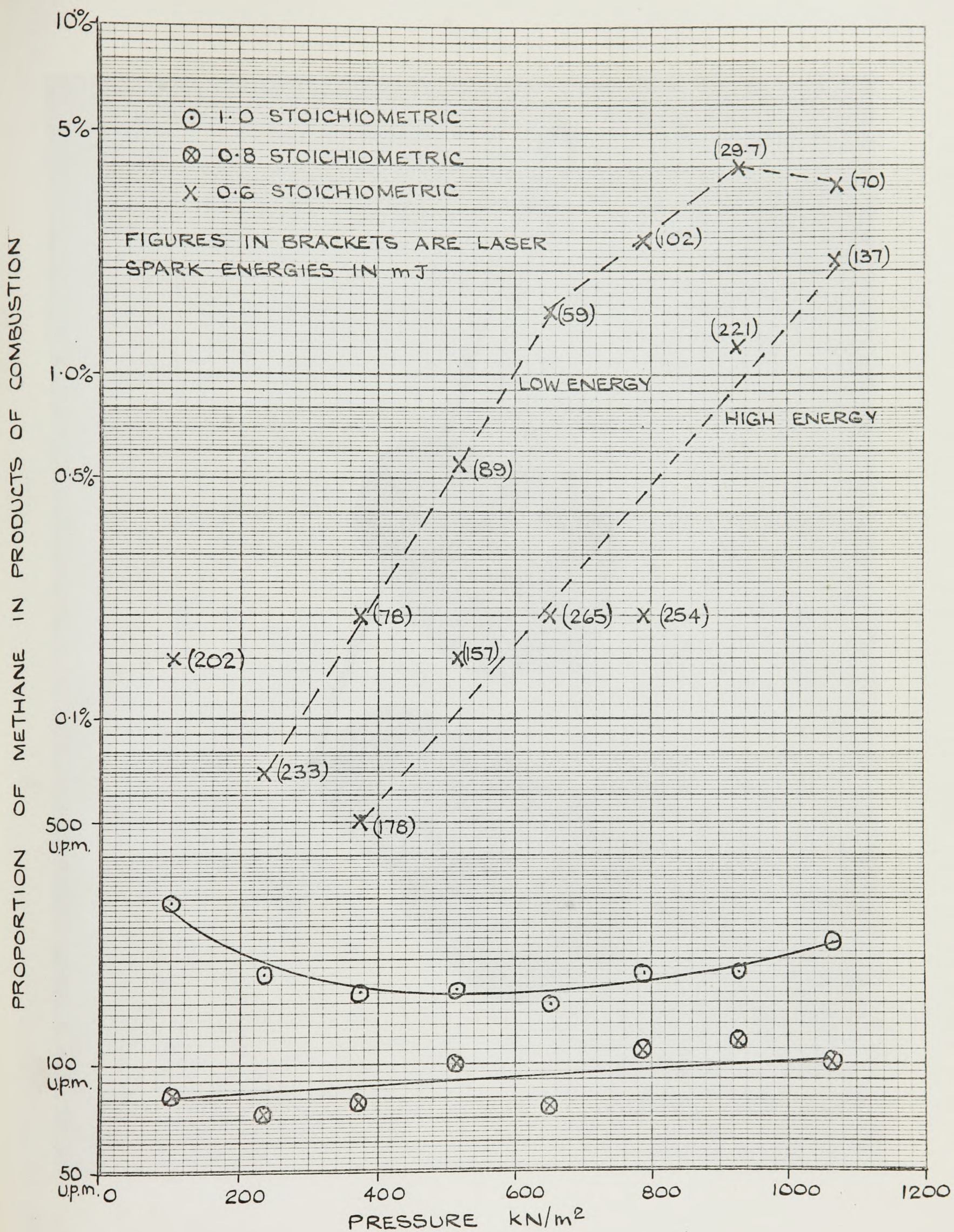


MEAN FLAME SPEED/ SPARK ENERGY FOR LASER
SPARK IGNITION OF 0.6 STOICHIOMETRIC METHANE /
AIR MIXTURES, 0-10 mm FROM FOCUS

FIG. 40



MEAN FLAME SPEED/ SPARK ENERGY FOR LASER
SPARK IGNITION OF 0.6 STOICHIOMETRIC METHANE/
AIR MIXTURES, 10-20 mm FROM FOCUS



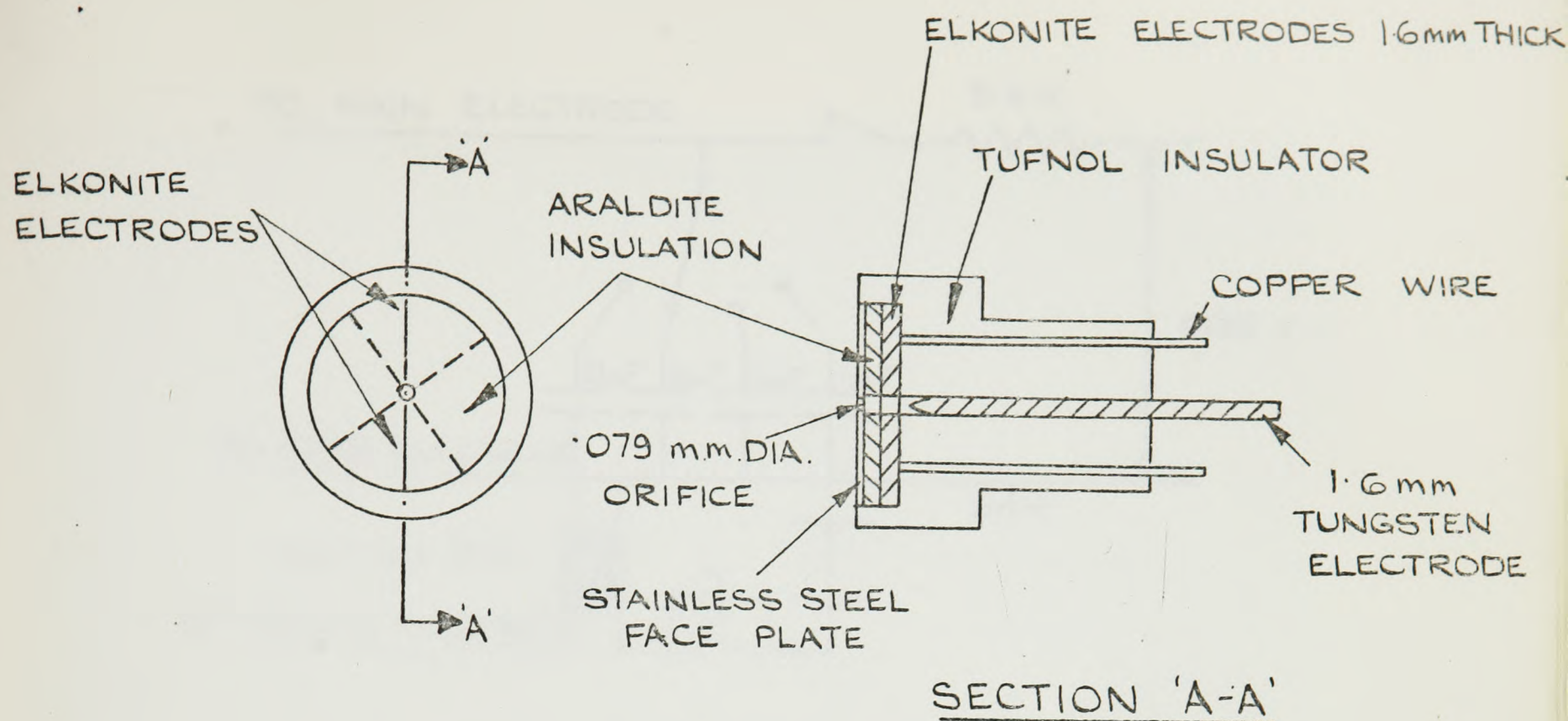
PROPORTION OF METHANE IN PRODUCTS OF COMBUSTION/
PRESSURE FOR LASER SPARK IGNITION OF METHANE/
AIR MIXTURES



FIG. 43 FIRST PLASMA PLUG (RIGHT) SECOND PLASMA PLUG (LEFT)

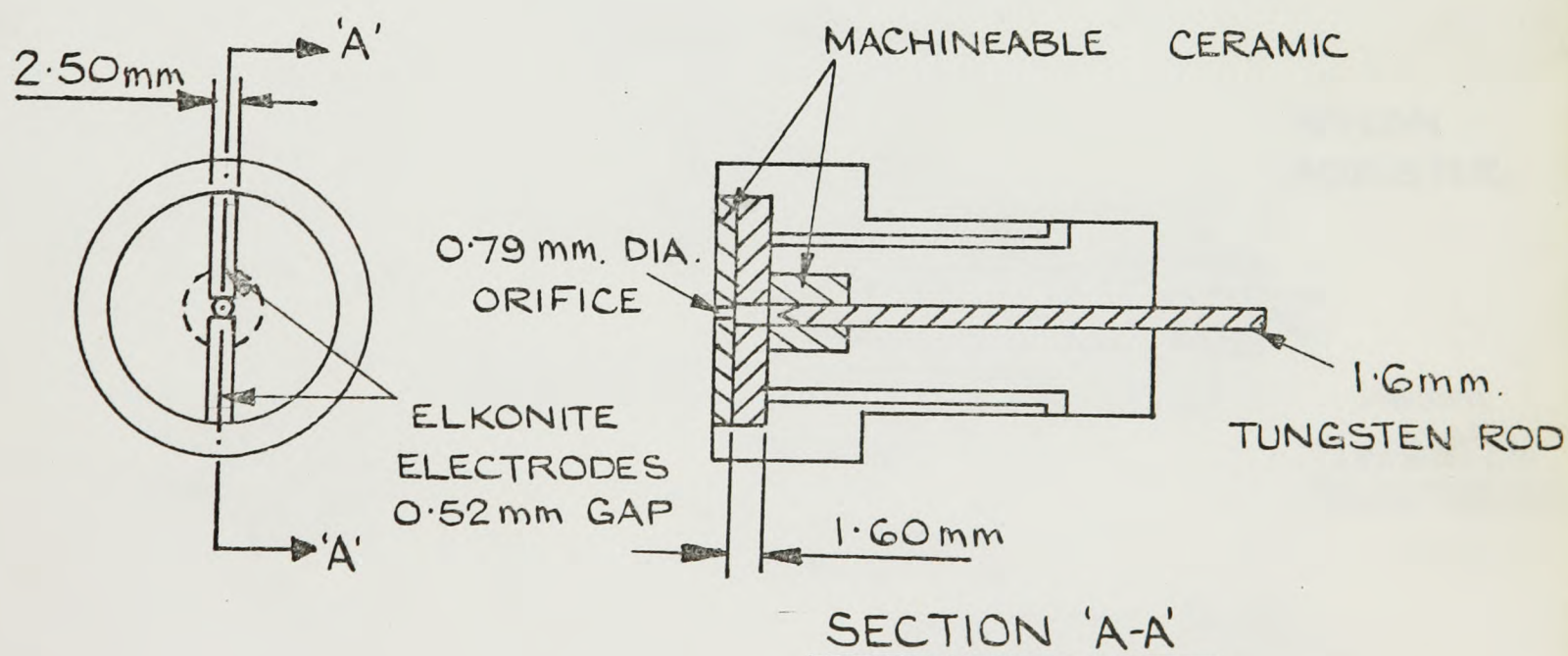
(4498)

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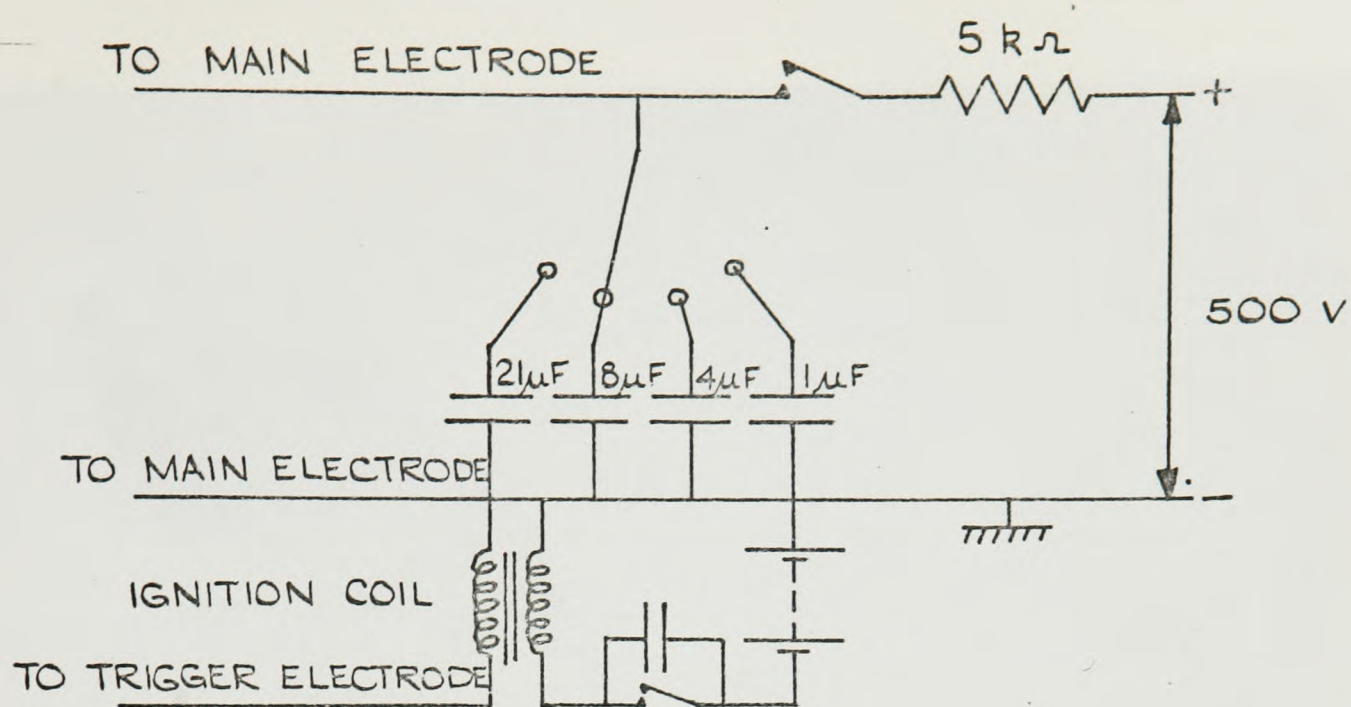
FIRST PLASMA PLUG IGNITER USING
ARALDITE INSULATION

FIG. 44



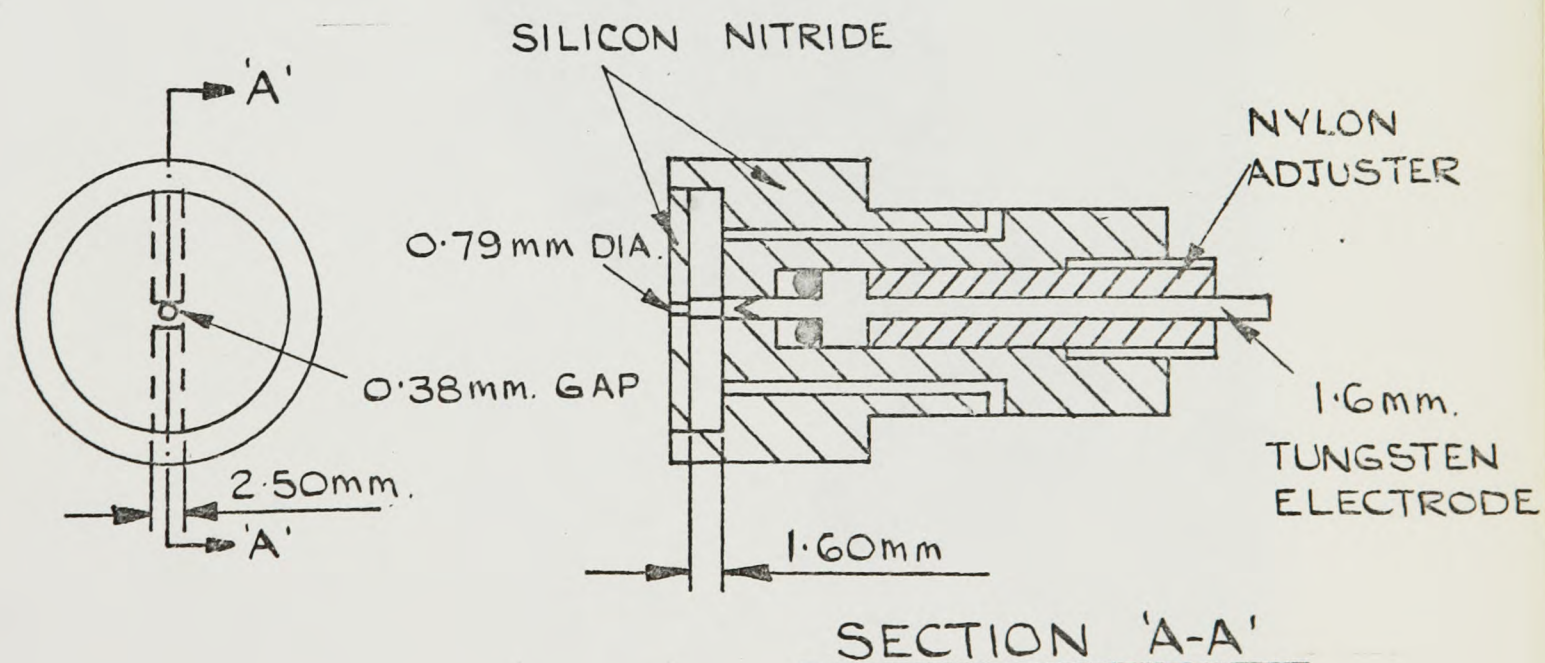
SECOND PLASMA PLUG IGNITOR USING
CERAMIC INSULATION

FIG. 45



ELECTRICAL CIRCUIT FOR OPERATION OF PLASMA PLUG

FIG. 46



SILICON NITRIDE PLASMA PLUG

FIG. 47

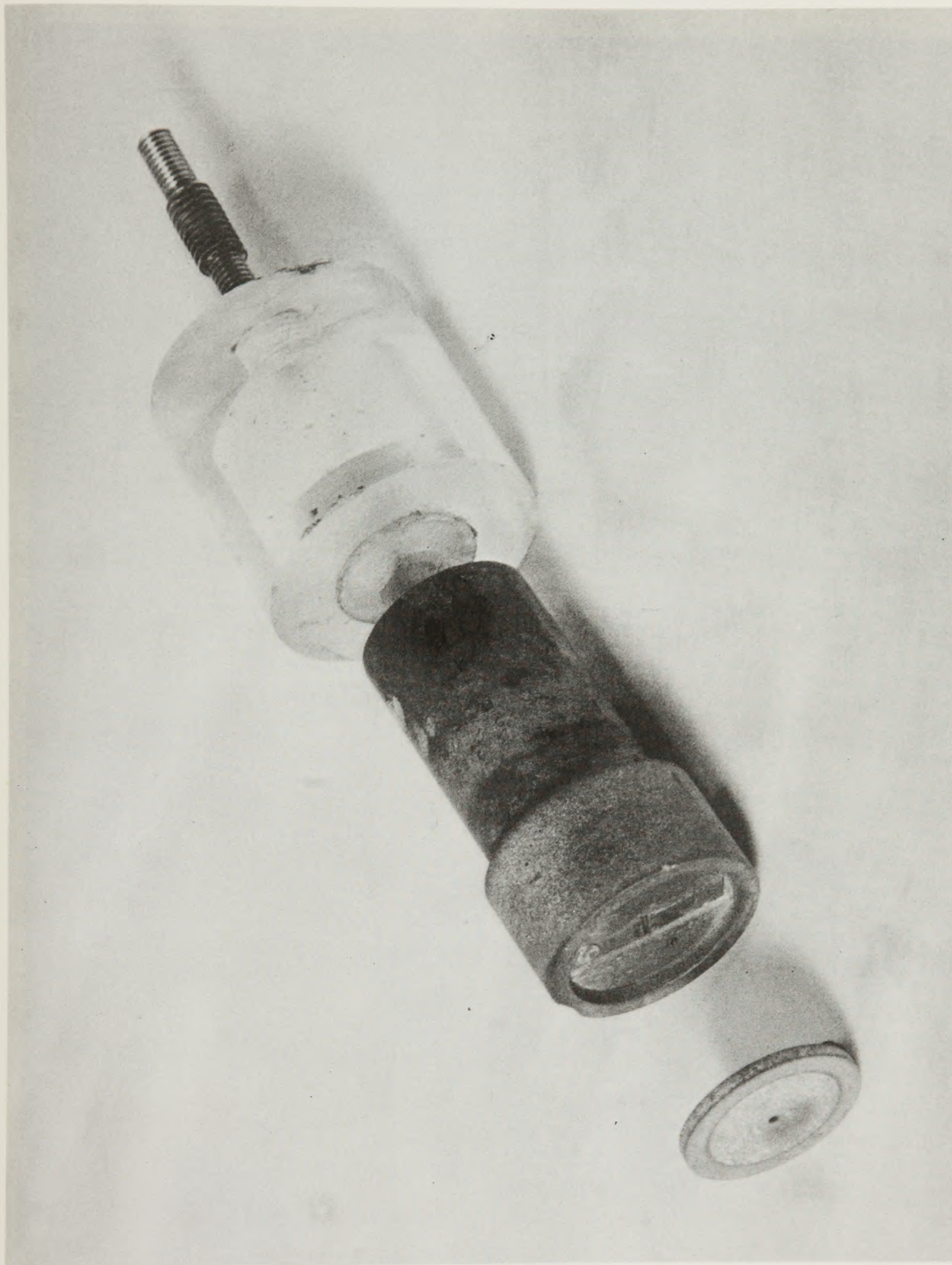


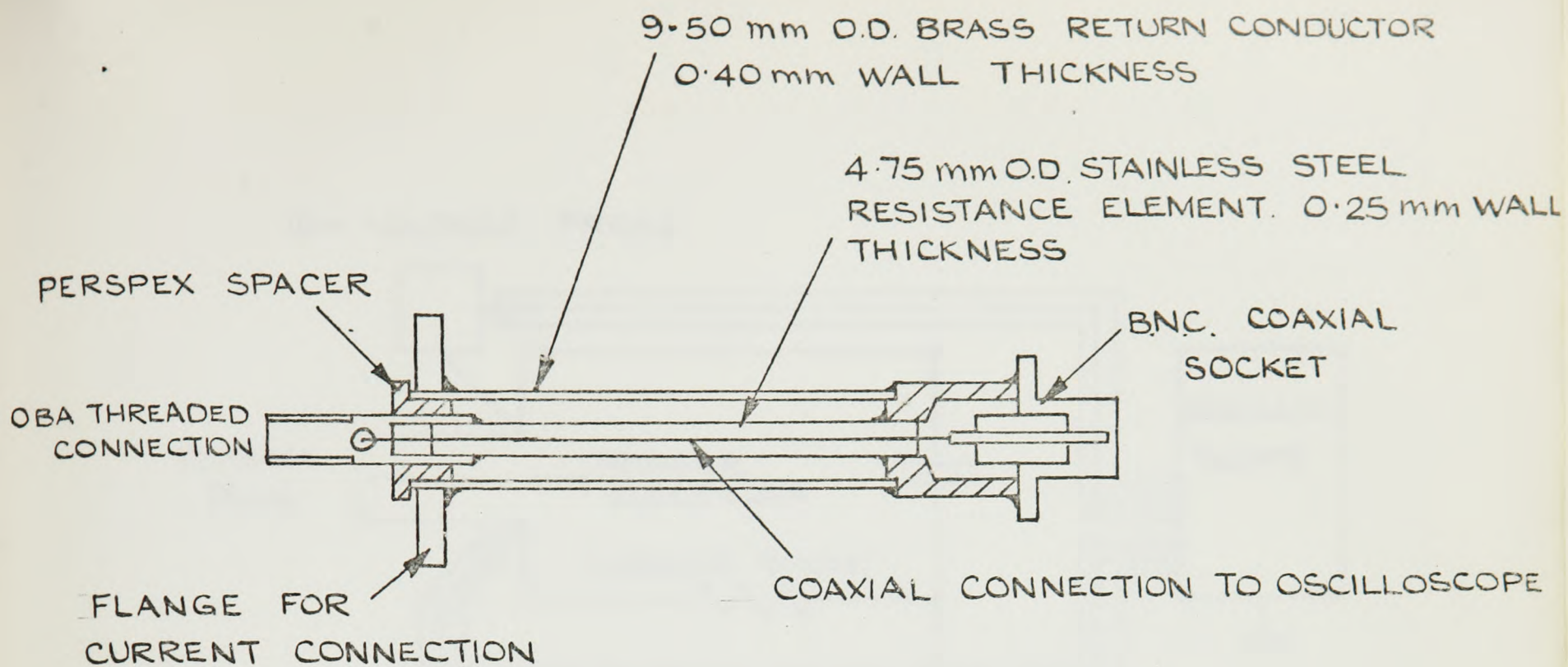
FIG. 48 SILICON NITRIDE PLASMA PLUG WITH EXTERNAL SPARK GAP

(4499)

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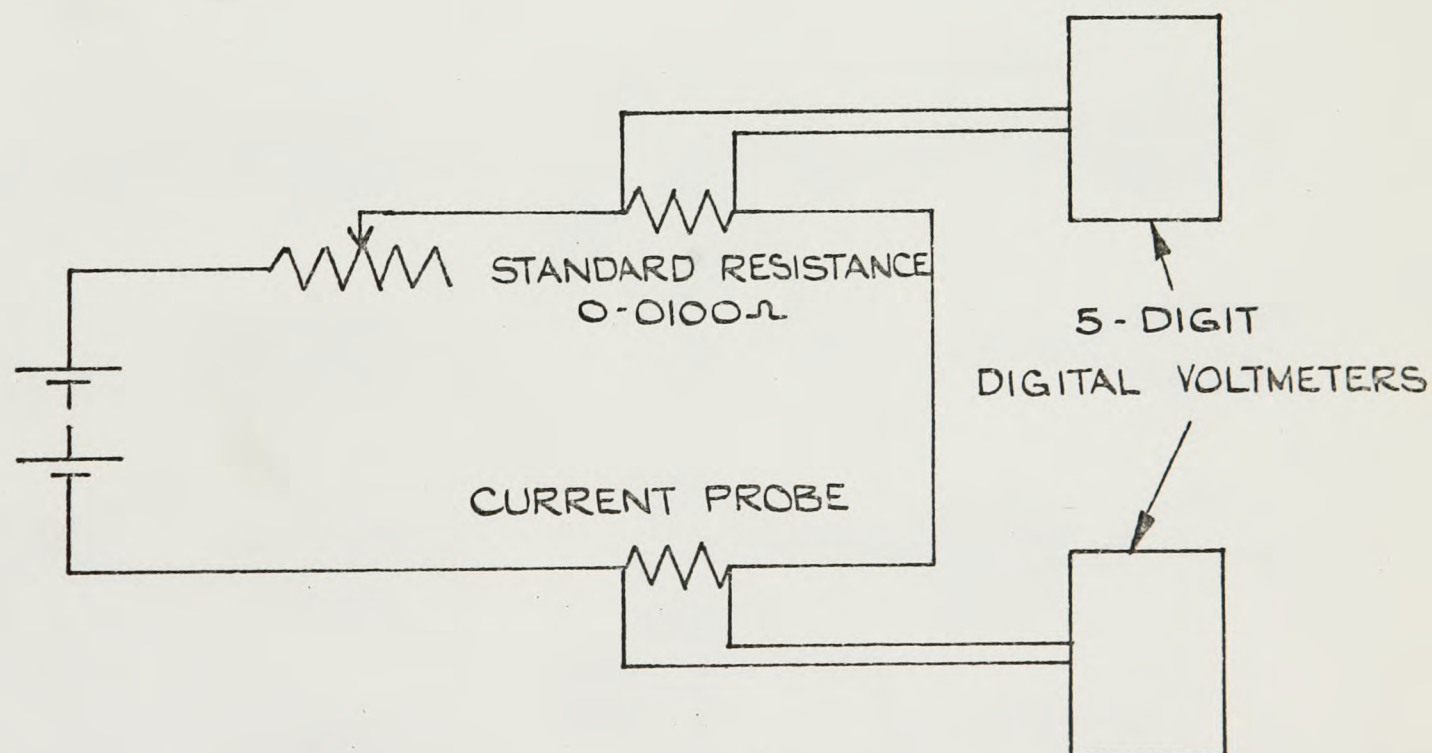
FIG. 49 COAXIAL CURRENT PROBE



ALL METAL TO METAL JOINTS ARE SOLDERED

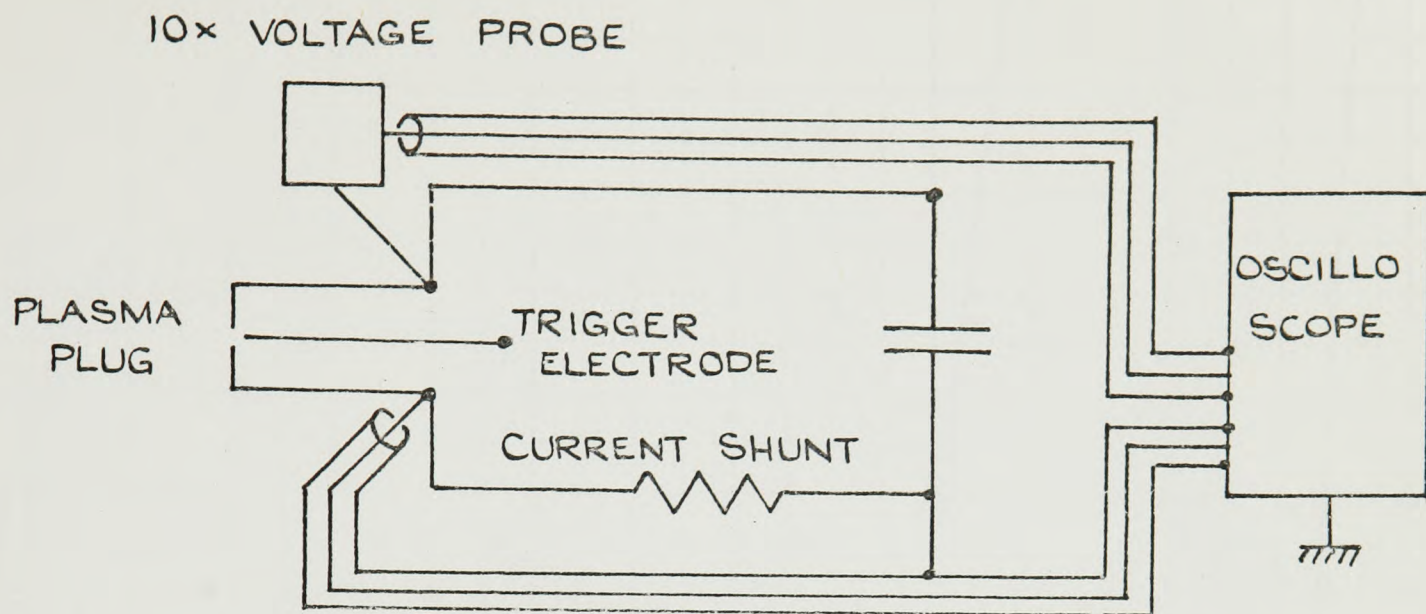
COAXIAL CURRENT PROBE

FIG. 50



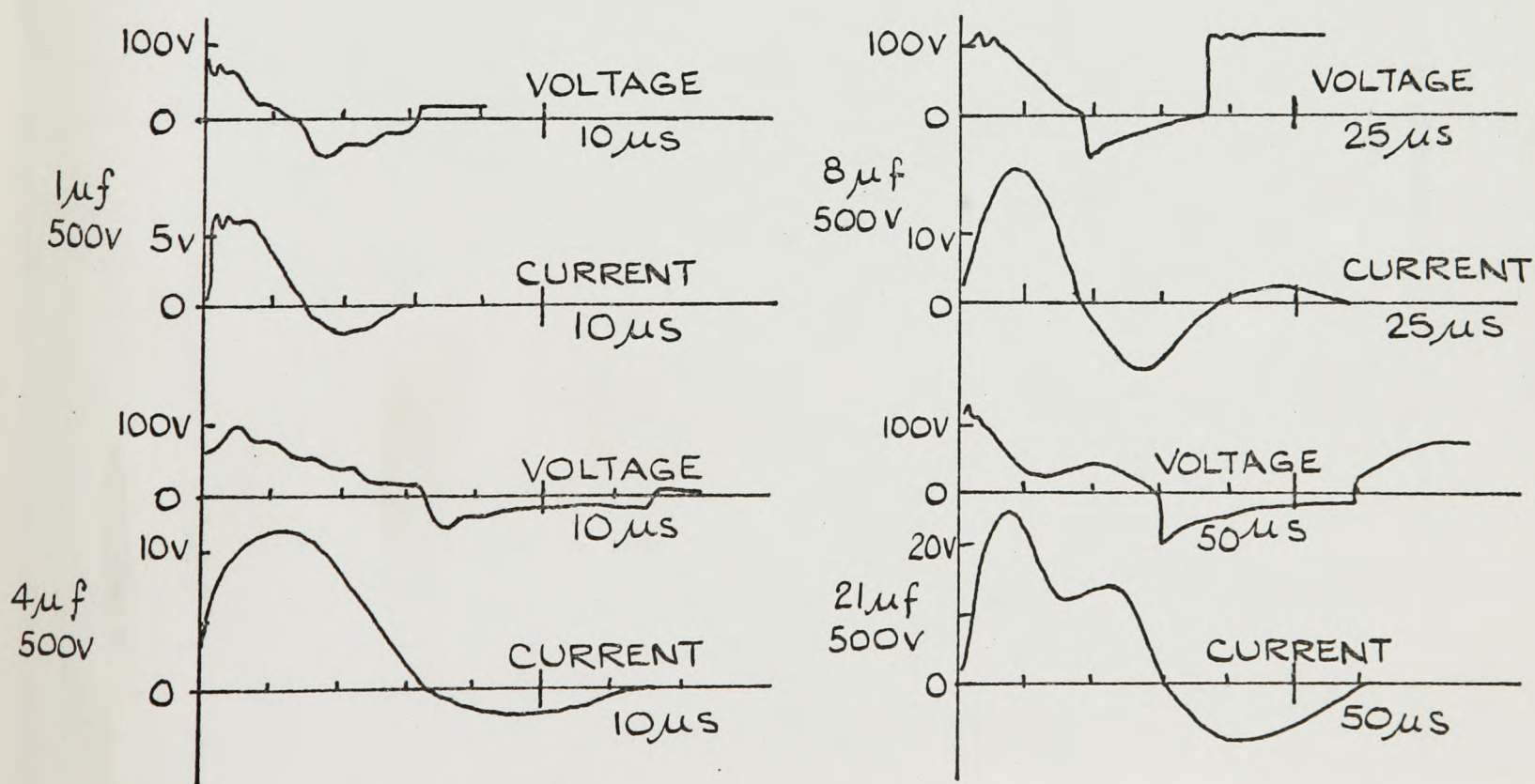
CIRCUIT FOR MEASUREMENT OF PROBE RESISTANCE

FIG. 51



CIRCUIT FOR ENERGY MEASUREMENT OF PLASMA PLUG DISCHARGE

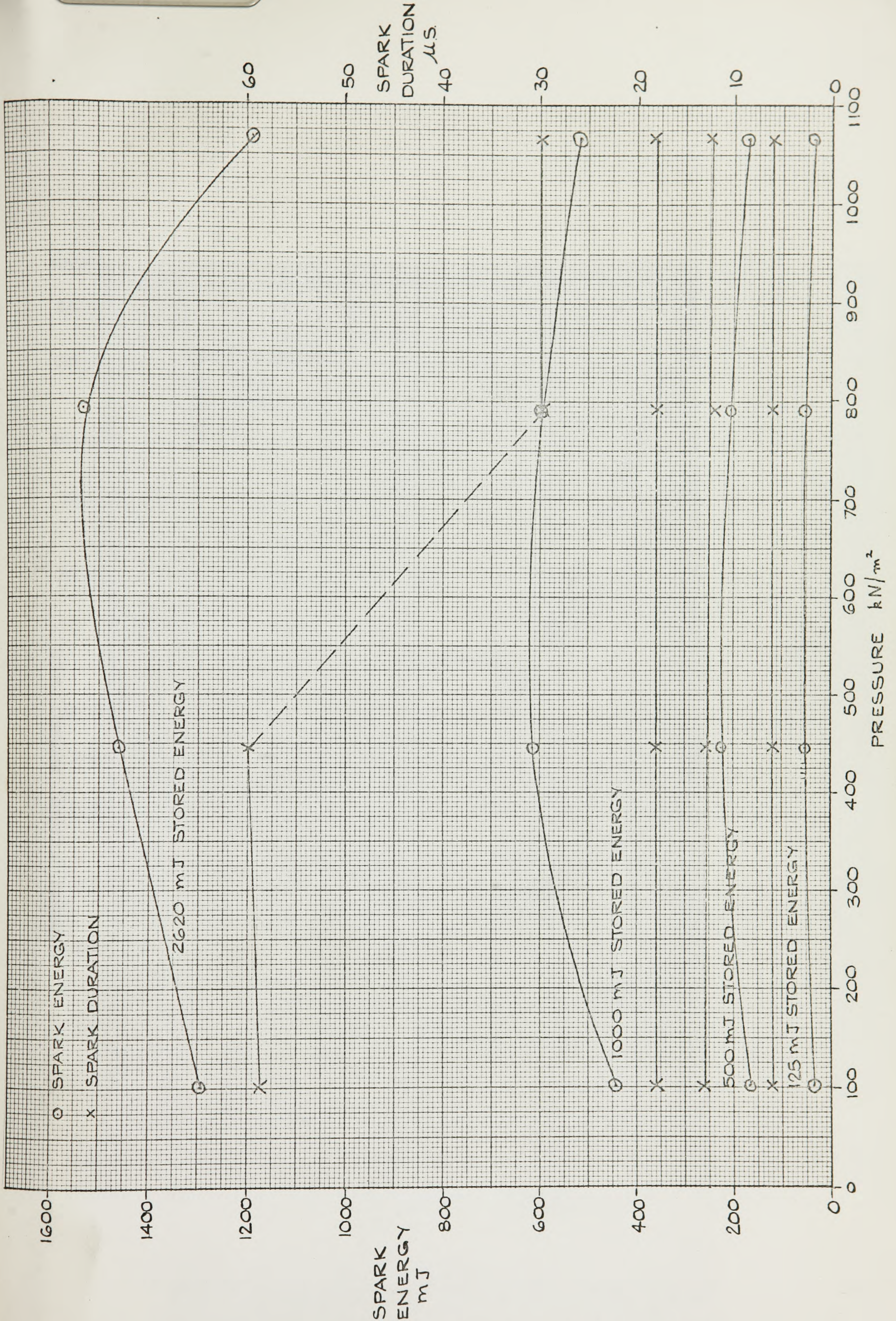
FIG. 52



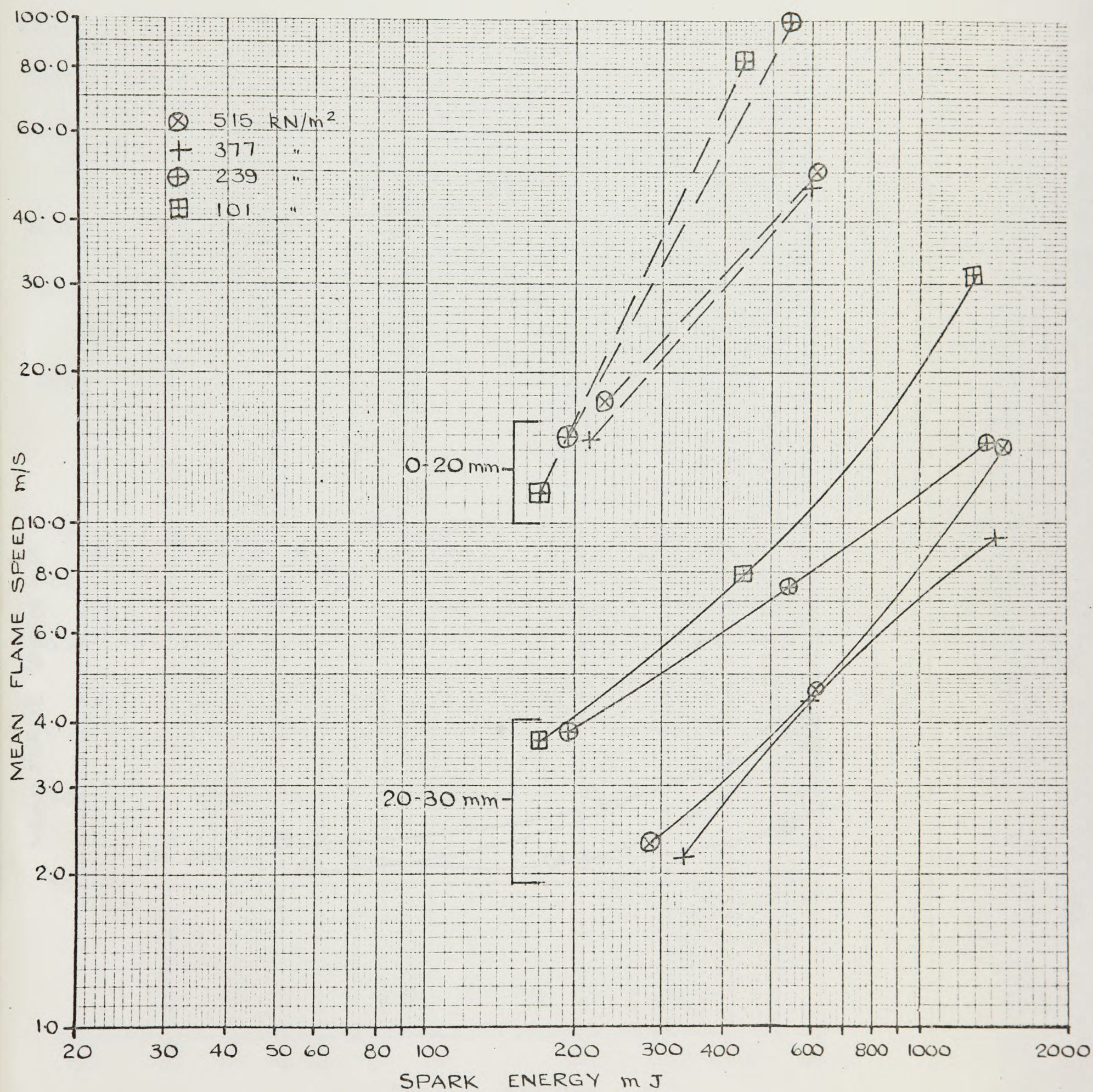
ALL TAKEN AT 101 kN/m²

OSCILLOSCOPE RECORDINGS OF VOLTAGE/ CURRENT MEASUREMENTS

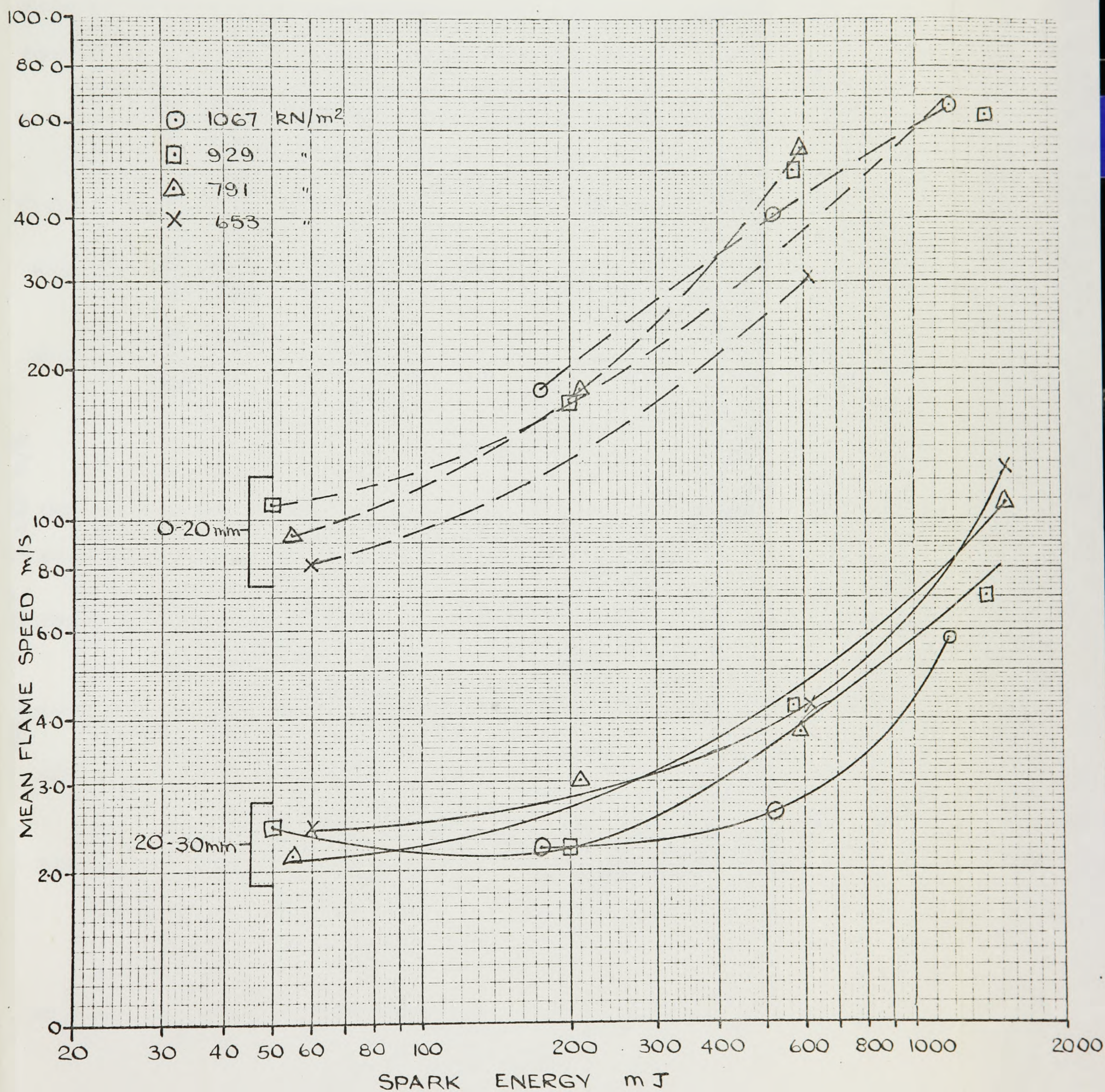
FIG. 53



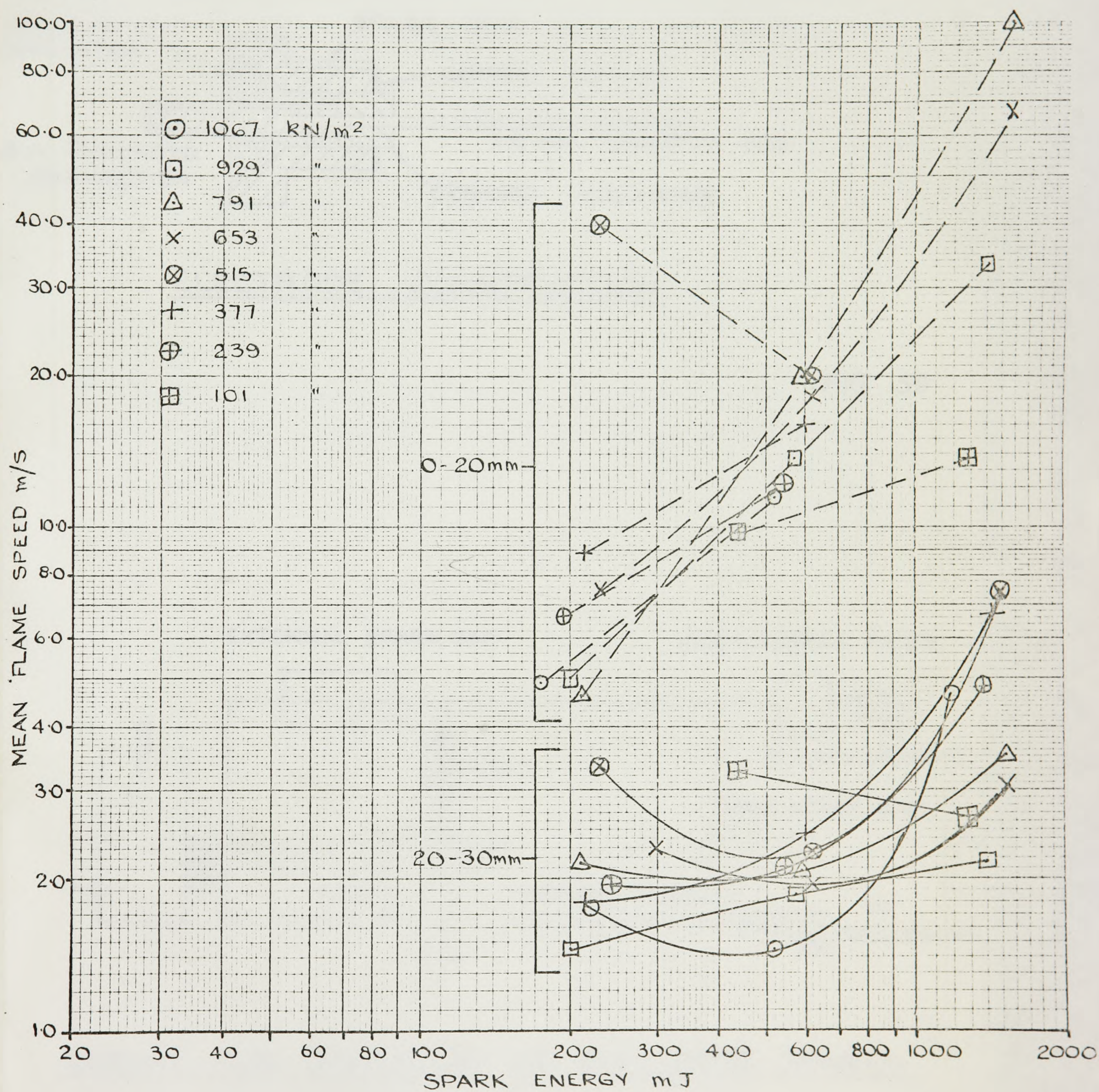
PLASMA PLUG SPARK ENERGY AND
SPARK DURATION / PRESSURE



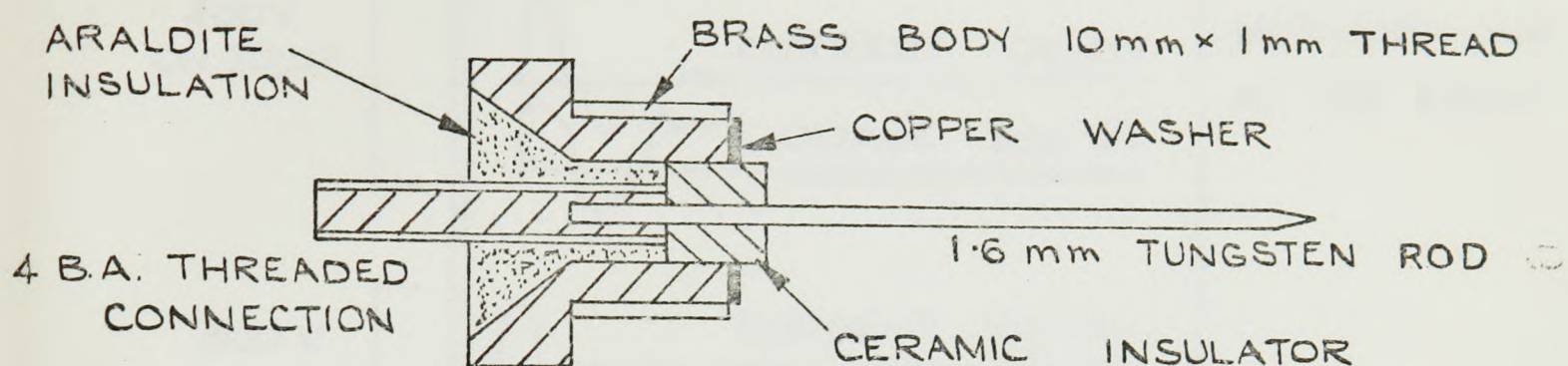
MEAN FLAME SPEED / SPARK ENERGY FOR PLASMA
PLUG IGNITION OF 1.0 STOICHIOMETRIC METHANE /
AIR MIXTURE AT PRESSURES FROM
101 kN/m² TO 515 kN/m²



MEAN FLAME SPEED / SPARK ENERGY FOR PLASMA PLUG
IGNITION OF 1.0 STOICHIOMETRIC METHANE/AIR MIXTURES
AT PRESSURES FROM 653 kN/m² TO 1067 kN/m²

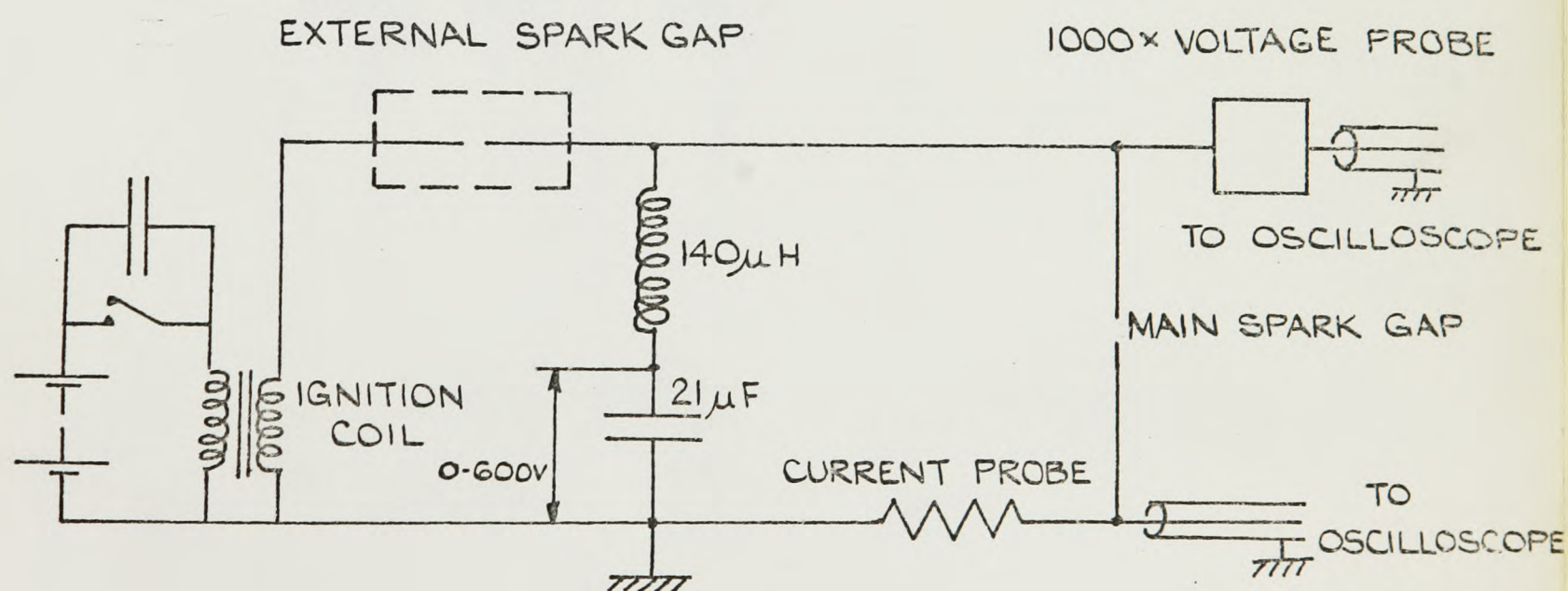


MEAN FLAME SPEED / SPARK ENERGY FOR PLASMA
PLUG IGNITION OF 0.8 STOICHIOMETRIC METHANE /
AIR MIXTURE



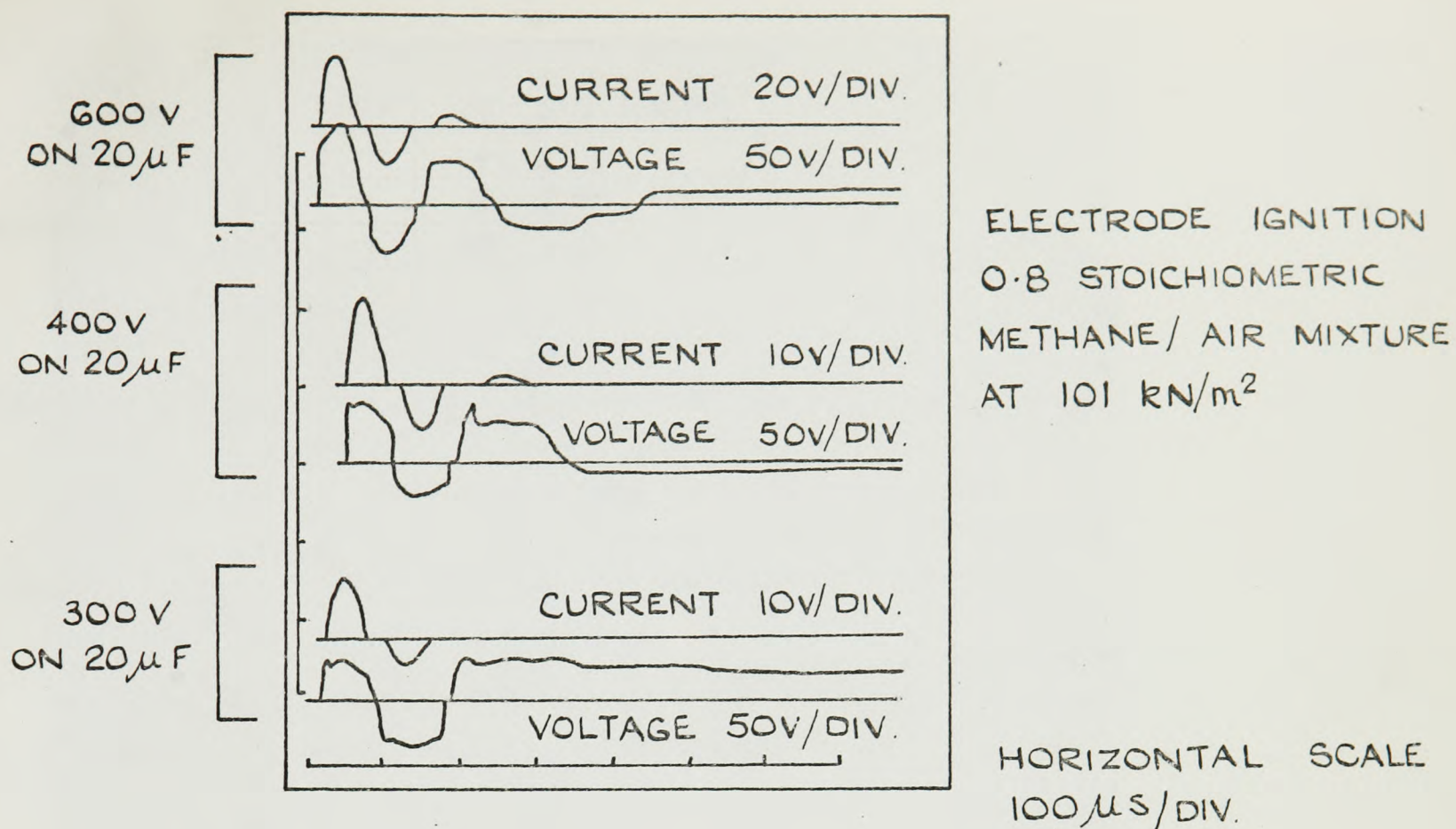
ELECTRODE CONSTRUCTION

FIG. 58



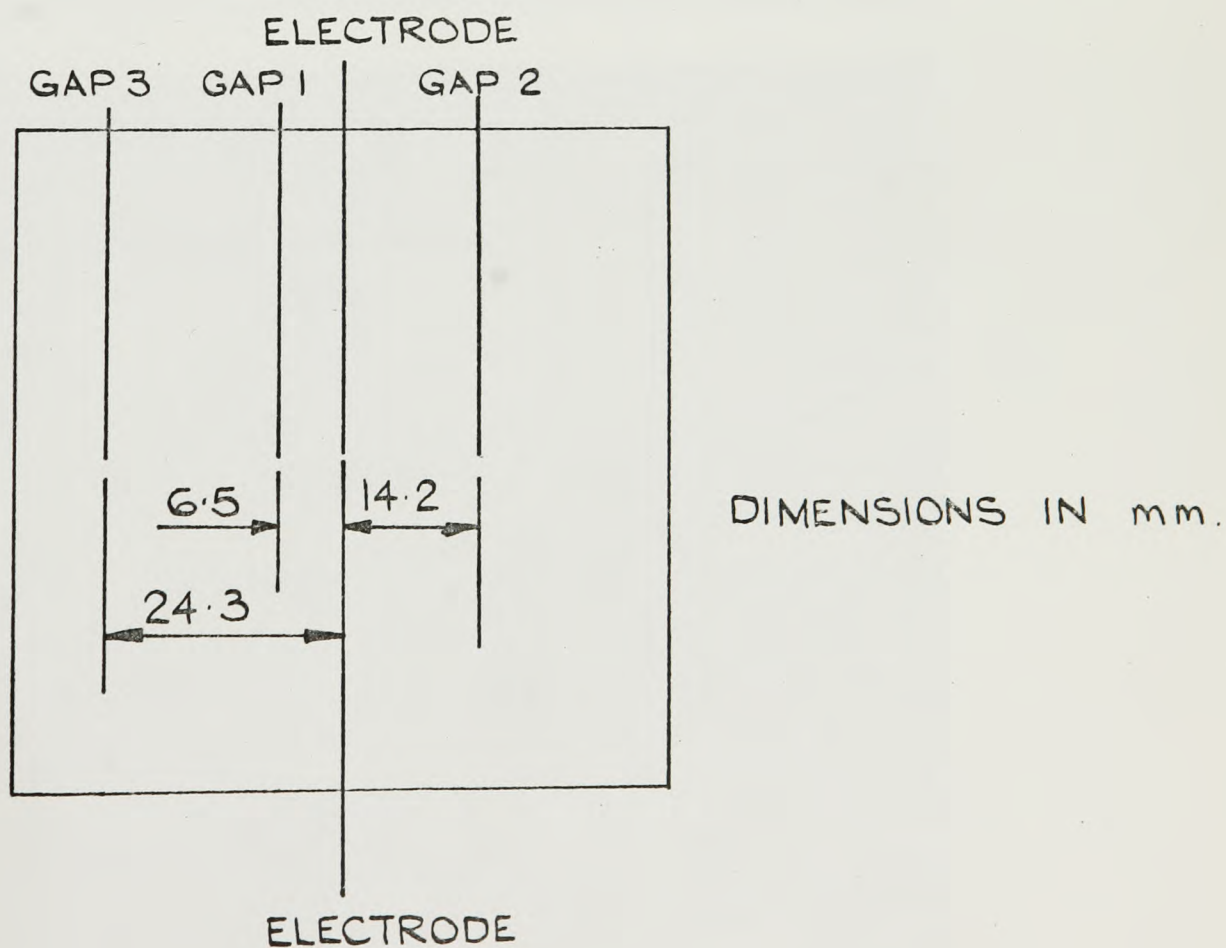
CIRCUIT FOR OPERATION OF ELECTRODE SPARKS
AND ENERGY MEASUREMENT

FIG. 59



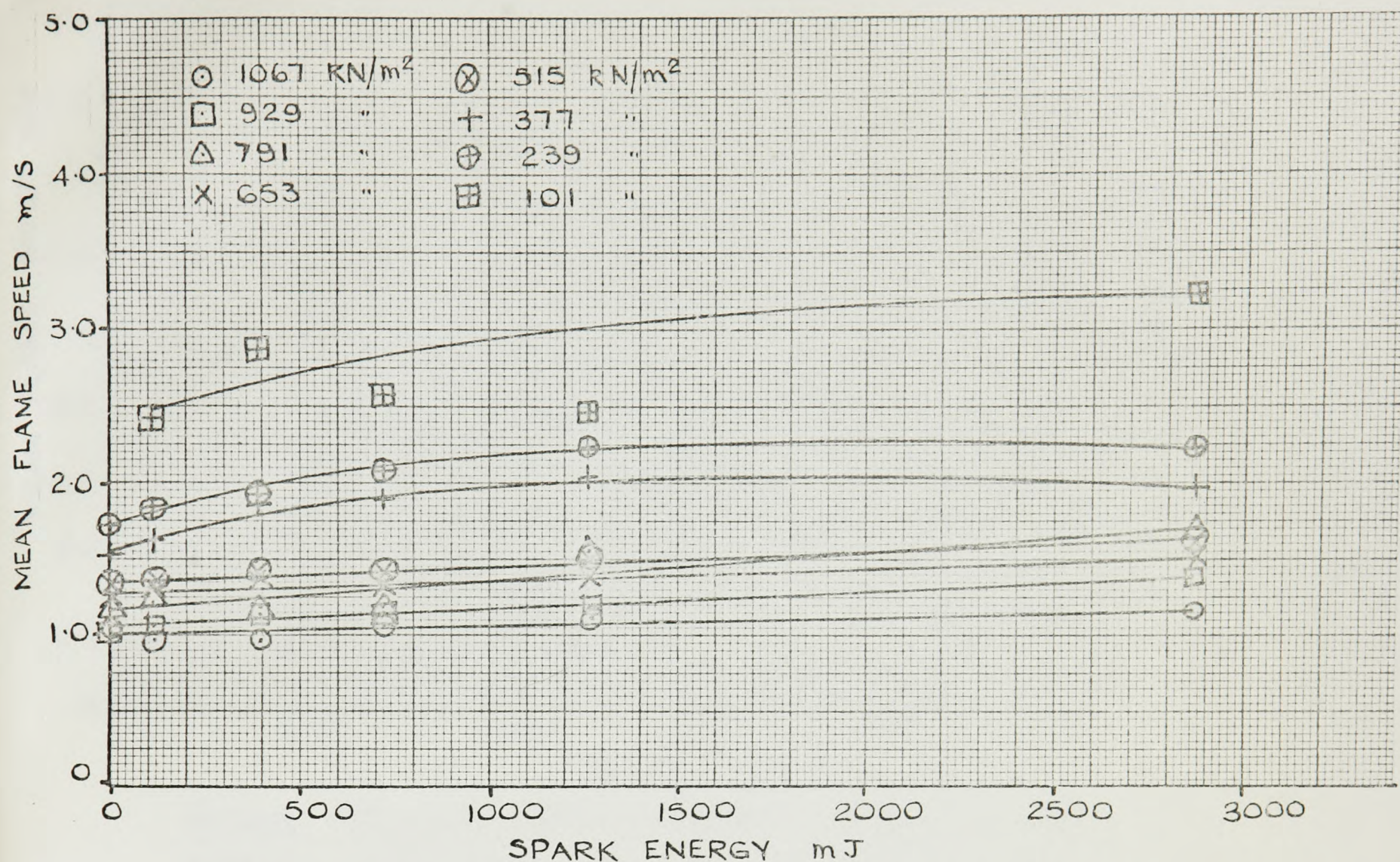
TYPICAL VOLTAGE/ CURRENT TRACES FOR
ELECTRODE SPARK ENERGY MEASUREMENTS

FIG. 60



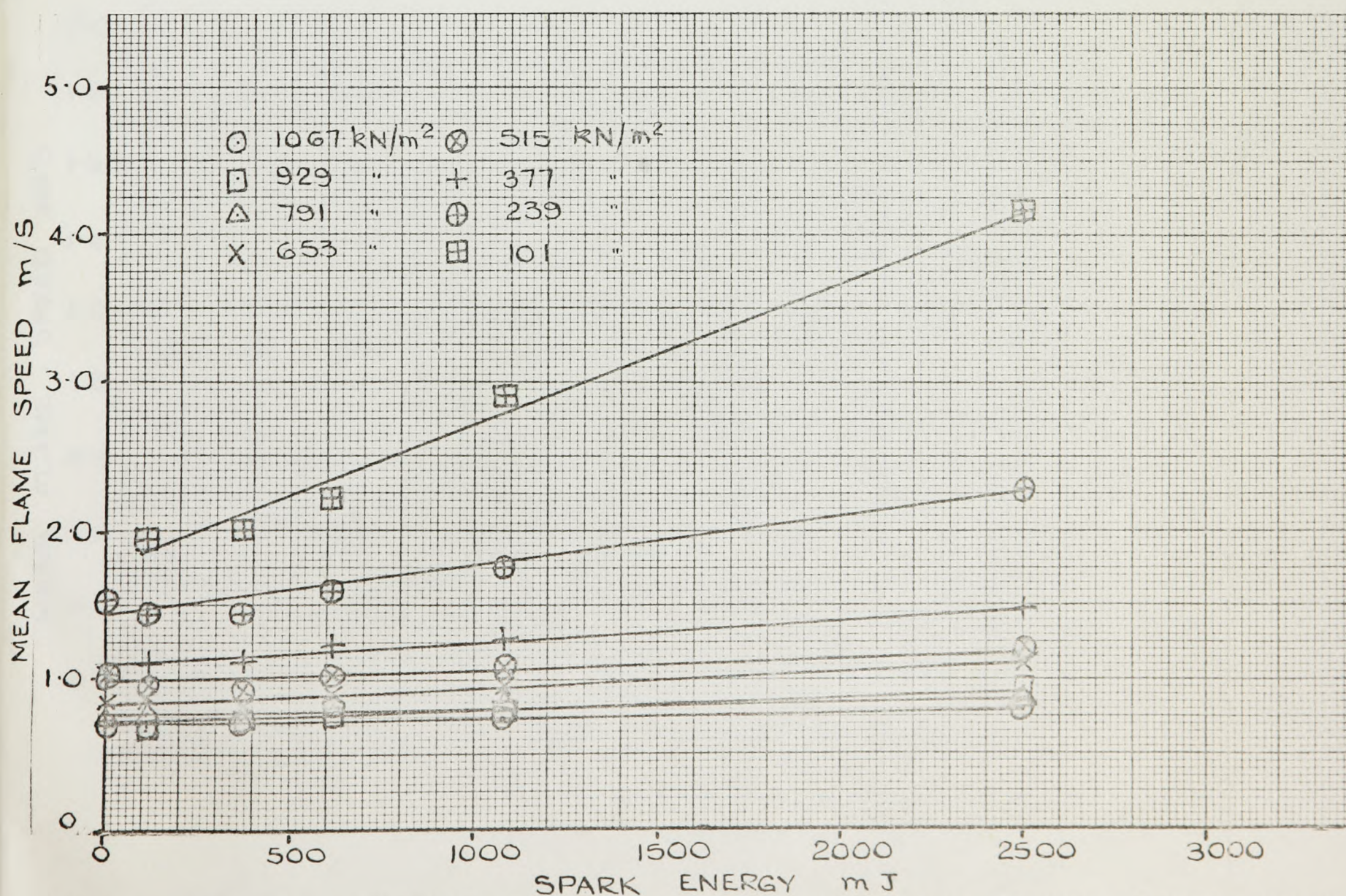
POSITIONS OF IONISATION GAPS IN
ELECTRODE IGNITION EXPERIMENTS

FIG. 61



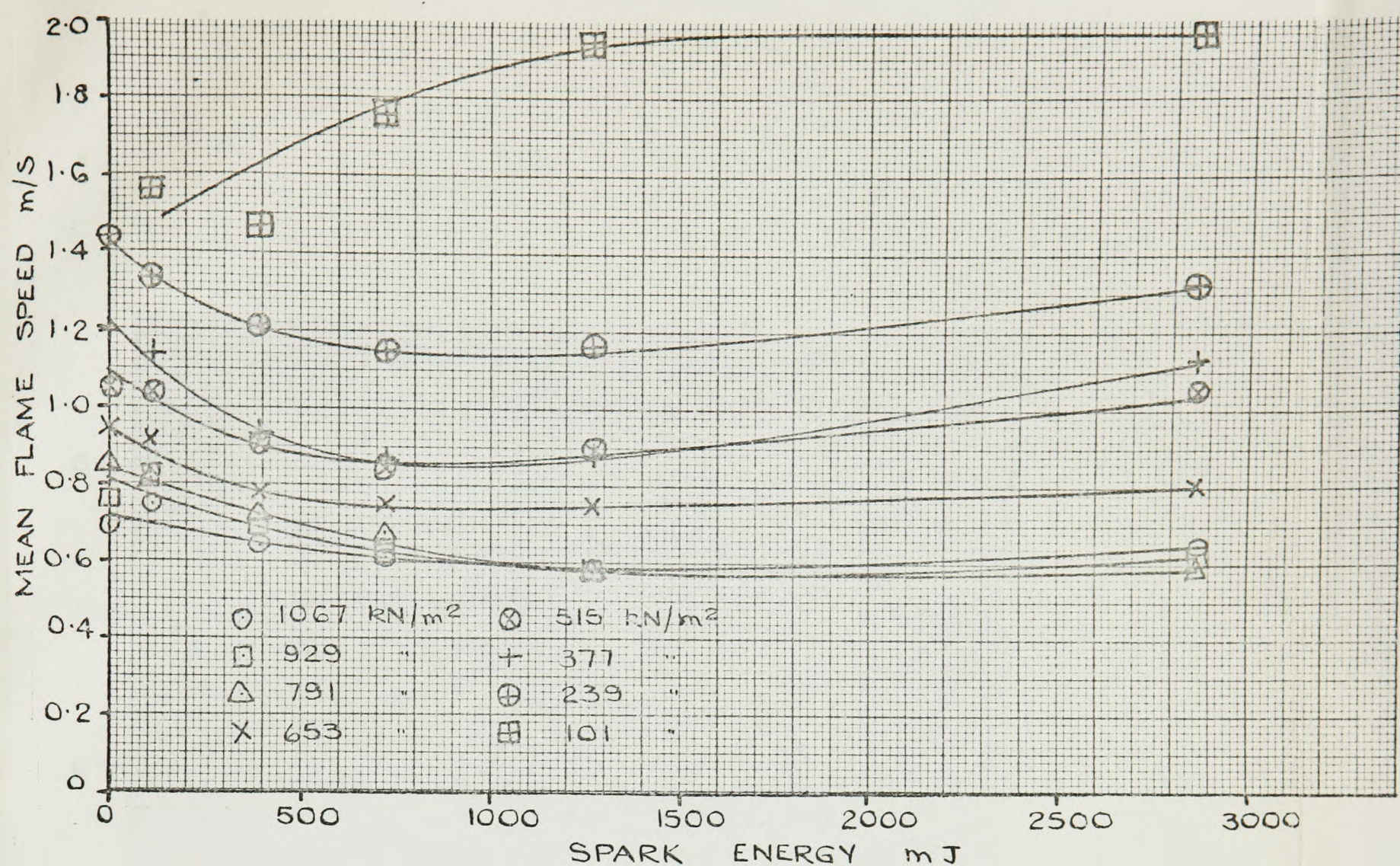
MEAN FLAME SPEED/ SPARK ENERGY FOR ELECTRODE SPARK IGNITION OF 1.0 STOICHIOMETRIC METHANE/ AIR MIXTURE 0-10 mm FROM IGNITION SOURCE

FIG. 62



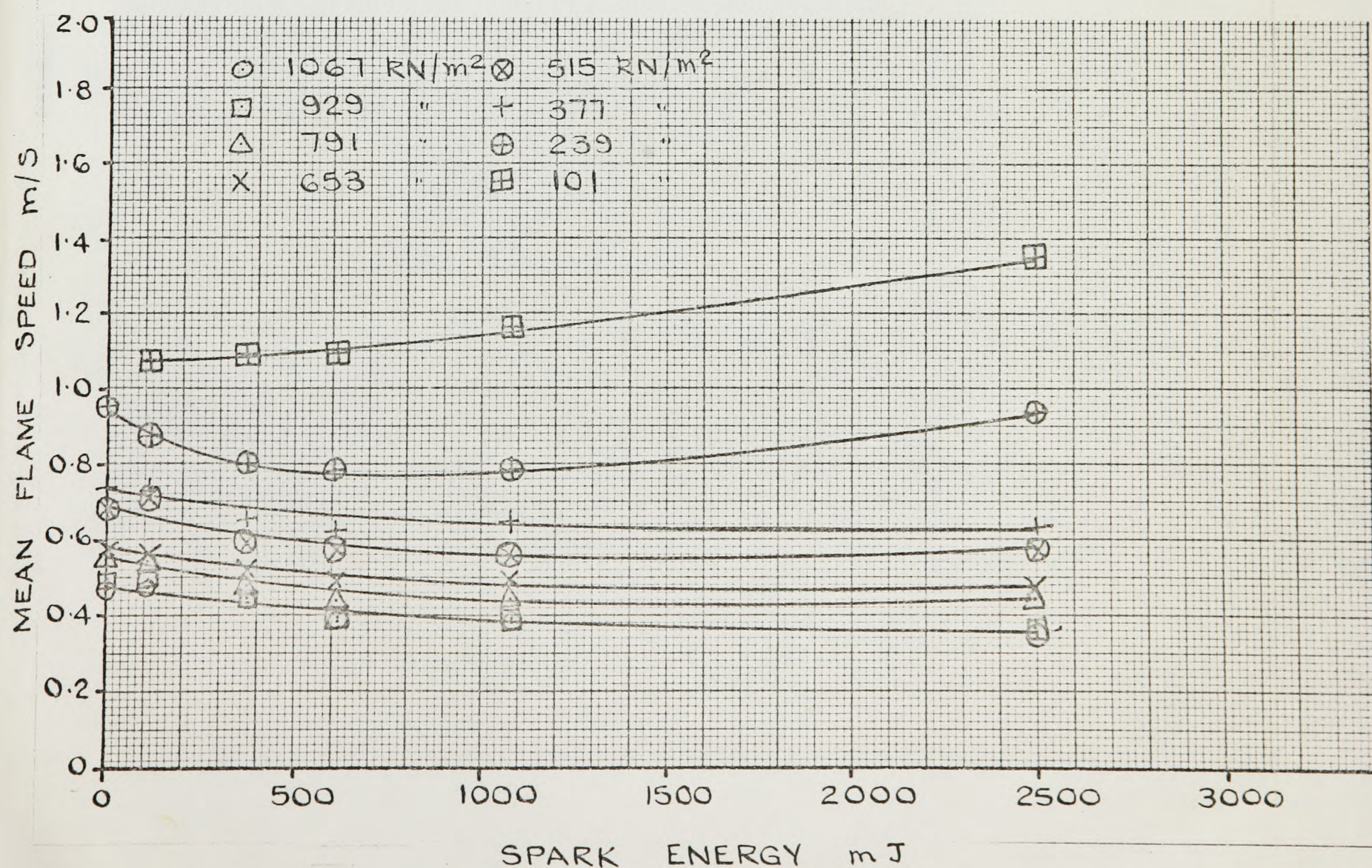
MEAN FLAME SPEED/ SPARK ENERGY FOR ELECTRODE SPARK IGNITION OF 0.8 STOICHIOMETRIC METHANE/ AIR MIXTURE, 0-10 mm FROM IGNITION SOURCE

FIG. 63



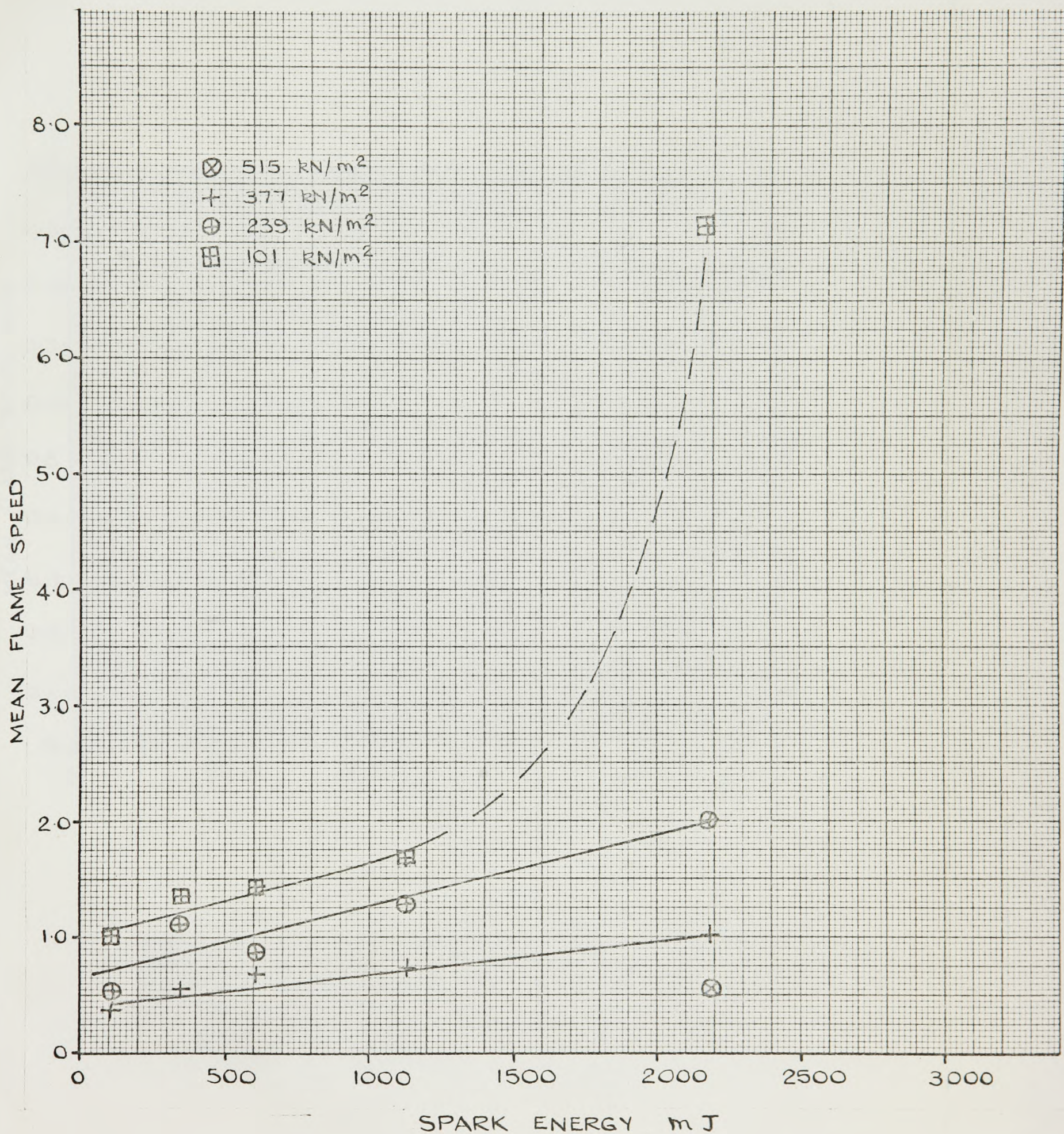
MEAN FLAME SPEED/ SPARK ENERGY FOR ELECTRODE
SPARK IGNITION OF 1.0 STOICHIOMETRIC METHANE/
AIR MIXTURES, 10-20 mm FROM IGNITION SOURCE

FIG. 64

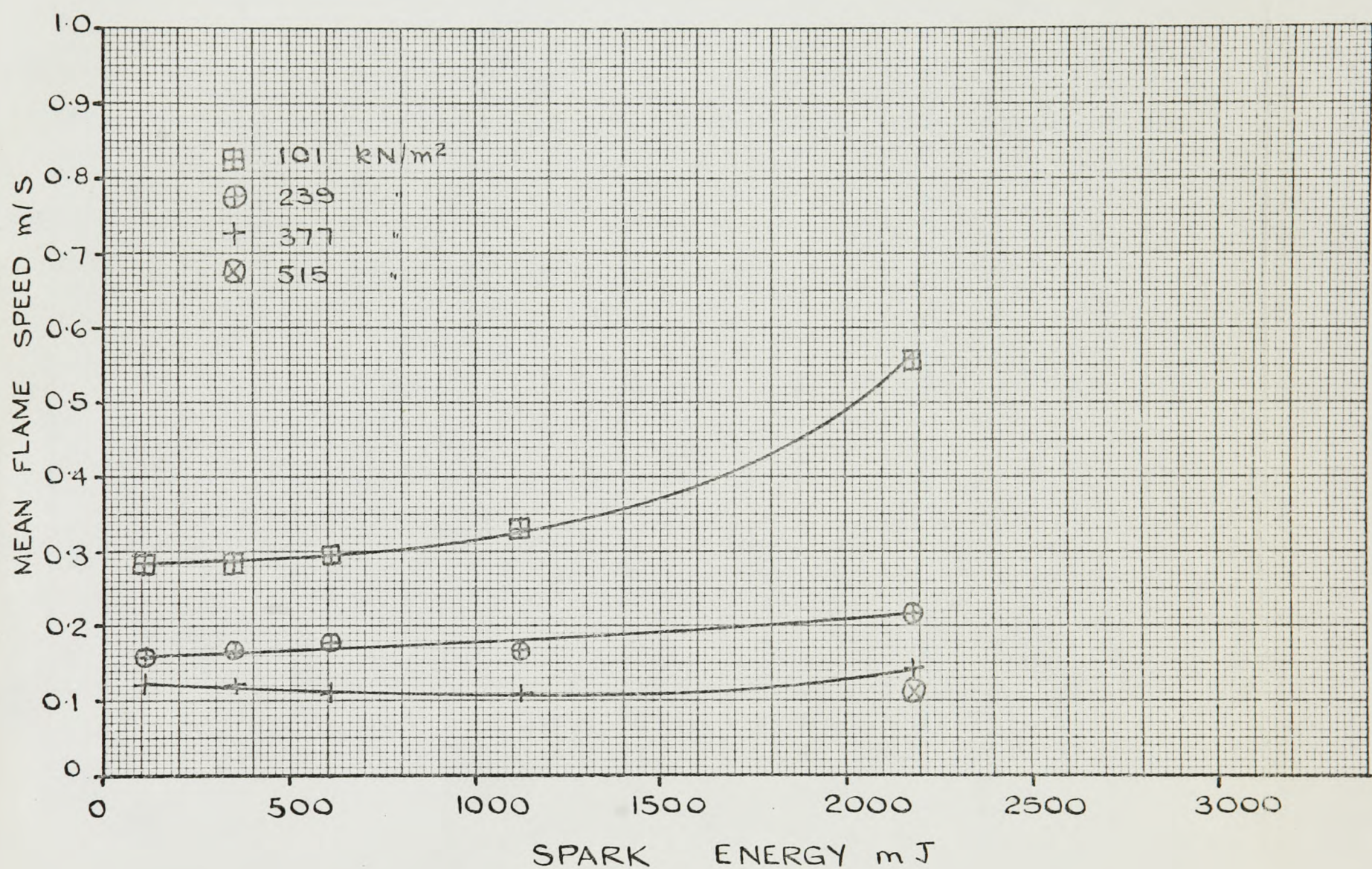


MEAN FLAME SPEED/ SPARK ENERGY FOR ELECTRODE
SPARK IGNITION OF 0.8 STOICHIOMETRIC METHANE/
AIR MIXTURES, 10-20 mm FROM IGNITION SOURCE

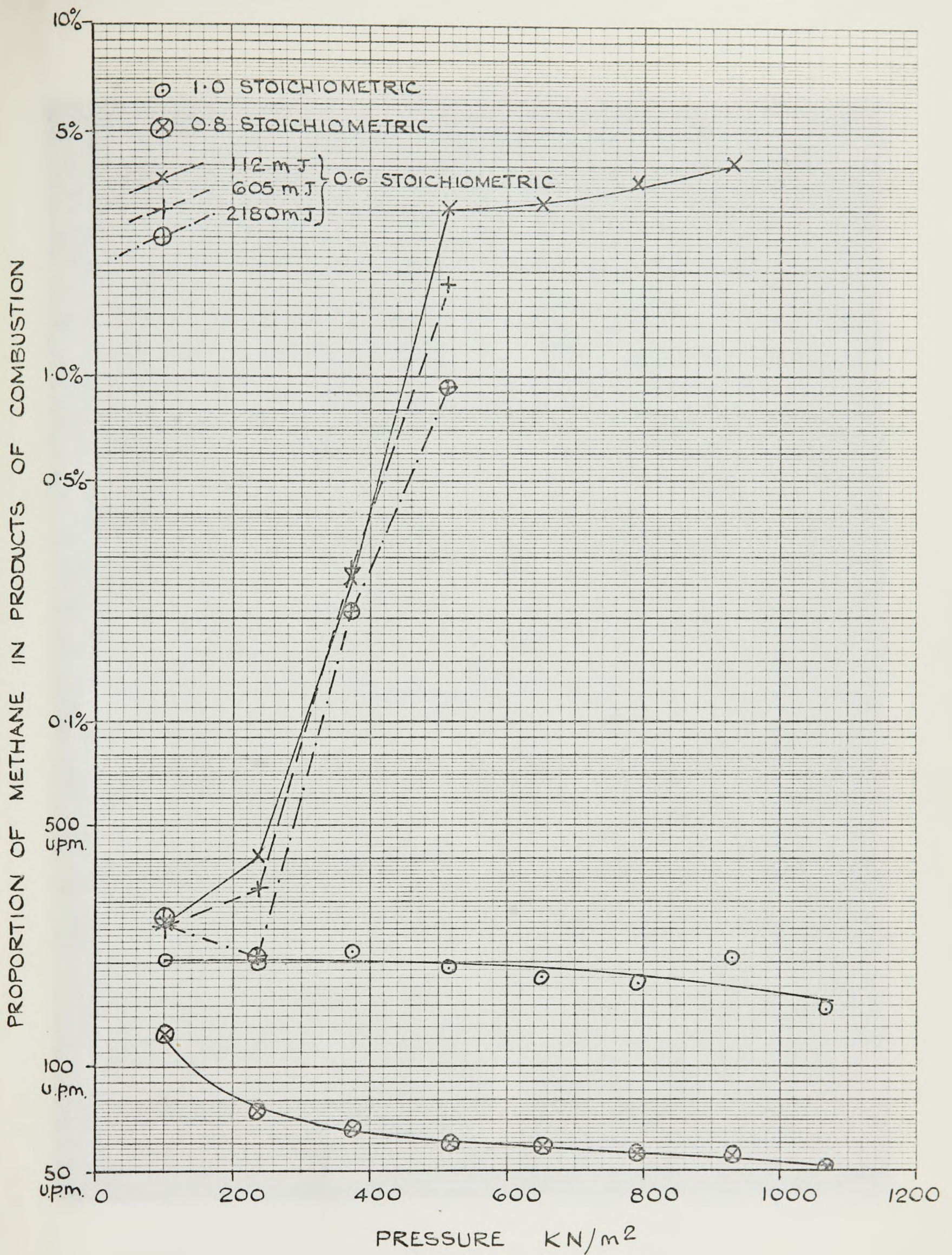
FIG. 65



MEAN FLAME SPEED / SPARK ENERGY FOR ELECTRODE
SPARK IGNITION OF 0.6 STOICHIOMETRIC METHANE /
AIR MIXTURES, 0-10 mm FROM IGNITION SOURCE



MEAN FLAME SPEED/ SPARK ENERGY FOR ELECTRODE
SPARK IGNITION OF 0.6 STOICHIOMETRIC METHANE/
AIR MIXTURES 10-20 mm FROM IGNITION SOURCE



PROPORTION OF METHANE IN PRODUCTS OF COMBUSTION/
PRESSURE FOR ELECTRODE IGNITION OF METHANE/
AIR MIXTURES

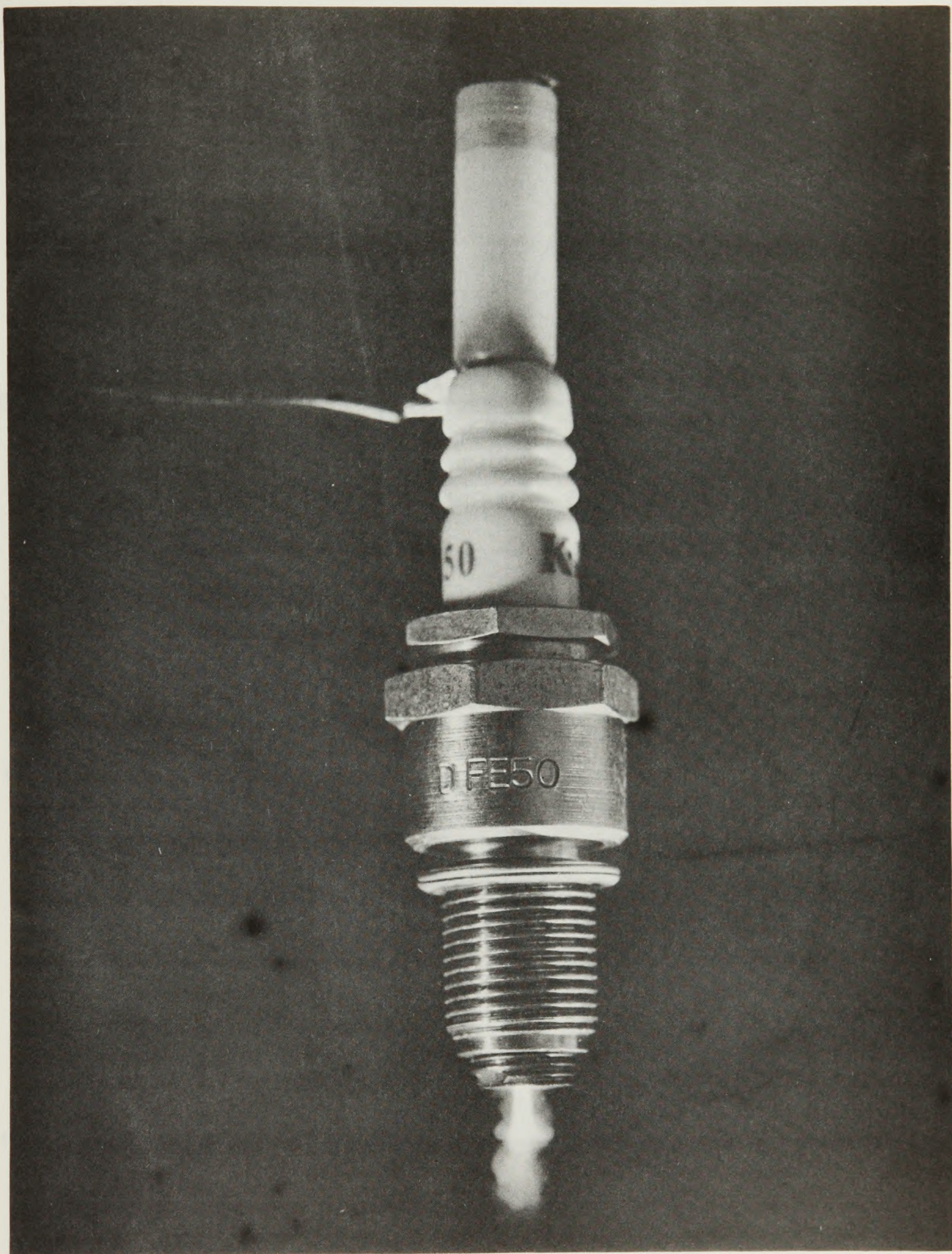
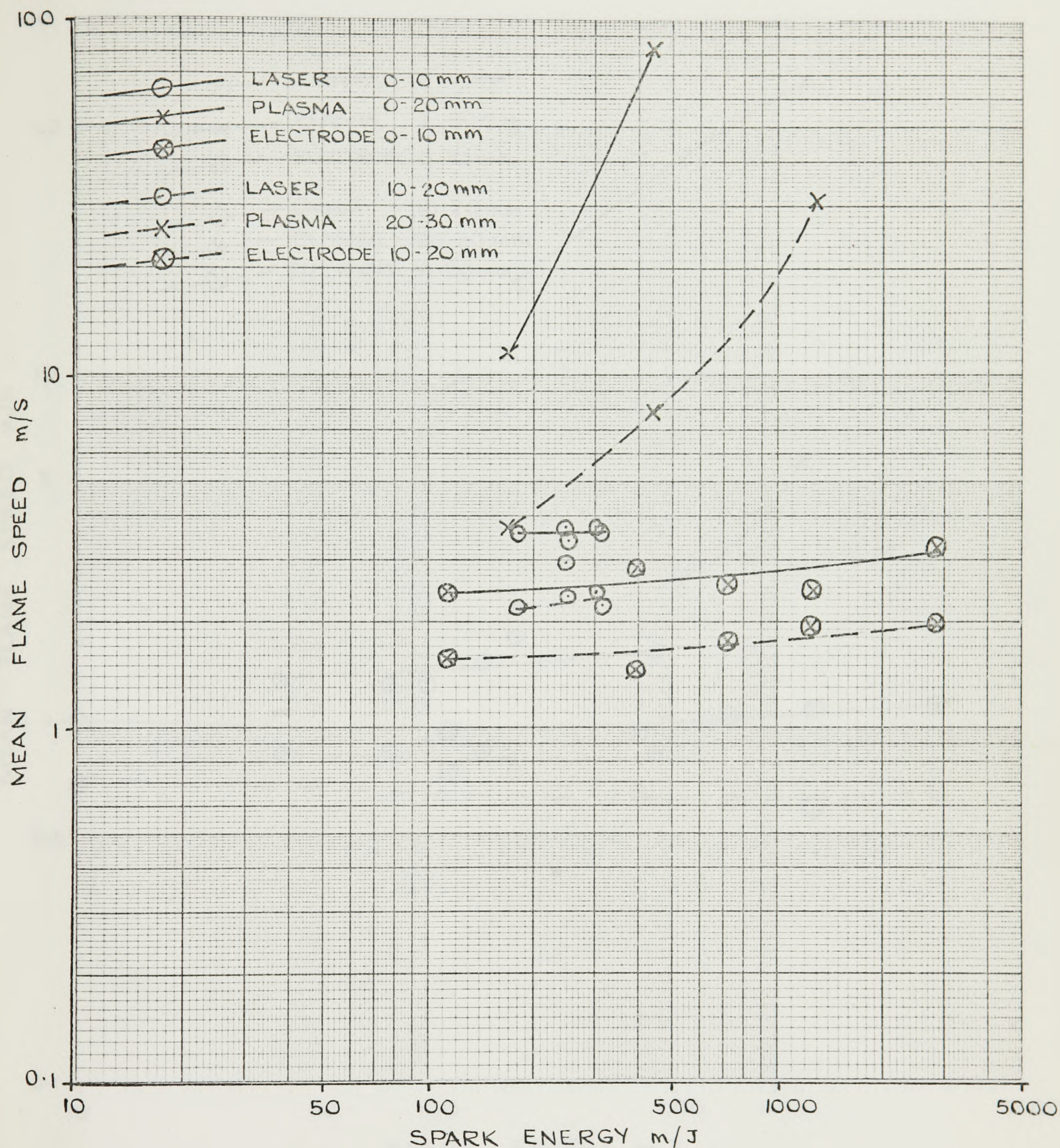


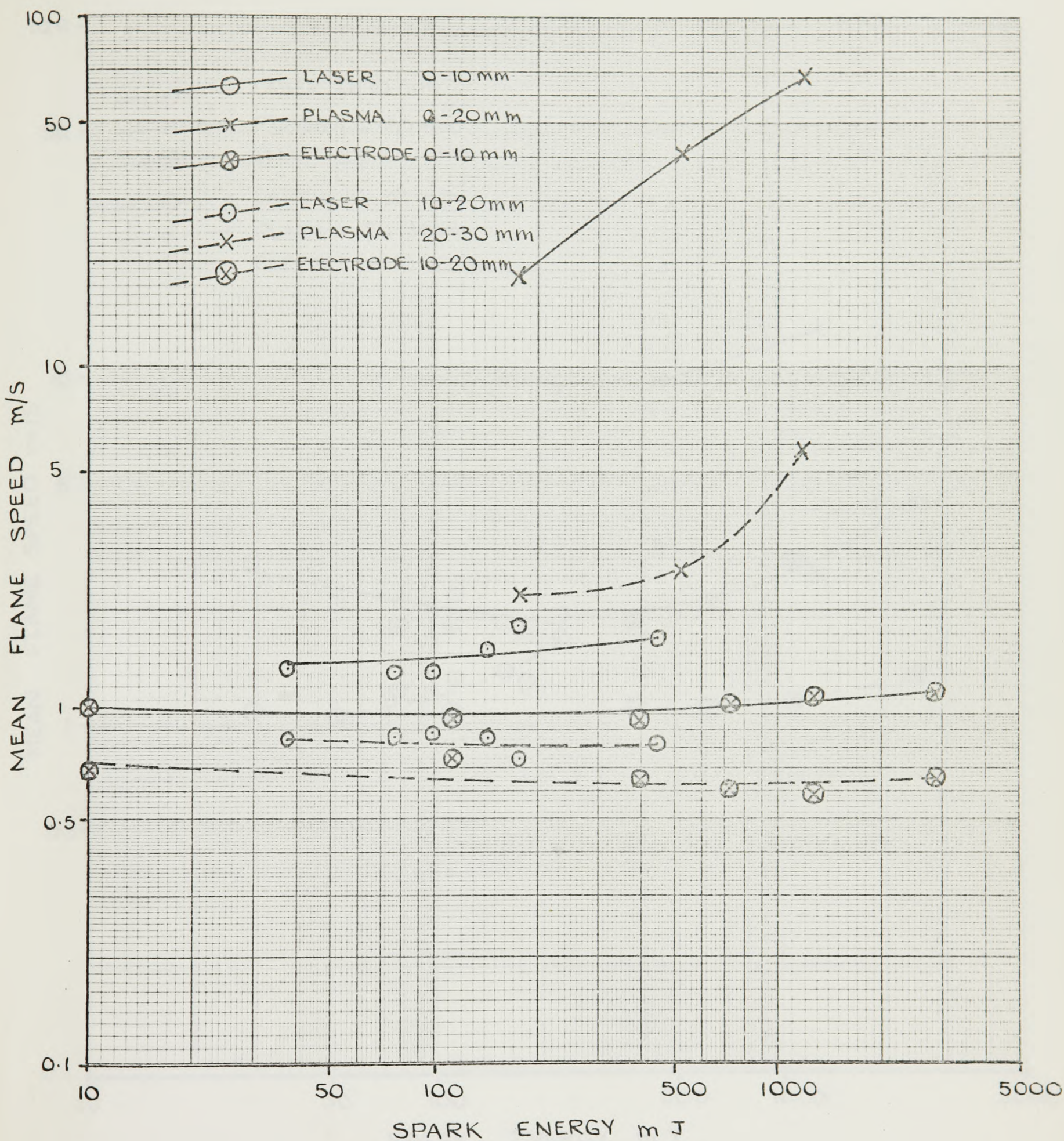
FIG. 69 14 mm PLASMA PLUG IN OPERATION IN AIR AT 101 kN/m²

(2445)

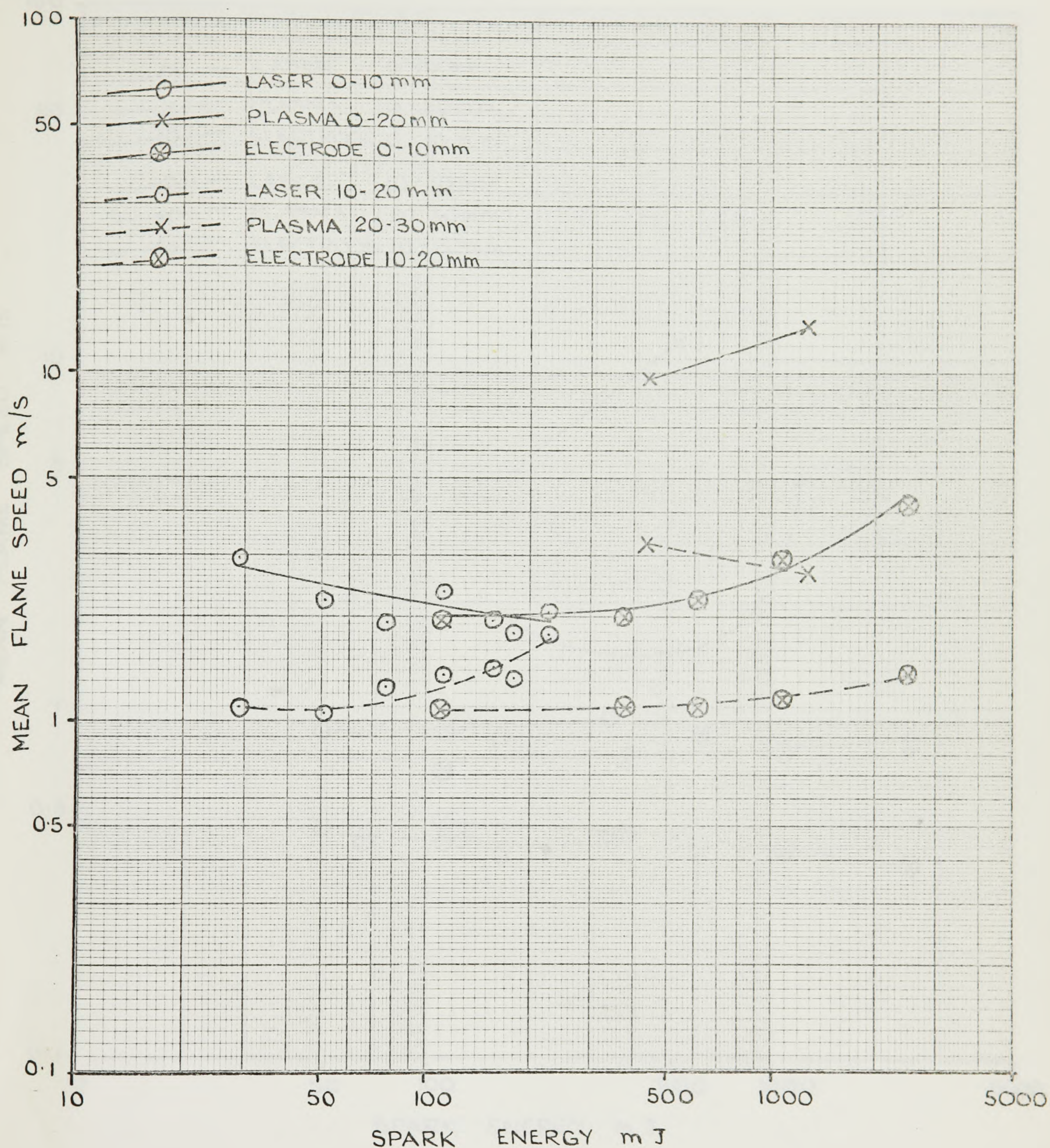
620/003/73



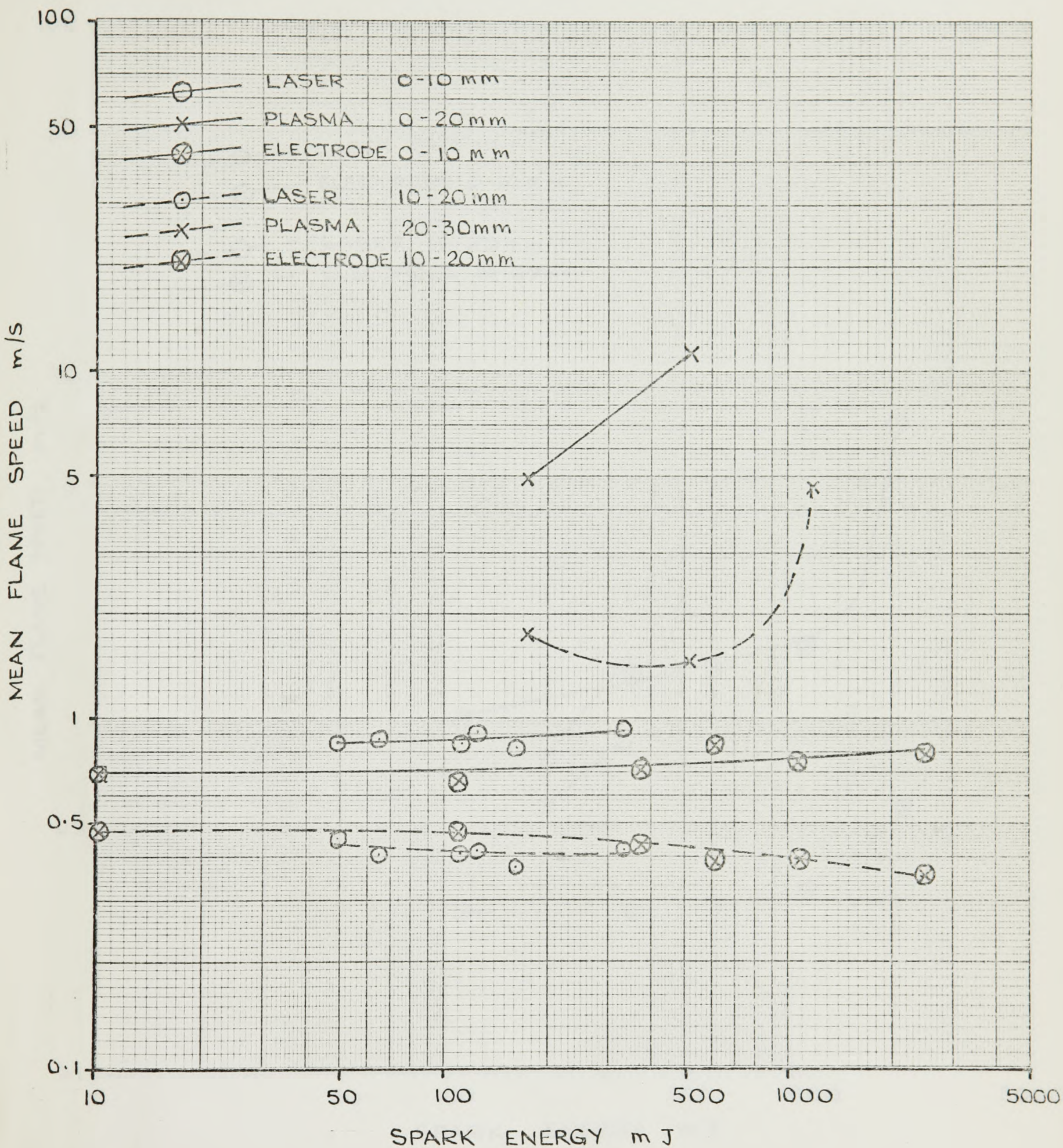
COMPARISON OF LASER, PLASMA PLUG AND ELECTRODE
IGNITION OF 1.0 STOICHIOMETRIC METHANE / AIR
MIXTURE AT 101 kN / m²



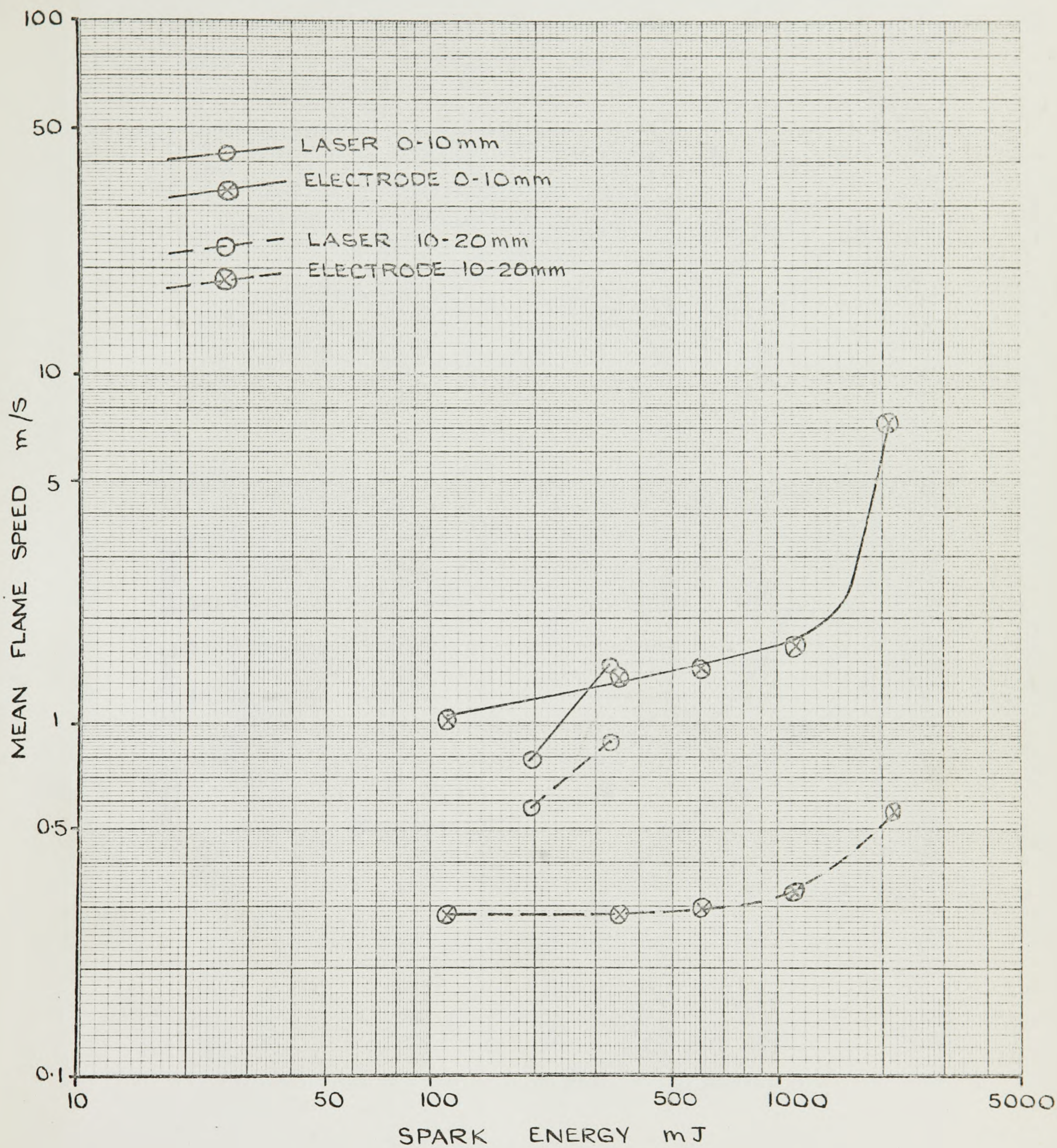
COMPARISON OF LASER, PLASMA PLUG AND ELECTRODE
IGNITION OF 1.0 STOICHIOMETRIC METHANE / AIR
MIXTURE AT 1067 kN/m²



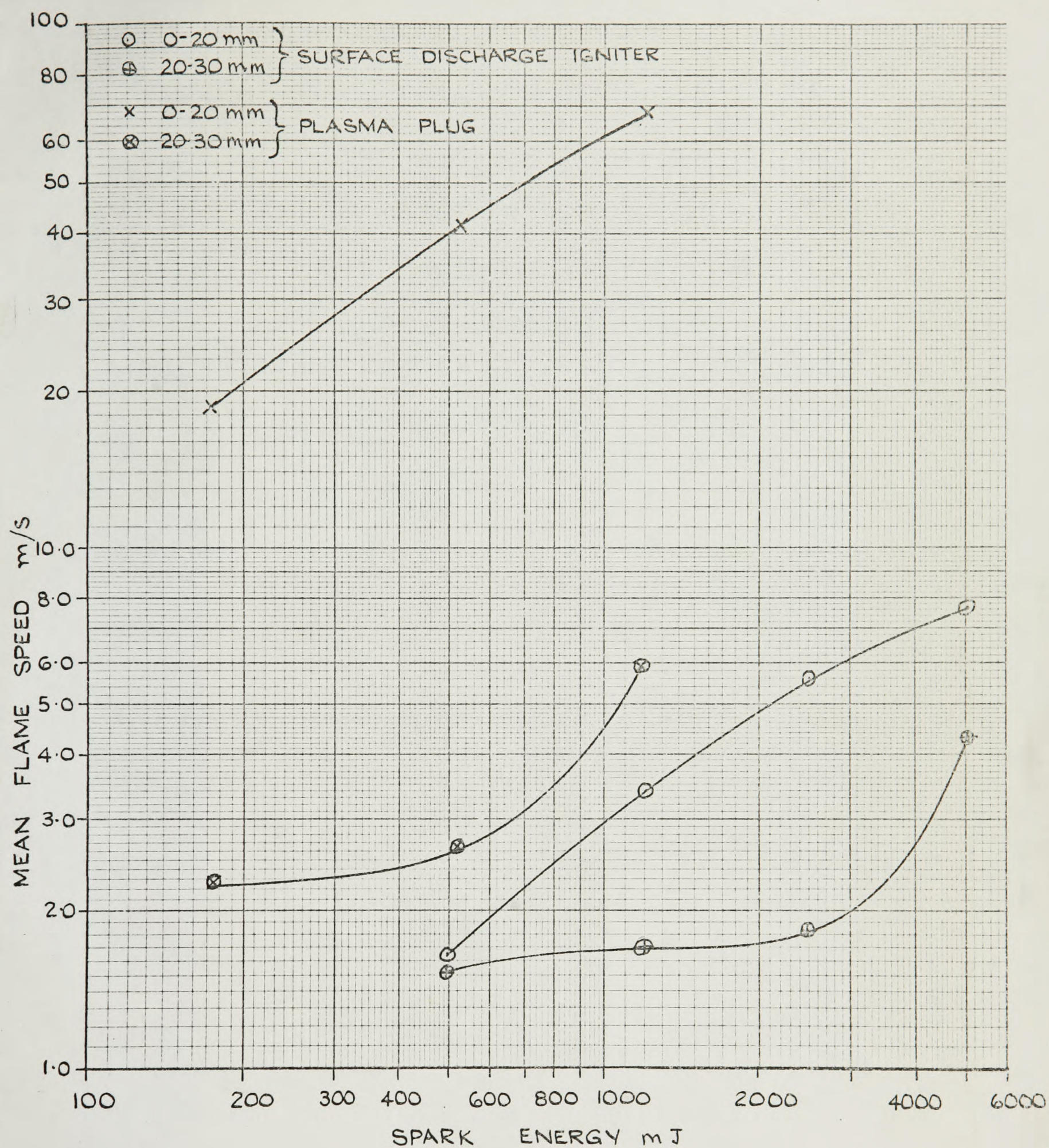
COMPARISON OF LASER, PLASMA PLUG AND ELECTRODE IGNITION OF 0.8 STOICHIOMETRIC METHANE/AIR MIXTURES AT 101 kN/m²



COMPARISON OF LASER, PLASMA PLUG AND ELECTRODE
IGNITION OF 0.8 STOICHIOMETRIC METHANE / AIR
MIXTURES AT 1067 kN / m²



COMPARISON OF LASER AND ELECTRODE IGNITION
OF 0.6 STOICHIOMETRIC METHANE/AIR MIXTURES
AT 101 kN/m²



COMPARISON OF PLASMA PLUG AND SURFACE DISCHARGE IGNITION OF 1.0 STOICHIOMETRIC METHANE / AIR MIXTURE AT 1067 kN/m²