ELECTRIC PLASMAS FOR FLAME STABILIZATION AND IGNITION IN FAST GAS STREAMS.

by

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A B S T R A C T

The object of this research is to study ignition and flame holding by plasma jets, ultimately in high velocity streams of gaseous fuel/air mixtures. One example of the underlying practical problem is often encountered in gas turbine engines during "flame out" at high altitude and when the fuel/air ratio is leaned off. The work is divided into three main parts; the first, studying intermittent plasma igniters, based on designs currently used in gas turbine engines; the second, dealing with continuously flowing plasmas for plasma jets and the third, testing of both pulsed and continuous plasma jets in fast flowing fuel/air mixtures.

The intermittent plasma igniters are surface discharge plugs, modified in order to improve their performance by adding different liquids to the plasma and/or by superimposing magnetic fields. It is found that liquid plasma media increase the extent of the discharge plume by up to 100%, depending on the type of liquid used. The magnetic field shortens the discharge plume by rotating the arc in the plane of the igniter surface, thereby creating a vortex. These experiments led to design proposals for new intermittent igniters, using a liquid supply through the surface of the igniter.

Compact continuous plasma jets in which the arc can be rotated either magnetically or aerodynamically around the circumference of a square-cut cathode inside a 45^{o} angled

anode were studied. Shadow and Schlieren photographs reveal hot and cold volume stratification and confirm the existence of hot pockets of gas containing radicals. These pockets are initially accelerated more than the colder gas while passing through a pressure gradient, due to their lower density. The pockets survive a few cm. downstream of the nozzle. The demonstration of the existence of the hot pockets led to optimization of the design using a tangential gas inlet to spin the arc aerodynamically. The power consumption of the plasma jet is between 0.5 - 1.5 kW. The sonic flow through the anode orifice develops into a turbulent rotating gas jet, as revealed by entrainment studies. A variety of gaseous feed stocks were used as plasma media. During the work, new cathode and anode shapes and new cathode materials were evaluated, leading to redesign of the anode-cathode configuration, better suited for running plasmas in air and methane.

The performances of the surface discharge plug, the pulsed and continuous plasma jet as igniters and flame holders were tested in a high velocity propane/air flow system which was built and instrumented specifically for this purpose at Smiths Industries Ltd. (the sponsors of this project). These tests showed the benefit of liquid additions to the surface discharge igniter, especially in the case of Avtur (an aviation fuel) and the advantage of using a cavity to partially contain the discharge, i.e. making it into a pulsed plasma jet. The results for the pulsed plasma jet demonstrate the effect of water as a radical source on the flammability limit,

lowering it to below the lean limit. The effect of Avtur is to further lower the limit, as compared with water. Varying the input energy to the igniter from 12J to 1.5J illustrates that the lower the energy input, the larger the amount of fuel needed to achieve successful ignition, even when the plug is wetted. The continuous plasma jet with a nitrogen feed showed considerably enhanced flame stability for propane/air residual flames persisting to well below the lean limit of flammability.

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C H A P T E R 1

INTRODUCTION

Improving ignition, increasing combustion rates with particular reference to flame holding in practical systems by generating radicals and making use, locally, of temperatures well above those of which unaugmented combustion is capable is the aim of the present work. This necessarily leads into the realm of low temperature plasmas. For this reason, the nature and methods of production of plasmas will be reviewed first.

1.1. Plasmas and Plasma Jets

Ionization of a gas can be achieved in a variety of ways, such as high energy radiation, heating by compression, electrical discharge or reaction. At the same time as gas molecules are being split into ions and electrons, the reverse reaction - recombination of the ions and electrons generated - takes place. The ionized gas is called a plasma and when the rates of the ionization and recombination reactions are equal, the plasma is called an equilibrium plasma. Plasmas can be classified in terms of:

1. Ionization level: either fully ionized, i.e. all molecules are dissociated into ions and electrons; or partially ionized, i.e. a fraction of the molecules is ionized, the rest being electrically neutral.

2. Overall temperature: either as low temperature plasma, 5000 - 10000 K; or as high temperature plasma, above 10000 K.

3. Ion temperature: either "cold plasma", i.e. gas molecules at low temperature and electrons at high temperature - the so-called nonthermal plasma; or "hot plasma", i.e. gas molecules and electrons have the same high temperature. The plasma is then approaching thermodynamic equilibrium and is called thermal.

Plasmas can be generated in several ways in the laboratory: e.g. by using high frequency discharges, shockwaves or arc discharges. For discharges, two criteria are important: the type of discharge, i.e. whether it is a glow, corona or arc discharge and the method of stabilization. Gas vortex, gas axial or magnetically for the arc discharge. In addition, the electric arc can be operated in a pulsed/intermittent or a continuous mode. According to Bradley et.al. (1981), the bulk heating of gas by electrical fields seems to be due to positive ions. In the reaction zone of a flame, this will change the reaction rate and play an important role in the cathode heating. If the cathode heating is increased as the corona develops, the temperature might rise sufficiently for thermionic emission from the cathode to take place and an arc discharge to be formed.

There exists a variety of designs for plasma equipment, depending on parameters, such as power consumption, type of discharge, method of stabilization, use, etc. The uses of plasmas are extensive and comprise applications such as cutting, welding, chemical application, ignition and flame holding.

The plasma dealt with in this work will be partially ionized and of relatively low temperature. It will be generated in an electric arc, either as a pulsed discharge or, if continuous, rotated magnetically or by a gas vortex about a central cathode.

The use of continuous plasma jets for ignition and flame holding has been studied for several decades. Their initial development was due to attempts at electrical augmentation of flame temperature, a subject surveyed by Lawton et. al. (1969). The advantages of plasma jets for augmenting flames, as compared with induced turbulence, seeding and high frequency alternating discharges was demonstrated by Chen et. al. (1965), with specific reference to achieving large heat transfer rates, large ion concentration in gases and as a way of generating specific products by quenching the hot gas at various stages. They concluded that the most promising methods would be either to feed the reactants into stationary discharges or through discharges rotated by magnetic fields. The discharge has to rotate at such a speed as to allow every part of a fast gas stream to experience the passage of the discharge at least once. Kimura et. al. (1974) investigated the effect of magnetic fields on seeded and unseeded flames augmented by high voltage low current discharges. They found that, for unseeded flames, a stable rotating arc would be formed when an appropriate axial magnetic field was used and concluded that magnetically rotated arcs of low current with relative small arc diameter would be useful for producing a controllable amount of unmixedness and for enhancing heat transfer from flames.

The initial investigation into plasma jets as flame stabilizers was by Harrison et.al. (1971). Using a magnetically rotated plasma jet, through which a variety of reactants were passed, they showed that small additions of energy could be used to heat a small proportion of the gas stream to very high temperatures, generating radicals. These radicals would increase the reaction rates and, hence, flame stability throughout the combustion volume. They reported that a 10% increase in chemical energy flux produced a 700% increase in throughput, using a nitrogen plasma with argon as the carrier gas. This compares with less than 100% increase expected from a perfectly stirred system. Increasing the energy input is reflected in higher combustion rates and better flame stability. Nitrogen proved to be marginally the most effective radical source, compared to water, oxygen and methane. The effect of high temperature radicals on combustion rates was studied by Kimura et.al. (1976). They used a small stirred reactor equipped with electrodes, between which an arc was generated. This arc discharge produced radicals. They concluded that high temperature radicals generated by arc discharges actively take part in increasing combustion rates and showed that this was the case when the reactor was filled with a propane/air mixture outside the flammable region. The feasibility of using a plasma jet to improve flame stability and to promote combustion in supersonic fuel/air streams was demonstrated by Kimura et. al. (1981). Their plasma jet was fed with either hydrogen, nitrogen or argon and required around 5kW in power. Their results showed that a plasma jet, using a relatively small amount of electrical power, was very effective for flame

stabilization and promotion of combustion. They also reported that the effectiveness of a nitrogen plasma on enhancing combustion is nearly equal to that of a hydrogen plasma, although, if electric power input is taken into consideration, the nitrogen plasma is superior to the hydrogen plasma. Heat losses in a hydrogen plasma are larger than those in a nitrogen plasma, because the thermal conductivity of hydrogen is large.

Jagoda et.al. (1980) studied the highly turbulent region in the wake of a magnetically rotated DC-arc plasma jet. They used various Schlieren and shadow methods. Mixing in plasma jets and entrainment is important. The arc only heats a small proportion of the gas flowing through the arc channel, creating large temperature differences. Many of the desirable reactants are not suitable for passing through the discharge and, therefore, have to be entrained into the plasma jet beyond the arc region. The visualisation of the test region showed a finely structured V-shaped wake, consisting of two regions (Jagoda et.al. 1980). It was found that the inner of these two regions is highly turbulent; the scale of turbulence is dependent on the flow through the plasma jet and the arc rotation rate. The outer region has much slower eddies whose characteristics are related to the flow through the plasma but not to the arc rotation rate. It is in this region that most of the entrainment takes place. The density distribution in the central region looked like one in a region in which heat is released. Such behaviour would be caused by pockets of excited or ionized gas being carried

downstream. Jagoda et.al. (1980) suggested that these pockets would explain the rapid reaction rates,observed in the wake of plasma jets by Harrison et.al. (1971).

Consider pulsed plasmas: In 1973, a modified spark plug was developed into a plasma jet. Waterson (1973), in his PhD thesis, compares the ignition performance of a standard spark plug with a modified version, a pulsed plasma jet. He found that this plasma jet will allow combustion to take place at leaner fuel/air ratios. Since then, the pulsed plasma jet has been extensively studied, varying the energy input, the size and shape of the plasma jet nozzle and the volume of the cavity.

Not until 1978 was the pulsed plasma jet fed with a specific media in order to generate radicals, (Weinberg et.al., 1978). This research demonstrated the effectiveness of specially generated radicals in increasing burning velocity and combustion rates. Subsequent research, using either a liquid feed plasma jet, Orrin et.al. (1980), or a metal hydride insert in the plasma jet, Grant et.al. (1983), have confirmed the effectiveness of radicals in increasing burning rates and decreasing flammability limits. However, the performance of a pulsed plasma jet also depends on aerodynamic effects, such as penetration of the jet and the amount of turbulence generated, which can enhance combustion rates without using a liquid or gaseous feedstock. (Cetegen et.al. (1980), Orrin et.al. (1980), Topham et.al. (1975), Smy et.al. (1982).) According to Clements et.al. (1981), several mechanisms can be responsible for the ejection of the plasma away from the

plasma jet. They tested three different types of plasma jets, so designed that the pressure and/or the magnetic force were the reason for expulsion of the plasma. For one of the plasma jets they used, it had earlier been shown that the ejection of the plasma was due to the IXB force and, therefore, a magnetic effect (Bradley et.al., 1974). For the two others, the main effect was due to pressure build-up in the cavity. Clements et.al. (1981) concluded that the dominant mechanism responsible for ejection is pressure. However, in the analysis of the operation of any type of plasma jet, both forces have to be taken into consideration.

In 1979, Smiths Industries were trying to upgrade their surface discharge igniters and designed and tested what they called a "focus discharge" igniter, i.e. a pulsed plasma jet based on a surface discharge igniter geometry confined in a cavity. This showed the same improvement in performance as the above-mentioned pulsed plasma jets.

The early continuous DC-arc plasma jets were not useful as a practical tool because of the need for a separate carrier gas, usually argon, to protect the cathode,and extensive water cooling, to protect the anode. This meant that a large proportion of the electric input was dissipated to the cooling water and carrier gas. A large solenoid, requiring a separate electric power circuit, was necessary to rotate the arc discharge. The cathode suffered from uneven erosion, operated with a molten tip and thereby generated difficulties in controlling the gap between the anode and cathode with any accuracy. The importance of this emerged subsequently, when

it was found that the gap should be controllable to within a few tens of μm, about, say 300 μm, which appeared to be the optimum for nitrogen. Thus, the previous design of the DC-arc plasma jet required much additional equipment that would be far too heavy and bulky to be carried around, e.g. in an aircraft turbine.

Recently, a new design for a magnetically rotated DC-arc plasma jet has been developed which requires no carrier gas, no extensive cooling and no solenoid. Instead, a small, compact, permanent magnet is used to rotate the arc. The gap between the anode and cathode can be set and maintained accurately. (Chan et.al., 1980). This plasma jet was tested for a variety of feedstocks and performed well during extended operation.

These developments turn out to be particularly relevant to gas turbine engines, especially at higher pressures and for land based systems when going to leaner mixtures.

For several years, the gas turbine engine industry has suffered from relight problems at high altitude. This is currently being dealt with by continuous sparking. As engines are increasingly being designed for greater fuel efficiency, flame holding and ignition have become problematic. Fuel price increases have emphasised the need for leaner burning engines. These problems prompted Smiths Industries and Imperial College to start looking for more efficient igniters and for methods of maintaining flame stability under difficult conditions.

1.2. Gas Turbine Engines

Gas turbine engines are popularly linked with aircraft jet propulsion, but they are also used on land, e.g. to generate electricity. The combustion takes place at constant pressure and increasing volume, whereas in piston engines, the combustion takes place at constant volume. The working cycle of a gas turbine engine can be represented as in FIG. 1. According to a publication by Rolls Royce (1971), Point A represents air at atmospheric pressure that is compressed along the line AB. From B to C, heat is added to the air by combustion between added fuel and air at constant pressure, thereby increasing the volume of gas. Pressure losses in the combustion chamber are indicated by the drop between B and C. From C to D, the gases resulting from combustion expand through the turbine and jet pipe back to atmosphere. During this part of the cycle, some energy in the expanding gases is turned into mechanical power by the turbine; the remainder provides the propulsive jet, on its discharge to atmosphere. The exit velocity of the gas stream is in the region of 650 m/s. FIG. 2 shows the relationship between temperature, pressure and velocity for the air as it passes through the engine. The higher the combustion temperature, the greater the expansion of the gases; the limitation depends on the temperature the turbine blades can tolerate. The airflow through the engine is continuous, so that volume changes become changes in velocity. The combustion chamber has to be designed for recycling hot products to help the flame to stabilize at the higher velocities. The air velocity is initially reduced to 25-30 m/s, but it is further lowered by creating a region of low axial velocity, by combining

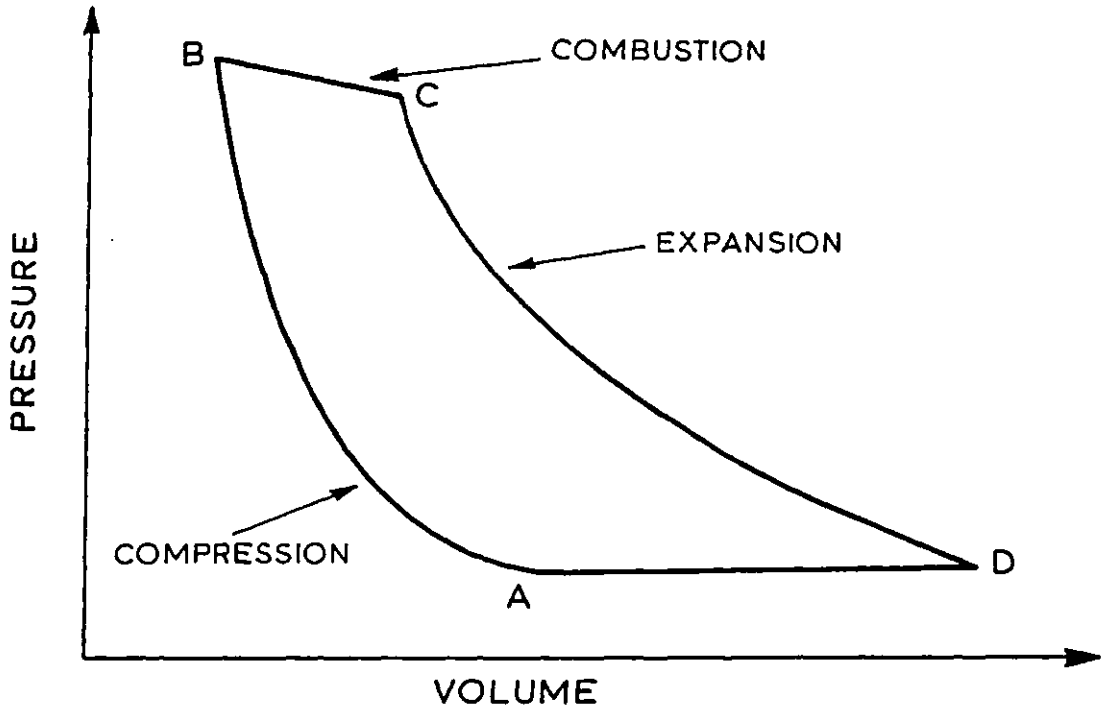


FIG. 1:1. The working cycle of a gas turbine engine, from Rolls Royce (1971).

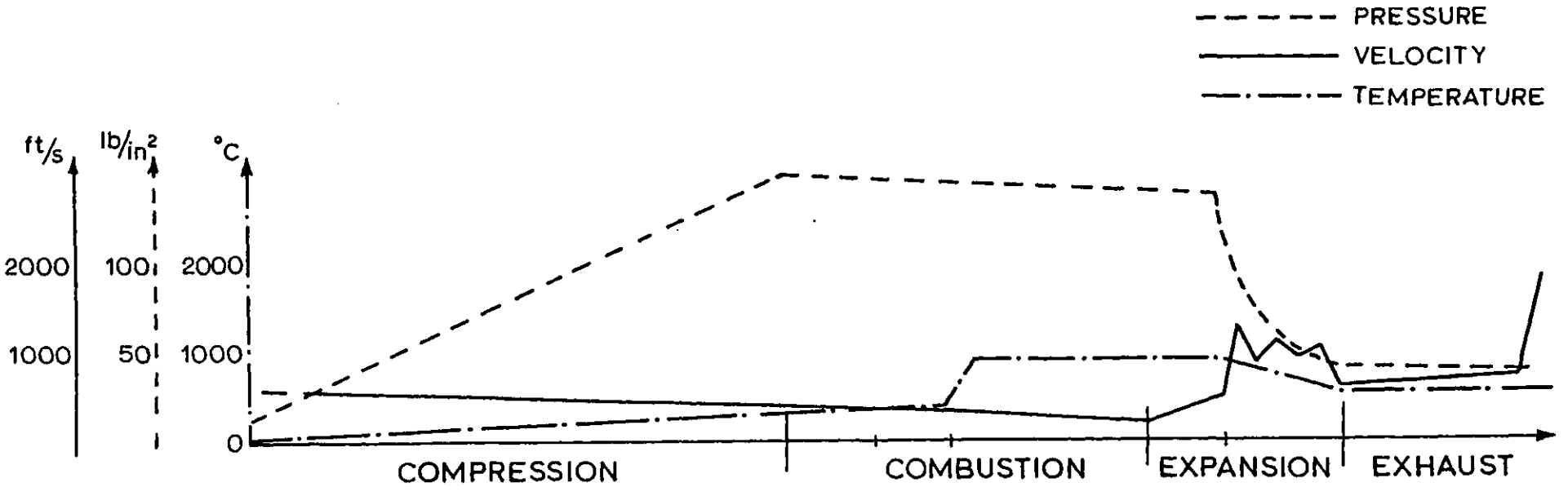


FIG. 1:2. Variation in pressure, temperature and air velocity for air passing through a jet engine, from Rolls Royce (1971).

swirling inlet air with axial inlet air, so forming a recycling zone, FIG. 3. The fuel is either sprayed into the combustion chamber as liquid droplets or prevaporized before entering the combustion chamber, where an electric spark initiates combustion. The fuel is selected for its ease of ignition by choosing one that easily vaporizes, especially at low temperature and whose viscosity allows good atomization. Further downstream in the combustion chamber, the remaining air is introduced to cool the combustion products and the flame tube walls. Complete combustion has to be achieved before the remaining air is added, since the air will cool the combustion products with corresponding lowering of the combustion efficiency. A variety of designs for gas turbine engine combustion chambers are available, depending on the manufacturing company and the type of engine.

Start up procedures for a gas turbine engine require two separate systems to operate either jointly or separately. Initially, gas, electric or hydraulic pressure is used to rotate the turbine blades until they achieve adequate airflow for combustion. Secondly, the combustion is initiated by an ignition system, e.g. a surface discharge igniter, FIG. 4. A complete theory for spark ignition has yet to be postulated. The commonly used theory stipulates that the minimum ignition energy has to be released into a critical volume larger than the quenching distance, so as to raise the gas temperature to the flame temperature, Lewis and von Elbe (1961). Igniters are normally positioned flush with,or slightly recessed from, the combustion chamber walls to minimize high temperature

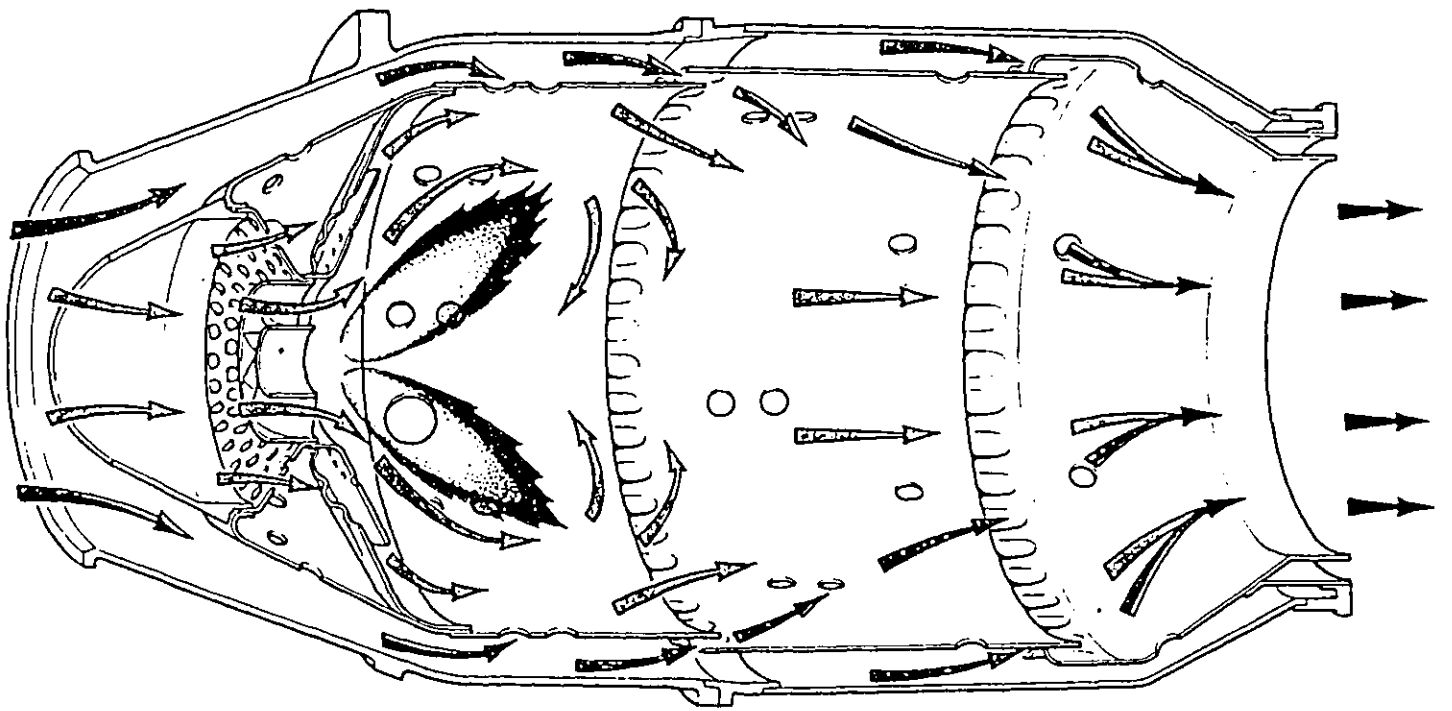


FIG. 1:3. Airflow through a combustion chamber in a jet engine, from Rolls Royce (1971)

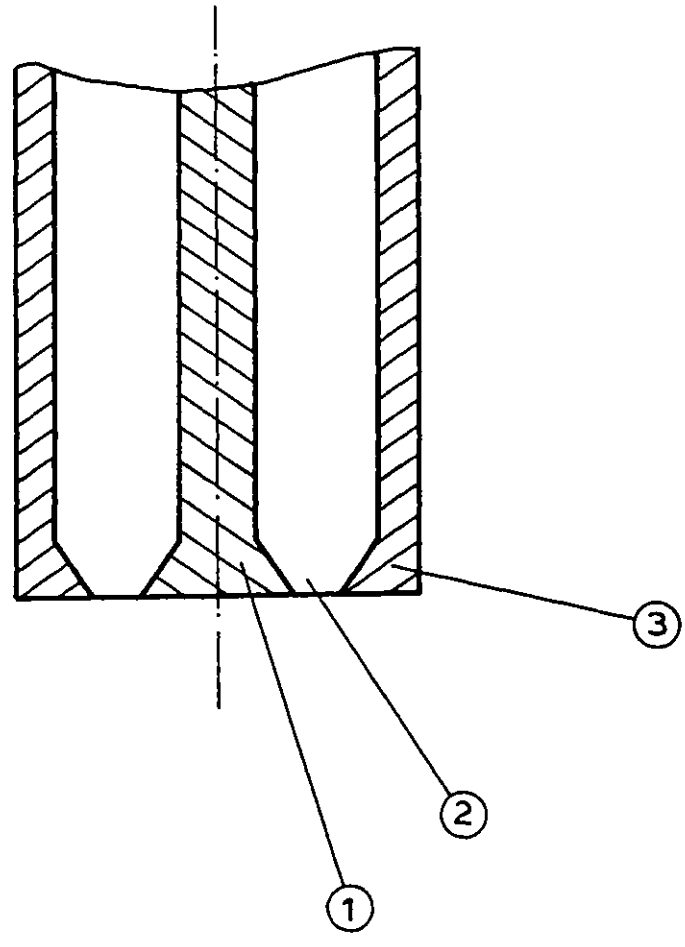


FIG.1:4. Surface discharge igniter.

1. Centre rod electrode
2. Ceramic insulator
3. Outer cylindrical electrode

damage, due to combustion taking place. This means the discharge has to travel from the igniter tip to a zone of stoichiometric fuel/air and to initiate combustion there, i.e. the spark kernel temperature has to be equal to, or above, the adiabatic flame temperature, and its size larger, or equal to, the relevant quenching distance. The need for projecting the discharge away from the igniter tip is evident. The energy input to the spark plug can be varied between 3J and 12J; the value chosen depends on factors, such as starting, weather and relight conditions. The lower the input energy to the igniter, the better; this improves plug life. However, the flow conditions are highly turbulent. Abdel-Gayed et.al. (1978) report that the presence of turbulence will narrow the limits of flammability but that it is possible to reduce this effect by increasing the spark energy. The spark ignition of turbulent gases have been studied by Akindele et.al. (1982). They found that a shock wave moving radial outwards was formed after initial breakdown. They concluded that this moving shockwave might be responsible for the spreading of the hot gas kernel and the ultimate attainment of ignition, once the kernel has grown to the critical size. The critical size for the hot spark kernel has to be at least the thickness of the turbulent flame front at that instant. They demonstrated that an increase in ignition energy leads to a larger spark kernel and it is, therefore, possible to ignite leaner and turbulent mixtures. The spark energy is released in a short time, approximately 150 μs.

When "flame out" occurs at high altitude, the relight can present problems. FIG. 5, from a publication by Rolls Royce

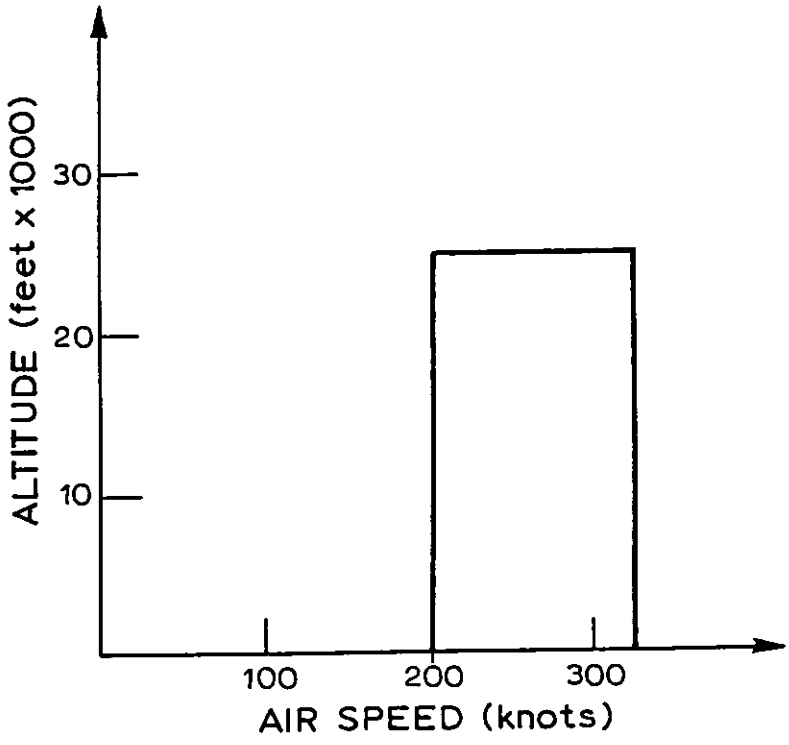


FIG. 1:5. Flight relight envelope from Rolls Royce (1971).

(1971) shows a typical flight relight envelope. Most commercial aircraft fly at about 10,000 m and military aircraft even higher. From FIG. 5, it is evident that relight is a problem, which is why most pilots choose to operate the ignition system continuously, although it is not designed for this. Ballal et al. (1978) have shown that minimum ignition energy for gas turbine engines after flame-out at high altitude depends on air pressure and temperature. In addition, fuel droplet size and high turbulence in the combustion zone adversely affect the ignition energy required. They point out that for heterogeneous liquid fuel/air mixtures, the ignition process is not limited by chemical reaction kinetics, but is evaporation controlled. For gaseous fuels, they found that the minimum ignition energy increases with increasing thermal diffusivity and turbulent intensity and decreases with increasing density and burning velocity, whereas for liquid fuel, the dominant effects are the fineness of the spray and the fuel volatility. The main reasons for difficulty in relighting are low air pressure, high turbulence and relatively poor atomization quality.

It will be apparent from the foregoing that there is a real possibility of overcoming relight and stabilization problems in gas turbine engines by the use of intermittent or continuous plasma jets, as igniters and flame holders in fast gas streams. Fundamental work towards this ultimate objective is the subject of this thesis. The aims were also to optimize the continuous plasma jet previously developed at Imperial College for practical use and to develop a pulsed plasma jet, either based on the Smiths Industries spark plug design, or

a new design to allow for production of plasmas in specific media.

C H A P T E R 2.

INTERMITTENT PLASMA PLUG

2.1. Introduction

Sparkplugs for aviation gas turbine engines are normally surface discharge plugs as these permit a higher energy discharge and avoid excessively high voltages. The surface discharge plug comprises a solid rod electrode surrounded by an insulating ceramic ring and a cylindrical outer electrode, FIG. 1. The discharge takes place between the end of the centre electrode and the outer cylindrical electrode. The ceramic insulator is finished with a thin layer of a semi-conducting material, whose function is to facilitate ionization and allow low voltage sparks to be generated. This is possible because the electric resistance of the semi-conducting material decreases with the increasing temperature, experienced in the initial pre-sparking stage. Surface discharge igniters are either manufactured "flush fired" (the semi-conducting layer is flush with the electrode surfaces) or "recess fired" (the semi-conducting layer is below the electrode surfaces), FIG. 1 b and c.

The igniter is used with an ignition unit which stores energy from the electrical supply system of the aircraft in a bank of capacitors, which releases the energy at a set

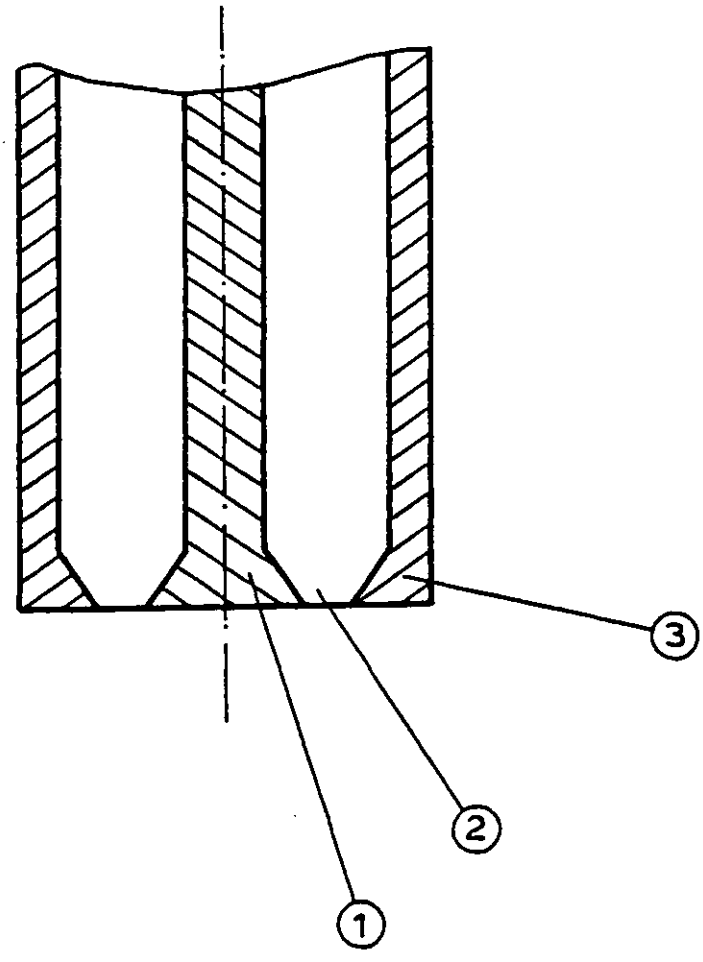


FIG. 2:1. Surface discharge igniter.

1. Centre rod electrode
2. Ceramic insulator
3. Outer cylindrical electrode

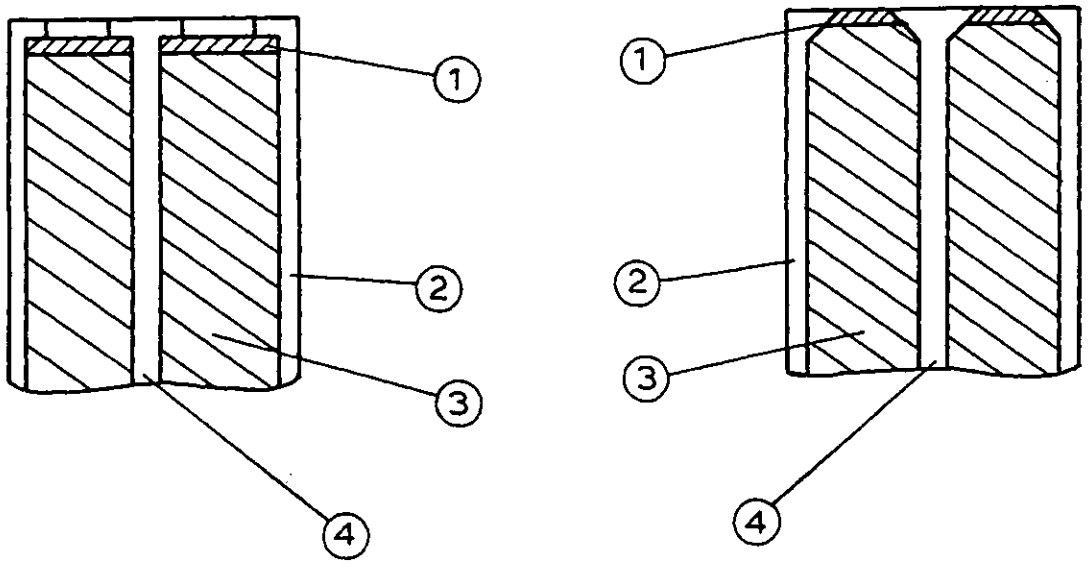


FIG. 2:1. Recess fired (b) and flush fired (c) surface discharge igniter.

1. Semiconducting layer
2. Outer electrode
3. Ceramic
4. Centre electrode

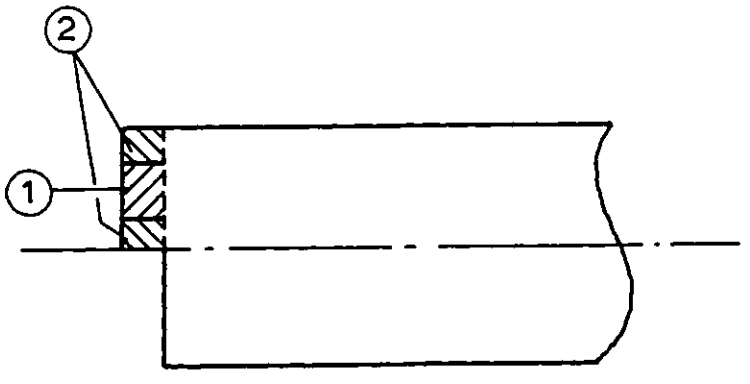


FIG. 2:1.d. 2-dimensional surface discharge igniter.

1. Ceramic
2. Electrodes.

potential - normally 2kV - in a high voltage-low current discharge across the electrodes. FIG. 2 shows a simplified outline of the circuitry. The spark duration is normally around 100 - 150 μs although Steiner et.al. (1966) suggest that the spark duration is less important than the initial energy release.

In a publication by the Department of Aircraft Propulsion (1967), it is demonstrated that spark energy is increased by an increase in gap width or a reduction in the depth of recess. So a large gap "flush fired" igniter achieves maximum incendivity. This means a slimmer central electrode which, when combined with an increased spark energy, leads to a shorter plug life. Therefore, a compromise has to be achieved between incendivity and plug life. Plug life will also be affected by factors such as higher heat transfer to the plug surface due to higher compression ratios, temperatures above 600^{o}C due to oxidation of plug surface and the chemical composition of the gas adjacent to the plug (which tends to be more oxidizing in modern gas turbines). Therefore, the position of the igniter in the combustion chamber will also affect plug life as well as ignition performance. The plug has to be close enough to the primary zone for the hot spark kernel to reach the combustion zone. For this, a "flush fired" igniter is best, as it ejects its hot kernel the furthest distance. Nor is it likely to suffer as much from an eventual fuel wetting as the "recessed fired" igniter. The second consideration is that carbon from the flame zone

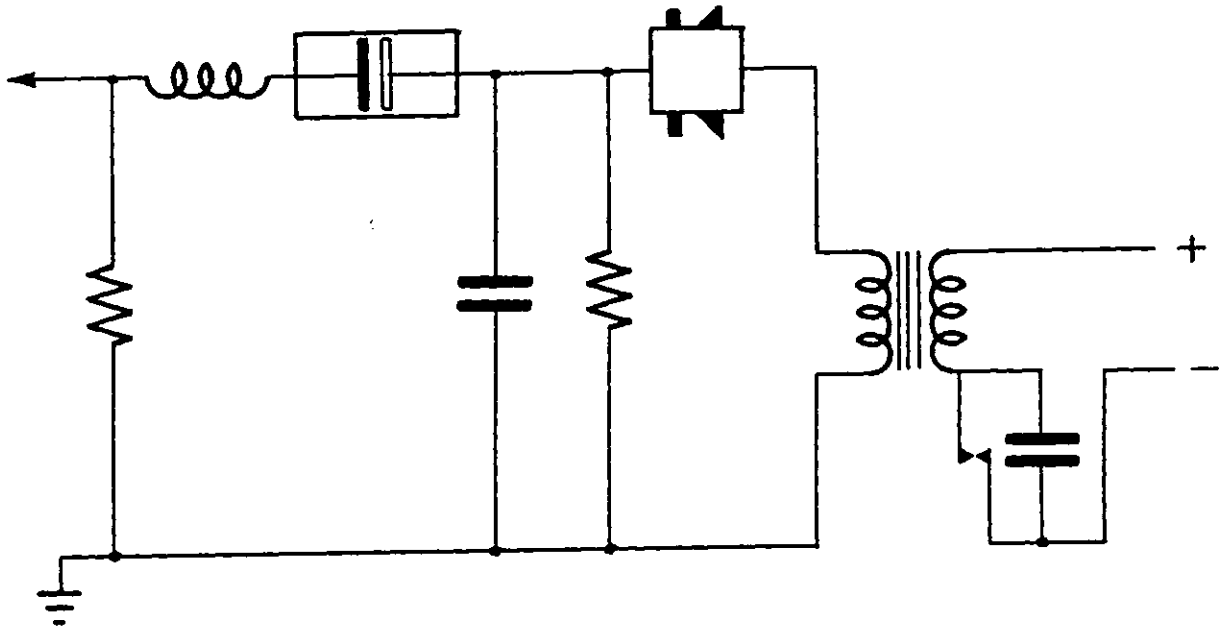


FIG. 2:2. Electric circuit for ignition unit for surface discharge plugs.

should not be deposited on the plug. Normally a plug is fitted on the cylindrical portion of the flame tube near the outer edge of the fuel spray. It should protrude far enough into the combustion chamber to clear the cooling air for the walls and so allow the hot spark kernel to reach the combustion zone. FIG. 3 shows the effect of protrusion on incendivity. However, the further into the chamber the plug protrudes, the shorter its life.

The ignition process in a gas turbine engine according to Lefebvre et. al. (1957) occurs in three distinct phases:

Phase 1. Formation of a flame kernel whose size and temperature will determine whether it will propagate or not.

Phase 2. Subsequent propagation of the flame to the whole primary zone.

Phase 3. Particularly for tubular combustion chambers the flame has to spread to adjacent flame tubes. (There is not one igniter in each flame tube).

All three phases have to be successful to achieve complete ignition and different conditions will adversely affect the different phases. For this research, phase 1 is of most interest. The survival of the spark kernel depends on whether the heat release by combustion exceeds the rate of heat loss. Heat losses depend on the gas velocity,

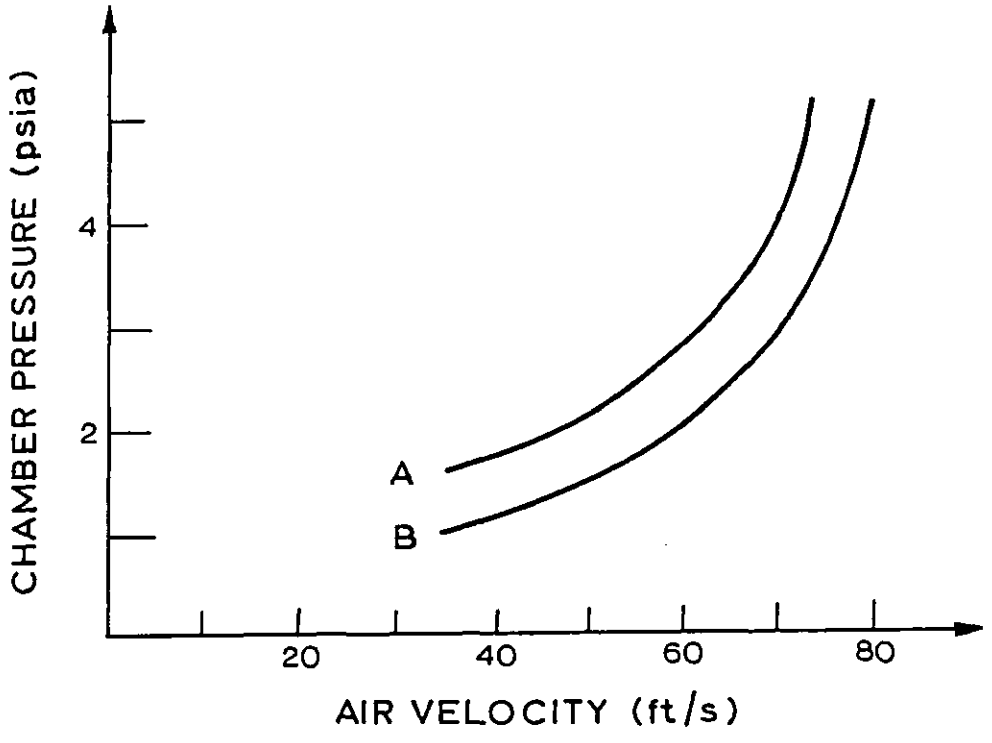


FIG. 2:3. The effect of plug protrusion into the combustion chamber of a gas turbine engine on incendivity.

A. Flush with wall

B. Protruding 12 mm.

turbulence and excess fuel present close to the igniter. That release being highest for stoichiometric conditions therefore depends on the fuel/air ratio close to the plug and on the size and temperature of the kernel, which depends on the energy released and the duration of the spark. The energy release in a surface discharge plug has been investigated by several authors, e.g. Plooster (1971), Watson (1954), Mak (1979). According to Mak (1979), who carried out a calorimetric study on energy losses, the losses experienced in a 12J and a 3J spark are as shown in TAB. 1 which for the 12J case leaves 0.86J of energy to impart to the gas and for the 3J case 0.26J . Critchley (1975) and McMahon (1974) found that the kernel size will increase when the spark energy is increased. Emphasizing that only high energy sparks can ensure ignition as the larger the flame kernel the bigger the chance it will survive the journey to the primary zone. Some energy will be lost on vaporizing the fuel; approximately 25% more energy is required in terms of minimum ignition energy, when using kerosene as compared to a chemically similar gaseous fuel (see Rao and Lefebvre, 1976).

For the initial experiments in the present work on intermittent plasma plugs, a standard surface discharge igniter, supplied by Smiths Industries, was used. The effect on plug behaviour of adding small amounts of different liquids to the igniter surface, adding a magnetic field and coupling two igniters together and firing them simultaneously were to be investigated. Previous work on both intermittent and continuous plasma jets have shown the benefits of radicals in

	12J		3J	
	%	J	%	J
circuit losses	48	4.99	58	1.62
igniter losses	16	1.62	11	0.3
electric heating losses	25	2.60	18	0.5
spark radiation losses	3.5	0.37	3.9	0.11
kernel energy + shockwave dissipation	8.2	0.86	9.3	0.26

TAB. 2.1. Energy losses in a surface discharge igniter. From Mak (1979), with permission from the author.

decreasing the lean flammability limit and increasing the burning velocity. It was anticipated that liquid addition to the surface of an igniter might generate radicals. The interest in magnetic fields was due to the possibility that it might throw the ignition kernel further away from the igniter. Coupling two igniters together would form an orifice or constriction in the way of the discharge and a simple plasma jet would thereby be formed. Series or parallel coupling of the two igniters should demonstrate the attraction-repulsion force acting on the two discharges.

2.2. Plug Design

Intermittent plasma plugs for use as igniters in internal combustion engines have jointly been developed at Berkeley, California and Imperial College. Weinberg et al. (1978) demonstrated that a gaseous fed plasma plug would decrease the lean limit of flammability and increase the flame propagation rate for methane/air mixtures. Using a variety of liquids in the plasma cavity, Orrin et.al. (1981) concluded that the larger the number of H-atoms present in the liquid the more effective the ignition. Smiths Industries (1979) investigated the possibility of using an intermittent plasma plug as an igniter in gas turbines. This led to the development of a "focused discharge igniter", FIG. 4, subsequently called a surface discharge based plasma jet. It is possible to change the size of the orifice diameter and the shape of the cavity. This igniter worked well with a variety of liquids, such as water and aviation fuel (Avtur). This report shows the effects of liquids and plug shape on

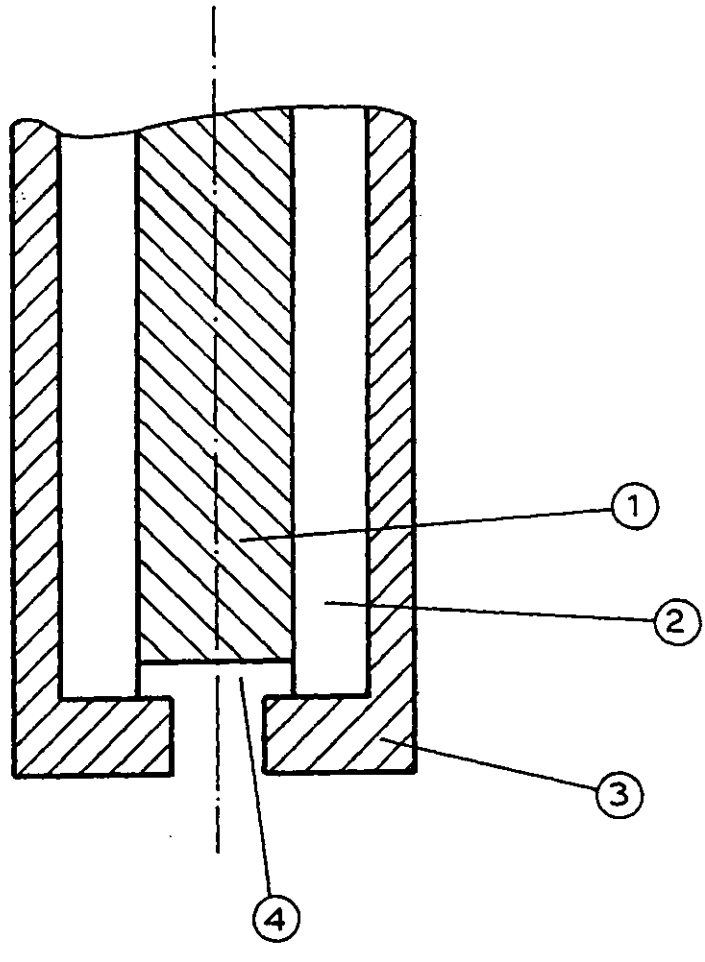


FIG. 2 : 4 "Focus discharge" igniter. (surface discharge based pulsed plasma jet.) Cavity volume 14 µl.

1. Centre rod electrode
2. Ceramic insulator
3. Outer electrode
4. Cavity

the ignition envelope. The smaller the orifice diameter, the further downstream the plasma is ejected, although there is an optimum diameter below which quenching sets in. The report also points out that water produces the same effect visually as aviation fuel. However, the surface discharge based plasma jet was never tested in a real situation and therefore any changes due to radicals produced when using water or fuel are not accounted for.

In the present work, when designing the initial plug for intermittent plasma plug experiments, two factors were taken into consideration. First, the need for correlation between existing spark plug behaviour and that of the wetted surface discharge plug. In order to do this, it was decided not to confine the discharge from the wetted plug. The effect of radicals could be observed by making sure the discharge took place in a specific media, i.e., by wetting the plug. Secondly, by using a surface discharge igniter and allowing the various liquids to soak into the semi-conducting layer seemed preferable to the complicated arrangement necessary for wetting the surface discharge based plasma jet.

It was therefore decided to use a standard surface discharge igniter for these preliminary experiments. When necessary, the plug was modified so as to force it to spark in a specific place, FIG. 1d. This will be referred to as the two dimensional plug.

2.3. Experimental Results

As previously mentioned, a standard surface discharge plug, supplied by Smiths Industries, FIG. 1, was used for these experiments. High speed cine-photography at 4000 frames per second of a two-dimensional plug confirmed results already published by Bradley et.al. (1974) that, during ignition, the discharge plume is ejected away from the plug surface, probably due to the IxB-force. This projection away from the plug helps to explain the low level of erosion of the ceramic material and projects the plume further into the combustion chamber. FIG. 5 shows some of the high speed cine-photographs.

Several still photographs of the extent of the discharge plume at different power inputs for dry surfaces were initially taken to provide a base for the study of wetted surfaces lengthening the discharge plume. The surface - basically the ceramic between the two electrodes - was next wetted with small amounts of either water, methanol or dichloroethane. The reason for choosing these specific liquids are that water, not being a fuel, can only contribute OH and H radicals to the ignition, whereas methanol, being a fuel, can contribute a variety of radicals and extra fuel to the ignition. Dichloroethane is a combustion inhibitor. The amount of liquid has to be small enough for the plug not to expend all its energy displacing the liquid as a droplet spray. The decay of the size of the discharge plume with number of shots was measured and compared with the initial wetted plume size and that for the dry surface.

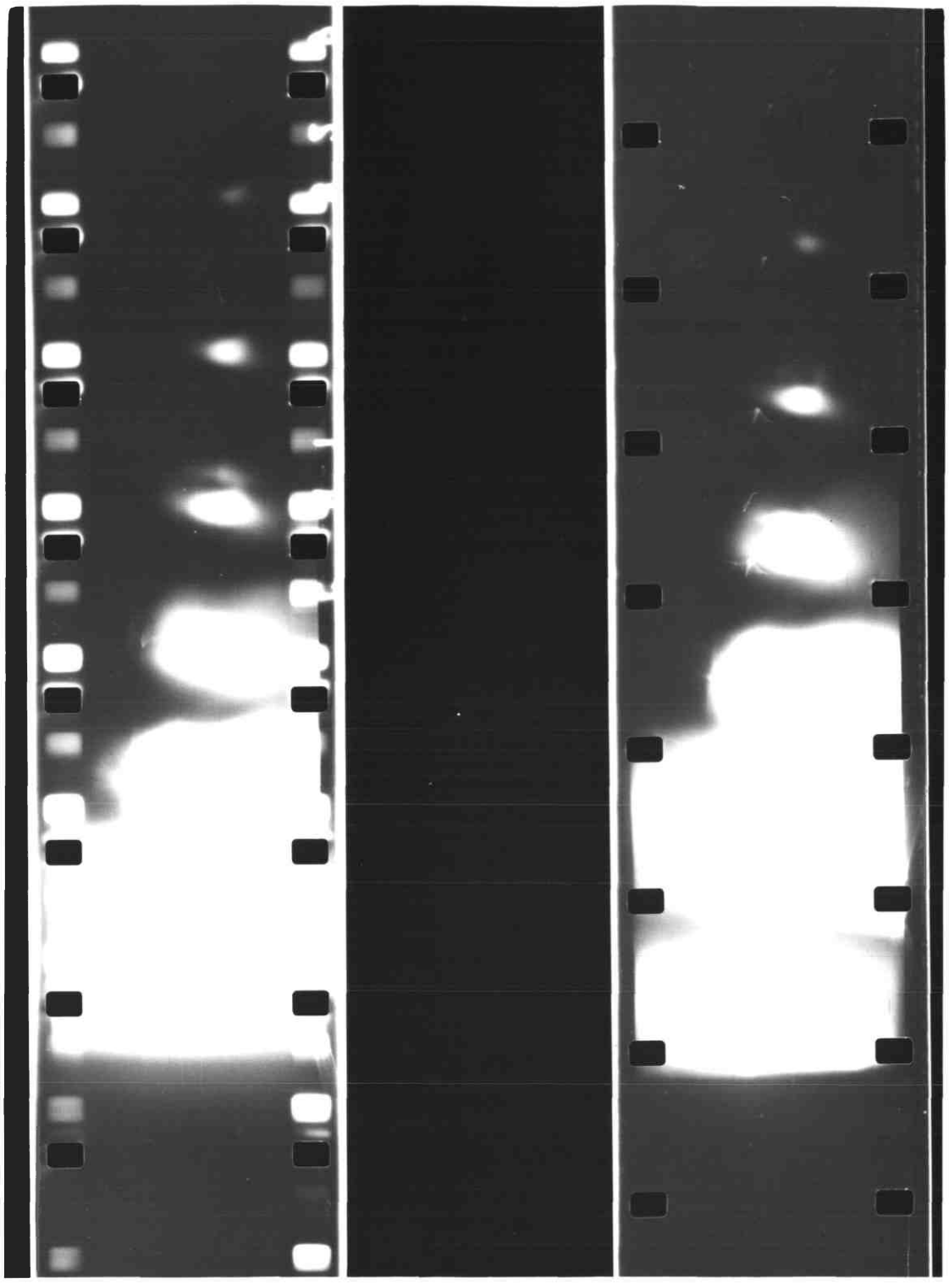


FIG. 2:5. High speed cine-photographs of the spark kernel growth. Sequence starts at the top of the page. Camera speed 4000 frames/s.

Addition of water or methanol distinctly lengthens the discharge by approximately 50% - 100%. It remains longer for more than 10 shots after the initial wetting. The extent of the discharge depends on the liquids used; it is longer for methanol than for water. A combustion inhibitor, dichloroethane, will initially lengthen the discharge, but this lengthening disappears within two shots and the discharge reverts to its standard length. Colour photography of the wetted plug discharge shows a white inner cone with a blue rim and a light brown surrounding area, evidence of the radicals generated, whereas the dry discharge has a white inner cone with a blue rim. FIG. 6 shows some of the photographs of the different discharge plumes.

The temperature of the discharge plume is far higher than is necessary to achieve ignition. It is therefore desirable to try to spread the discharge. Using a series of permanent ring magnets around the tip of the igniter with the magnetic field at right angle to the surface of the igniter was therefore investigated. These fields would either rotate the discharge clockwise or anticlockwise, depending on the direction of the field. Investigation of the influence of a magnetic field, applied as described previously, on a dry surface discharge igniter showed that strong fields, up to 2600 Gauss, rotate the discharge more than weak fields, from 90^{o} to 180^{o} and occasionally 270^{o}. Viewed laterally, the extent of the discharge was shorter down to a quarter of the original value for a discharge in the absence of a magnetic field. However, a vortex is formed, which would help mixing

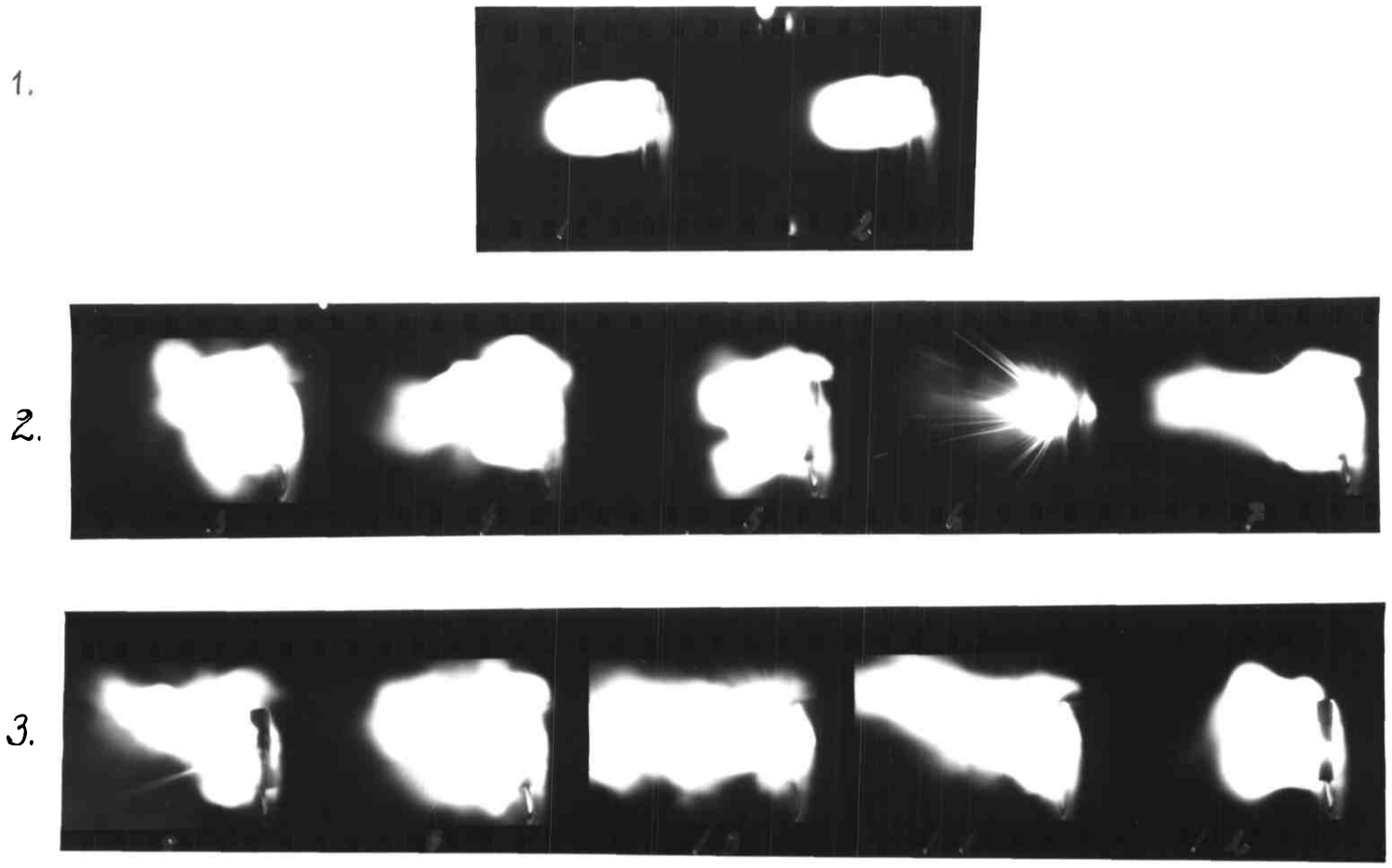
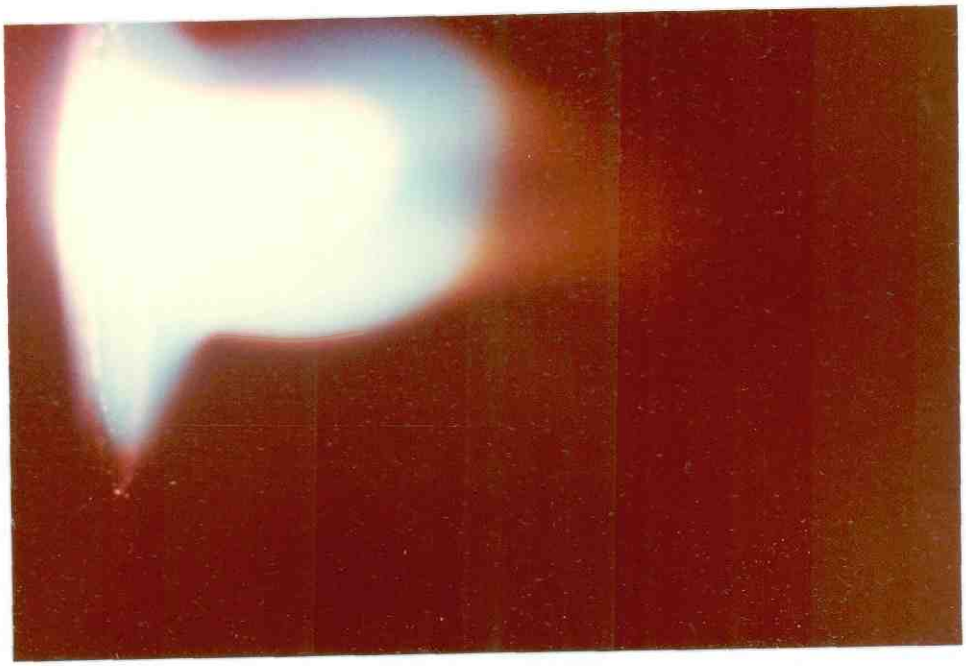
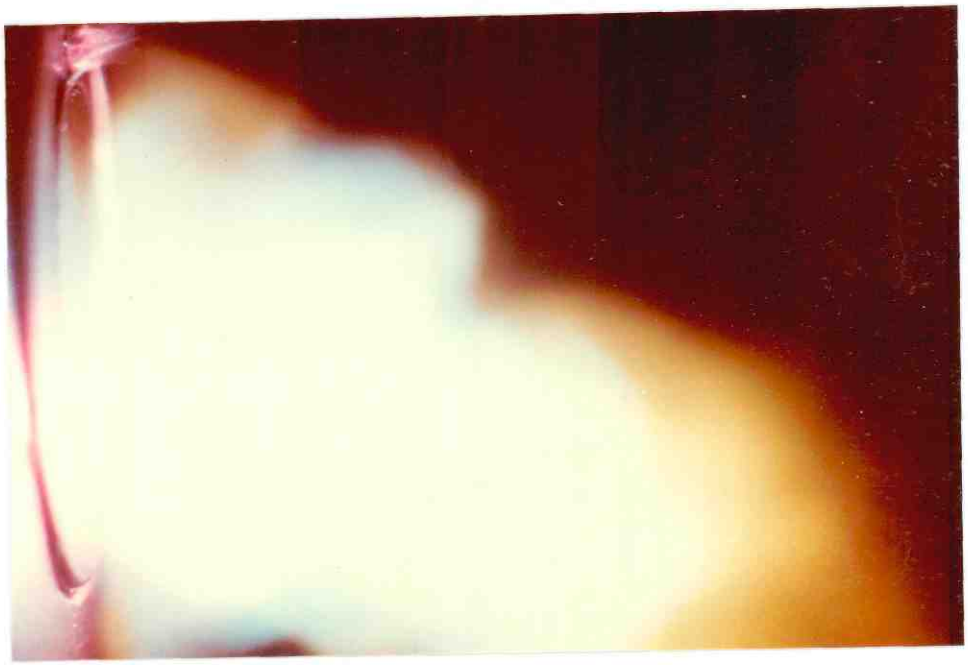


FIG. 2:6a : Sideviews of a surface discharge plug.

1. Unwetted
2. Wetted with water (once)
3. Wetted with methanol (once)



1.



2.

FIG. 2:6b : Colour photographs of a surface discharge plug, sideview.

1. Unwetted
2. Wetted with methanol

in a gas turbine engine, FIG. 7. Combining the effects of a magnetic field and wetting the surface initially lengthens the discharge plume, as in the case of liquid only, while the effect of the magnetic field slowly develops, rotating and shortening the discharge. The discharge length under the influence of both effects can be made to approximate the length of the standard discharge, the two effects cancelling each other out as far as the lengthening-shortening is concerned. It is worth noting that, although the length can be changed by adding liquid, the vortex due to the magnetic field still persists. The volume of gas heated by the discharge is bigger for a magnetically rotated wetted discharge, as the base area,due to the vortex, is bigger than for the non-magnetic case. Thus, the benefit of combining the two effects would be to induce more mixing and, therefore, enhanced entrainment due to the magnetic field, while the liquid addition would be expected to generate radicals.

Coupling two surface discharge plugs together, forming an orifice or constriction in the path of the discharge, would form a simple plasma jet, FIG. 8. Initial experiments between series coupled or parallel coupled igniters showed that the series coupled ones gave the largest discharge plume. The effect of firing two series coupled igniters facing each other into a small cavity filled with different liquids was monitored. Again, the amount of liquid in the cavity proved critical. If too much was added, a droplet spray was ejected from the cavity with no discharge plume. If a smaller amount of liquid was added or if successive shots were fired, the discharge plume was projected outside the cavity, occasionally igniting any left-over traces of liquid outside the cavity.

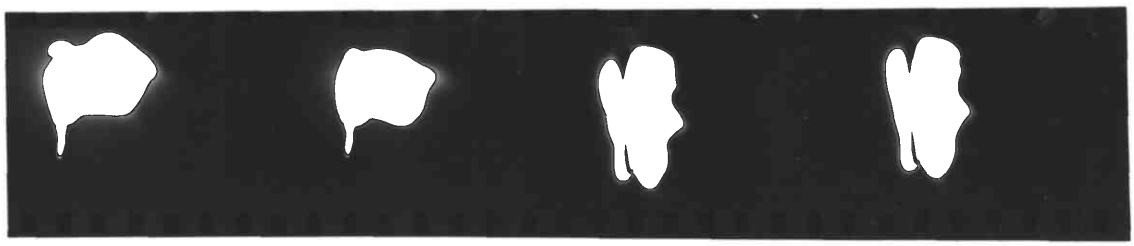
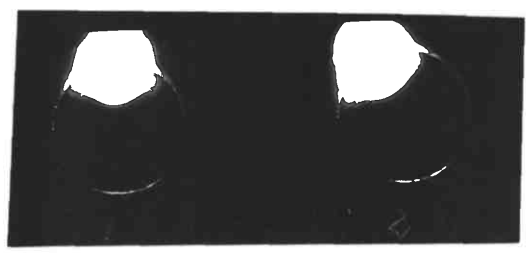
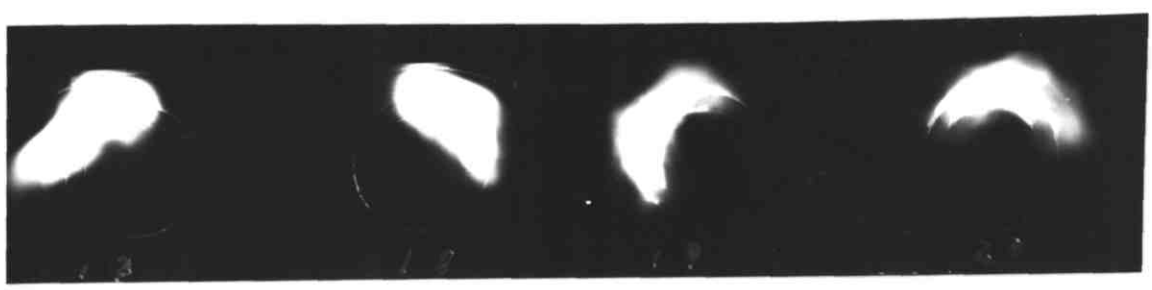


FIG. 2:7a : Sideview of a surface discharge plug with and without a magnetic field.
1. Without field
2. With 2600 Gauss field



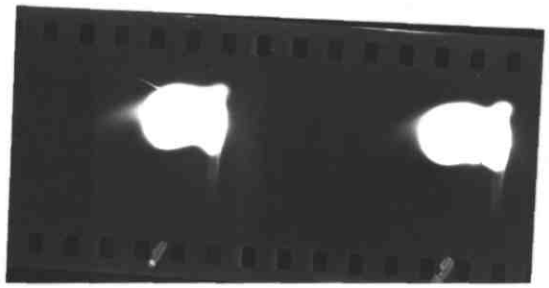
1.



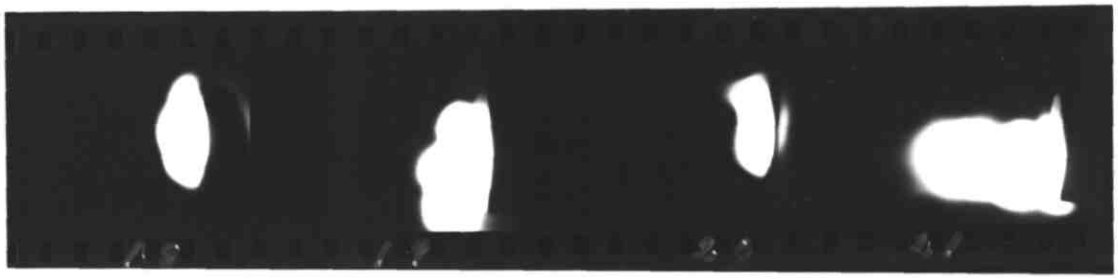
2.

FIG. 2:7b : Frontview of a surface discharge plug with and without a magnetic field.

1. Without field
2. With 1200 Gauss field



1.



2.

FIG. 2:7c : Sideview of a surface discharge plug demonstrating the combined effects of liquid wetting and magnetic field.

1. No field, no liquid
2. 2600 Gauss field and methanol

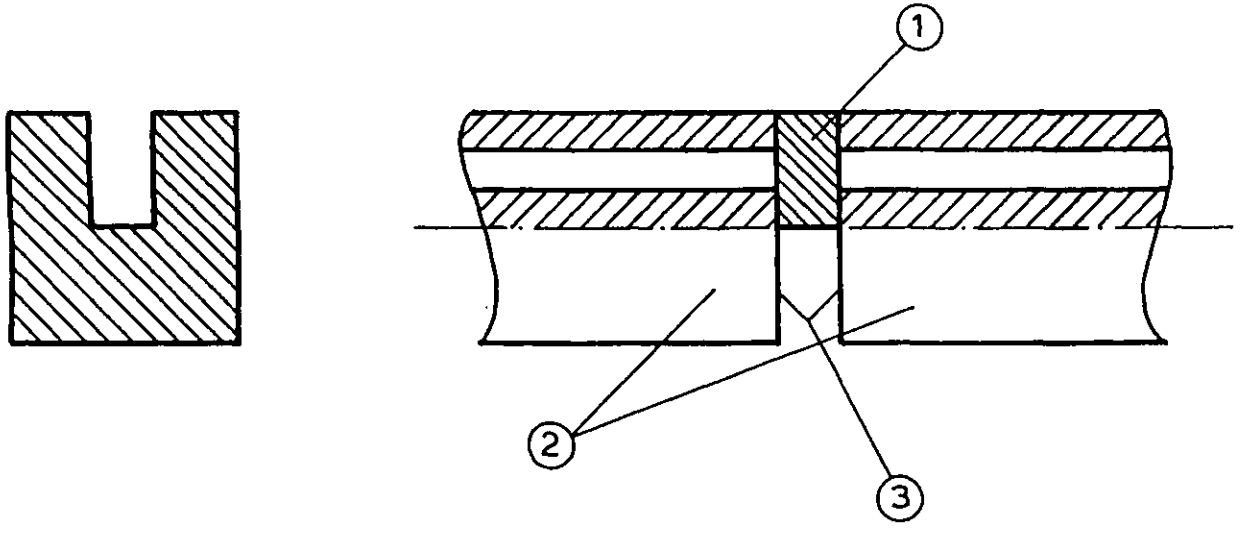


FIG. 2:8.a. Two surface discharge igniters coupled together with a small cavity between them.

1. Cavity
2. Igniters
3. Sparking prevent on these areas.



FIG. 2:8b : Sequence of firings with two igniters coupled together. Cavity filled, once, with methanol.

Most of these experiments were conducted with an energy input of 1.5J or 3J, as for higher values the light from the discharge completely blackened out the photographs.

2.4 New Plugs

These experimental results are strongly indicative of new possibilities for intermittent plugs as ignition devices. Chapter 4 will deal with the experimental arrangements necessary to simulate a real situation. However, the results show the definite advantages of liquid additions as this projects the discharge plume further into the combustion chamber, quite apart from the generation of radicals referred to in other work. For these reasons, new plug designs were considered. If the ceramic semi-conductor can be used as a sinter, it would be possible to use that as a way of adding liquids to the plug surface. FIG. 9 suggests some ways of arranging this in practice. Alternatively, small holes could be drilled in the electrodes and liquid allowed to seep through to the surface, FIG. 10. Finally, the plug could be arranged in the combustion chamber so as to receive a spray of liquid fuel on its surface. The amount would have to be carefully controlled since an excess would be expected to be counter-productive.

The range of igniters discussed in this preliminary investigation is wider than the range tested in the fast flowing gas stream. It is anticipated that some of these plugs will become redundant with the introduction of the continuous plasma jet discussed later. However, the devices are

summarized here since they may be found to be of use in other applications.

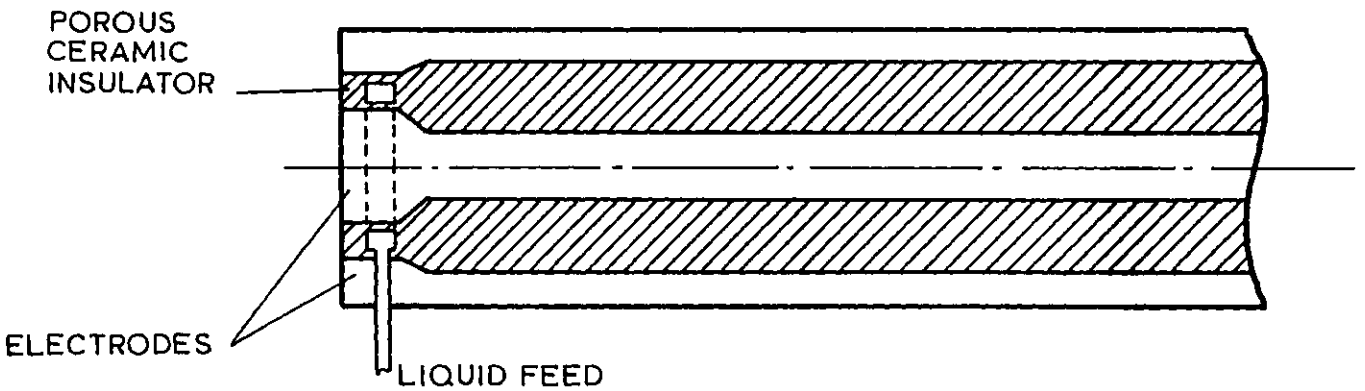


FIG. 2:9.a. Suggested plug design using liquid feed through a sinter.

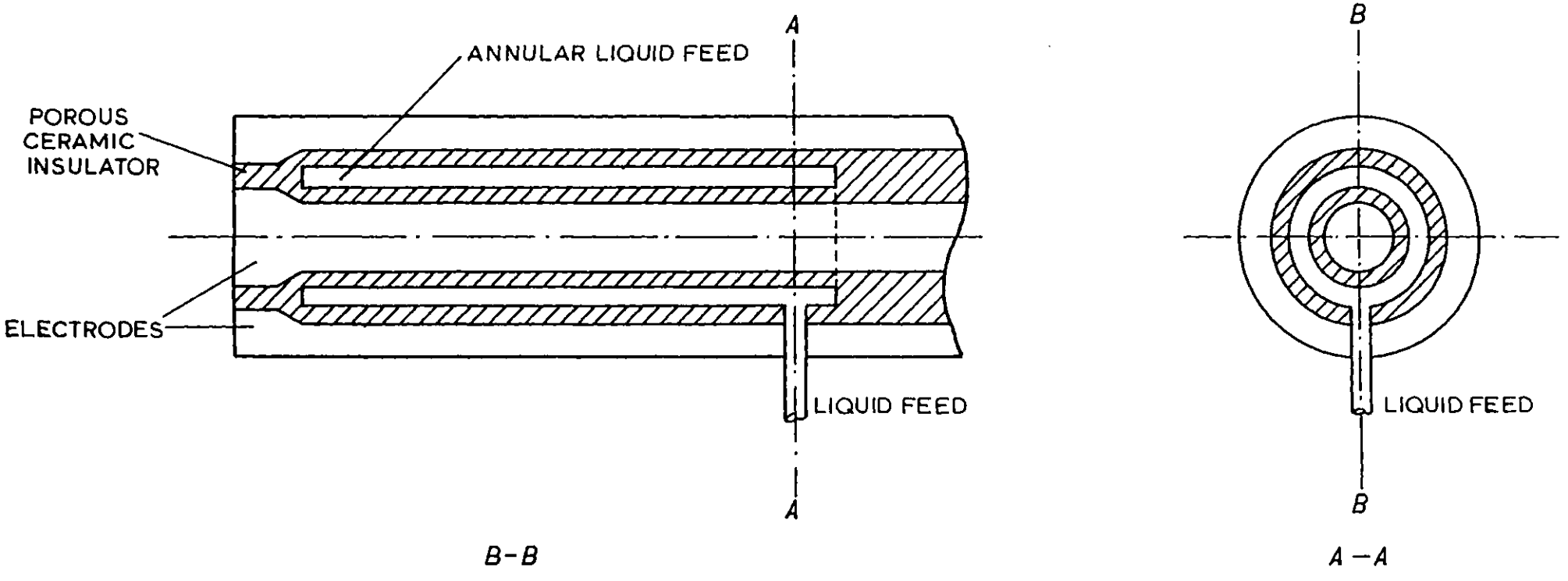


FIG. 2:9.b. Suggested plug design using liquid feed through a sinter.

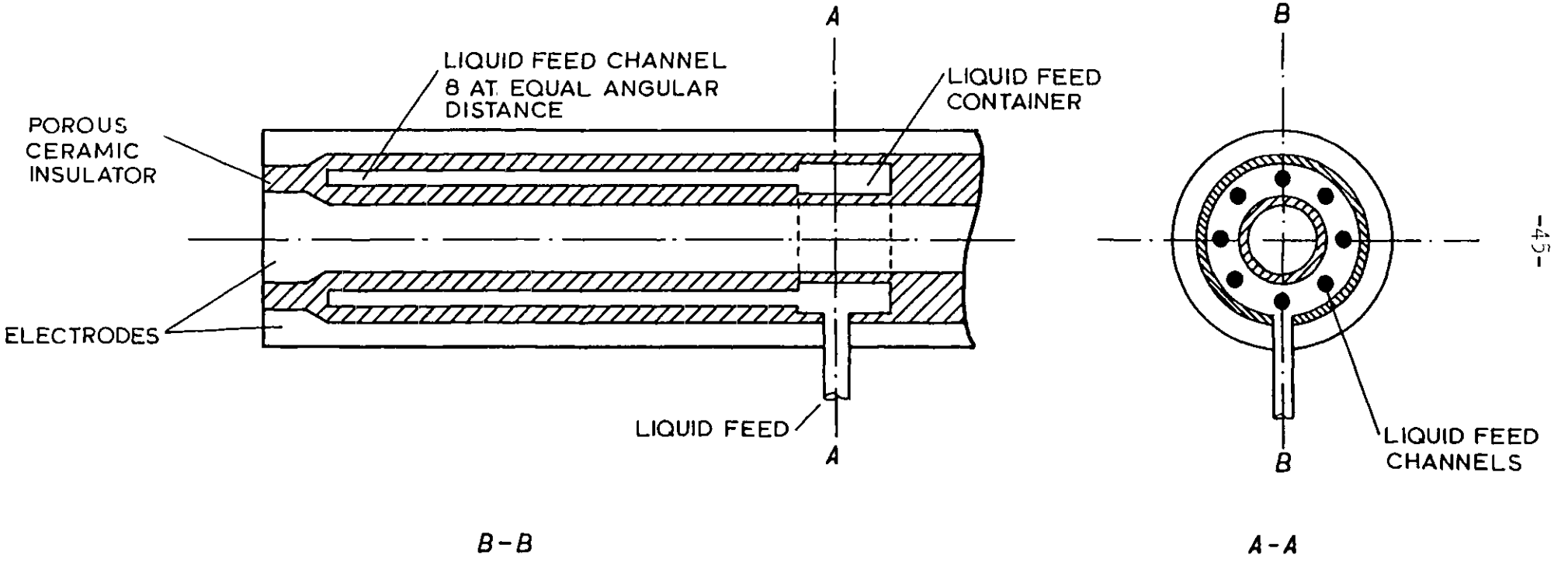


FIG. 2:10. Suggested plug design using liquid feed through a sinter.

C H A P T E R 3

CONTINUOUS PLASMA JETS

3.1. Plasma Jet Development

Continuous DC-arc plasma jet research has been in progress for some twenty years. The low power, compact plasma jet design developed by Chan et.al. (1980) is the precursor of the plasma jet used in this work. The main features of this plasma jet, FIG. 1, are the square cut cathode and the 45^{o} angled sloped anode, which, together with a permanent magnet, induces the arc to move uniformly around the circumference of the cathode. The present design allows the distance between the anode and cathode to be set with precision, thus minimizing erosion or uneven wear of the electrodes. The sharp edge of the cathode is maintained by rotating the discharge, using a magnetic field. The large throughput of gas helps to cool the electrodes and eliminates the need for argon sheeting of the cathode. The need to cool the anode is reduced. The power input is approximately 1kW, of which 80% reaches the gas, Malik (1979). The plasma jet is compact, easy to handle and does not require extra equipment. The flow rate for different feed-stocks is maintained at sonic velocity through the nozzle, by controlling the pressure drop across it. This provides the most stable operating conditions. The gap between the anode and cathode and the power consumption could be varied to suit the different

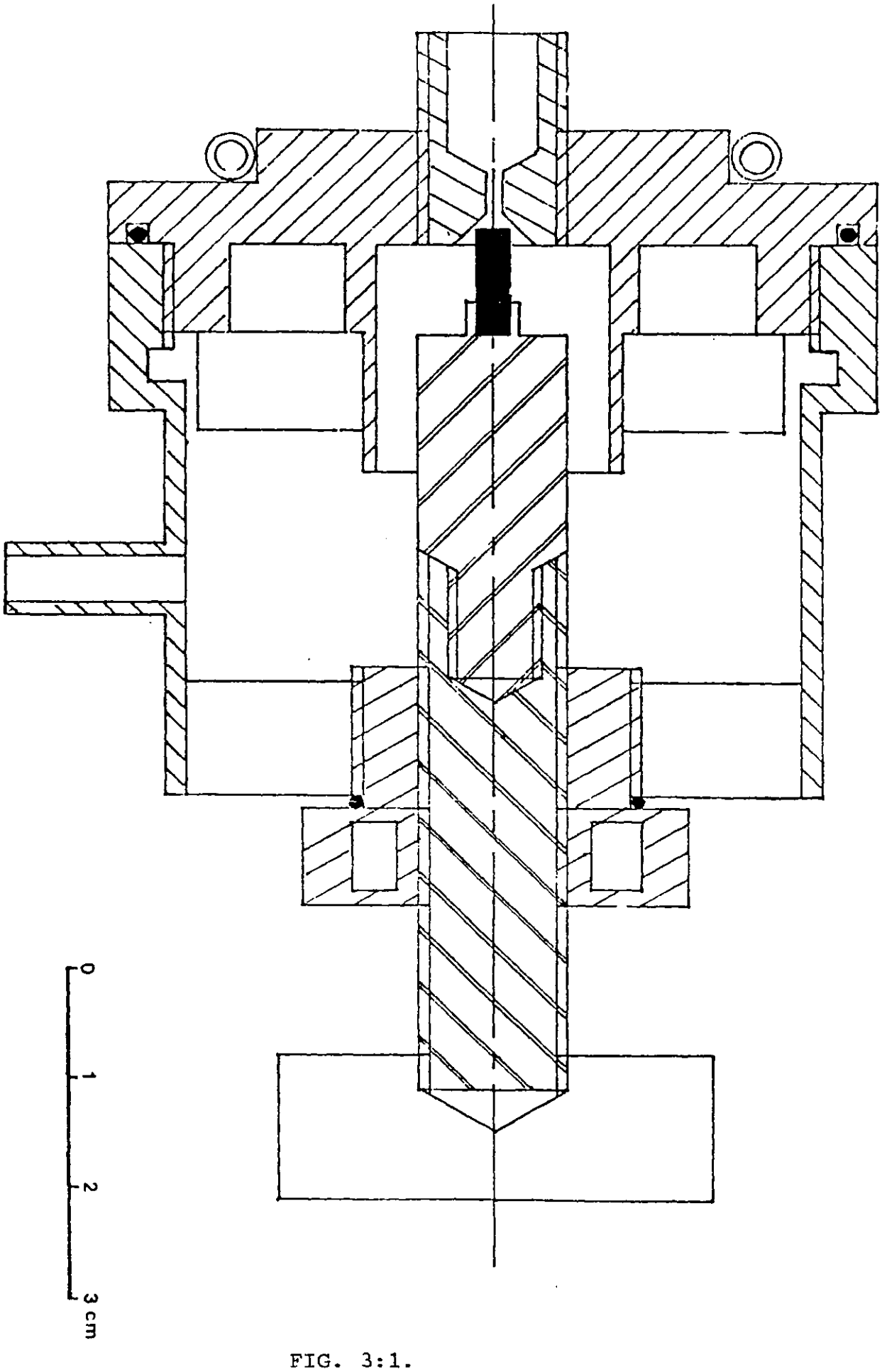


FIG. 3:1.
Original magnetically spun plasma jet developed by Chan et al. (1980)

plasma media used.

In the present work, the design of the Chan et.al. (1980) plasma jet was modified to make it more flexible and to introduce new features. The new design is illustrated in FIG. 2. It has facilities for changing the strength of the magnetic field, using several permanent magnets that can be stacked together. A single samarium cobolt magnet which gives a strong magnetic field, 1300 Gauss, can also be used. The gas input mode can be varied between tangential and axial. The sliding cathode support was designed such that the concentricity of the anode and cathode is assured, irrespective of position, which was difficult to achieve with the screw-threaded cathode support previously used. By attaching a micrometer screw to the sliding cathode support, it is possible to set the gap between the anode and the cathode accurately, down to 1 μm.

A three phase power supply, FIG. 3, was designed and built to facilitate changing resistance, thus allowing the use of higher currents and voltages, in contrast to the two welding generators previously used.

Initial running conditions for argon and nitrogen were established. Argon arcs proved easy to strike and gave no running problems in terms of cathode or anode erosion, blow-off or power fluctuations, even when run for extended periods. The argon arc ran well when no magnets were present, although the noise level and the power consumption were higher than for an arc with magnets. It is possible to see the external

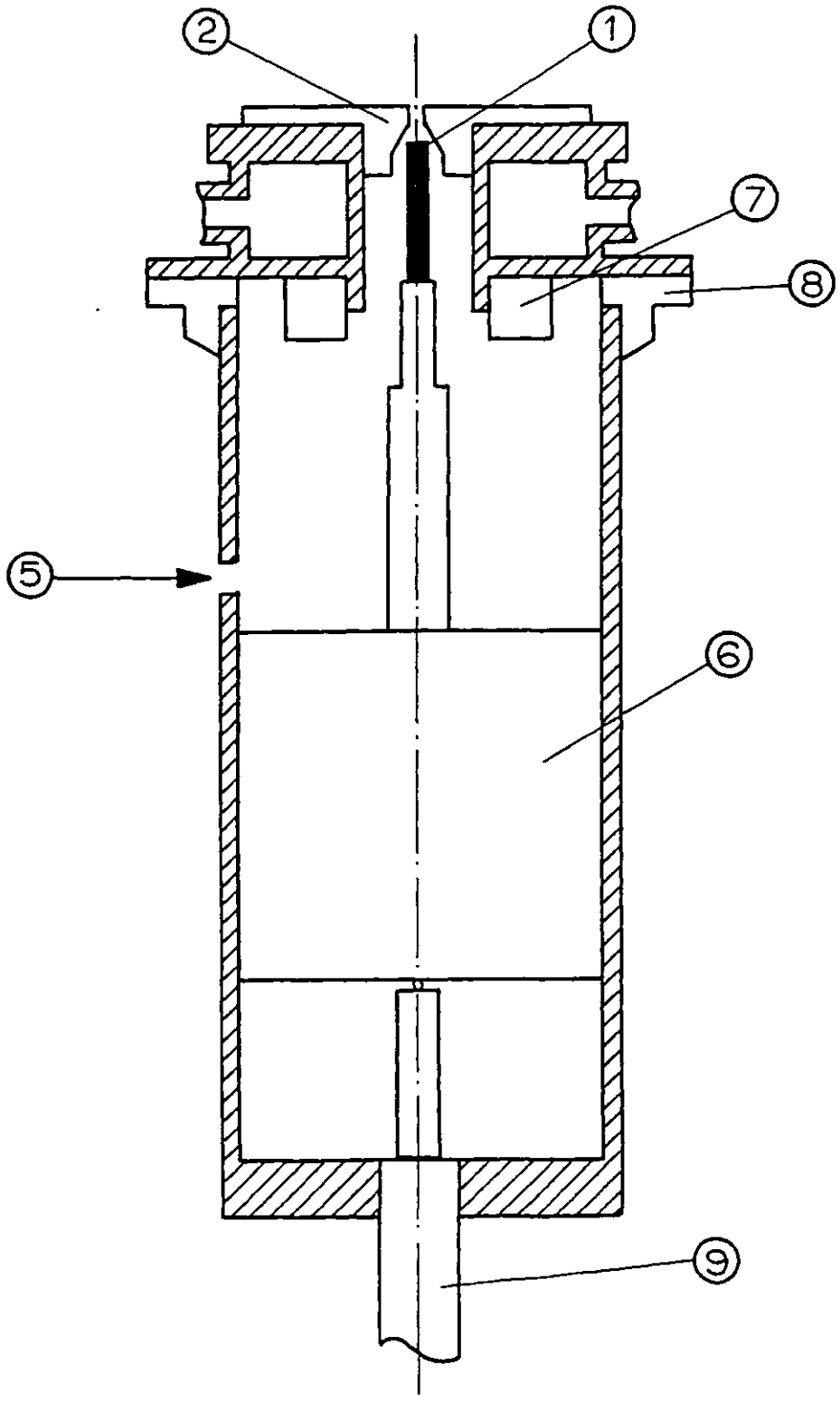


FIG.3:2 Magnetically rotated continuous plasma jet.

1.	Cathode	7.	Magnets
2.	Anode	8.	Insulation
5.	Gas inlet	9.	Micrometer screw
6.	Sliding Cathode		Support

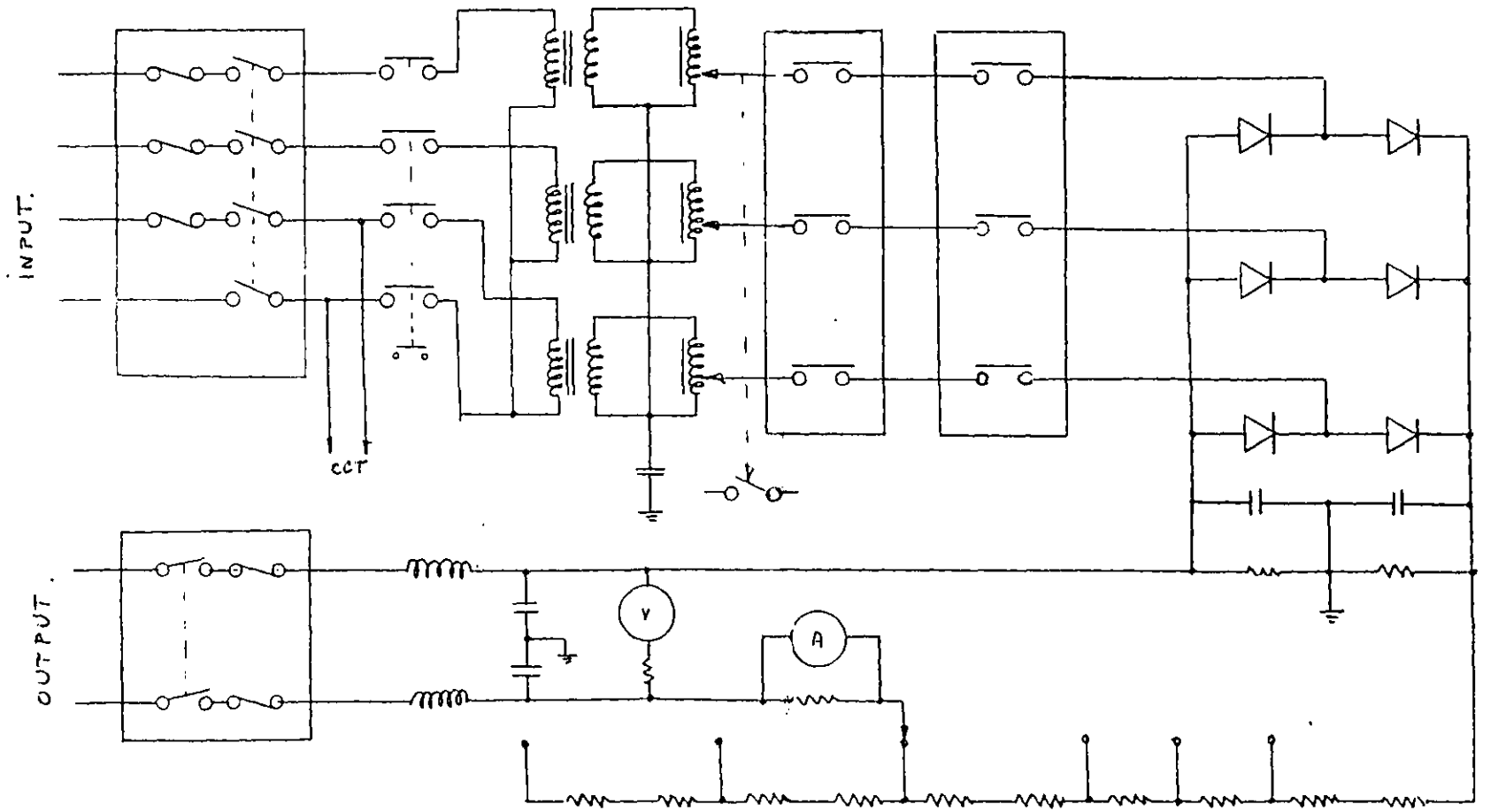


FIG. 3:3. Three phase power supply for the continuous plasma jet.

plasma cone moving from side to side in the exit of the anode channel when there is no magnetic field present, whereas for a magnetic field, the external cone remains steady. Changing the polarity of the two electrodes, varying the cathode and anode shape and the gap, together with magnetic field changes, made no appreciable difference to the way an argon arc performs.

A nitrogen arc requires a higher running power (800 - 1000 W, compared to 300 W for argon) and a smaller gap (300μm.) but also performs well during extended operation. When the magnetic field was removed and the anode and cathode shapes changed, an increase in noise level and plasma movement was observed, as with the argon plasma jet. The nitrogen arc became unstable when the gap was varied approximately $\pm$ 200μm. The arc refused to strike, or if lit, ejected a stream of metal tracers from the melting cathode when the polarity of the electrodes was reversed. The reason is that the gradient of conductivity versus energy input graph is much less for monatomic argon than for diatomic nitrogen. Running conditions and results can be found in section 3.2.

3.1.(2) The Structure of Plasmas and Further Development in Plasma Jet Design

The reduction of NO by N generated from a nitrogen plasma jet was studied by Behbahani et.al. (1982), with special reference to the energy requirement and the efficiency of the process. They were interested in NO-removal from combustion products. Their plasma jet was the magnetically spun plasma jet, developed by Chan et.al. (1980), described previously in this section. The NO-reduction reaction:

$$NO + N \longrightarrow N_2 + \tfrac{1}{2} O_2 \qquad (1)$$

$K_1 = 1.6 \cdot 10^{13}$ cm^3 mol^{-1} (Baulch et. al., 1973) is a useful tool in determining the number of nitrogen atoms present at different heights above the plasma jet. This NO-titration reaction made it possible to study the structure of the plasma.

When studying NO-removal by nitrogen plasmas, Behbahani et. al. (1982) found that removal efficiencies were surprisingly high and remained so for appreciable distances downstream, up to 2 to 3 cm. Initially, they considered the survival time to be due to excited nitrogen molecules. Calculations of equilibrium concentrations of excited nitrogen molecules yielded amounts which were far too low at the temperatures and pressures experienced in a plasma jet. Behbahani et. al. (1982), therefore, did a more detailed examination of the plasma jet. They found that the arc only heats a fraction of the gas. This agreed well with their experimental results. However, if only a proportion of the gas is heated, hot pockets, i.e. regions of hot gas surrounded by cooler gas, must be generated. A shadow photograph confirmed the existence of areas of hotter gas, surrounded by cold gas. These areas could be due to lower temperatures than those (8000K) postulated for the hot pockets. Behbahani et. al. (1982) finally used ionization probes to show the existence of small hot pockets. They concluded that these hot pockets contained dissociated nitrogen that diffused out of the pockets to react with the NO, following reaction (1). It was accordingly decided to explore the possibility of further improvements.

The rotation of the arc is necessary to maintain electrode shapes and separation. However, there are various ways of moving an arc in an anulus, either by using magnetic fields or by aerodynamically induced gas swirl. Either will rotate the arc with respect to the electrodes but the motion with respect to the gas is quite different. The magnetic field forces the arc to move through the gas. Vortex rotation maintains the arc in contact with the same ionized pockets of gas for longer periods. Until now, it had been desirable to spread the discharge through the anulus, using a magnetic field. However, the existence of hot pockets suggested that using gas swirl to rotate the arc would benefit the plasma structure. This meant promoting thermal unmixedness.

A new plasma jet, using aerodynamic gas swirl was designed. Although the magnetically rotated plasma jet had already been fitted with tangential inlets, these were of much larger diameter than the exit nozzle and did not impart much spin momentum to the gas. The first aerodynamically spun plasma jet was a modified car spark plug body fitted with a thoriated tungsten cathode and a stainless steel cap with space for the anode and the tangential gas inlet. This design was much simpler, lighter and smaller than the magnetically spun plasma jet. A spring was fitted into the plasma jet between the shoulder of the insulation and the anode to "guide" the gas around the cavity and help maintain the spin momentum. Cooling water could be added in the form of a copper coil where necessary. FIG. 4 shows the early aerodynamically spun plasma jet. Using the NO-titration technique discussed earlier, Behbahani et al. (1983) found that the aerodynamically spun

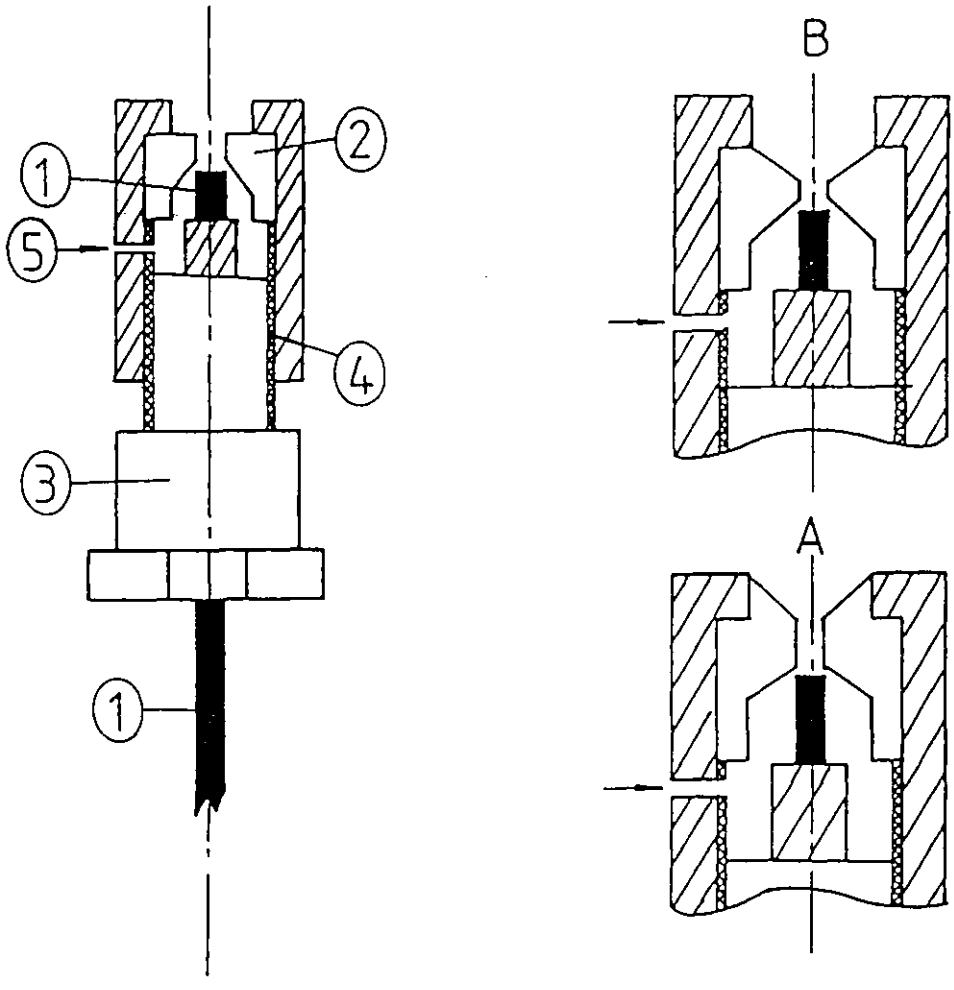


FIG. 3: 4. Initial aerodynamically spun plasma jet, various anode configurations,

1. Cathode
2. Anode
3. Spark plug body
4. Fine thread for gap adjustment
5. Tangential gas inlet

plasma jet performs marginally better than the magnetically spun plasma jet. Ionization probe tests (Behbahani et.al., 1983) showed that the aerodynamically spun plasma jet generates a larger number of hot pockets with a higher relative velocity.

Schlieren and shadow photographs, using a 40 nano-second pulsed ruby laser in an optical system in the Z-configuration (Weinberg, 1963) were taken of both the magnetically and the aerodynamically rotated plasma jet. See FIGS.5 and 6 (magnetically rotated) and FIGS. 7 and 8 (aerodynamically spun). These photographs show areas of high and low temperatures, the high temperatures being due to hot pockets. The hot pockets have a diameter of about 1 mm. They are generated because the arc only heats a fraction of the gas and large temperature variations therefore occur. The reason these hot pockets survive so far downstream is that regions of high temperature gas have greatly reduced inertia, density and, accordingly, experience a higher acceleration in a pressure gradient. It seems probable that any stratified temperature field placed in a sufficiently large pressure gradient will be torn apart and dispersed in this manner. The high viscosity of gases at these high temperatures is, presumably, responsible for the finite survival times of these hot pockets and, therefore, the distance they travel. So, the hot pockets are initially accelerated in comparison with the surrounding gas. However, as they pass downstream, the pockets decelerate quite quickly. They should enhance the ignition capabilities of the plasma jet as they represent radical sources. The existence of hot pockets for the intermittent plasma jet have been confirmed,

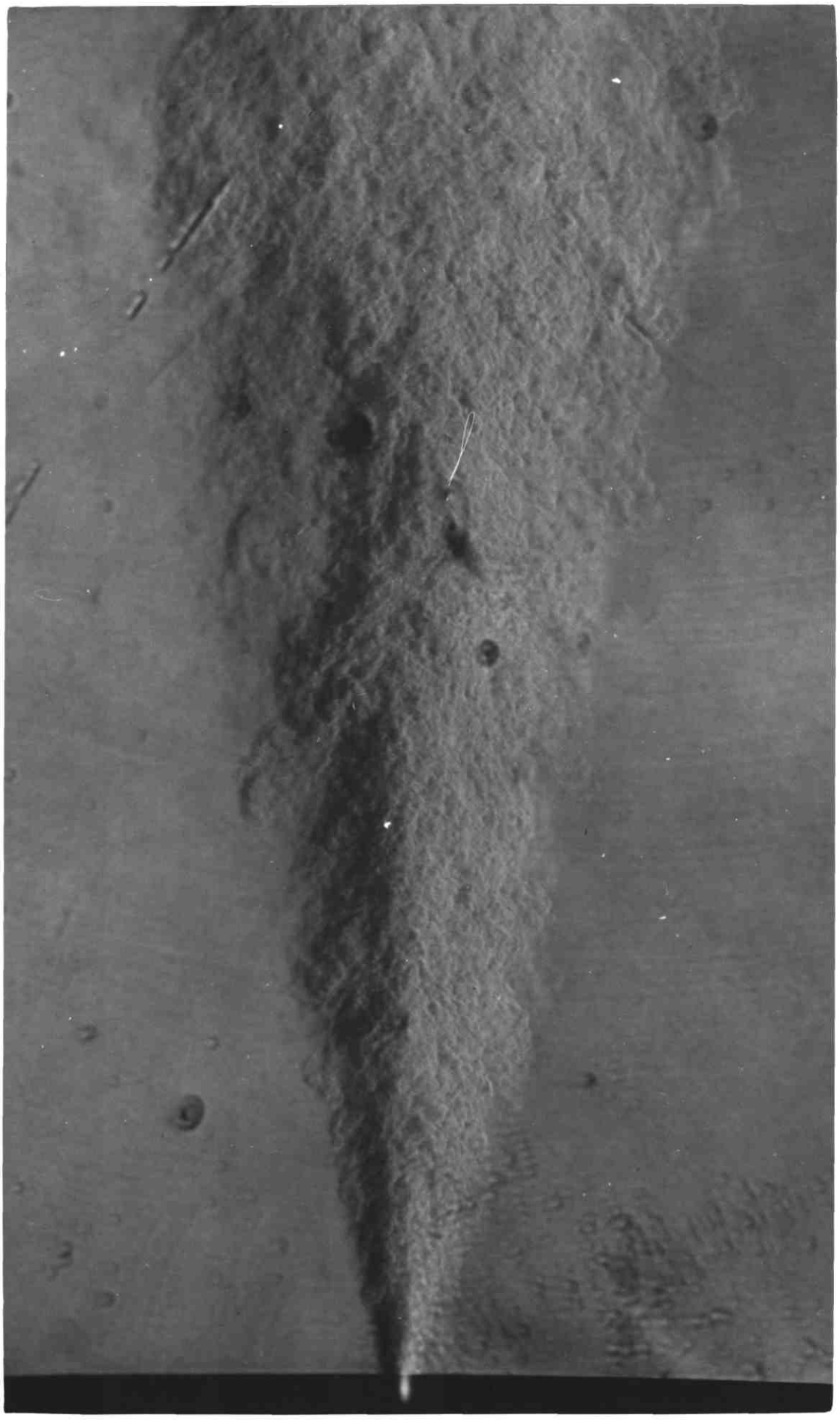


FIG. 3:5. Schlieren photograph of magnetically rotated nitrogen plasma jet. (510 cm^3/s; 1260W).

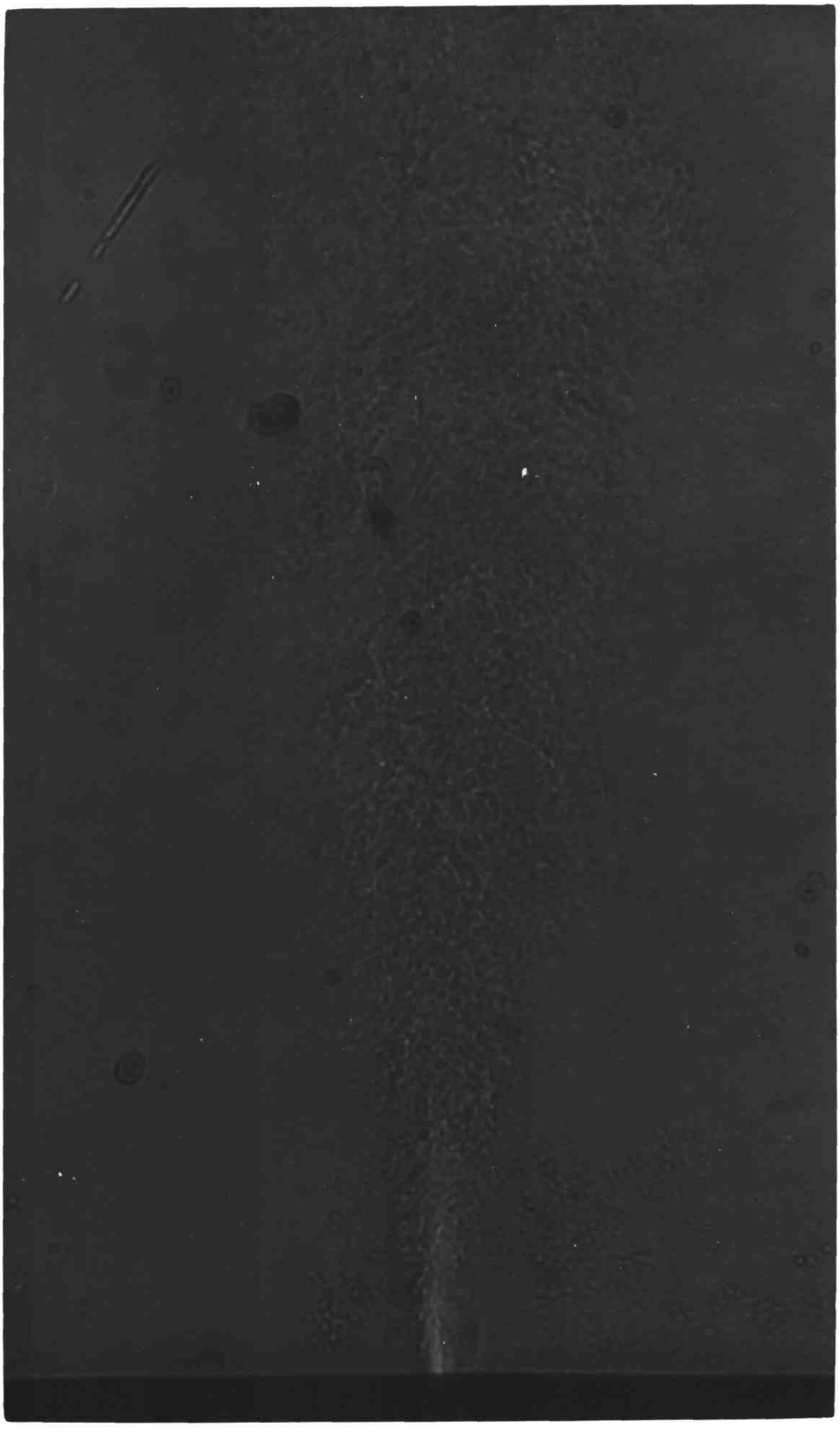


FIG. 3:6. Shadow photograph of magnetically rotated nitrogen plasma jet. (510 cm^3/s; 1260W).

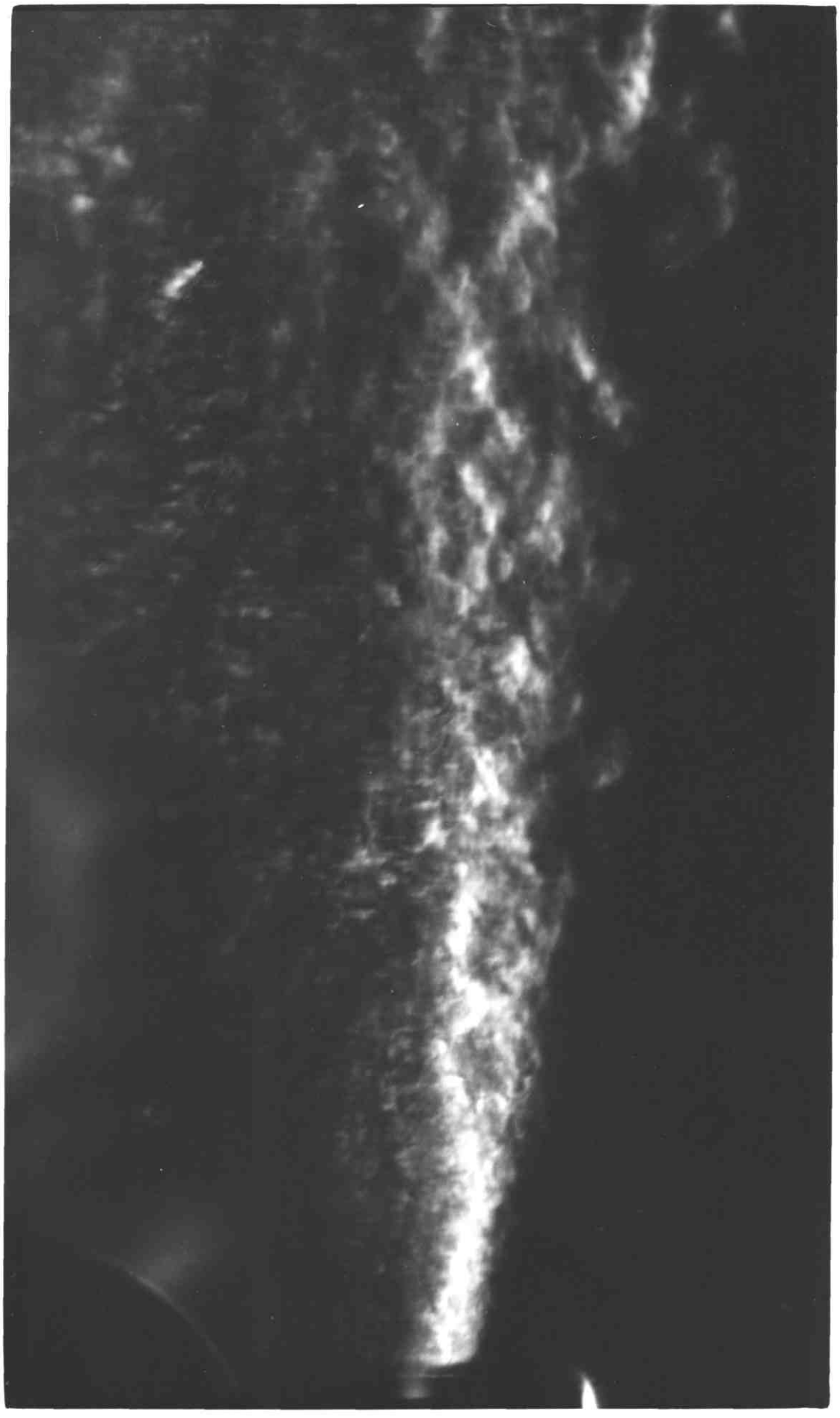


FIG. 3:7. Schlieren photograph of aerodynamically rotated nitrogen plasma jet (200 cm^3/s; 1100W).

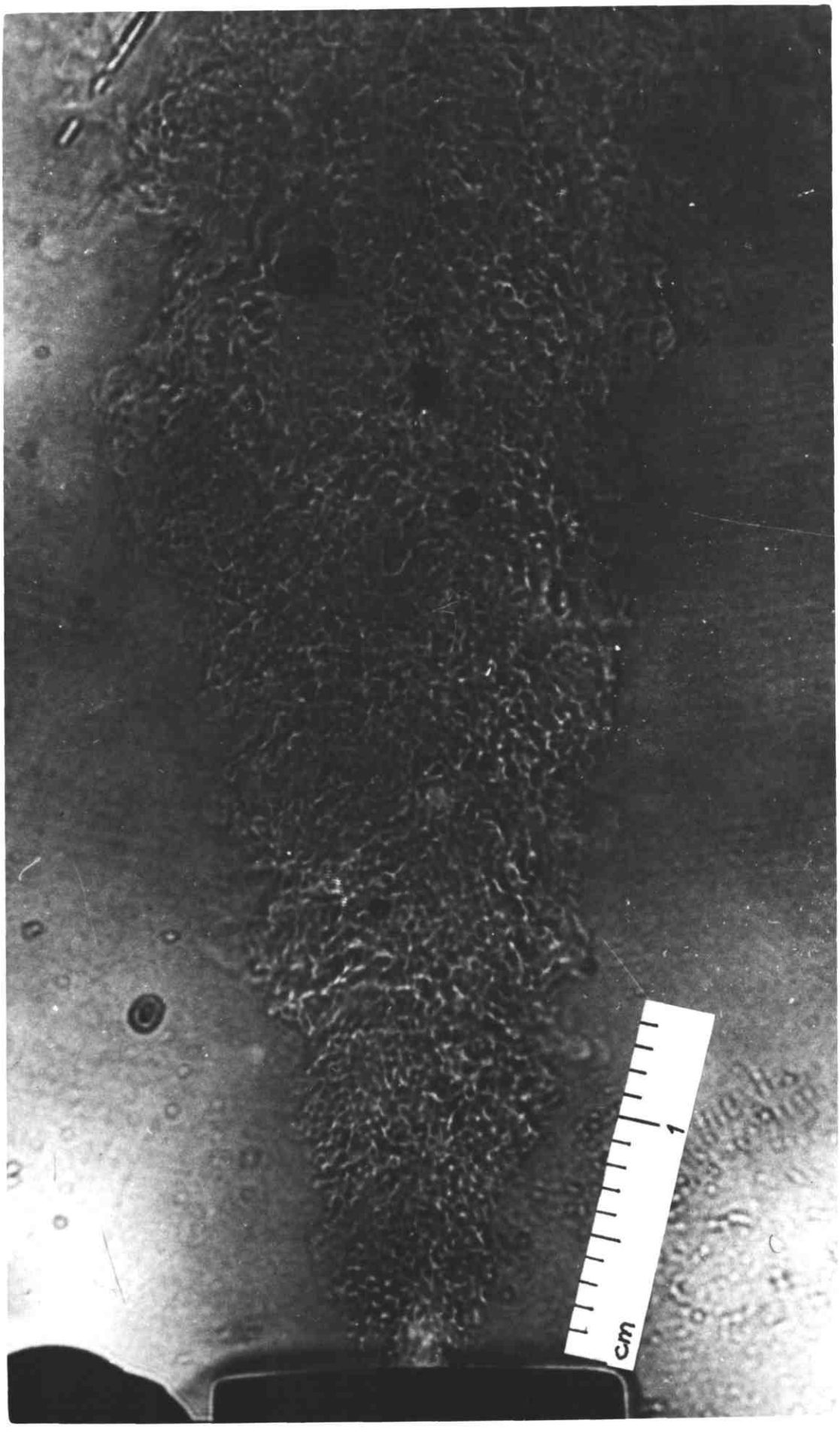


FIG. 3:8. Shadow photograph of aerodynamically rotated nitrogen plasma jet (160 cm^3/s; 1100W).

using streak photography, Cavolowsky et. al. (1983), and using the reaction of nitrogen atoms, generated in a pulsed plasma, with oxygen, Smy et. al. (1983).

Although the aerodynamically spun plasma developed around the body of a car spark plug was easy to manufacture and performed well, it was not possible to achieve perfect alignment of the anode and cathode. The hot plasma eroded away some of the anode channel. This was due to the screw thread wobbling against the steel cap. The screw thread was used to adjust the gap between the anode and cathode. A more rigorously designed plasma jet would be needed for continuous work, especially on flammable feedstocks. The new version of the aerodynamically spun plasma jet allows exact alignment of the anode and cathode, easy replacement of the cathode and control of the gap size; FIG. 9 shows the new plasma jet.

It is possible to detect "dents" in the plasma plume on the Schlieren photographs. These indentations in the outer contour appear regular enough to be taken as a sign of the arc rotation and approximate calculations, using the flow velocities, distance between two "dents" and the time, yield an approximate value for the frequency of the arc rotation, 5kHZ. This agrees well with the value achieved while examining the frequency of arc rotation on the magnetically rotated plasma jet. Several methods for detecting arc rotation were tried. The split anode, alone, gave acceptable results. Initially, a search coil with and without a ferric centre was employed, but the disturbance from the power leads and the distance from the arc to the coil made it impossible to obtain

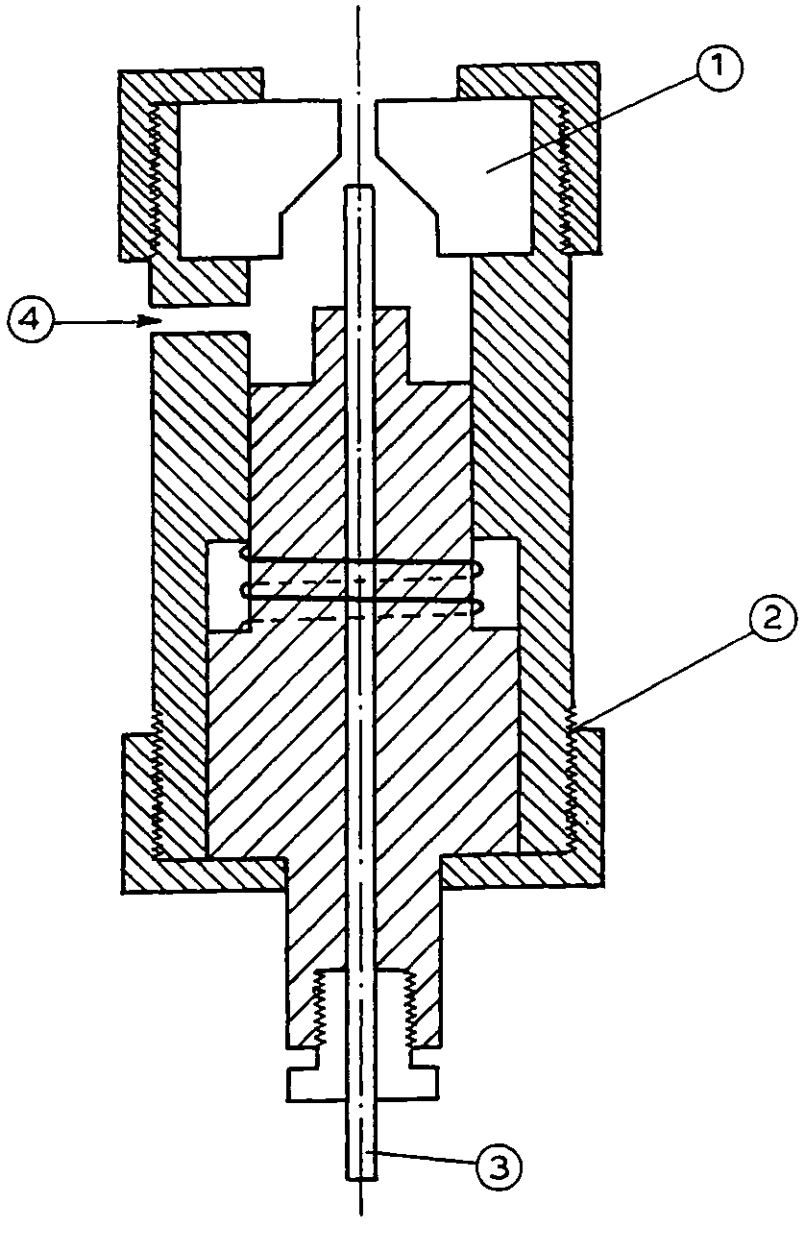


FIG. 3:9. New aerodynamically spun plasma jet.

1. Anode
2. Fine thread for gap adjustment.
3. Cathode
5. Tangential gas inlet.

any useful signal. A small tape recorder head was also used as a coil, with similar results. A quartz optical fibre was used to monitor the arc light as the arc spun past the fibre inside the anode. It proved difficult to position the fibre to sense the light only when the arc passed it; the general light level in the cavity was too high. The optical fibre also suffered from thermal damage. Finally, an anode was split down the middle and each half was insulated from the plasma jet and from the other half, FIG. 10. The anode was then connected up to the plasma jet body,using plastic screws,and to an oscilloscope monitoring the current flowing in one half. Unfortunately, the anode remained well insulated for only a short time, but traces for an argon arc showed a value for the arc rotation of 1-4kHZ on the magnetically spun plasma jet. The oscilloscope simultaneously showed three different values for the arc frequency: 300-400 HZ, 1-4 kHZ and 10-15 kHZ. According to Dresvin (1977), there are two types of arc pulsation experienced on a continuous plasma jet; these are:

1. A low frequency, 500-600 HZ, longitudinal pulse of the entire jet core, due to displacement of the anode spot, periodic evaporation of the anode material with ejection of gases and non-smoothed pulsations of the rectified current. These low frequency pulses have no effects on the internal jet core structure.

2. A high frequency, approximately 50 kHZ, due to individual strata or ejection of gas on the relative uniform background of the jet core. The reasons for this phenomena are more complex. It is associated

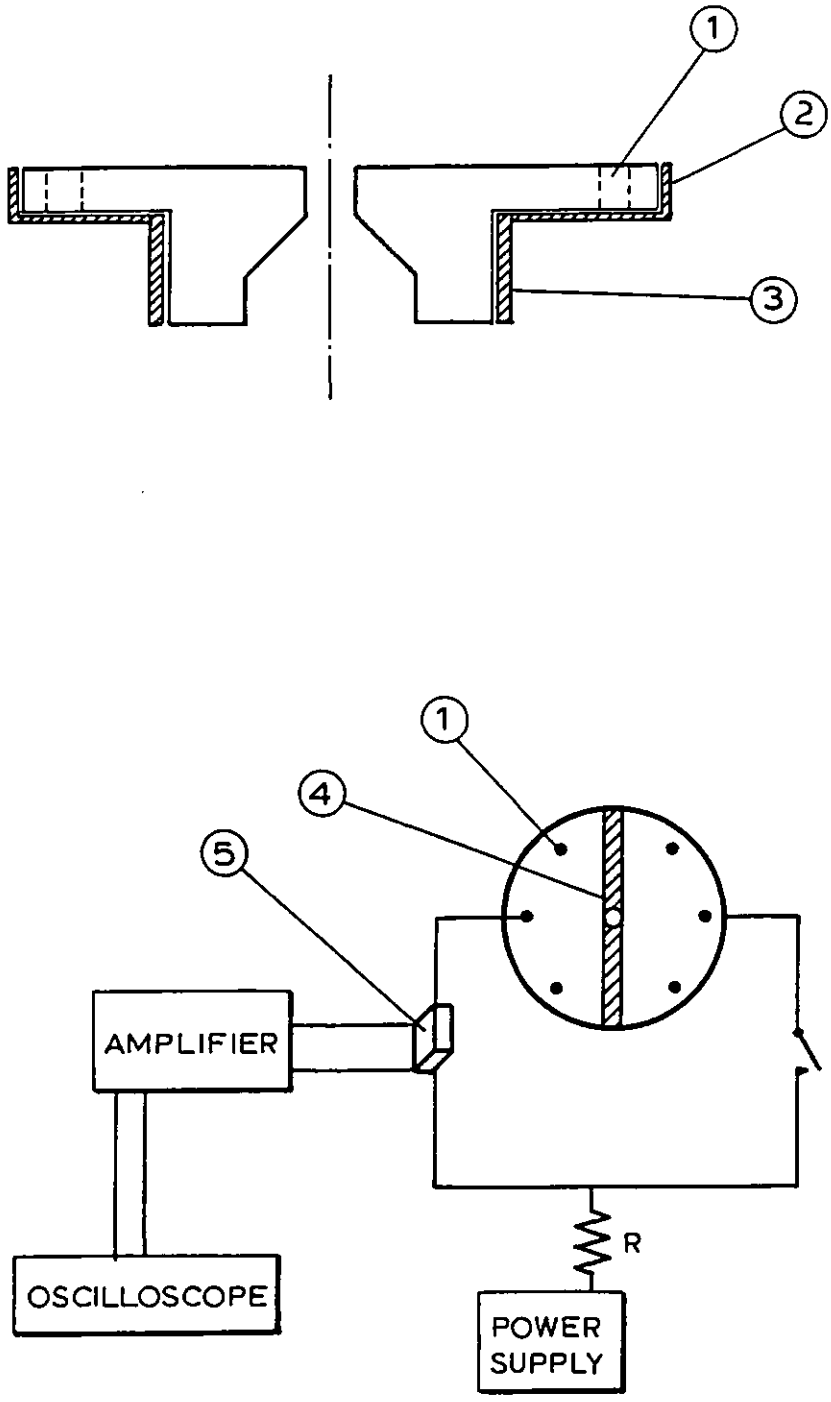


FIG. 3:10. The split anode and electrical connections.

1. Plastic screws
2. PTFE-tape
3. PTFE-sleeve
4. Glue + PTFE-tape
5. Current probe.

with the interaction between the cold gas which flows along the wall and compresses the arc and the arc column itself, which results in pulsations of the column, similar to a stretched string.

These arc pulsations were experienced on an axially fed, magnetically spun plasma jet, run on argon.

In case 2, Dresvin (1977) also reports that the frequency may change with flowrate and, therefore, the high frequency may vary between 10-50 kHZ.

It is, therefore, possible to associate the frequency values obtained in the split nozzle experiment as follows:

300-400 HZ - with low frequency pulsation most likely due to the power supply.

10 - 15 kHZ - with high frequency pulsations, perhaps evidence of the hot pockets mentioned later.

1 - 4 kHZ - with the movement of the arc. This value also compares well with the 5 kHZ evaluated from the Schlieren photographs.

In view of the difficulties associated with this experimental measurement, it seemed more reasonable in the case of the aerodynamically spun arc to assume that its rate of rotation would be approximately equal to that of the gas which carries it. A rough calculation of the gas rotation, assuming the gas rotates as a solid body and whose angular momentum is equal to the angular momentum of the injected gas, yields a

value of 5-20 kHZ for the gas rotation. This higher value conforms well with the results from the ionization probe study (Behbahani et. al., 1983) which shows a larger number of hot pockets for the aerodynamically spun plasma jet, compared to the magnetically rotated. From examination of the anode and cathode, after an extended run, it is clear that the arc moves continuously around the circumference of the cathode, as no erosion marks are visible. The Schlieren photographs show the same "dents" in the emerging plasma plume as are visible on the Schlieren photographs for the magnetically rotated arc.

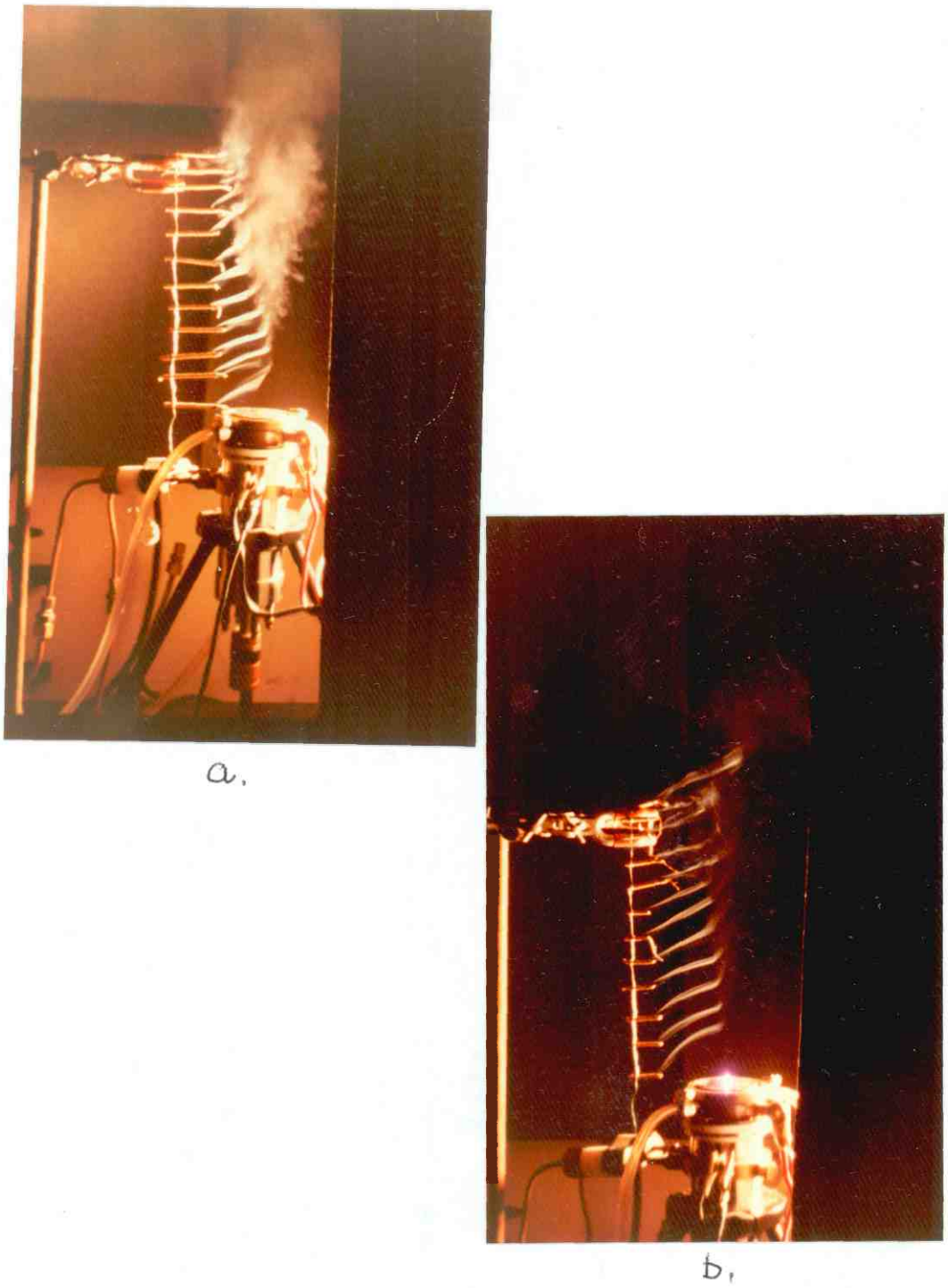
3.1. (3) The Use of Flammable Feedstocks and Entrainment Pattern

The magnetically rotated plasma jet was run on pure hydrogen, as the interest of this research was to establish running conditions and feedstocks for plasma jets, subsequently to be used for ignition and flame-holding purposes. Running a hydrogen arc would not pose a safety problem in the absence of premixing and if the plasma jet was surrounded by a diffusion flame. Hazard would exist following a flashback or blow off. A recently published sequence of papers by Khalgatgi (1981) shows that there is no risk of a fast flowing, turbulent, pure hydrogen diffusion flame blowing off, if the nozzle diameter is larger than 1 mm. However, there was concern that if the hydrogen plasma jet did not ignite on contact with the surrounding air, a large cloud of flammable hydrogen/air mixture could be generated. This was resolved by fitting a ring of pilot flames around the base of the plasma jet to provide an ignition source.

A ring of copper tubing, diameter 60 mm., with holes every 12^{o}, was made. The holes faced inwards and upwards at an angle of 45^{o}. The ring was situated on the top of the plasma jet and fed with propane. Each propane diffusion flame was at a distance of 40 - 45 mm. from the hydrogen plasma. However, this did not prevent the propane diffusion flames from lifting off and blowing off during operation of a hydrogen plasma. This indicated some considerable velocity, induced by the plasma jet. For this reason, the entrainment pattern was studied.

According to Beèr (1972), the rate of entrainment of gases into a jet is dependent on the density difference between the jet and the surroundings. When jet densities are higher than those of the surrounding gases, entrainment is reduced and, conversely, a low density jet (high temperature) penetrating into a cold environment has a higher entrainment rate than a jet in a constant density system.

The entrainment pattern was studied, using a strip of smoking josticks to visualize the pattern. The jet draws the surrounding air towards its turbulent expanding central cone. FIGS. 11a and b illustrate this. The effect of the plasma jet on the entrainment is to draw in surrounding gas from well below the plasma jet top (100 mm.) to well above the plasma jet (500 mm.), in an expanding radius of up to 250 mm. The pattern of gas flow inside a vessel was also studied, FIGS. 12a and b, in order to ascertain the effect of surrounding walls on the entrainment pattern. Similar considerations would apply in a combustion can (of course,



a.

b.

FIG. 3:11 : Entrainment pattern around a plasma jet. Smoke generated by josssticks.

a. Cold flow, no arc

b. Helium arc

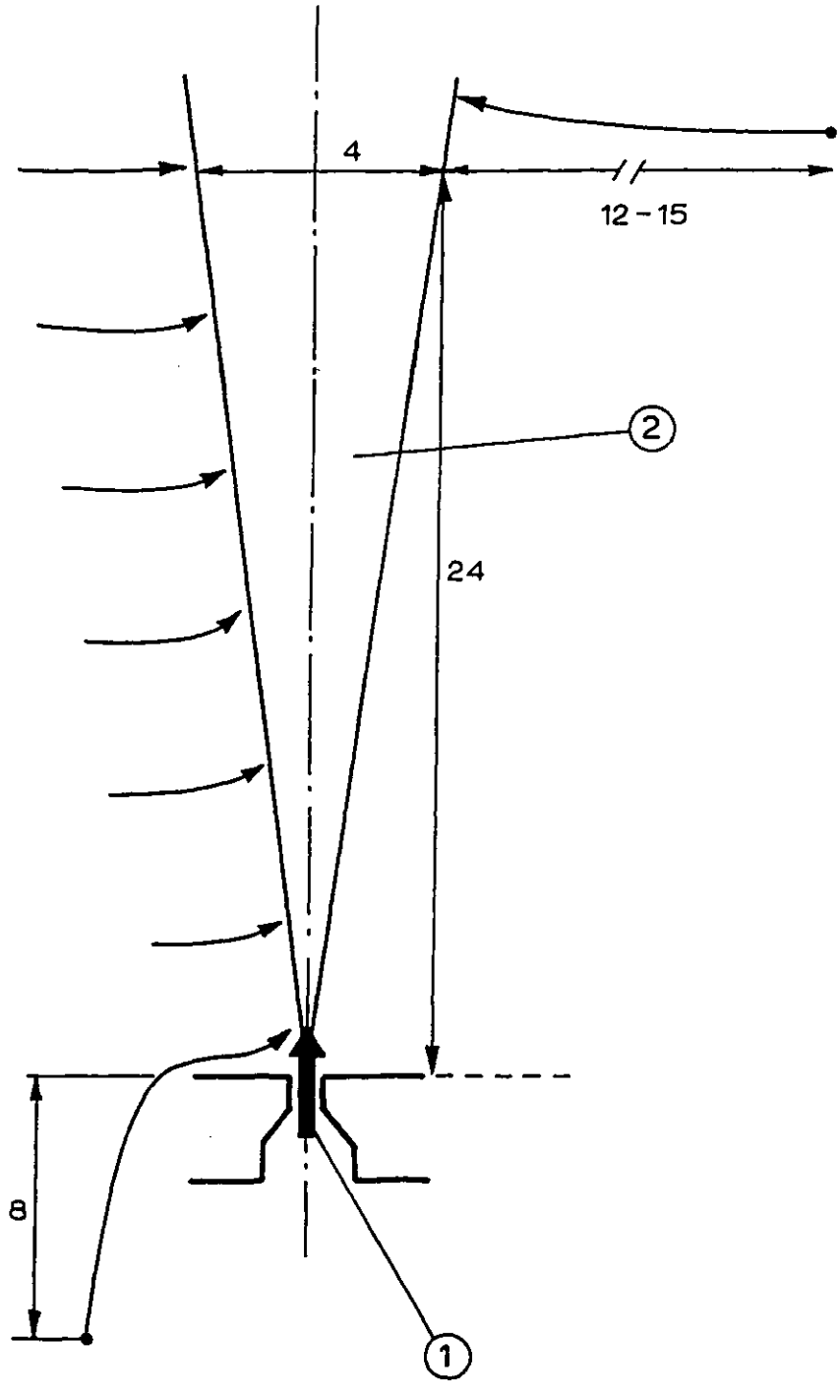


FIG. 3:11.c. Entrainment pattern around a plasma jet. Distances in centimetres.

1. Anode exit
2. Central Cone

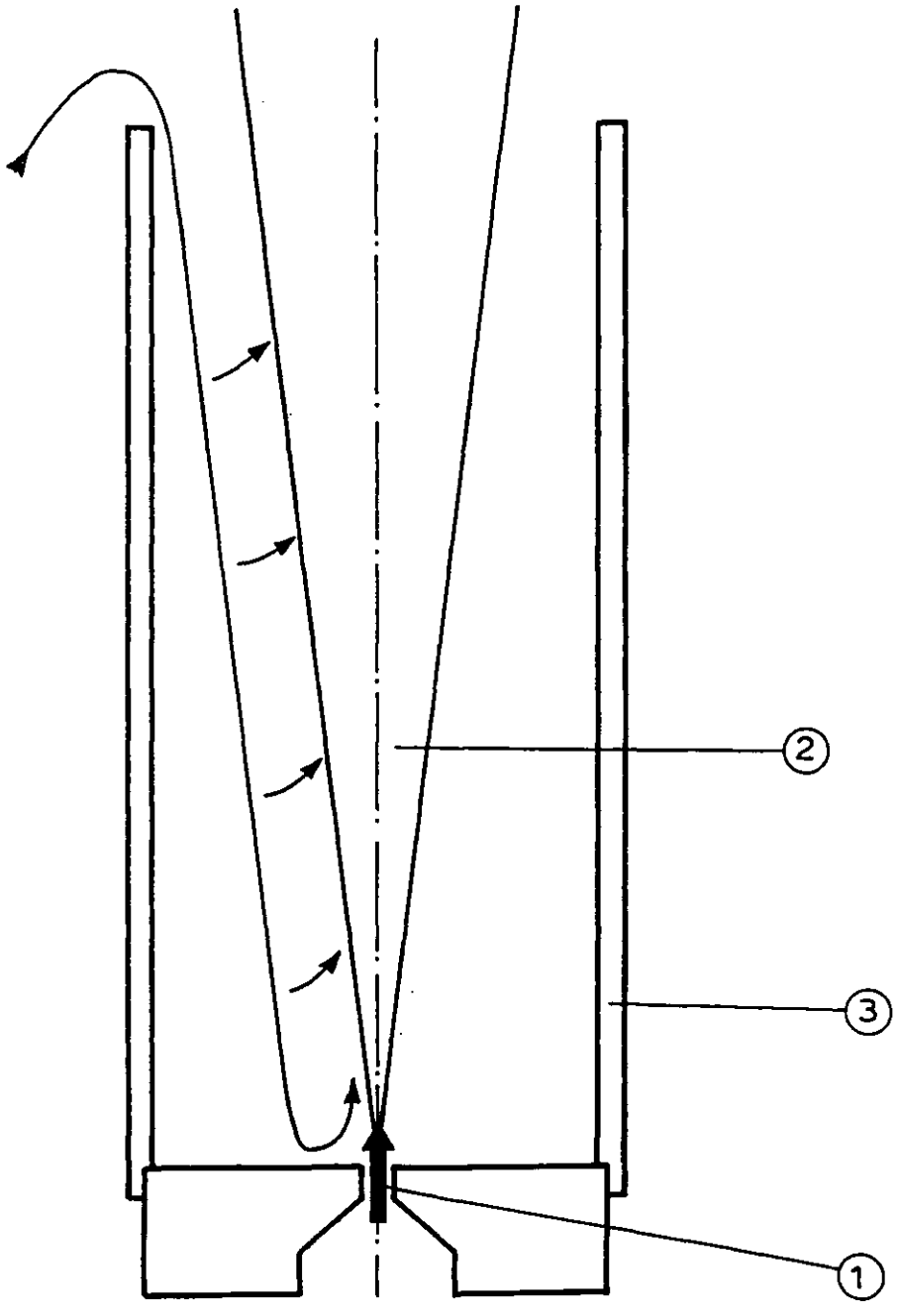


FIG. 3:12.a.
Entrainment pattern around a plasma jet exiting into a 7cm. in diameter, 14cm. high cylinder.

1. Anode exit
2. Central cone
3. Cylinder

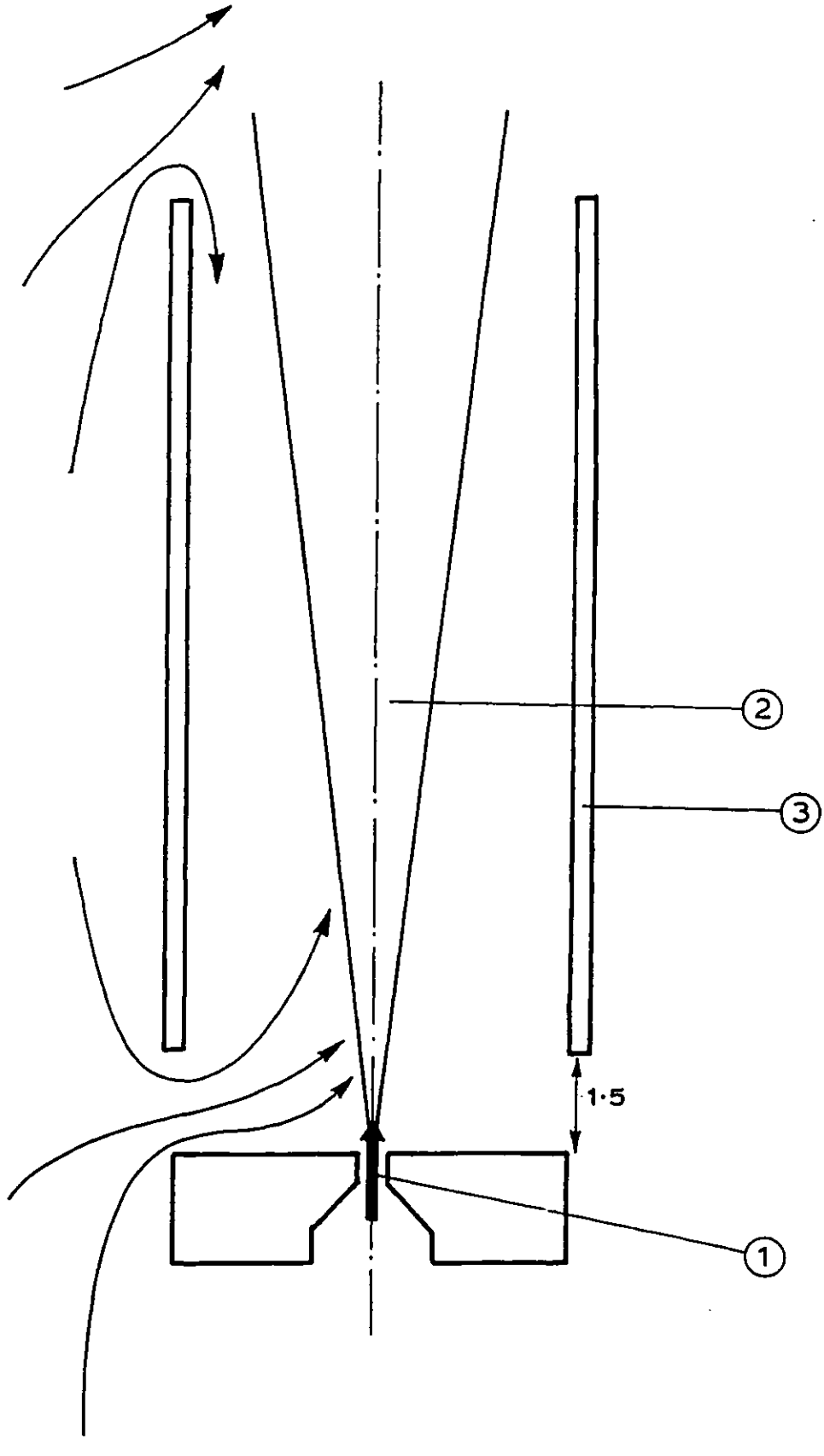


FIG. 3:12.b.
Entrainment pattern around a plasma jet.
The cylinder is held at 1.5cm. from the surface of the plasma jet.

1. Anode exit
2. Central cone
3. Cylinder

the dimensions would be rather different). Results showed that the plasma jet would entrain surrounding gas into the vessel down to the base of the plasma jet and then into the expanding central cone. The vessel dimension allowed the entrained gas to pass between the central cone and the walls of the vessel. These experiments confirmed that the entrainment velocity,due to the sonic plasma jet, was large enough to ensure very good mixing with the surrounding gas, even without ducting one into the other. This is important for reactor design involving plasma jets and, in particular, led to a redesign of the NO-reduction experiments.

Combining the entrainment results with the knowledge that hot pockets survive for 20 to 30 mm. downstream, suggested a new way of cleaning up exhaust gases. The exhaust gas should be entrained into the first few centimetres of the plasma and then exit. The final design consisted of an inner cylindrical tube, made of quartz, suspended about 15 to 20 mm. above the plasma jet. The jet momentum was used to pull a mixture of either air + NO or nitrogen + NO into close contact with the plasma jet. FIG. 13 shows the outline of the rig. These experiments showed quite comparable NO-removal efficiency with those obtained in earlier work by Behbahani et.al. (1982), where NO was injected directly into the plasma stream using a capillary, although in this case the flow through the plasma jet is only 2.4% of the total flow in the surrounding cylinder. Variation in height above the plasma jet of the inner tube and its diameter were also tested. The efficiency remained the same for a height above the plasma jet of 40 mm.

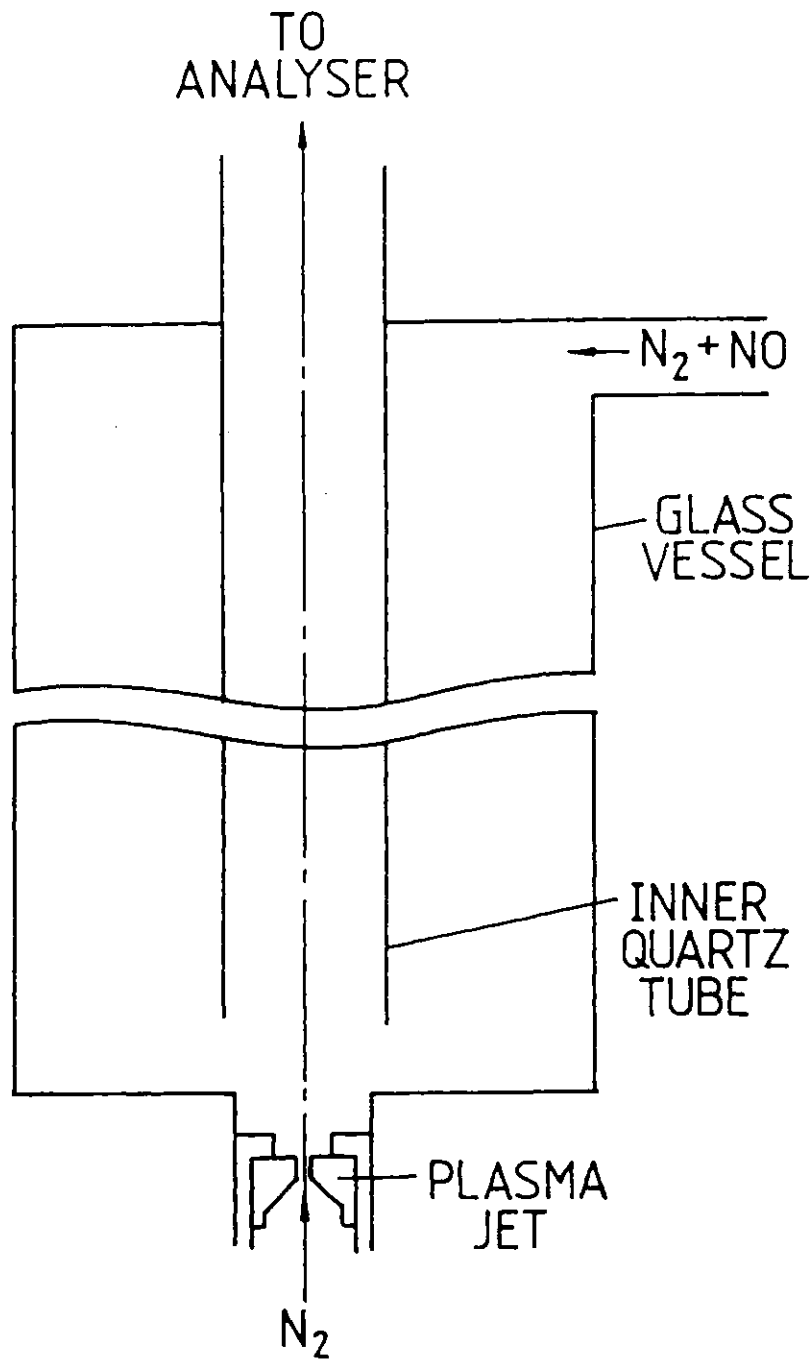


FIG. 3:13. Apparatus for simulation of NO-removal from exhaust gases.

Another reaction studied, because of its relevance to a related research project going on in the laboratories, was the effect of different plasma media on the oxidation of SO_2 to SO_3. SO_2 is a major exhaust gas pollutant and it can be removed by oxidation to SO_3. The SO_3 so formed would react with the water vapour present in combustion gases to form small droplets which can be removed from a gas stream by electrostatic precipitation.

The large scale entrainment of surrounding gas into the plasma jet raises an important issue regarding the choice of a suitable plasma medium. Although hydrocarbons as feedstock provide the most obvious source for hydrogen atoms for flame stabilization, in practice, difficulties may arise, due to soot formation in the plasma jet and, especially in the case of liquid fuels, pyrolysis in any hot part of the plasma jet body. In view of the entrainment findings, it may matter much less what feedstock is being used. It may turn out to be possible to use whatever feedstock produces the most stable and convenient plasma and allow other components of the mixture to be entrained. As gas turbine engines have a supply of compressed air readily available, the use of an air plasma was, therefore, investigated.

3.2. Specific Feedstocks for Plasma Jets

3.2.(1) Argon Plasmas

Argon is one of the most commonly used feedstocks for plasma jets. Arcs in argon are stable and easy to initiate. They cause no, or minimal, wear of the cathode and anode, even after extended operation. The reason argon behaves this way is that it is a monatomic gas and, as such, cannot dissociate. The temperature of an argon arc, therefore, rises quickly with increase in power input, leading to ionization. Argon produces electrons at much lower power inputs than diatomic gases, e.g. nitrogen. Because of its stability, argon has been extensively used as a plasma medium, either on its own, if possible, or together with traces of other gases, when necessary.

The power consumption for an argon arc on the magnetically and on the aerodynamically rotated plasma jet is around 300W. FIG. 14 shows a typical argon arc on the magnetically rotated plasma jet. Current-voltage characteristics for an argon arc on the magnetically spun plasma jet, (a), (Behbahani, 1981) and on the aerodynamically spun plasma jet of the initial (b) and new (c) design are shown in FIG. 15. From these curves it is possible to deduce that the arc resistance changes. Because the voltage remains steady for increasing currents, it follows from Ohms law that the arc resistance must drop. The arc resistance, therefore, seems to be dependent on temperature. When the current increases with constant voltage, the power input increases, this increases the enthalpy and, therefore, the temperature. It is interesting to note that



FIG. 3:14 : Argon plasma jet on the magnetically rotated plasma jet.

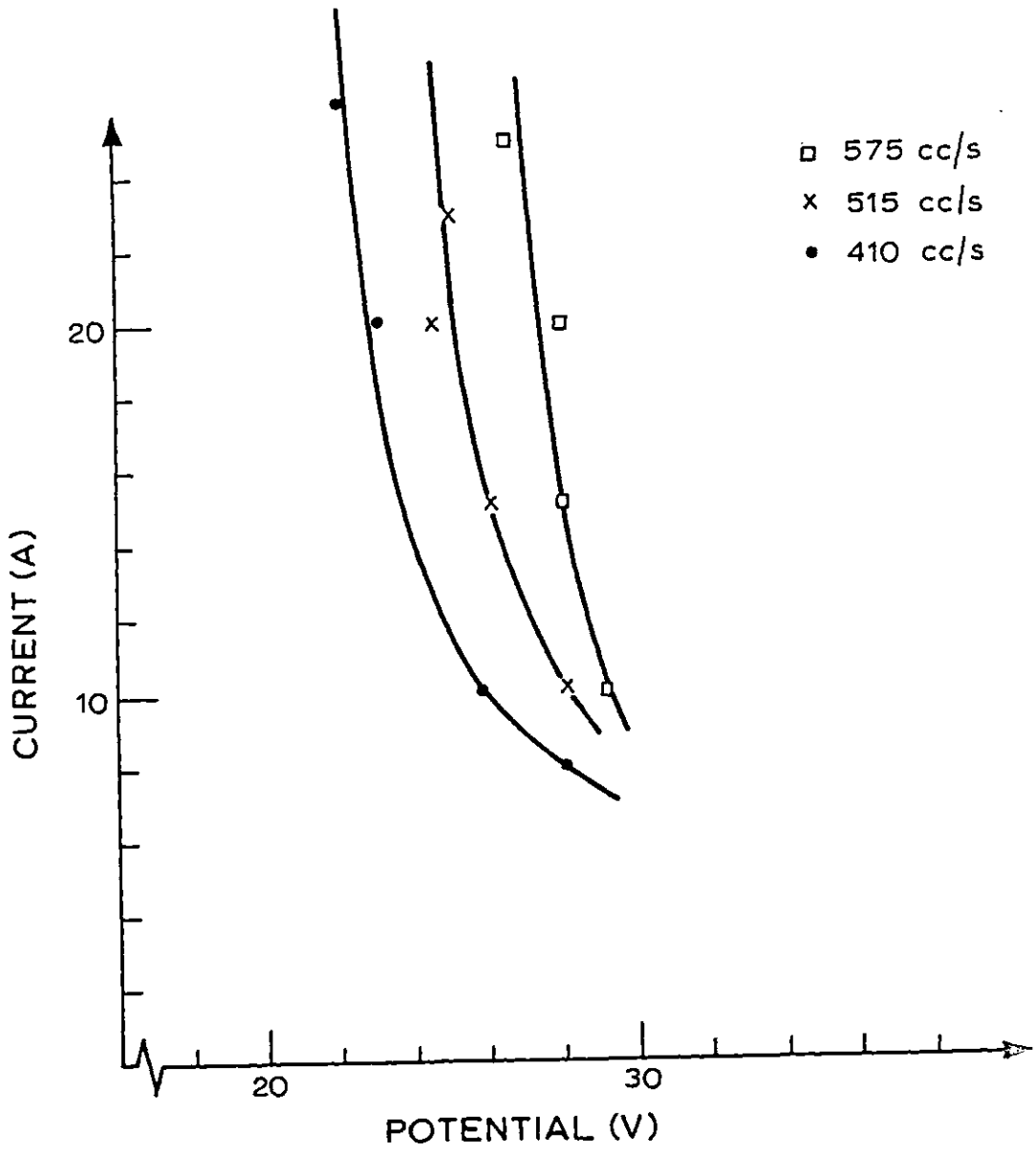


FIG. 3:15. a. Current-voltage characteristics for various argon flow rates on the magnetically spun plasma jet - from Behbahani, (1981)

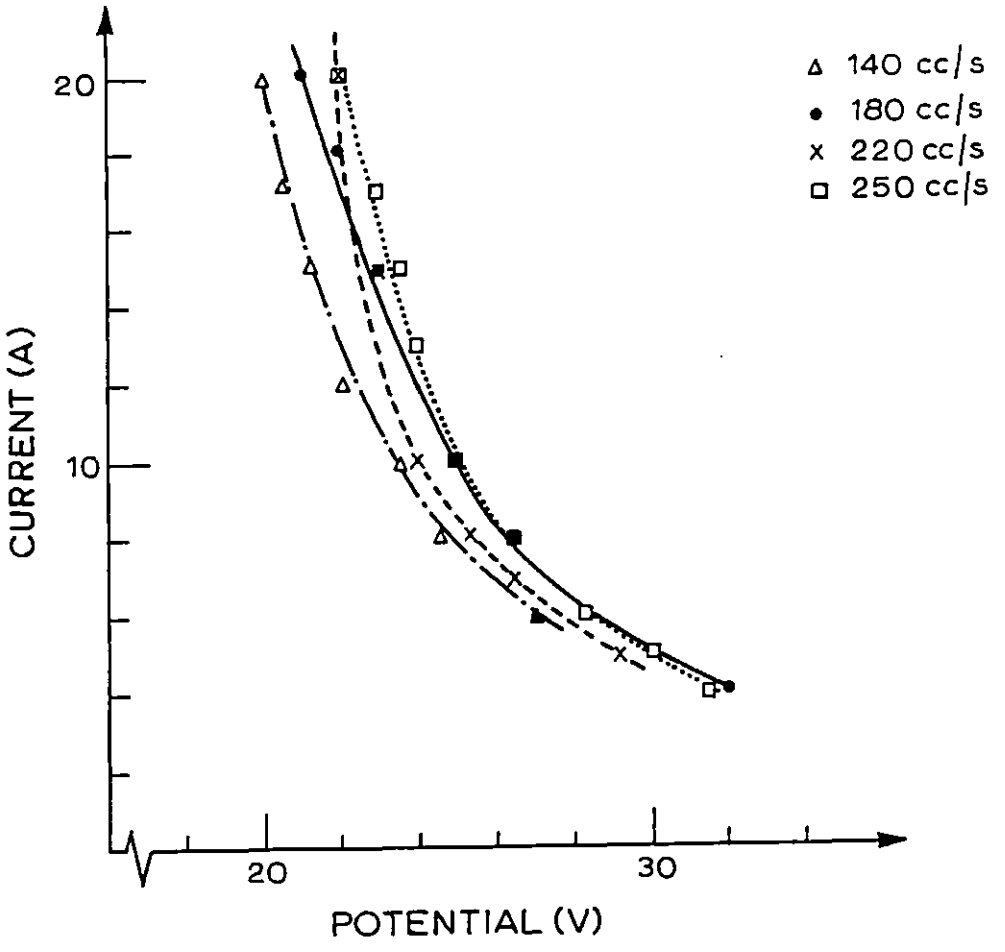


FIG. 3:15.b. Current-voltage characteristics for various argon flow rates on the initial aerodynamically spun plasma jet.

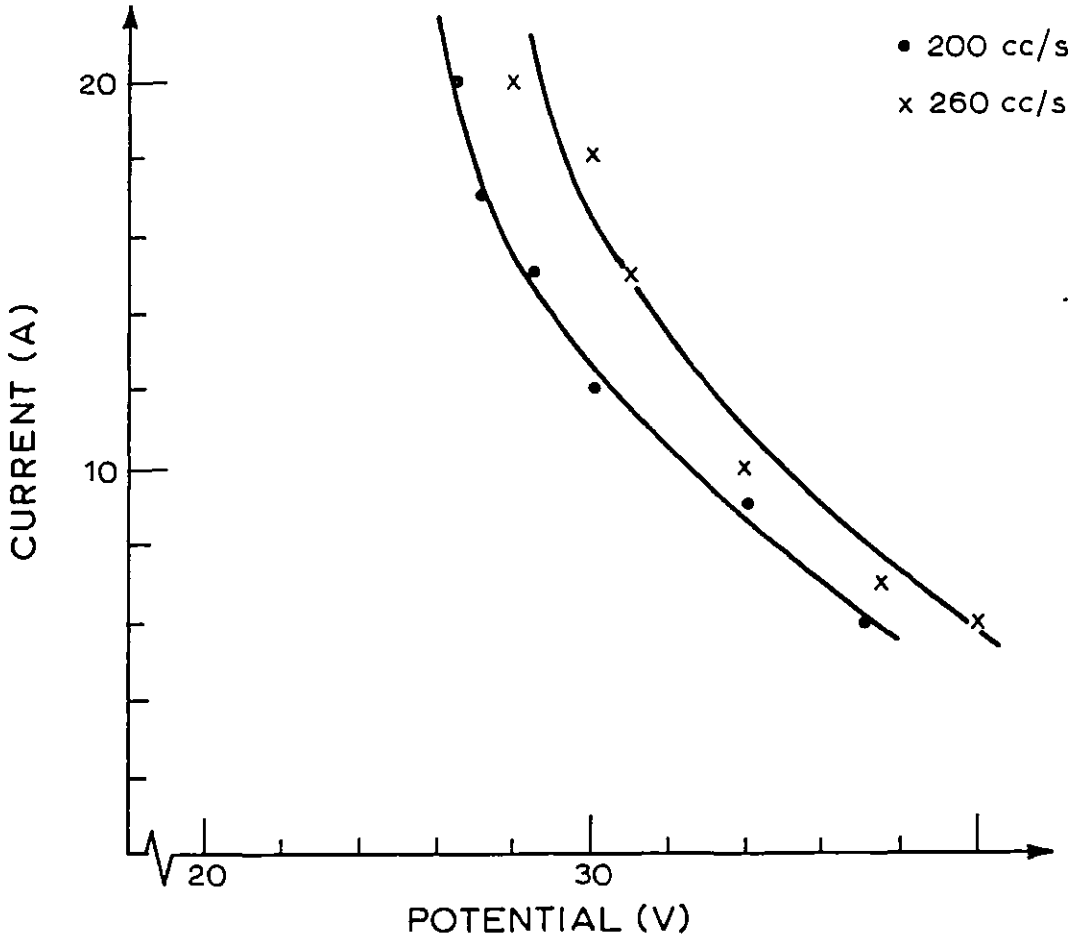


FIG. 3:15.c. Current-voltage characteristics for various argon flow rates on the new aerodynamically spun plasma jet.

the power consumption remains steadier for the aerodynamically spun plasma jet when the flow rate is increased, whereas for the magnetically spun plasma jet, the power has to be increased as the flow rate is increased. Initial experiments demonstrated that the arc length, i.e. the distance between anode and cathode, could be varied from 400 μm to 1500 μm, without changing the power consumption. The current drops and the voltage increases, indicating that the arc resistance increases. So, the resistance is also dependent on arc length. The normal gap between anode and cathode is 600 μm for argon.

Comparing power consumption for one flow rate of argon, while varying the anode/cathode configuration, reversing the potential of the electrodes, running an arc without tangential flow and magnetic field with (FIG. 16a) 600 μm gap; (FIG. 16b) 550 μm gap shows no great difference in the current-voltage characteristics for any of these cases. Visible and audible evidence from these runs indicate that reversing the potential and running without tangential flow and magnetic field produces a noisier plasma that oscillates from side to side in the exit hole of the anode, whereas changing the anode/cathode configuration makes no difference to the performance of an argon arc.

Because of its stability, an argon arc was used for the entrainment studies and for the arc rotation work, as was previously mentioned in section 3.1. Argon arcs were also used while trying to record the hot pocket velocity using high speed cine-photography in a shadow system. Unfortunately,

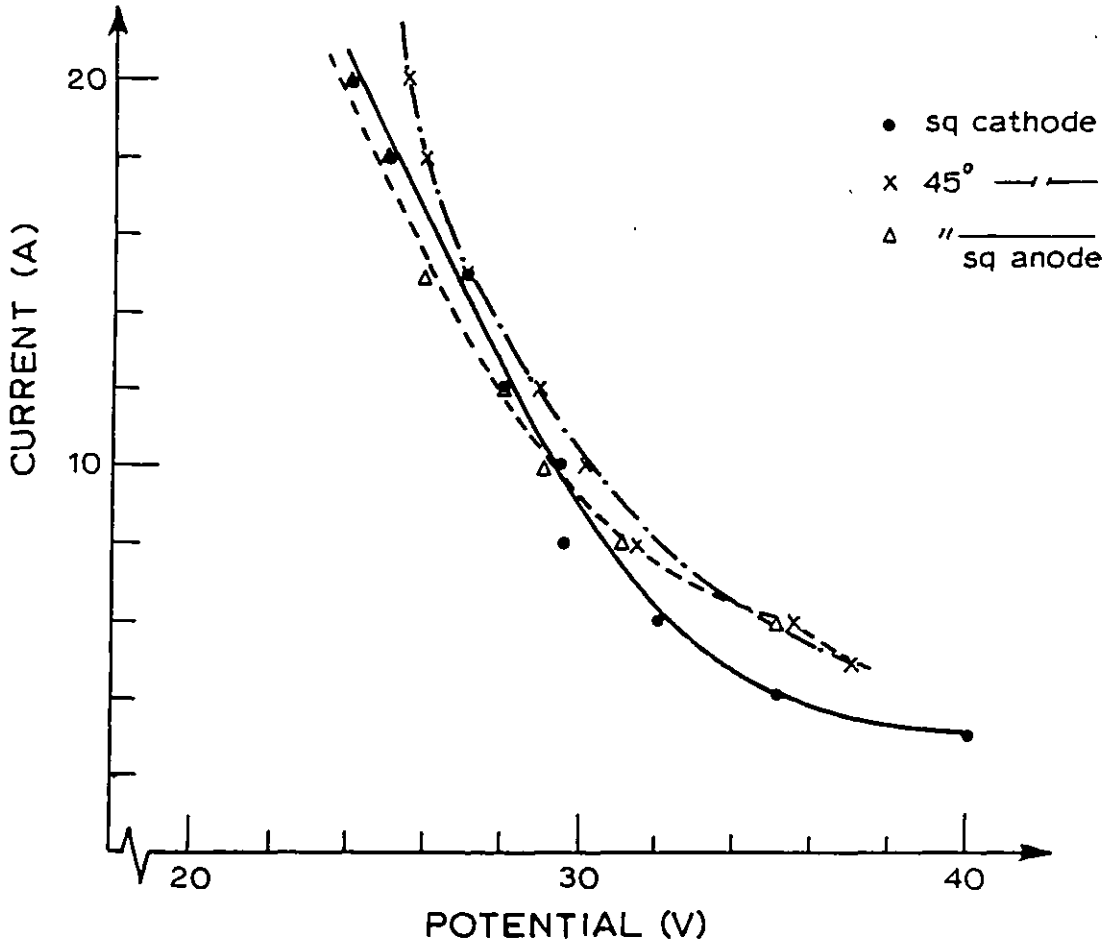


FIG. 3:16.a. Current-voltage characteristics for various anode-cathode configurations. Argon arc (660 cm^3/s) on the magnetically spun plasma jet. Gap 600 μm.

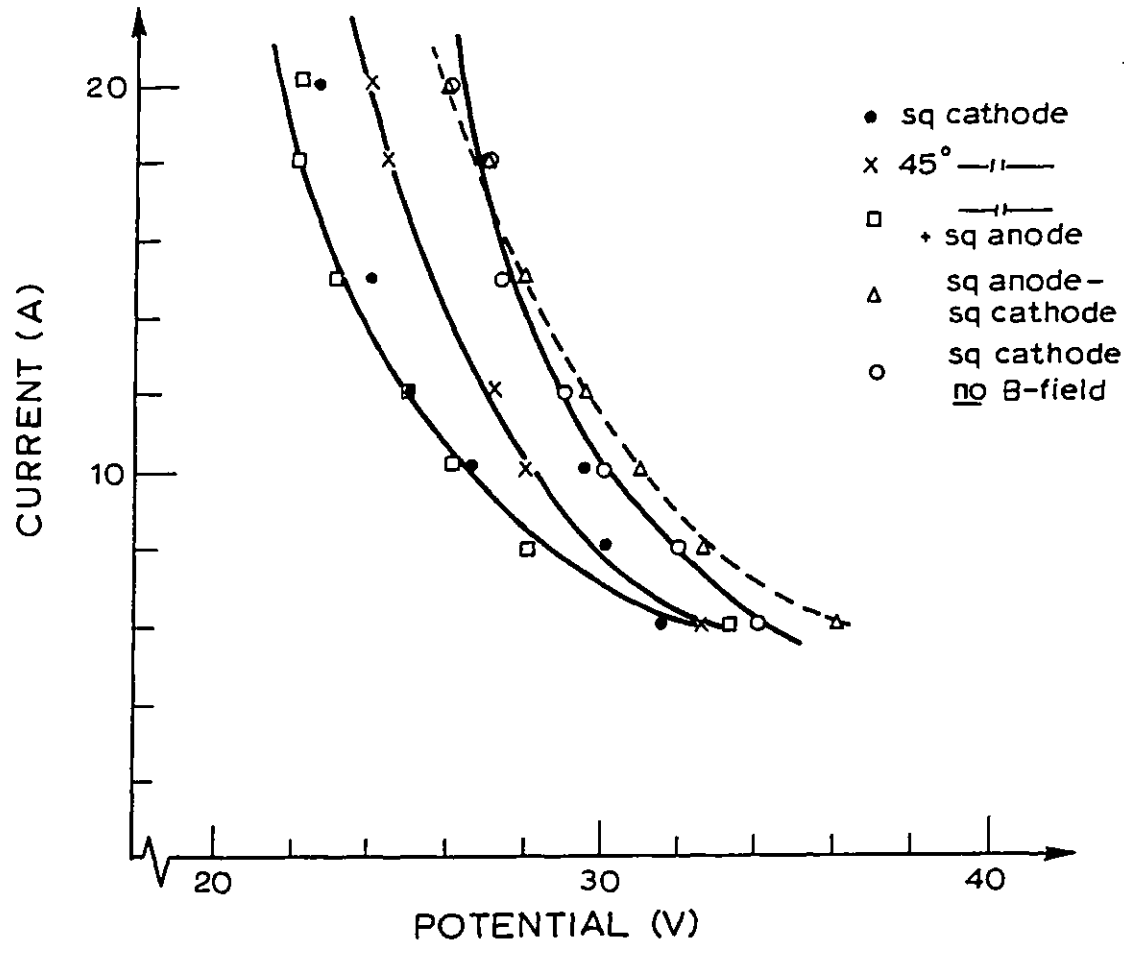


FIG. 3:16.b. Current-voltage characteristics for various anode-cathode configurations. Argon arc (660 cm^3/s) on the magnetically spun plasma jet. Gap 550 μm.

the framing rate of 10,000 frames per second proved far too slow to show the velocities. Secondly, it is not possible on shadowgraphs to accurately determine the difference between warm and hot pockets.

The effect of bringing a metal sheet close to the plasma jet (2mm away from the exit hole in the anode) was studied and no changes in power-consumption, flowrate or jet height could be detected.

3.2. (2) Nitrogen Plasmas

Nitrogen as a plasma medium has been used for over a decade, Harrison et al. (1971). However, it was not until the work of Chan et al. (1980) that it was possible to stabilize a nitrogen plasma without large quantities of argon.

The nitrogen arc is stable but consumes more power (700-1200W) and requires a smaller gap between the anode and cathode (300 μm) than an argon arc. A typical nitrogen plasma has an inner white cone with an outer green envelope due to NO-reactions, FIG. 17. Current-voltage characteristics for nitrogen plasmas can be found in FIG. 18; (a) for the magnetically spun plasma jet (Behbahani, 1981); (b) and (c) for the aerodynamically spun plasma jet of the initial and the new design. As with the argon plasma, the power consumption is more stable during flow variations, using the aerodynamically spun plasma jet. The gap between the anode and cathode can be varied between 250 μm and 800 μm, the optimum value being 300 μm.

Nitrogen arcs were also run for different anode-cathode con-



FIG. 3:17 : Nitrogen plasma jet on the magnetically spun plasma jet.

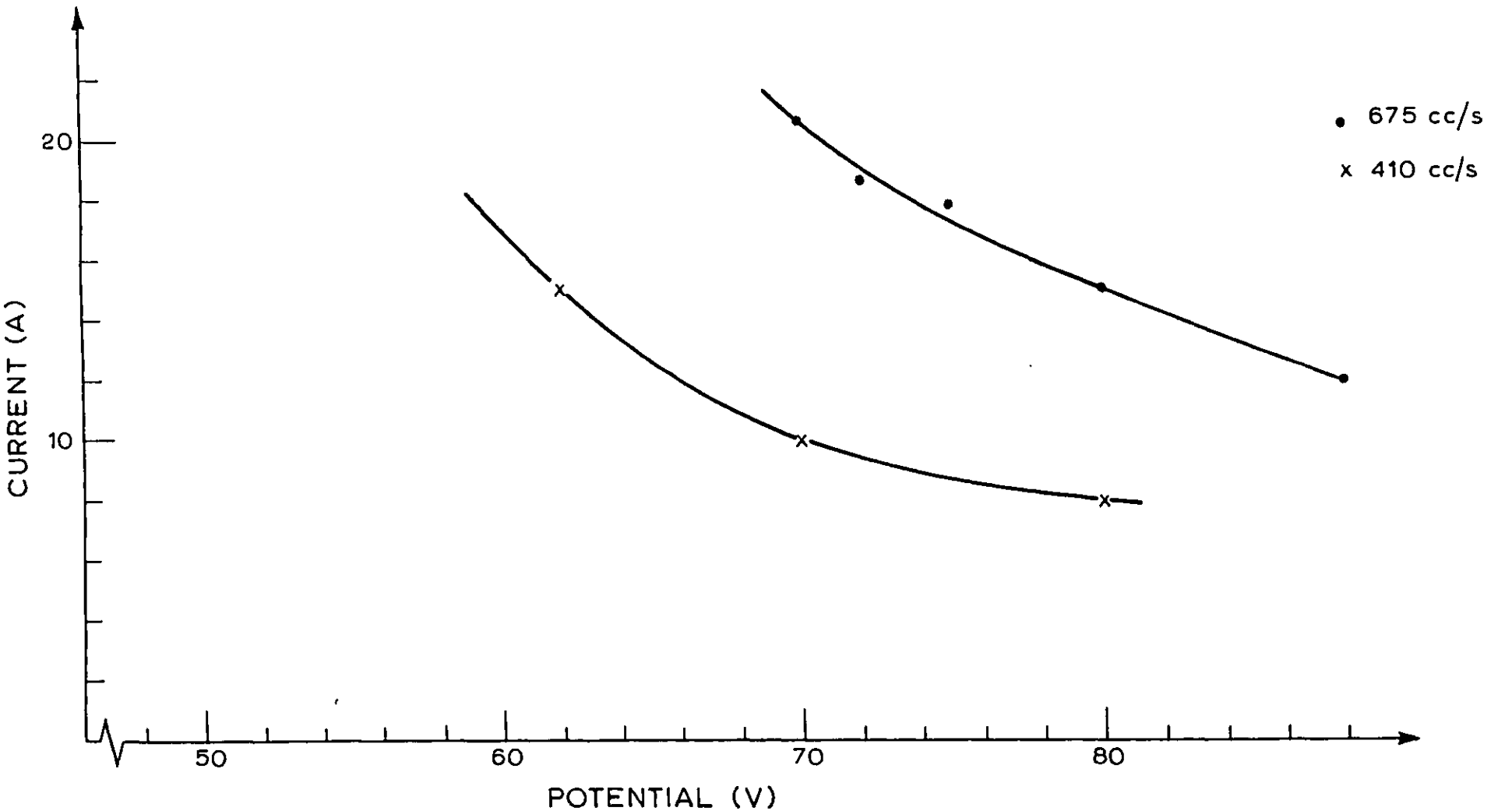


FIG. 3:18.a. Current-voltage characteristics for various nitrogen flowrates on the magnetically spun plasma jet. - from Behbahani (1981).

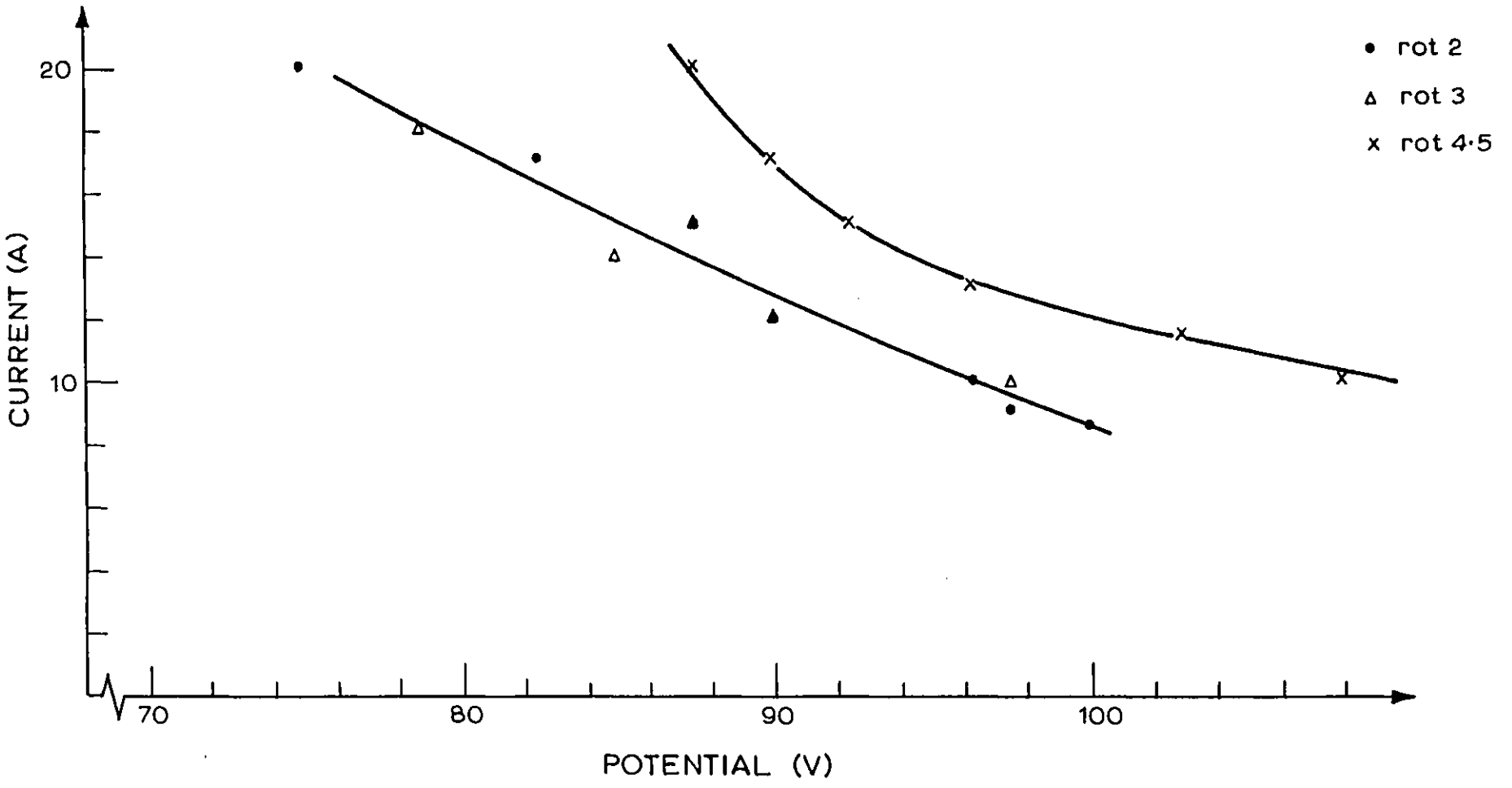


FIG. 3:18.b. Current-voltage characteristics for various nitrogen flowrates on the initial aerodynamically spun plasma jet. (rot 2=270 cm^3/s; rot 3=330cm^3/s; rot 4.5=400 cm^3/s.)

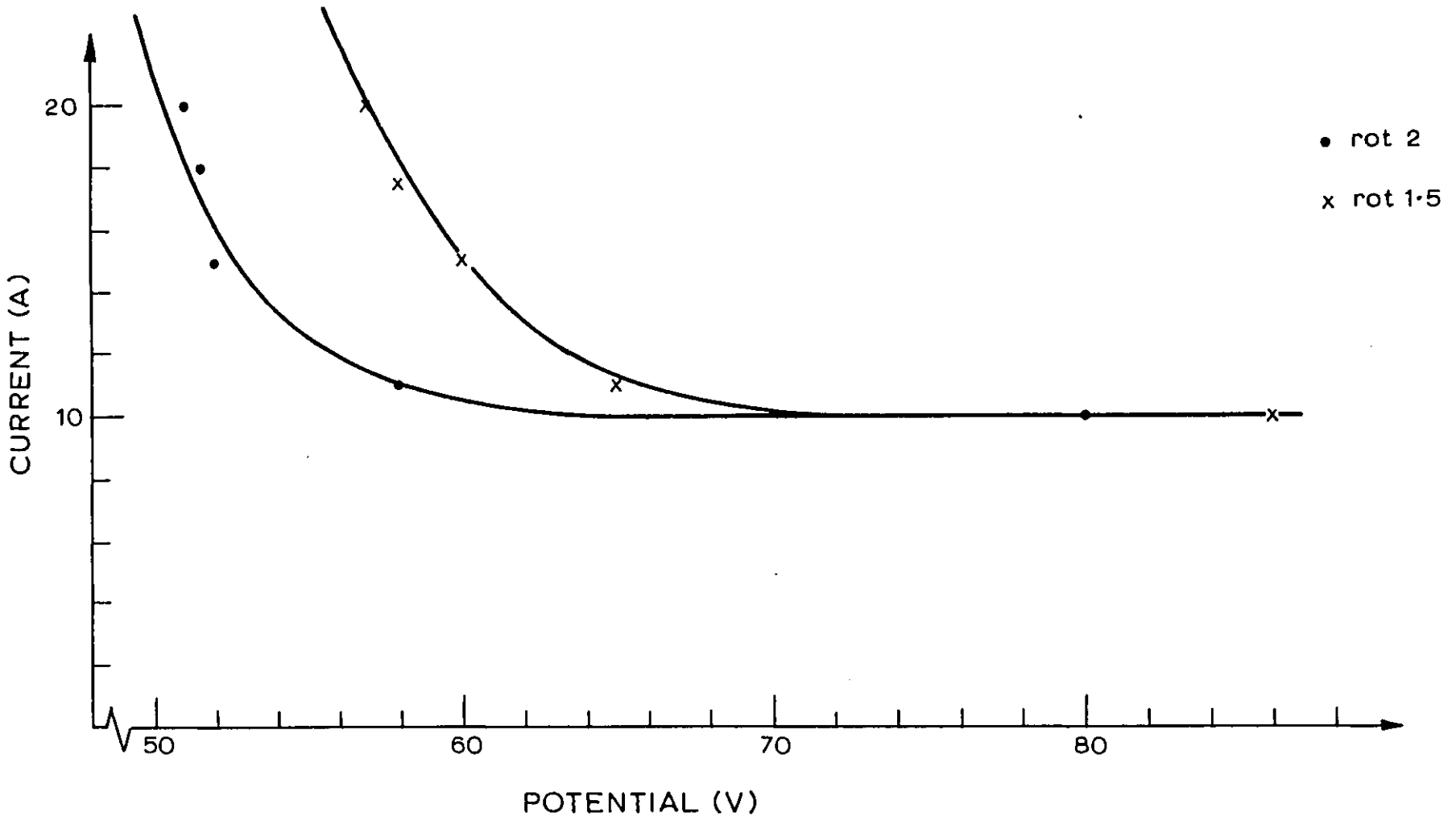


FIG. 3:18.c. Current-voltage characteristics for various nitrogen flowrates on the new aerodynamically spun plasma jet. (rot 2=270 cm^3/s;rot 1.5=250cm^3/s.)

figurations and without a tangential flow and magnetic field. The results showed the same fluctuations in jet behaviour as observed for an argon arc. Tungsten was chosen as a cathode material because of its low work function which makes it a good electron emitter. When reversing the potential of the electrodes, it is to be expected that the nitrogen arc might not strike, as nitrogen is a diatomic gas and would ionize in an arc, not generate electrons. This was found to be the case, although it was possible to get a nitrogen arc to run with the potential of the electrodes reversed by initiating the arc in argon and then slowly changing the feedstock to nitrogen. Severe melting of the tungsten electrode occurred in this case and the arc ran for a short while. Schlieren and shadow photographs were taken for a nitrogen arc, using a 40ns pulsed ruby laser (15J energy), as described in Section 3.1. FIGS. 5, 6, 7 and 8 show these photographs.

Exposing a metal sheet surface or a metal corner to the nitrogen arc makes the top end of the plasma plume, i.e. the outer envelope, bend slightly in the direction of the metal surface, making the plume outline more hazy; occasionally, the plasma plume will broaden, FIG. 19a. The initial effect is due to chemical reaction taking place on the metal surface and to the constriction of the entrainment pattern. The effect of confining the jet totally within a tube was studied, using glass tubes of various sizes. No changes in the plasma jet behaviour could be observed, as long as the diameter of the tube was larger than 3 cm. For all cases, the tube height was 10 cm. However, when the tube diameter was narrowed, the plasma jet started to oscillate. The outer cone of the

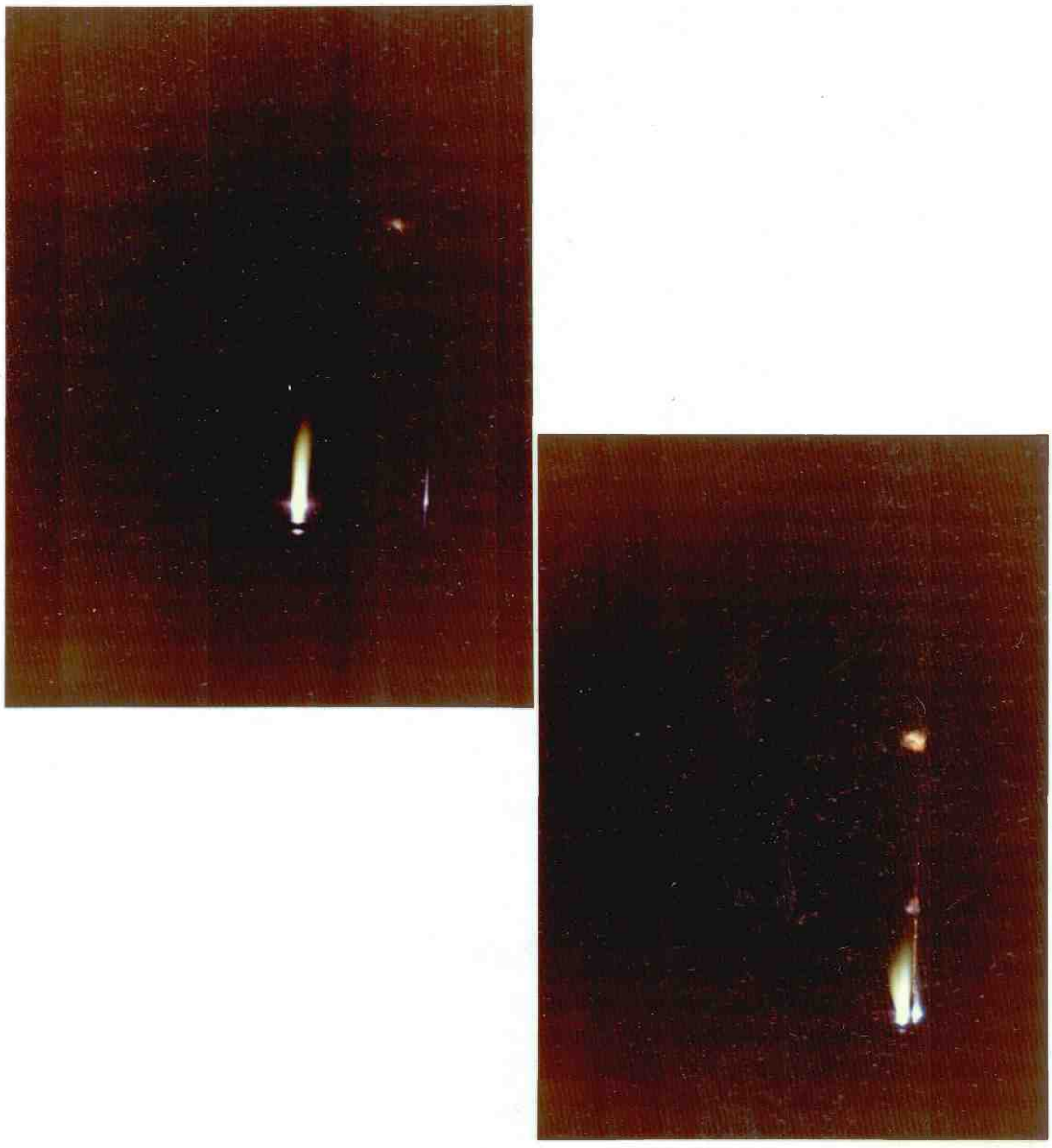


FIG. 3:19a : Effect of a metal sheet close to the nitrogen plasma jet.

plasma plume started expanding towards the wall of the tube and, having reached it, contracted to its normal size before repeating the sequence. This is probably due to fluctuations in the entrainment pattern of air from the outside. These fluctuations would occasionally create a low pressure zone between the expanding jet and the cylinder wall, which would be evened out by the expansion sideways of the jet, see FIG.19b.

Studies of entrainment patterns around expanding jets and for jets expanding inside a cylinder simulating a reactor or combustion chamber were studied by the NO-titration method described previously in Section 3.1.

Earlier studies (Behbahani et al.,1982) showed that the radicals generated in a nitrogen plasma jet survived 20 to 30mm downstream. It was, therefore, necessary to arrange for all the entrainment to take place within this distance. This would also be of relevance to the possibility of entraining a mixture of fuel/air into close contact with a plasma jet, as discussed in Section 3.1. The system used, FIG. 13, consisted of an inner quartz tube suspended at varying heights above the plasma jet. Surrounded by an outer quartz tube. The gas enters in at the top of the outer tube, is drawn down towards the plasma jet and exits through the central tube. The system was tested for two different incoming gas mixtures, 2500ppm NO in air and in pure nitrogen by measuring the remaining NO and NO_x in the exit gases using a chemiluminescent $NO/NO_x(NO+NO_2)$ analyser calibrated for NO/NO_x up to 2500ppm. These tests were carried out on the aerodynamically spun plasma jet, as this is simpler and had shown higher efficiencies, compared to the magnetically

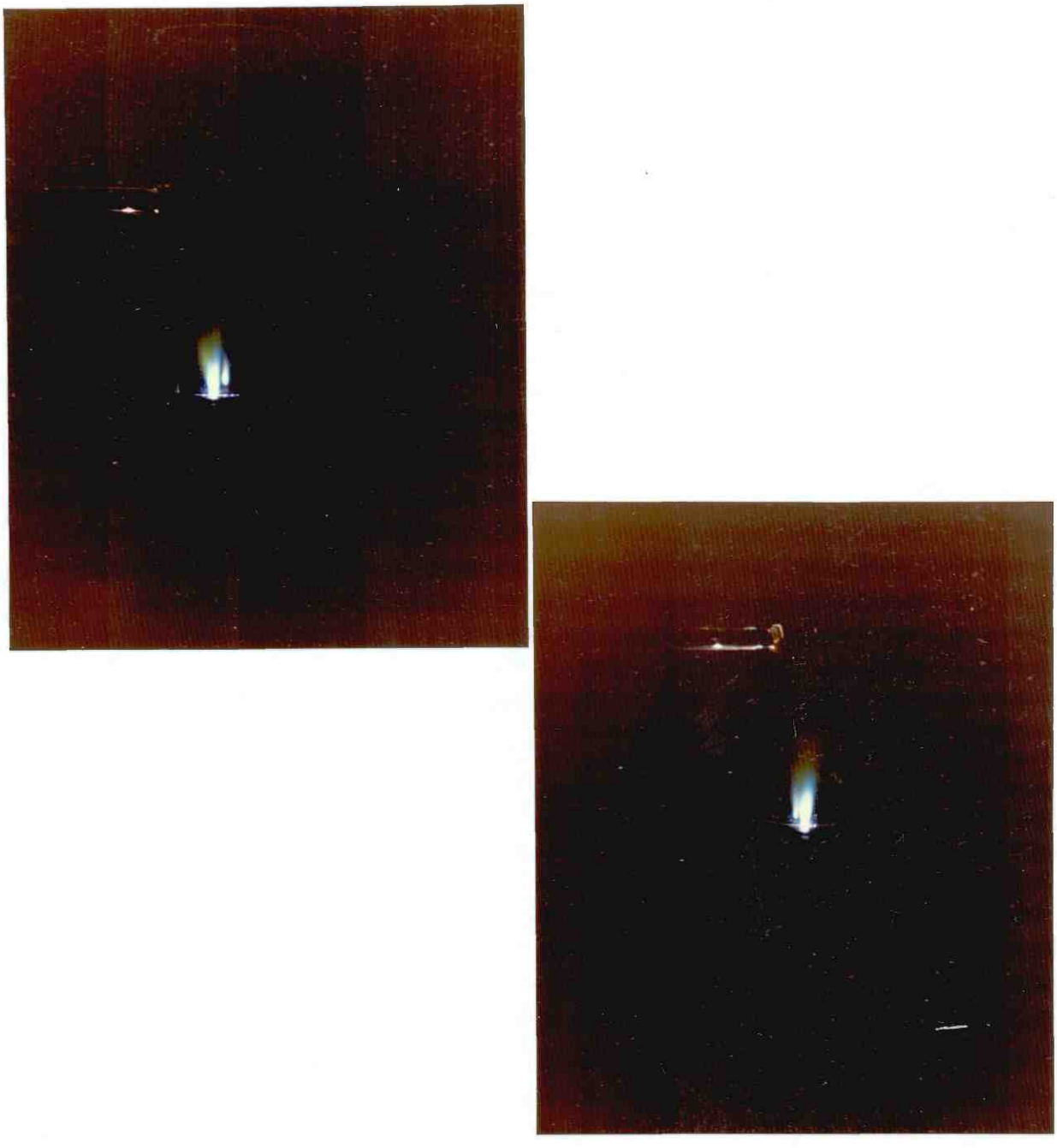


FIG. 3:19b : Effect of a glass tube, diameter 2cm., around a nitrogen plasma jet.

spun plasma jet, Behbahani et al. (1983). These measurements are also relevant to the removal of oxides of nitrogen from exhaust systems. Therefore, experiments were pursued somewhat beyond the immediate relevance to the present work and the findings are included for general interest.

The amount of NO/NO_x generated in a nitrogen plasma when it entrained air was monitored and this amount initially increased with the external airflow, FIG. 20. The height above the plasma jet and the shape of the end piece of the inner quartz tube was also varied. FIG. 21 shows the case for an external feed of nitrogen containing 2500 ppm NO represented as two graphs; one, the residual NO/NO_x as a function of external flow and the other, the efficiency against the external flow. The efficiency η is expressed as the energy used in dissociation to produce the concentration of nitrogen atoms divided by the total energy input. It is interesting to note that for flowrates up to 10 l/s of nitrogen, the residual NO stays steady at 1500 ppm, indicating that not all the hot nitrogen atoms generated by the plasma have reacted with the NO present. The residual NO-concentration should increase eventually as the flow of external nitrogen increases. For these cases, no NO_2 is generated. The calculated experimental efficiency shows close agreement with results arrived at when NO was directly injected into the plasma stream. The case of NO in nitrogen is possibly closest to any practical applications, as maximum NO concentration is experienced in a stoichiometric fuel/air flame, i.e. no excess air would be present in the exhaust gases. However, the system was also tested using an air + 2500 ppm NO mixture, FIG.22. The results here are much more difficult to interpret

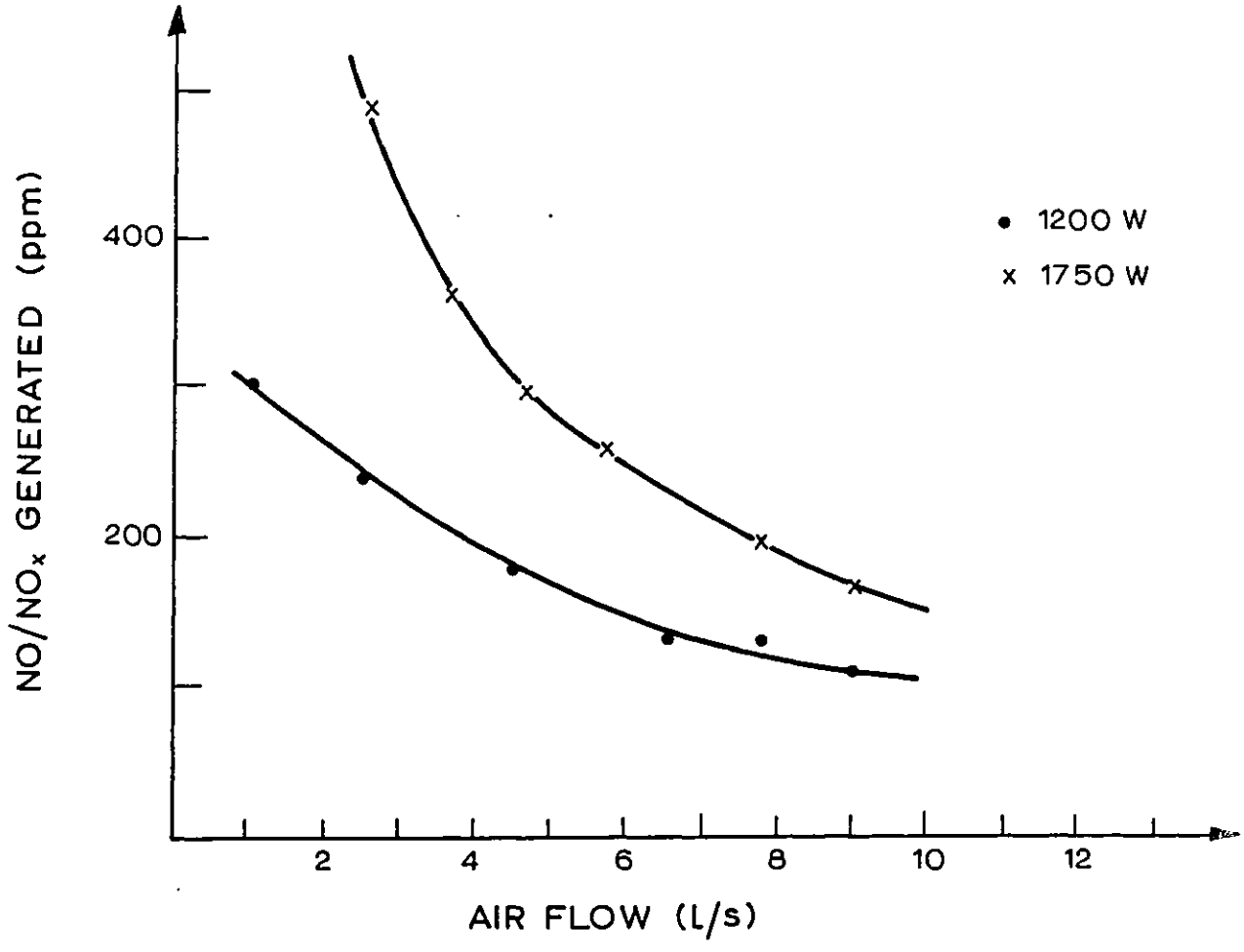
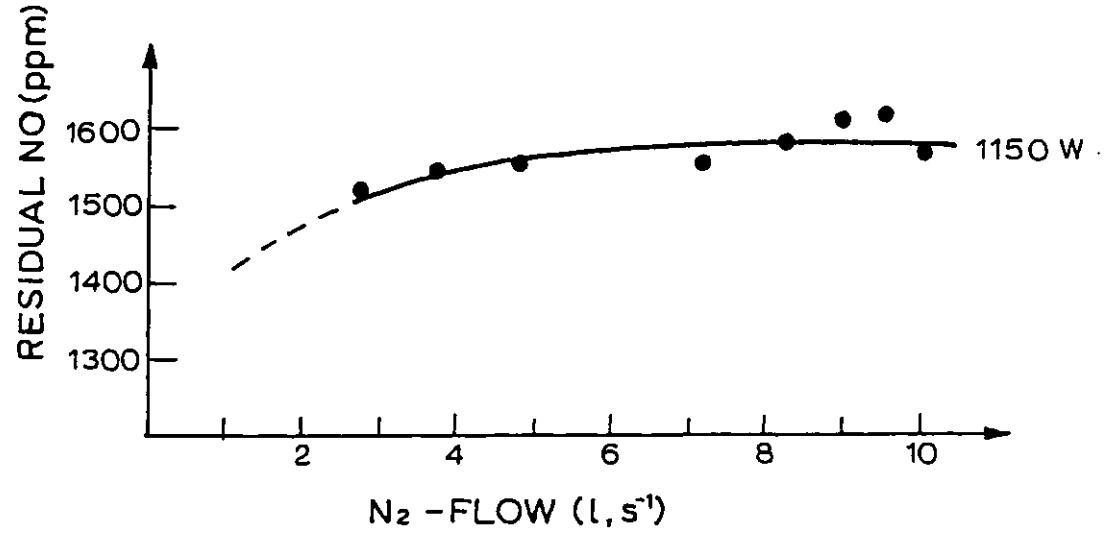


FIG. 3:20. Amount of NO-generated by a nitrogen plasma jet (500 cm^3/s) exiting into an airstream of varying flowrate.



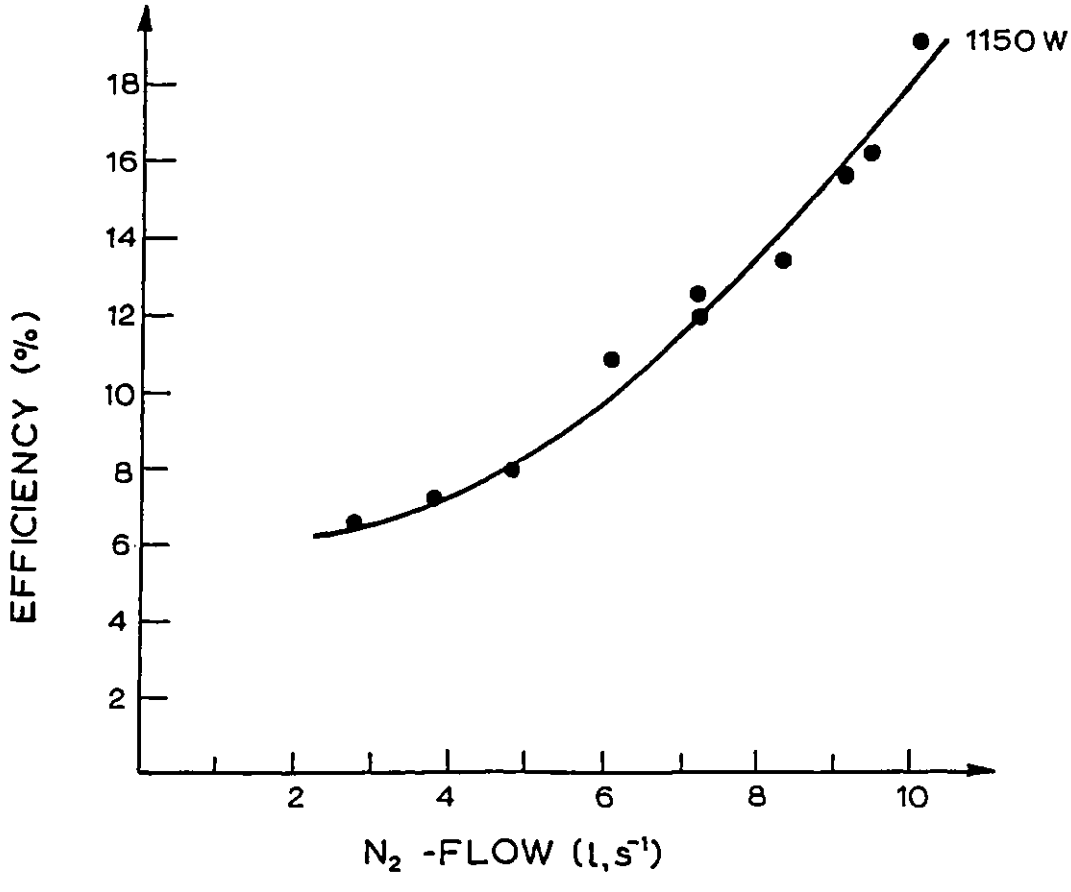


FIG. 3:21.

a) Residual NO as a function of external nitrogen flow. Initial NO concentration 2500ppm.

b) Experimental efficiency as a function of external nitrogen flow.

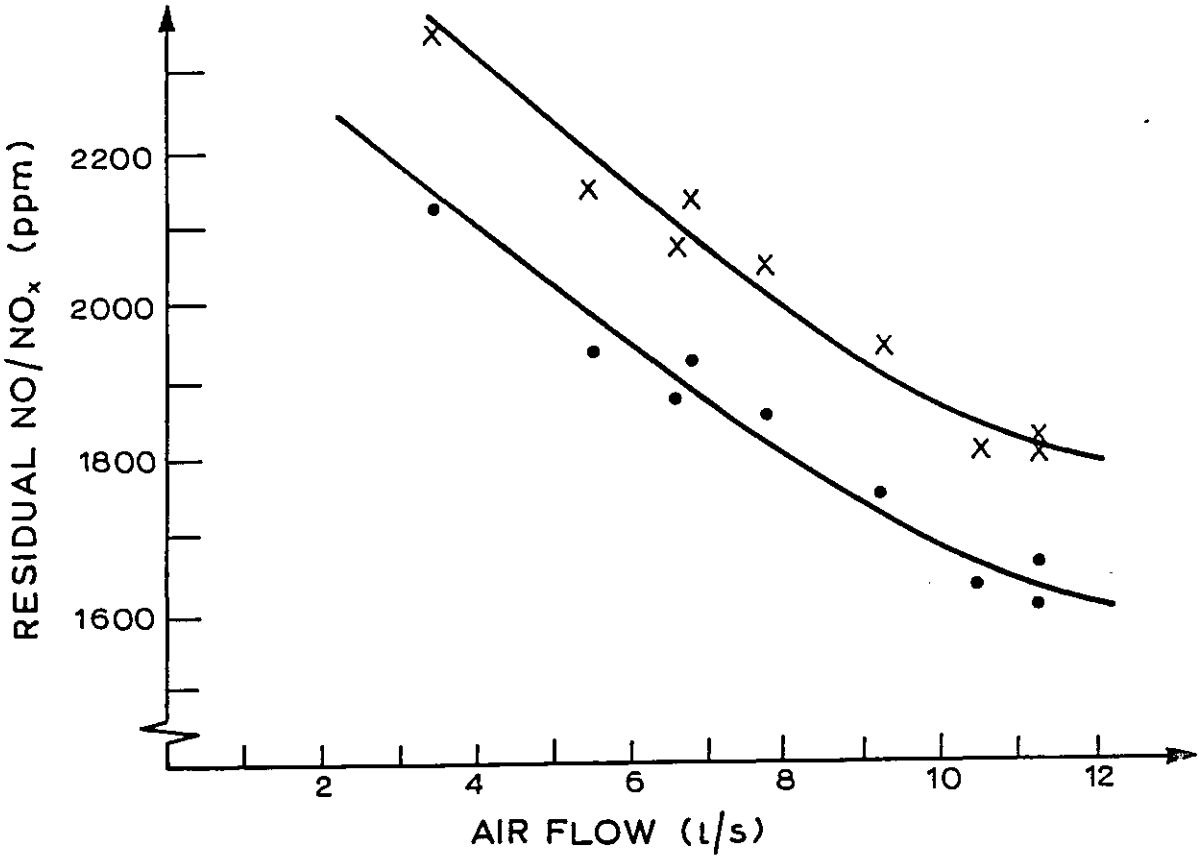


FIG. 3:22.a.
Residual NO/NO_x as a function of external air flow. Initial NO concentration 2500 ppm. Nitrogen plasma jet (500 cm^3/s; 1200W).
• NO; x NO_x

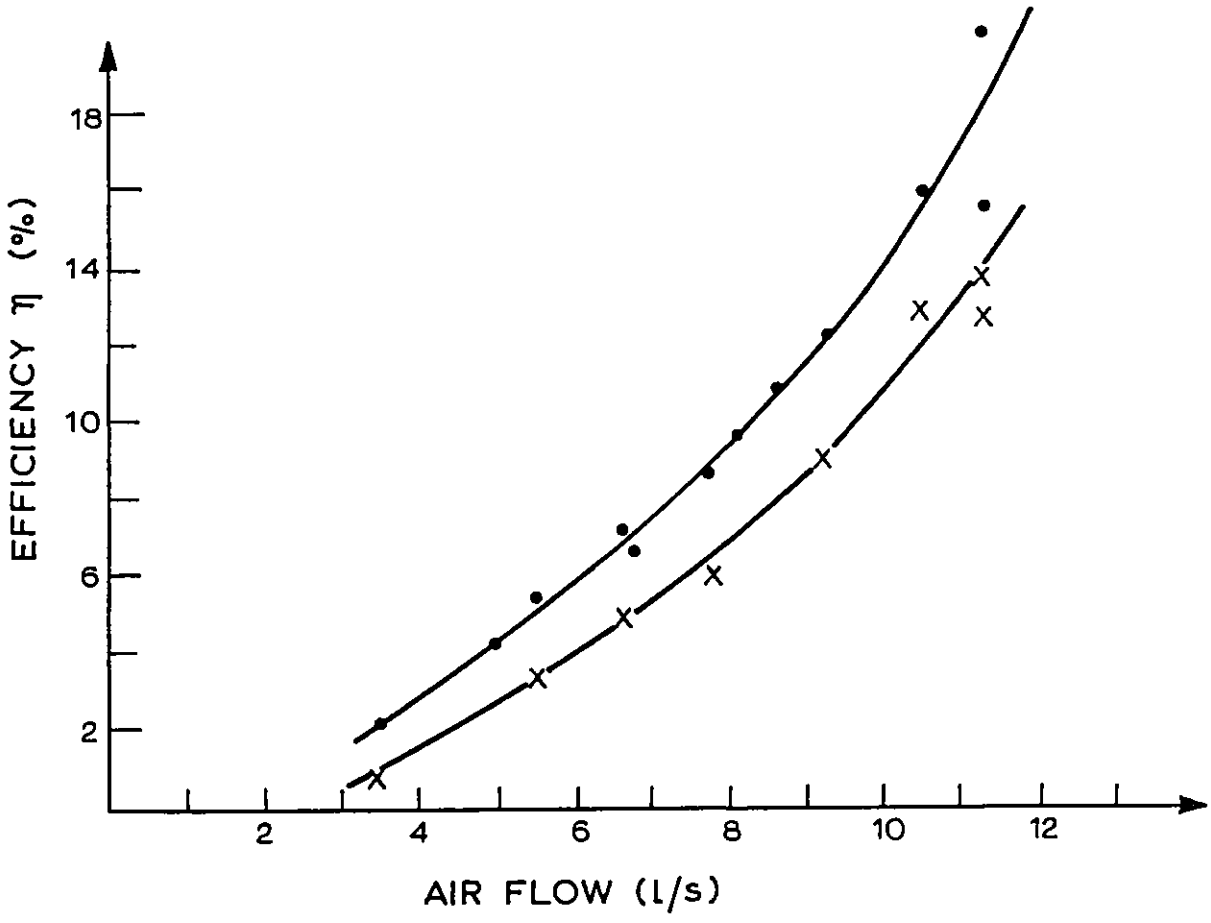


FIG. 3:22.b.
Experimental efficiency as a function of external airflow. Nitrogen plasma jet (500 cm^3/s; 1200W).

• NO; x NO_x

because of the presence of oxygen. From Baulch et al. (1973), possible reactions between nitrogen and oxygen are as follows:

$$N_2 \longrightarrow N + N \qquad (1) \qquad K = 3,7\ 10^{21}T^{-1.6}e^{-\frac{113200}{T}}$$

$$O_2 + N \longrightarrow NO+O \qquad (2) \qquad K = 6.4\cdot 10^{9}Te^{-\frac{3150}{T}}$$

$$NO + O \longrightarrow NO_2 \qquad (3) \qquad K = 1.1\cdot 10^{15}e^{\frac{940}{T}}$$

$$NO_2+O \longrightarrow NO+O_2 \qquad (4) \qquad K = 10^{13}e^{-\frac{300}{T}}$$

$$NO + N \longrightarrow N_2+O \qquad (5) \qquad K = 1.6\cdot 10^{13}$$

$$NO + O \longrightarrow O_2+N \qquad (6) \qquad K = 1.5\ 10^{9}Te^{-\frac{19500}{T}}$$

$$O_2 \longrightarrow 2O \qquad (7) \qquad K = 9.8\ 10^{24}T^{-2,5}e^{-\frac{59380}{T}}$$

The amount of hot nitrogen atoms present from the plasma jet should be the same as for the previous case with an external feed of nitrogen + NO. Because the power input and the flow-rate through the plasma jet were the same. The dissociation energy for oxygen is about half that for nitrogen, so the hot emerging plasma gases will dissociate some of the oxygen in the airstream. Oxygen atoms will also be freed by reaction (5) which is the one responsible for removing NO in the previous set of experiments with the external feed of nitrogen and NO. Some oxygen atoms generated will oxidize NO to NO_2, thus increasing the NO-removal efficiency. However, NO_2 is not a useful alternative to NO, so the efficiencies for the air+NO case are calculated on the basis of added NO less residual

NO_x ($NO+NO_2$). It is worth noting that η increases as the flow of air + NO is increased, as was the case for nitrogen + NO. There should be an external flowrate for which this trend is reversed. This is borne out by FIG. 23, which shows the residual NO/NO_x and efficiency for one flowrate of air + NO with varying nitrogen flow through the plasma jet. Unfortunately, the equipment did not permit external flowrates above 14 l/s of air. Varying the shape of the inner quartz tube, making it wider or adding a funnel at the end, gives the same value for the efficiency, η . FIG. 24 shows these results. The height above the plasma jet of the inner quartz tube, FIG. 25, makes no appreciable difference to the efficiency η. This is interesting as earlier work, Behbahani et al. (1982), had shown that the hot pockets only survived up to 2 cm. downstream. The current entrainment work shows that as long as the external feed is entrained within the first 4 cm., the efficiency remains the same.

3.2. (3) Air Plasmas

The result of the entrainment work suggested that it might be possible to obtain radicals from the gas entrained into the plasma jet. Therefore, one of the objectives of this work was to look for other convenient plasma media. High pressure air is available on aircrafts.

However, air as a plasma medium introduces erosion problems, due to its oxidizing properties and oxygen's high electron affinity. Tungsten (the cathode material) reacts with oxygen at temperatures above 500^{o}C, forming a variety of

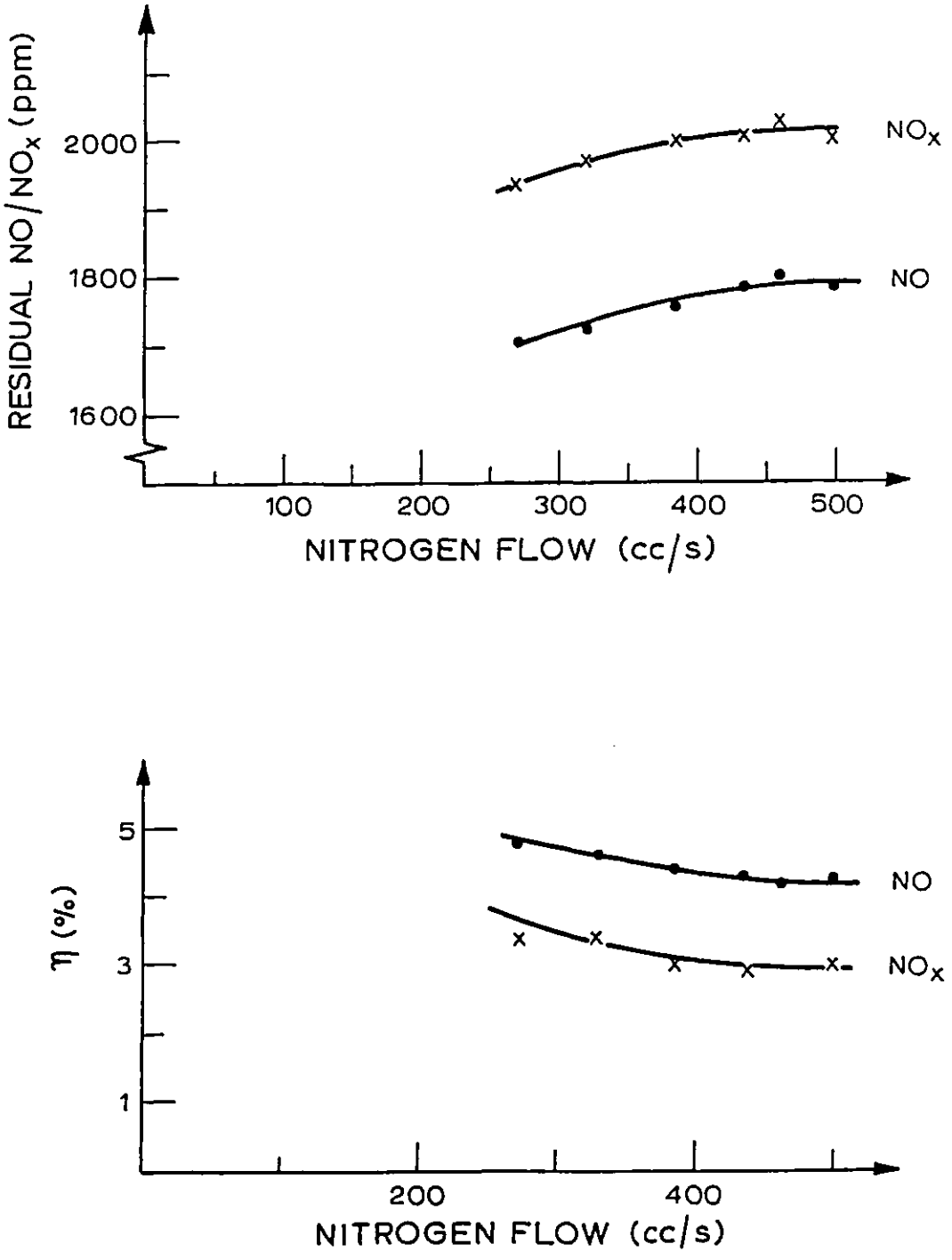


FIG. 3:23. a) Residual NO concentration for varying nitrogen flow through the plasma jet. Initial NO concentration 2500 ppm. External air flowrate 31/s.

b) Experimental efficiency for varying nitrogen flow through the plasma jet.

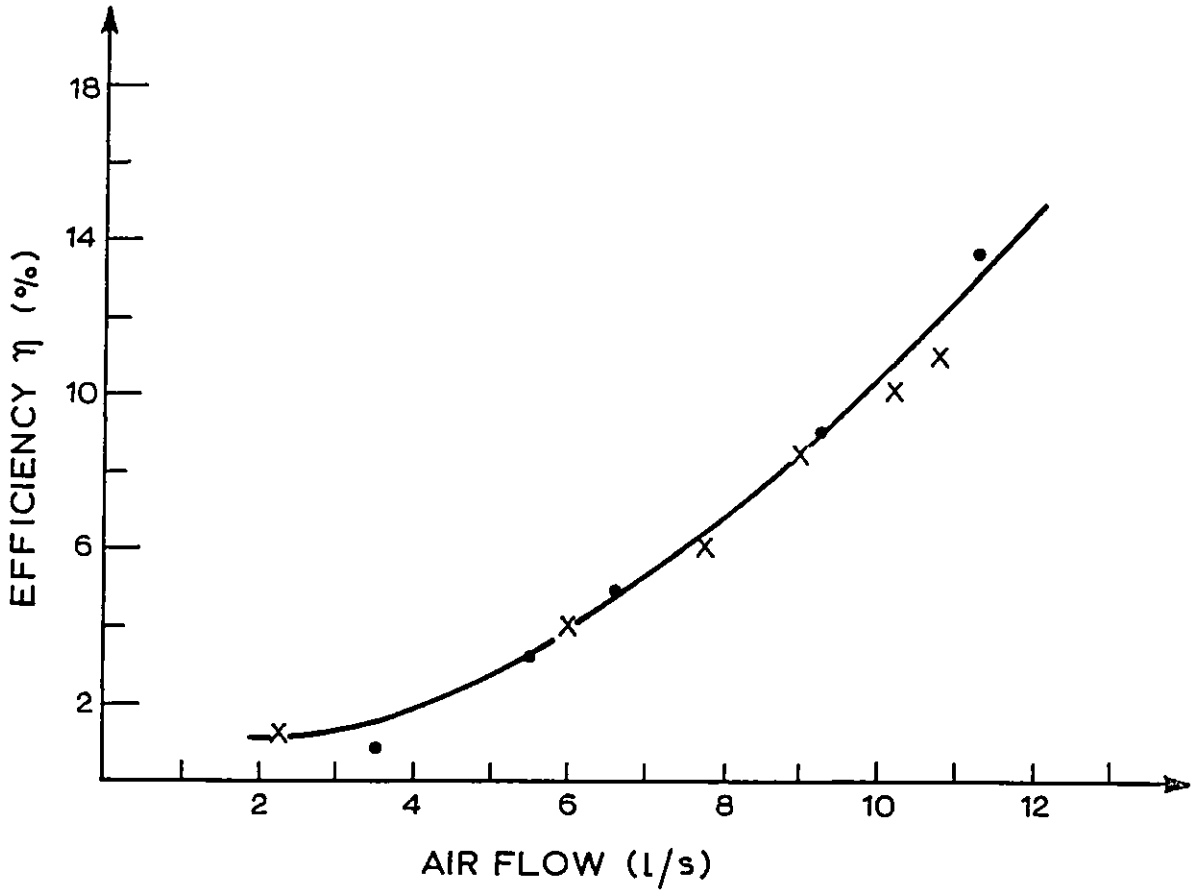


FIG. 3:24. Experimental efficiency of NO-removal as a function of external ari flowrate, for various configurations of the inner tube.

• Funnel; x tube OD = 2cm.

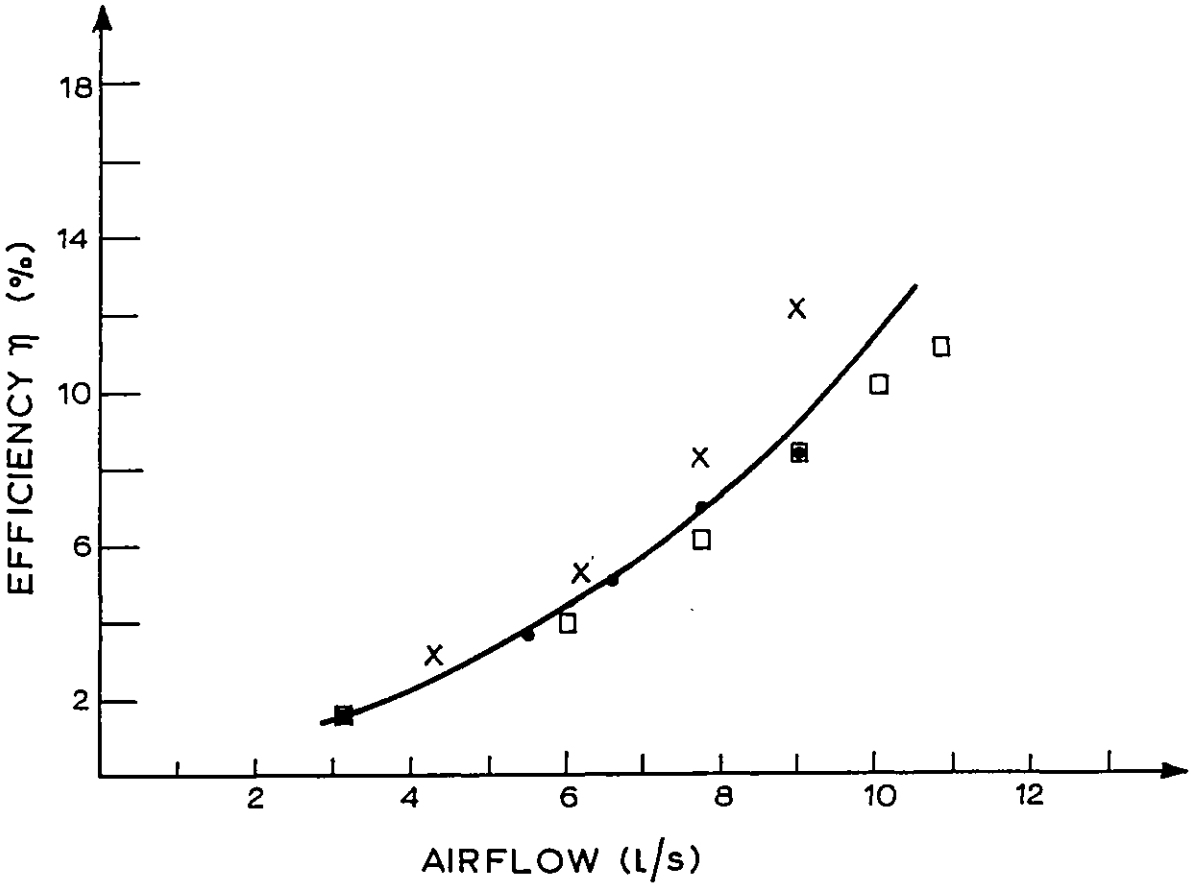


FIG. 3:25. Experimental efficiency of NO-removal as a function of external air flow rate, for various heights above the plasma jet of the inner tube.
□= 2cm; x = 3 cm; • = 4 cm.

colourful tungsten oxides. According to Rieck (1973), the most common ones are:

WO_2 (brown)

W_4O_{11} (blue)

WO_3 (yellow)

Pure yellow WO_3 can act as an insulator. However, if slightly less oxygen is present than is required for WO_3 formation, other tungsten oxides will be formed and increase the electrical conductivity. The solution is to keep the cathode temperature down by fast arc rotation, cooling and low power consumption, if tungsten is to be used as a cathode material. An alternative cathode material was, therefore, considered. The requirements being a low work function, high melting point and low susceptibility to oxidation. According to a literature survey, several different materials have been used in either pure oxygen or air. TAB. 1 lists these materials. However, none of them proved useful; normally the cathode eroded away immediately. The failure of zirconium is interesting, since it performed well using pure oxygen plasmas, according to Weatherby et al. (1965). However, zirconium will react more rapidly with the nitrogen present in an air plasma to form zirconium nitrite than it will with oxygen to form zirconia. Zirconia (melting point 2700^{o}C) is needed to keep the arc running. Zirconium nitrite is an insulator and its formation effectively prevents arcing and makes it impossible to restrike the arc. The failure of these materials necessitated a return to tungsten as a cathode material. One possible way to reduce the cathode temperature which has not so far been considered is to lower the work function, which is 4.5 eV for pure tungsten, (Rieck, 1973). Normally, this is done by addition

Material	Reference, Comments
Mild Steel (mp. 1798K)	Petrov et al. (1970)
Stainless Steel (mp. 1700K)	Petrov et al. (1970)
Tungsten "A" (mp. 3640K)	used in highly oxidizing atmosphere as spark plug material by Smiths Industries.
Tungsten "HPF3" (mp. 3640K)	
Nimonic 75 (mp. 1660K)	
Copper (mp. 1355K)	Baddour et al. (1967)
Brass (mp. 1297K)	Copper alloy
Iridium (mp. 2683K)	
Zirconium (mp. = 2133K)	Weatherley et al. (1965.) Zirconia formed in O_2, mp. = 2973K.
Hafnium (mp. = 2500K)	
Molybd-enum (mp. 2883K)	Same periodic group as tungsten.
Tantalum (mp. 3269K)	close to tungsten in periodic tables.

TAB. 3.1. Cathode materials for air plasma jets.

of thoria, whose work function is 3.31 eV. Tungsten rods are commercially available with 1%, 2% or 4% thoria contents. Experiments showed that by using a 4% thoriated tungsten cathode, with a 45^{o} angle cut-off (FIG. 29) in the aerodynamically spun plasma jets, it was possible to run air plasmas for ten minutes.

The need for optimizing the anode channel diameter was shown by Behbahani et al. (1983). FIG. 26. They conclude that the optimum diameter for the aerodynamically spun plasma jet is between 1.9 and 2.5 mm. The air plasma was, therefore, run with a 1.9 mm. anode channel diameter fitted with an exit cone of 45^{o} to minimize erosion as the jet expands, due to recombination of the free radicals generating heat around the channel edge.

Running conditions for an air plasma are a gap of 500 - 550 μm (approximately the same as for argon) and a power consumption of around 1 - 1.5 kW. FIG. 27 shows current-voltage characteristics for varying air flowrates for the aerodynamically spun plasma jet. It performs well on both types of aerodynamically spun plasma jets. A typical air plasma, with its larger cone than argon or nitrogen arcs, can be seen in FIG.28. The reason the air plasma is more stable on the aerodynamically spun plasma jet is that the cavity is smaller so that the incoming gas more effectively cools the cathode than for the magnetically spun plasma jet. Increasing the magnetic field from 300 Gauss to 2600 Gauss by using samarium cobolt magnets, which are the same size as the permanent magnets but have much higher field strength, makes no appreciable difference to

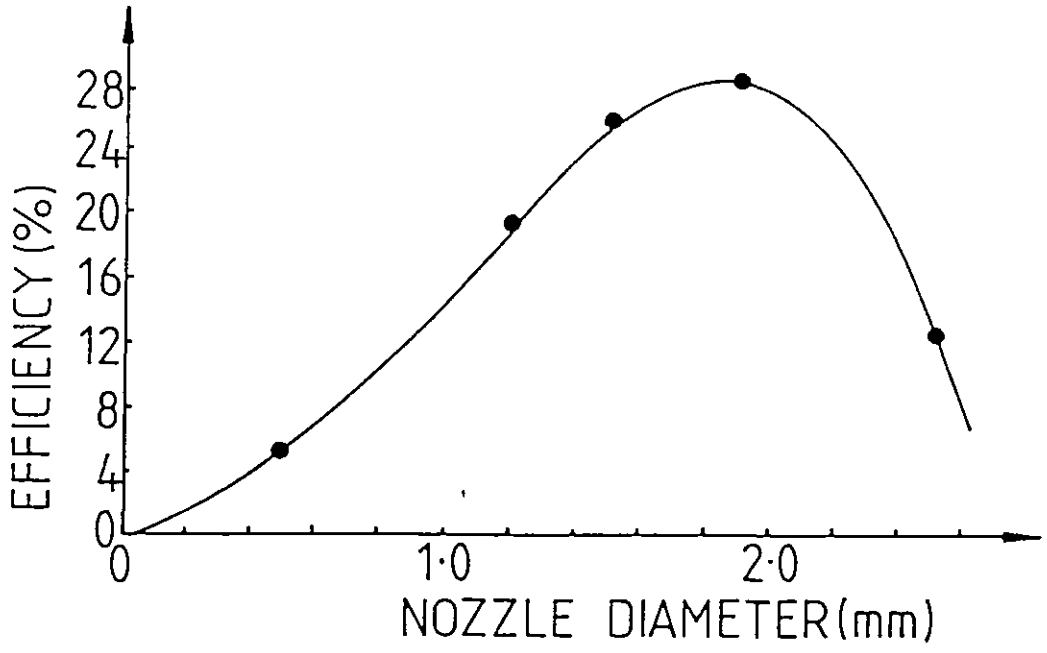


FIG. 3:26. Experimental efficiency as a function of nozzle diameter. Flow rate 250-330 cm^3/s of nitrogen. Power 875W. NO-inlet 3mm downstream of nozzle; - from Behbahani et al. (1983).

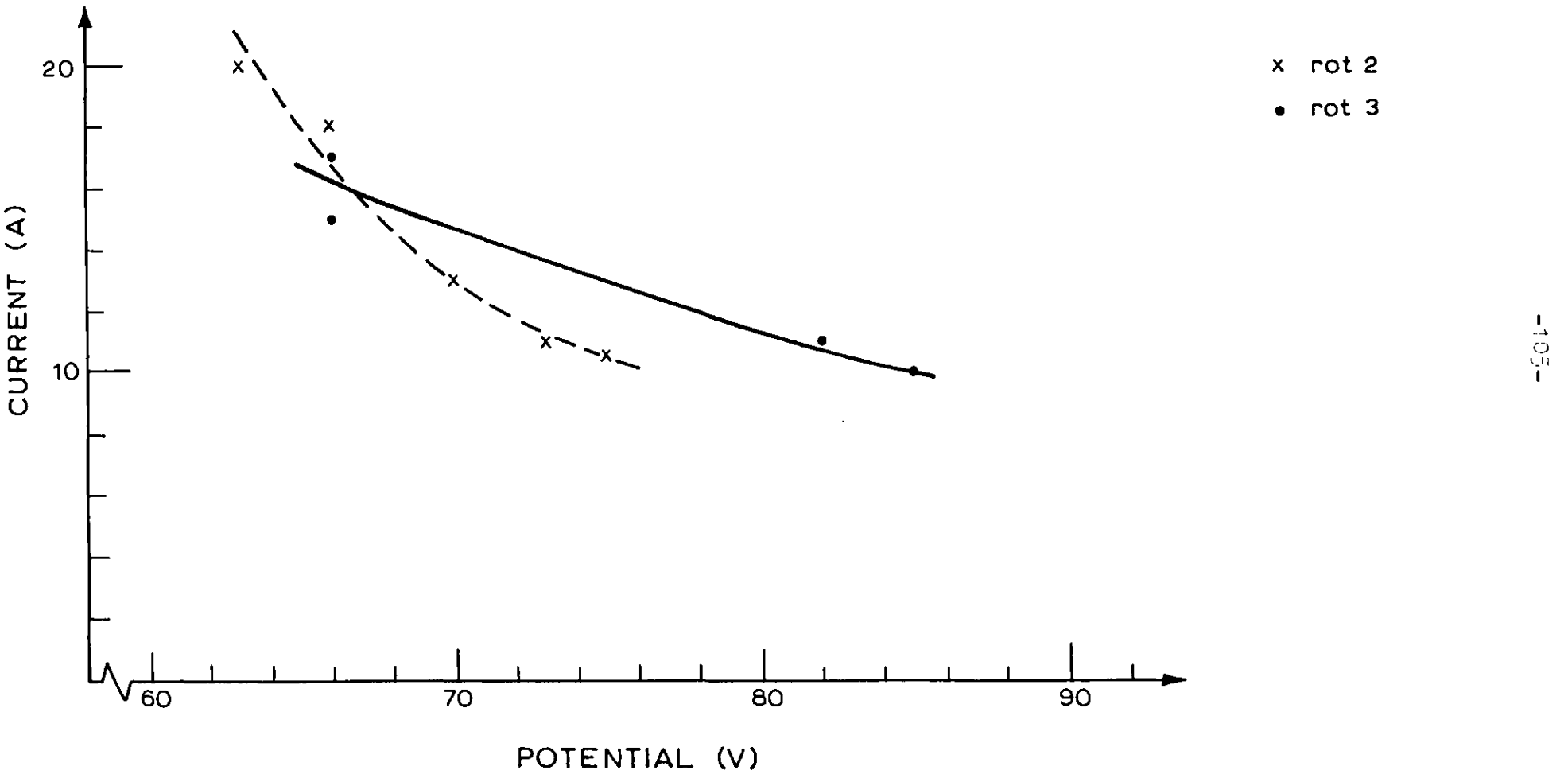


FIG. 3:27. Current-voltage characteristics for an air plasma on the initial aerodynamically rotated plasma jet.
(rot 2 = 270 cm^3/s; rot 3 = 330 cm^3/s)



FIG. 3:28 : Air plasma on the magnetically spun plasma jet.

the performance or running time of an air plasma.

Different geometrical shapes of the cathode were tried, because the original square-cut electrode became severely pitted in the centre (as if a hole was dug out of it). The various shapes considered were a rounded-off electrode, a pointed electrode and a 45^{o} angled-off electrode, see FIG. 29. The 45^{o} angle cut-off electrode performed best. Its angle corresponds to the slope of the anode. The reason being that, as oxygen attracts electrons, the arc requires more electron emission from the cathode and, therefore, a higher cathode temperature. With the square-cut cathode, the arc strikes from the sharp edge of the cathode , the flat area behind the arc receives less cooling and a lot of heating from the vortex, so the arc moves to the hot spot so formed. The balance between heat loss and heat gain is better for the 45^{o} angle cut-off electrode. From a fluid mechanics point, this cathode configuration is better, except when the gap between anode and cathode is choked, which happens if the gap is less than 225 μm. This configuration should give a stable arc. There will be less eddy formation round the edge of a 45^{o} angle cut-off cathode, with a resulting smoother gas flow.

Air plasmas generate large amounts of NO/NO_x. The amount was measured using a NO/NO_x chemiluminescent analyser calibrated for up to 2500 ppm of NO/NO_x. The exhaust gases from an air plasma were diluted with nitrogen and then passed through the NO/NO_x analyser. The result showed that a maximum of 3% NO_x

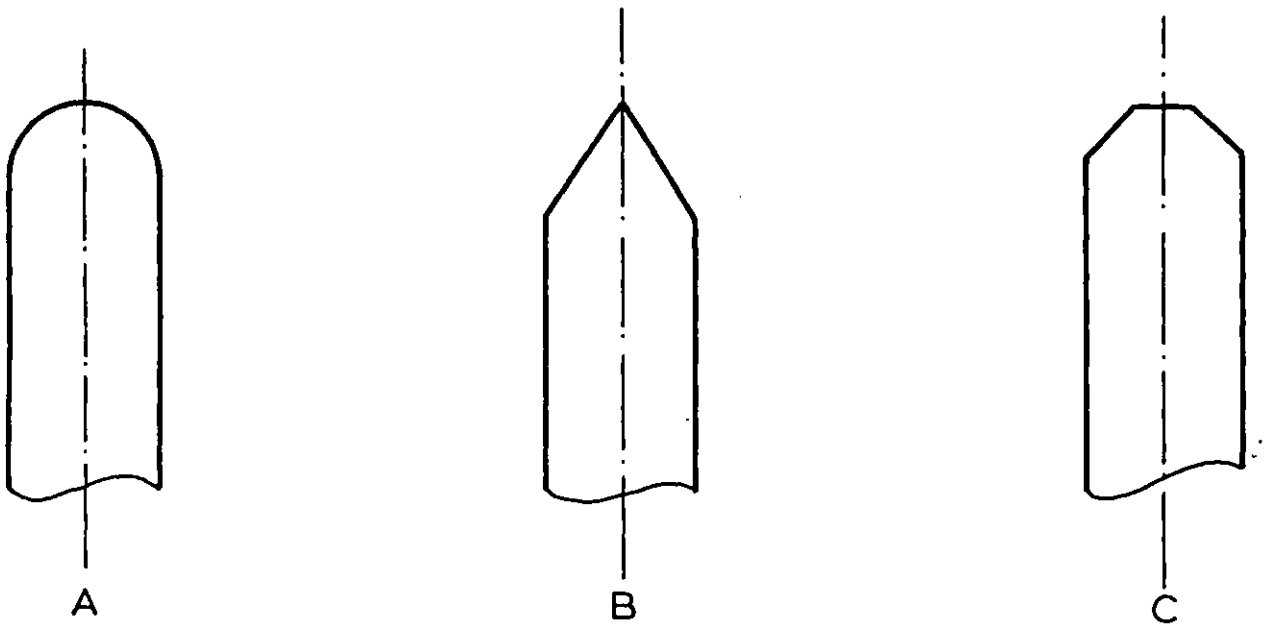


FIG. 3:29. Various cathode shapes.

A. Rounded

B. 45^{o} angle tip

C. 45^{o} angle cut off.

is generated. This compares with a maximum of 0.3% NO for a nitrogen plasma exiting into surrounding air. The difference may be due to the coexistence of nitrogen and oxygen atoms in the hot pockets for an air plasma, whereas for the nitrogen plasma, the hot pockets contain only nitrogen atoms. These atoms diffuse out of the pockets and react with either the nitrogen or the oxygen present in the surrounding atmosphere. According to Baulch et al. (1973), the following reactions between nitrogen and oxygen can take place:

Dissociation:	$O_2 + M \longrightarrow 2O + M$	(1)
	$N_2 + M \longrightarrow 2N + M$	(2)
Recombination:	$N + O + M \longrightarrow NO + M$	(3)
	$N_2 + O \longrightarrow NO + N$	(4)
	$O_2 + N \longrightarrow NO + O$	(5)
	$NO + O + M \longrightarrow NO_2 + M$	(6)
	$NO_2 + O \longrightarrow NO + O_2$	(7)
	$O + O \longrightarrow O_2$	(8)
	$N + N \longrightarrow N_2$	(9)
NO-removal reaction:	$NO + N \longrightarrow N_2 + O$	(10)
	$NO + O \longrightarrow N + O_2$	(11)

Of the above, NO formation is largely controlled by reactions (4) and (5). The NO-removal is rate limited by (10). The air plasma generated about twice as much NO_x ($NO + NO_2$) as NO, i.e. the amount of NO and NO_2 formed are the same. This may be interpreted as follows. The dissociation energy for oxygen

is about half that for nitrogen. (495 kJ/mole O_2, compared with 942 kJ/mole N_2). Assuming similar quantities of dissociated nitrogen and oxygen are generated, extra oxygen atoms must be generated by reaction (5) and/or (10). The efficiency of the NO_x ($NO + NO_2$) generation was calibrated as:

$$\eta = \frac{\text{Energy used in breaking N and O-bonds}}{\text{Total energy used}}$$

η depends on running conditions but works out to between 6 and 12%. According to Dresvin (1977), the species found in an air plasma are: N_2, O_2, N^+, O^+, N, O, NO, e, O^-, O_2^+, N_2^+, N^-. Their presence depends on temperature. Dresvin (1977) states that 1.01×10^{20} molecules of NO/dm^3 are generated at 3000K in an air plasma; this compares well with the value found in the present work of 2.8×10^{20} molecules NO/dm^3. This gives a temperature estimation of around 3000K. FIG. 30 shows the temperature dependance of some of the major species in an air plasma calculated from data in Dresvin (1977). The amount of NO generated by an air plasma requires the laboratory to be well ventilated, as the threshold limit value for NO=5 ppm and NO_2 = 5 ppm; in this case around 16,000 - 30,000 ppm of NO_x is generated by the plasma jet. As in the previous section, some of the other potential chemical applications of the new plasma jet were considered, although they are not directly related to flame stabilization. Arc processes have been used for nitrogen fixation, as in the Birkeland-Eydes method. Partington et al. (1922) compares the different arc processes and arrives at a conversion of about 1%. Without trying to optimize NO formation in any way, the results obtained in the air plasma of 3% conversion compares well with commercial arc processes.

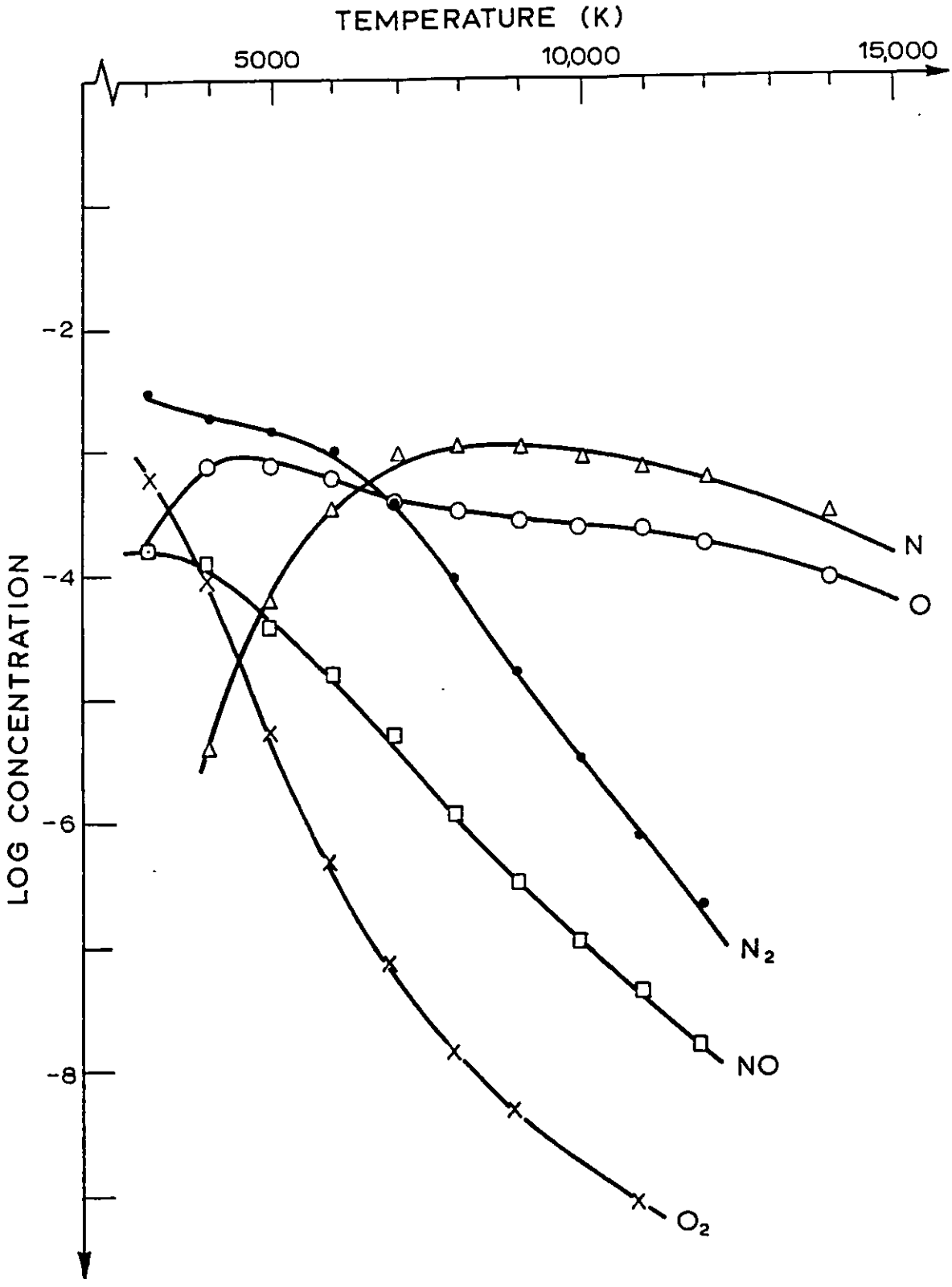


FIG. 3:30. Concentration of some major species in an air plasma as a function of temperature. Data from Dresvin (1977)

Another application was to explore the oxidation of SO_2 to SO_3. The conversion of SO_2 to SO_3 followed by reaction to sulphuric acid is of relevance to the removal of SO_2 from an exhaust gas stream. The aerosol formed can be removed using electrostatic precipitation. The oxidation of SO_2 is being studied by Dr. M. D. Carabine and Dr. M. G. Cisniega-Rojas. In collaboration with them, these experiments were carried out for comparison with the use of a Van de Graaff generator. An external air feed with a small amount of SO_2 was passed in through the outer cylinder and entrained into the plasma stream. From there, it passed up through the central tube to the exhaust and a gas sampling bag, which was filled with humid air so that the SO_3 formed would react to form H_2SO_4 droplets. The droplet size and distribution are then measured using a light scattering technique. Three types of feedstock were used with the aerodynamically spun plasma jet. TAB. 2 lists the running conditions and results for the air plasma. There was no SO_2 oxidation using an argon plasma, i.e. the plasma temperature is not high enough to dissociate any of the ambient air in the external stream or the number of oxygen atoms generated by the hot plasma too small to find and react with the low concentration of SO_2. Repeated experiments using a nitrogen plasma gave no indication of SO_3 formation. It would be expected that some oxygen atoms would be formed following the reaction:

$$N + O_2 \longrightarrow NO + O \quad (5)$$

In fact, a small amount of NO is formed by a nitrogen plasma exiting into air, FIG. 20. The amounts of oxygen atoms generated by reaction (5) however prove too small to react with the SO_2. This was also the case when the power input was increased. FIG. 20 shows that more NO and, therefore,

Plasma jet power consumption (W)	980	980	980	1330	1495	1495	1600
Air flowrate through the plasma cc/s	230	230	270	210	250	270	270
Air flowrate external l/min.	150	270	150	80	150	150	140
0.1% SO_2 flow external cc/s	160	180	160	118	40	30	35
Constation of SO_2 at start of reaction above plasma jet (vpm)	55.0	37.0	55.0	71.0	14.3	11.0	13.0
d_m (μm)	0.093	0.450	1.108	0.388	0.302	0.409	0.388
σ	0.515	0.282	0.095	0.115	0.100	0.119	0.450

TAB. 3.2. Running conditions and results from oxidation of SO_2 by an air plasma.

more oxygen atoms are generated when the power is increased. Aerosol formation was observed with an air plasma. This is to be expected as an air plasma produces oxygen atoms in large quantities in the hot pockets. These oxygen atoms react either with the SO_2 to form SO_3 or with the nitrogen present to form NO/NO_x. Both products were present in the gas sampling bags.

The problem of using an air plasma for flame stabilization would be the large amounts of NO/NO_x generated. There is in some countries legislation on how much NO/NO_x a gas turbine engine is allowed to produce, at least on ground level. Today, there is also serious concern about the amount of NO/NO_x generated at high altitude, as this might diminish the protective ozone layer. For a gas turbine engine, the amount of NO generate is around 400 - 500 ppm at the exit nozzle. Assuming the flow to be 400 m^3/s, one can calculate the contribution of an air plasma jet, assuming a NO/NO_x generation of 30,000 ppm with a flow of 250 cm^3/s. This corresponds to a value of 6.10^{-4}% of the total. NO flow is due to the air plasma. It is, therefore, possible to envisage the use of an air plasma as an igniter and flame stabilizer. Other uses for an air plasma could be in studying reactions involving nitrogen, oxygen and any externally added gases. Their use in exhaust gas streams is doubtful as, although they remove SO_2, they generate large amounts of NO/NO_x.

3.2. (4) Hydrogen and helium plasmas

Hydrogen plasmas are an obvious source of hydrogen atoms for flame stabilization work. The main experiments were not carried out using hydrogen, due to the associated safety

problems. However, hydrogen was stabilized before going on to examine the more useful hydrocarbons. They are more relevant in practice but may give rise to problems, due to sooting.

Hydrogen proved an easy plasma medium in which to strike an arc. Although from safety considerations the arc was always initiated in argon and hydrogen, then introduced. This was done to prevent build-up of hydrogen if the initiation failed. A few tests were run with pure hydrogen initially, just to test its initiation properties. Hydrogen arcs ran stable, without the large power fluctuation associated with an air plasma. An optimum gap of 400 μm was determined after testing a variety of gaps. This value is between the value for a nitrogen arc (300 μm) and that for an argon arc (600 μm). Typical running conditions were a power consumption of 1.7 kW with a current of 19A and voltage of 90V. Flowrates were varied between 5 and 15 l/min. The hydrogen plasma is red, due to the hydrogen α-line at 6563Å. FIG. 31a shows a typical hydrogen plasma.

Helium as a plasma medium was briefly tried in connection with testing for leaks in the flow system constructed for the experiments on hydrogen and hydrocarbon as plasma media. Helium being a small molecule has a slightly larger diffusivity than hydrogen and can, therefore, be used for testing for leaks in a flowsystem under pressure. (Using soapy water to detect any escaping gas.) The plasma jet body itself was also tested for leaks. Helium arcs proved easy to stabilize and strike, ran well and were also red in colour. This is due to the spectral

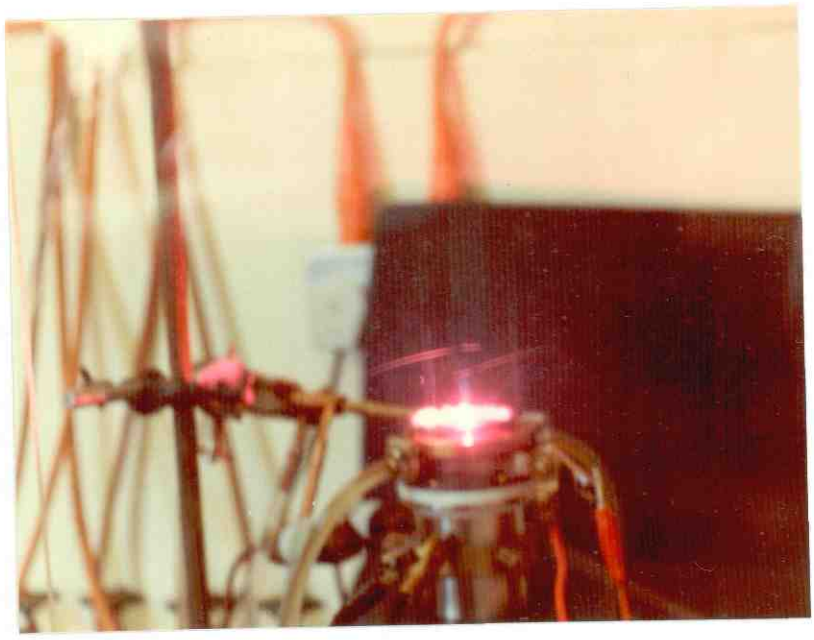


FIG: 3:31
a. Hydrogen Plasma

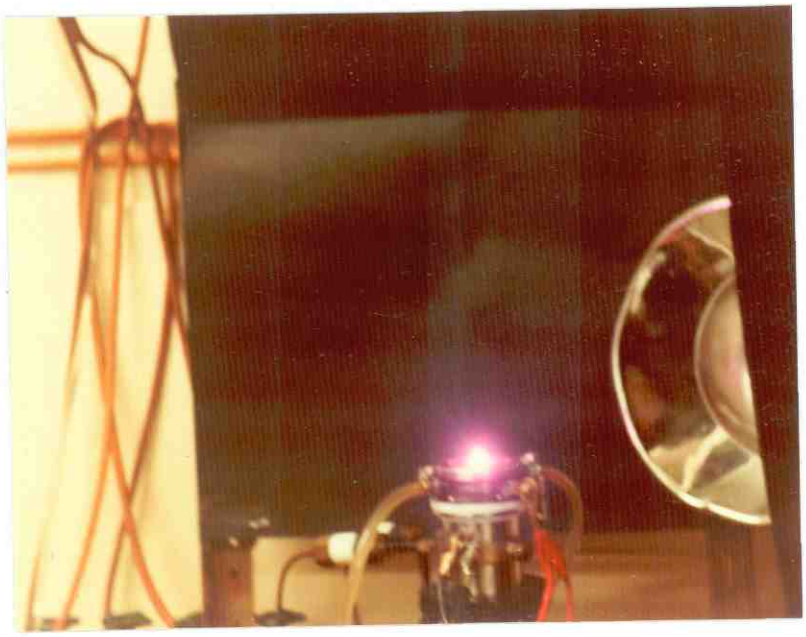


FIG. 3:31
b. Helium Plasma

lines of 6678Å and 7065Å in the helium spectra. Helium arcs run stably because helium, like argon, is a monatomic gas which cannot dissociate; it does not attack the electrodes and, like argon, its temperature rises quickly with increase in power input.

The new flow system, built for hydrogen and hydrocarbon feedstocks, consisted of two separate copper lines fitted with needle and stopvalves to regulate the flow. Copper was used on account of hydrogen's diffusivity and because pressures of up to 10 bars were envisaged. Calibrated orifice plates were used to meter the flow. The design and calibration procedure for orifice plates has been described by Ower et al. (1966). The orifice plates could be changed to allow a variety of gaseous feedstocks to be metered accurately. The interchangeable orifice plates were used to ensure a large range of flowrates, eg. 0-250 l/min for H_2, 0-120 l/min for CH_4. The two flowstreams are then mixed, to allow arcs to be run in a gas mixture, eg. Ar/H_2, Ar/CH_4. The final mixture is then metered again using an orifice plate and through a distributor chamber fed either tangentially (two directions) or axial to the plasma jet.

Safety hazards had to be taken into consideration before proceeding to run a hydrogen arc. The extraction system in the laboratory had to be tested to ensure that no flammable hydrogen/air mixtures would build up. The plasma jet was fitted with a ring of pilot flames to ensure that no hydrogen should escape unburnt. This ring of flames, however, lifted and blew off when the hydrogen through-put was increased, as was discussed in Section 3.1.

The hydrogen plasma was only stabilized on the magnetically rotated plasma jet for a short time, due to the safety problems which would arise if the jet were to blow off, in view of the large throughput of hydrogen. However, there is no reason to suspect that hydrogen would not run indefinitely as none of the initial start-up problems encountered with other plasma media, such as blow off after a few seconds, power fluctuations, electrode erosion, were experienced.

3.2. (5) Hydrocarbon Plasmas

Hydrocarbons would be the most desirable feedstock for the plasma jet, because they are readily available wherever combustion is used and because they have been shown to provide a source of radicals, which are specifically efficient in increasing flame propagation, at least in intermittent plasma igniters.

The use of hydrocarbons (methane, propane and ethylene) as the gaseous feedstock to the continuous plasma jet resulted in carbon being deposited on the cathode. The optimum conditions for hydrocarbon plasma jets were found to be a gap of 500 - 600 μm, with a power consumption of 1.5kW and a current of 17A and voltage of 90V. The plasma jets tended to blow off after two to three minutes, due to carbon deposition on the end of the cathode, forming a tip extending through the anode channel. This forced the arc to shift location until it rotated on the top of the anode. FIG. 32 shows the different stages a CH_4- plasma undergoes while slowly developing its surrounding flame. Initially, there is no flame, just the plasma jet. Slowly, a weak, blue premixed flame develops

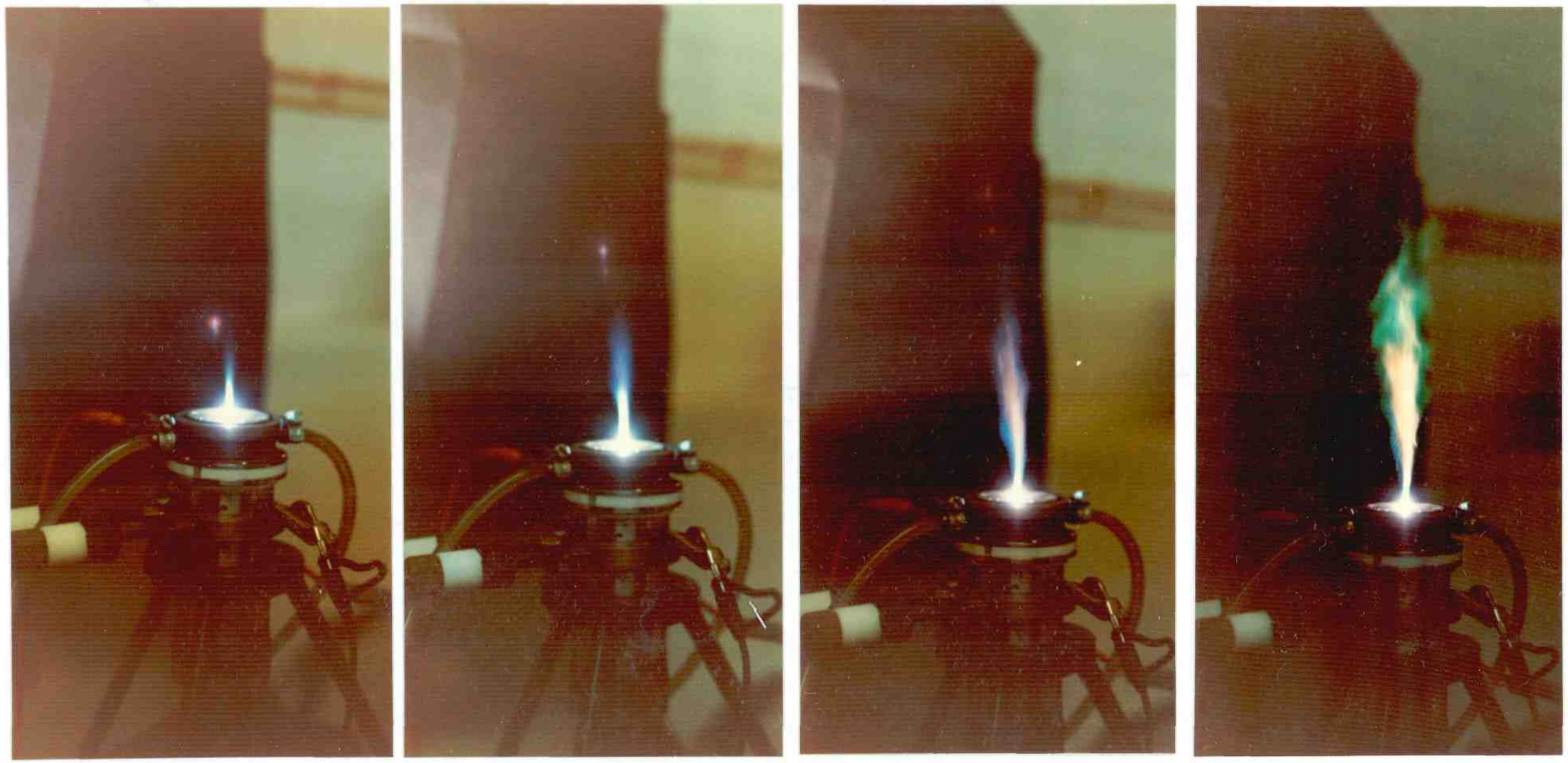


FIG. 3:32 : Flame development due to a methane plasma exiting into surrounding air.

which eventually changes into a yellow-orange diffusion flame.

X-ray diffraction and X-ray fluorescence analyses were used to determine what the tip formed on top of the cathode consisted of. The analyses revealed that it was graphite in which preferential orientation of the crystal planes had occurred. A classical analysis for total carbon yielded 98%. Appendix 1 contains the details of these analyses.

Several methods of preventing the carbon from depositing on the cathode were evaluated. Initially switching from propane to methane with a lower carbon content was tried, but no appreciable lessening of the deposition rate was found. With a flowrate of 520 cm^3/s of methane and a running time of 100 seconds, the tungsten electrode weight was increased by 0.0032g. Assuming this weight gain to be due only to carbon deposition, the deposition rate works out to 3.2×10^{-5} g/s at a flow of 520 cm^3/s of methane, i.e. approximately 8.7×10^{-6}% of the methane flowrate is deposited on the cathode. Putting a glass tube, diameter 3 cm., around the plasma jet reveals that the hot plasma carries a large proportion of carbon. The wall of tube is quickly covered with soot. Varying the strength of the magnetic field or the flowrate of methane had no effect on the running time of the arc or its stability.

The angle around the cathode edge was modified from square-cut to 30°, 45° and 60°. The carbon grows more rapidly on the 45° and 60° angle. The arc runs better with an angled-off cathode, because with no carbon deposition, the arc never

stabilizes, i.e., it blows off after 20 - 30 seconds. This bears out the argument in favour of a sloping 45^{o} angle cathode to minimize vortex formation around the tip of the cathode. Shortening the anode channel from 3 to 1 mm also gave no difference in running time, as the tip of carbon first expanded sideways instead of lengthwise. Moving the cathode away from the anode while the plasma jet was running gave a thin,rapidly-growing carbon tip and the difficulty in changing the gap as fast as the carbon grew proved overwhelming. The arc still moved to the top of the anode. Running a graphite electrode instead of a tungsten as cathode did not change the behaviour of the arc; it still deposited carbon on top of the graphite.

It should be possible to avoid the carbon deposition by chemical methods. Adding small amounts of oxygen was tried. The oxygen flow has to be low enough not to erode the cathode by oxidation, but high enough to react fully with the carbon deposit. Experiments have shown that it is not possible to achieve the necessary balance, i.e. either the oxygen flow was too low to cope with the carbon deposition or it was too high and eroded the cathode. In fact, the plasma combining methane and oxygen was no more stable than the pure methane plasma. Even allowing methane to run for a short while before introducing oxygen resulted in erosion of the cathode or, if the oxygen flow was low,in carbon continuing to build up on the cathode. Adding hydrogen to a methane plasma was then tried. The plasma jet ran well and stable with a 50/50 mixture of methane and hydrogen. The gap was 550 μm. The power consumption was high; 3.5 kW. It was not possible to

turn the power down as the current/voltage then started to fluctuate, i.e. the arc becomes unstable. The arc in hydrogen and methane ran for extended periods and was very hot (the perspex shield 30 cm. away from the jet started to melt). The inspection afterwards of the cathode revealed that the edge of it was slightly damaged, as if small crystals of carbon had been deposited on it. However, there was no carbon tip formation. The work on hydrocarbon plasma is to be continued and the findings will be reported elsewhere.

The use of plasma jets with hydrocarbon also has potential chemical applications. The quenching of high temperature streams of hydrocarbons has been extensively investigated before, e.g. Venugopalan (1971), McTaggart (1967). In view of the observation in this work that hot pockets co-exist with cold surrounding gas, interesting chemical reactions may occur, even in the absence of quenching, due to attack on the cold hydrocarbons by hydrocarbon radicals diffusing out of hot pockets. In collaboration with Mr. Cheriyan working in these laboratories, the methane plasma was sampled using a quartz sampling probe, illustrated in FIG. 33. The gas sampled was subsequently analysed using a gas-chromatograph to test for hydrocarbon content. Initial results showed only methane present in the gas and no higher hydrocarbons. The probe suffered extensive heat damage and it was, therefore, redesigned, FIG. 34. This would allow it to be held closer to the plasma exit. The probe is designed to aerodynamically quench the sample. It was also planned to sample the methane-hydrogen plasma. These results will be reported elsewhere.

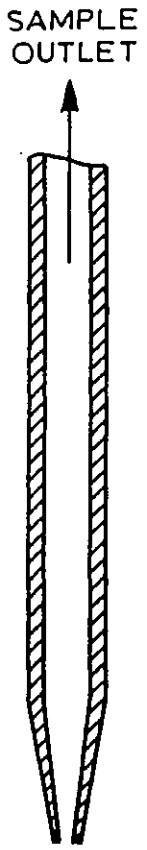


FIG. 3:33. Original quartz sampling probe.

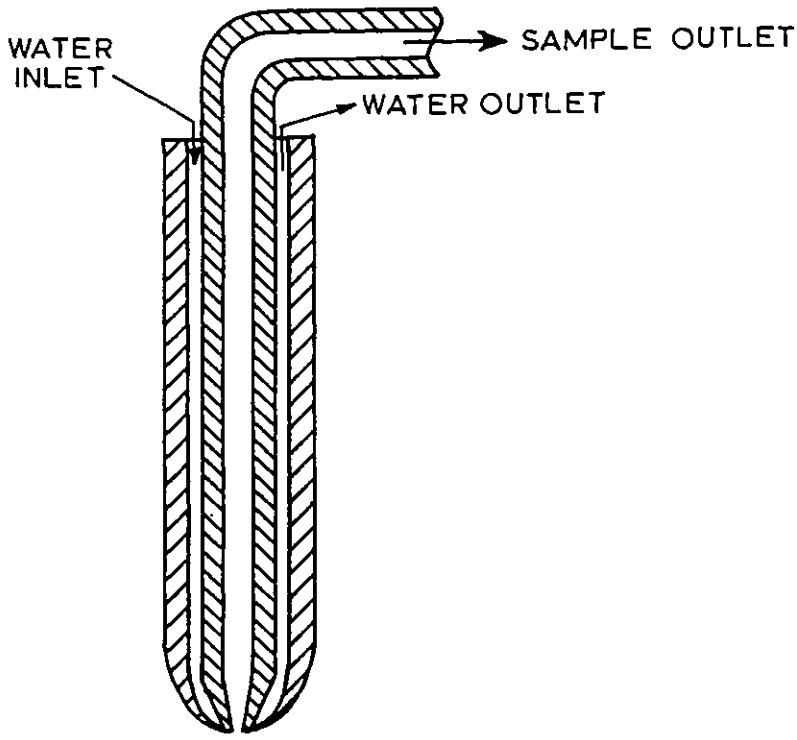


FIG. 3:34. The water cooled sampling probe.

CHAPTER 4

TEST FACILITY FOR IGNITION AND FLAME HOLDING STUDIES IN FAST GAS STREAMS

4.1. Introduction

The velocity of air in a gas turbine combustion chamber reaches close to 30 m/s in the primary combustion zone. To test the ignition and flame holding capabilities of the surface discharge igniter and the pulsed and continuous plasma jet, a system giving access to fast flowing fuel/air mixtures was constructed at Smiths Industries. This is capable of delivering air velocities between 5 m/s and 30 m/s.

Apparatus available at Imperial College would not have permitted studies at air flow rates of 5 m/s to 30 m/s. A 14 l/s flow of methane, i.e. 6% of the air flow, would require four gas cylinders of methane every thirty minutes, assuming that the pressure in the cylinders could be maintained, which would be difficult for these flows. (6% methane content is quoted as the absolute minimum, being only just above the limit of flammability.) The large air velocities also presented a problem. The flow system has to be large enough for the continuous plasma jet to be fitted horizontally in the fuel/air stream, i.e. a diameter of approximately 10 cm. is required. That would require the air flow to be 230 to 240 l/s and would also create problems associated with product

removal and safety.

At the same time, Smiths Industries required help in setting up a basic combustion facility on their site and were able to provide a fan that would, unloaded, achieve velocities of up to 60 m/s at the exit. It was decided to combine the two requirements and to design and set up a test facility at Smiths Industries for fast flowing lean fuel/air mixtures.

4.2. Flow System

The flow rig, FIG. 1, shows the general outline of the flow system, consists of a fan with an air intake regulator in the form of two overlapping discs to control the air flow, FIG. 2. The fan exit is connected to a 10cm. diameter cylindrical duct, 1 metre long. This duct is fitted with an orifice plate to measure the air velocities and a ring-formed fuel supply, FIG. 3. The fuel supply ring is positioned facing upwards, i.e. towards the oncoming air flow. Three different gauzes were also fitted in the duct, the final one at the exit to prevent flash back and the others to assist in mixing the fuel and air.

The orifice plate provides an easy and reliable way of measuring the airflow. The plate was calibrated after construction, using a pitot tube. The design and calibration procedure has been described by Ower et.al. (1966).

The mixing pattern was tested using a combustible gas indicator model 40 (dual range,general purpose type),

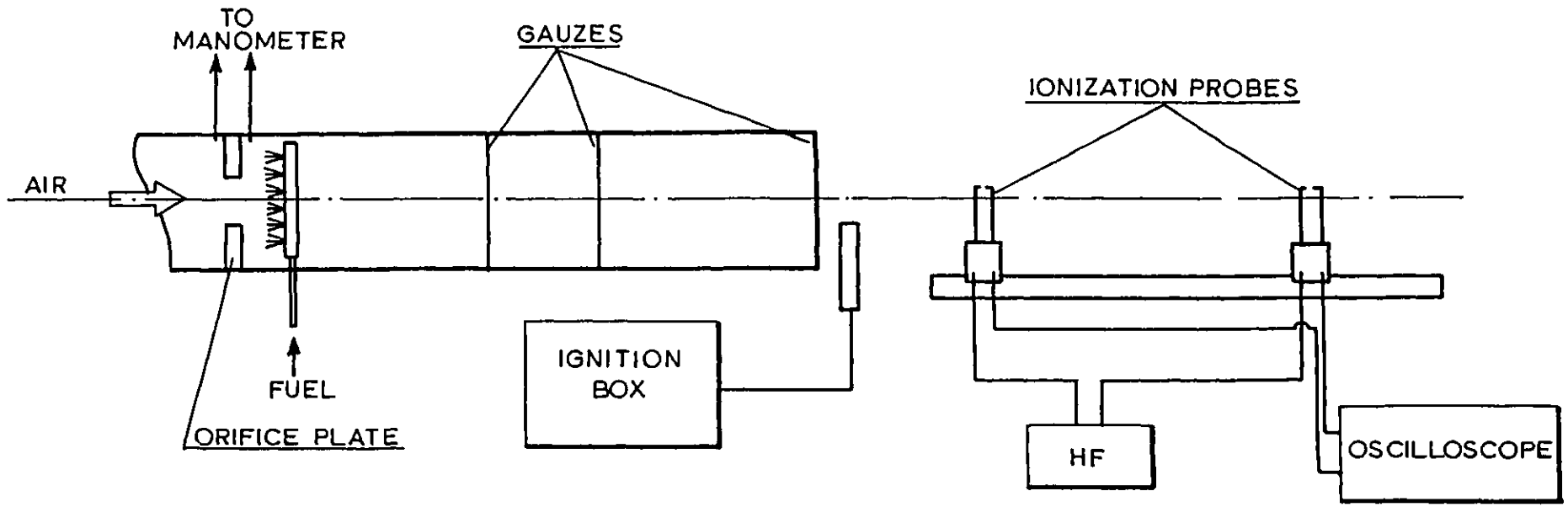


FIG. 4:1. The flow system at Smiths Industries for the high velocity propane/air mixture.

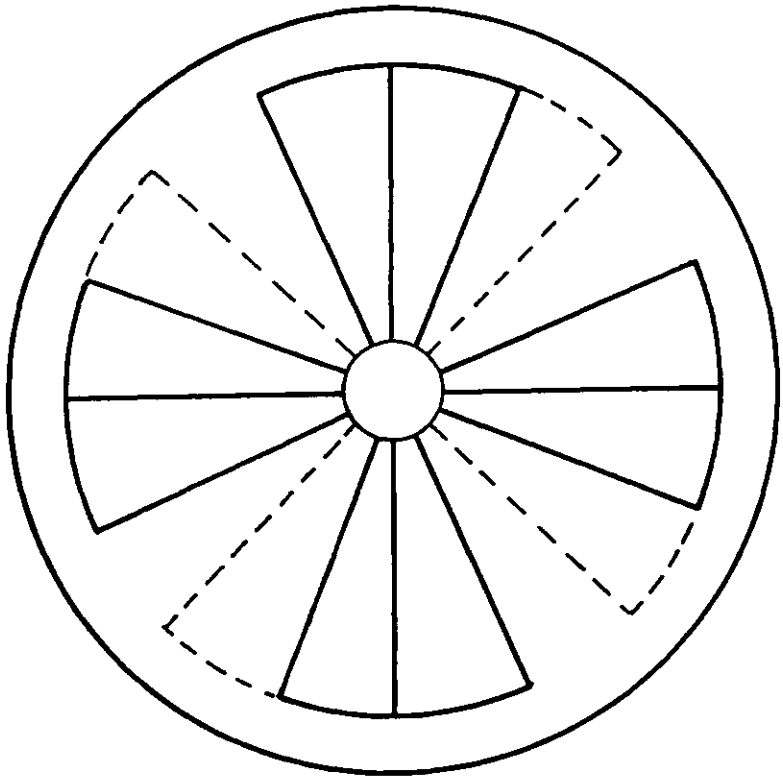


FIG. 4:2. Air intake control discs.

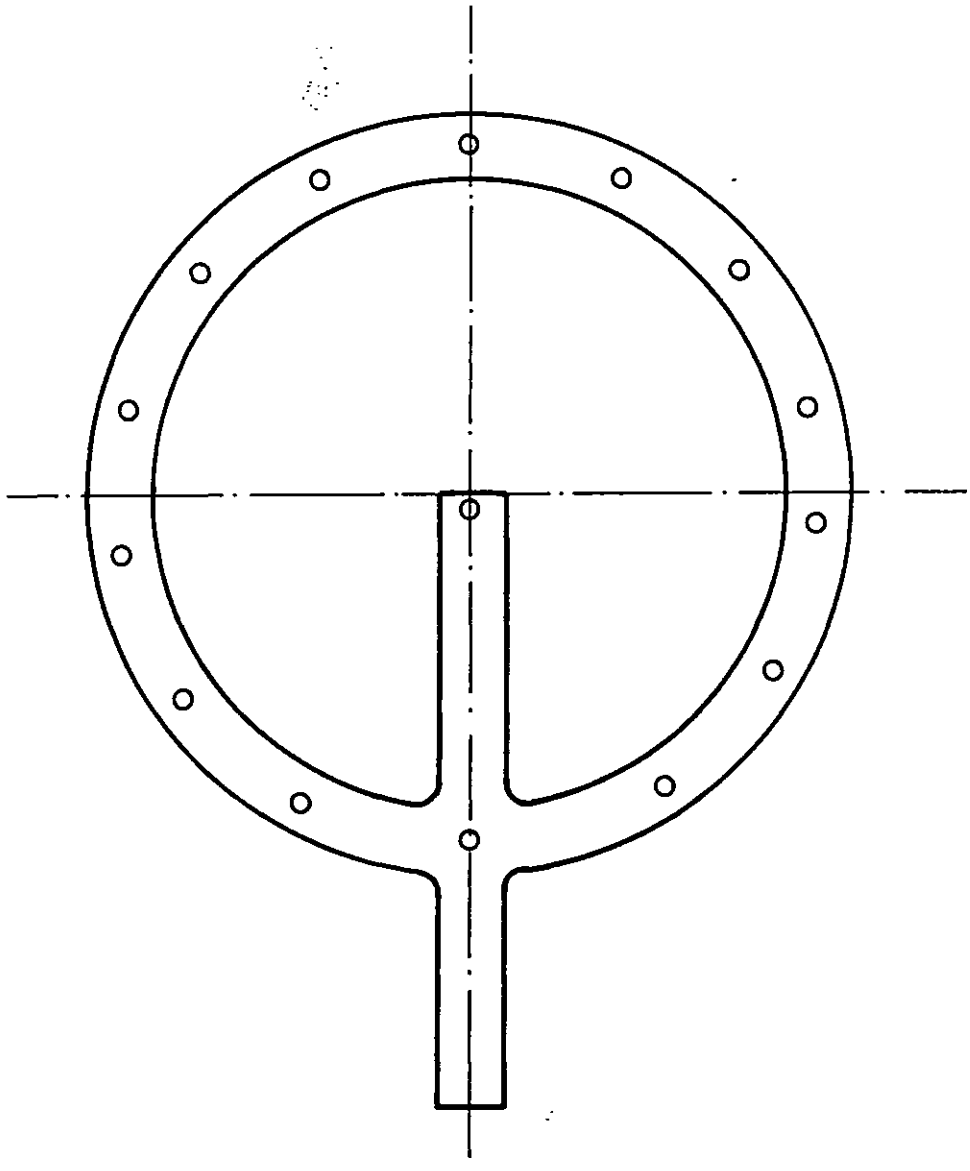


FIG. 4:3. Fuel distributing ring.

manufactured by the Mine Safety Appliances Company Ltd. The standard deviation was calculated to equal 0.26 at a propane pressure of 30 psig. Thus, although the mixing was not perfect, it was good enough for this purpose. It is worth mentioning that the mixing in a gas turbine engine between fuel and air in the combustion chamber is dependent on chamber design, airflow and fuel volatility and, therefore, fuel type and cannot be expected to be uniform. Pockets of fuel are likely to occur in the airstream, shifting the fuel/air ratio towards either the lean or the rich limit.

The propane/air mixture was allowed to stream freely out of the duct past the igniter or plasma jet. This did not present a safety hazard as the area of interest in this research is near the lean limit of propane in air and the laboratory is well ventilated and fitted with an emergency stop for the fuel feed.

4.3. Flame Detection Methods

For the fast flow velocities experienced in this research, it was anticipated that a successful initiated flame might grow, while being carried downstream by the gas flow. It was necessary to follow such growth and propagation of the flame front. The flame will be premixed as well. These two conditions would have to be taken into consideration when choosing flame detection methods. A variety of methods are available for following flame front developments. They are:

- High speed and cine-photography, using the flame's own luminosity.

- High speed and cine-photography, using an external light source and shadow or Schlieren recording.

- Spectroscopic, photometric or radiometric methods recording burnt product volume.

- Ionization probes, including saturation current measurements.

The laboratory dimensions or facilities did not permit either of the two first methods to be used. It was decided to use C_2-emission and ionization probes for detecting and following the flame front.

The propane/air mixture was ignited and the flame detected visually and graphically, using ionization probes spaced 50 cm. apart. For hydrocarbon flames, a peak of ionization occurs in the reaction zone and measuring the ionization level is a good way of detecting a flame. Lawton et.al. (1969) describes various ionization probe techniques. In these experiments, a simplified probe was used,as the main interest was not the level of ionization, just the presence of a flame. The ionization probe consisted of two nichrome wires, insulated from each other, with a separation distance of 3 mm. The voltage across the probe was 1.3 kV. The output from each probe was connected directly to a two channel storage ocsilloscope. The first ionization probe was placed 20 cm.

downstream of the igniter, followed by the second, 50 cm. further downstream.

The ionization probes used in this research were pointed and placed on an axis extending downstream from the centre of the duct exit. Occasionally, the flame would not travel straight downstream. This gives a non-response on the ocsilloscope, although there was a flame. The problem can be solved using a gauze-type ionization probe (larger area), parallel to the flow.

Initially, it was intended to use a second system for flame detection, C_2-emission. This technique relies on the presence of C_2 in the flame reaction zone. C_2-emission can be detected using a lens to focus the flame light onto a C_2-emission filter and then a photomultiplier. It was not possible to screen the photomultiplier completely from the igniter light without interfering with the fuel/air flow and the response time of the photodiod was not fast enough to react to both the ignition and flame separately.

This test facility was used for testing the standard surface discharge igniter and the pulsed plasma jet using a variety of liquids and magnetic fields, as well as testing the continuous plasma jet for a range of conditions.

CHAPTER 5

IGNITION AND FLAME HOLDING IN FAST GAS STREAMS USING PULSED IGNITERS

5.1. Introduction

In the previous chapter, the flow rig and flame detection system to be used for the ignition and flame holding experiments were described. For the intermittent ignition work, two limits for the amount of propane in air were determined. The lower, called the ignition limit, occurred when the igniter succeeded in igniting the fuel/air mixture. The flame so initiated grew while travelling downstream. The borderline cases between successful ignition and non-ignition were set at the point where the flame travelled to the second ionization probe, i.e. a distance of approximately 60 cm. Such flames were uniformly blue. The second, upper, limit was defined as that when the flame stabilized, usually on the first ionization probe. The reason for choosing two limits was that in a gas turbine engine, the initial flame kernel has to travel to a recycling zone where the fuel/air mixture is close to stoichiometric and the flow velocity lower. It was important, therefore, to achieve successful ignition, rather than flame stabilization, for these intermittent igniters. Secondly, the addition of radicals or fuel when the igniter is wetted would contribute to the initial ignition stage, rather than to the final flame stabilization. The

radical and/or fuel effect is short-lived, the arc discharge being over in 100 - 150 μs. However, it may be expected to contribute positively to the ignition limit.

The two intermittent igniters used, the surface discharge plug and the surface discharge based pulsed plasma igniter, are so closely related that their results will be presented together, their main difference being that the surface discharge igniter is flat, whereas the surface discharge based pulsed plasma jet has an orifice through which the discharge-heated gases are ejected and, therefore, the aerodynamic effects of orifice diameter and cavity size must be considered when discussing the distance the ignition kernel is projected. Although the kernel of the surface discharge igniter is also projected away from the surface, due to the IXB-force. (Bradley et.al. 1974), the aerodynamics is unlikely to be the same. FIGS. 1a and b show the outline of both these igniters.

In addition to testing the igniters when dry and when subjected to a magnetic field, the cavity or the surface, as the case may be, was wetted with different liquids, namely Avtur (a jet engine fuel), water, methanol or dichloroethane. Water was used to test the radical effect in the absence of fuel addition on the ignition limit. The spark should break the water molecule into OH- and H-radicals, both important for the propagation of a flame and ignition. Methanol and Avtur (aviation fuel) may also contribute fuel to increase the fuel/air ratio locally, in addition to increasing the radical concentration. Dichloroethane is a combustion inhibitor and

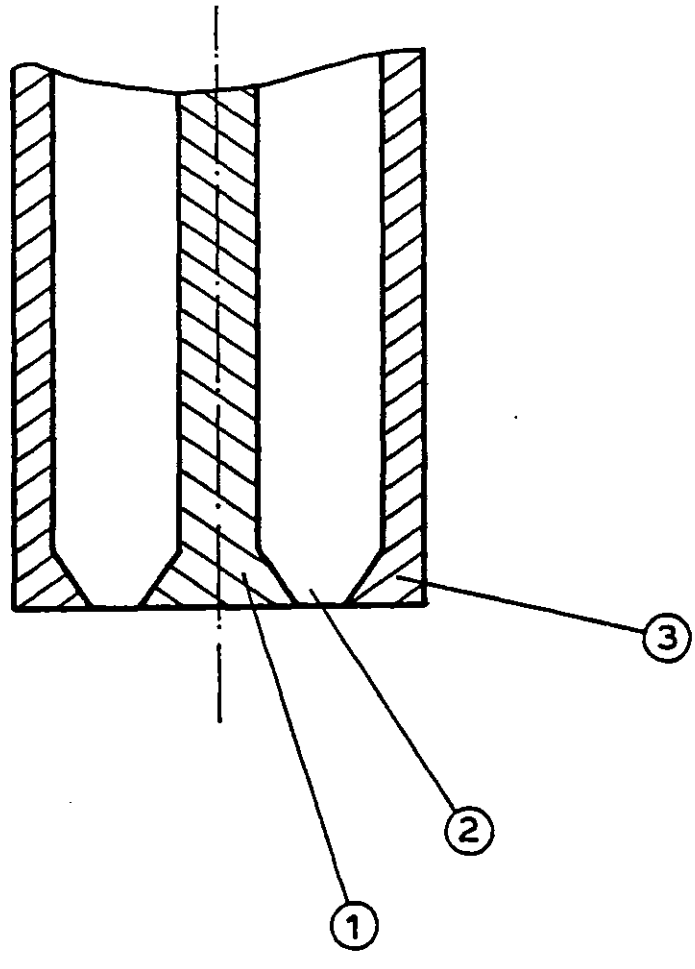


FIG. 5:1a Surface discharge igniter.

1. Centre rod electrode
2. Ceramic insulator
3. Outer cylindrical electrode

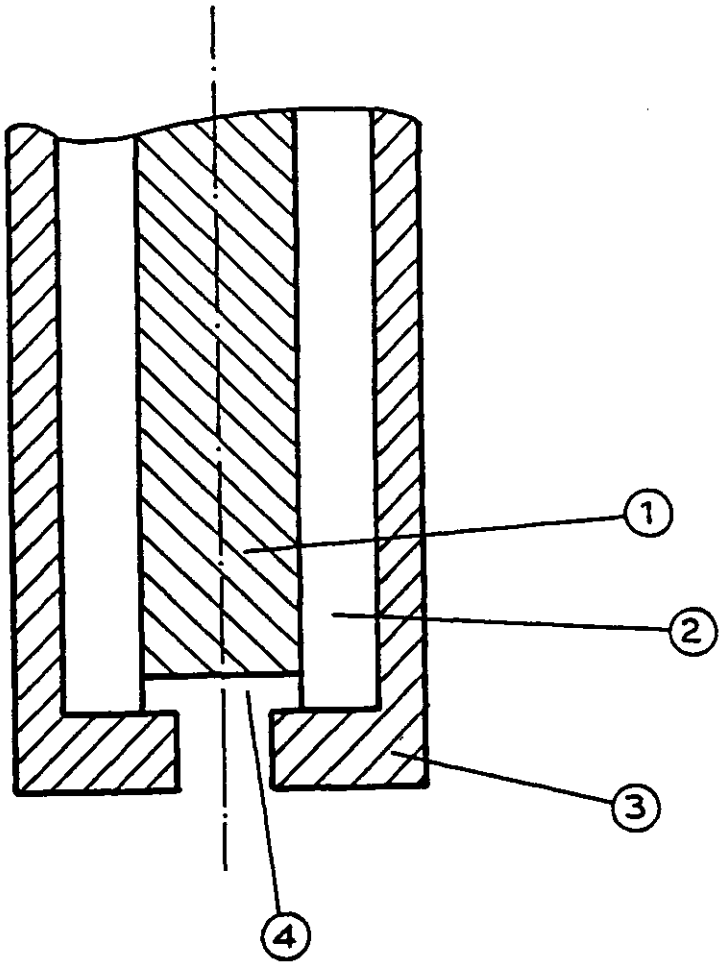


FIG. 5: 1b "Focus discharge" igniter. (surface discharge based pulsed plasma jet.) Cavity volume 14 µ l.

1. Centre rod electrode
2. Ceramic insulator
3. Outer electrode
4. Cavity (14µl)

may, therefore, be expected to prevent successful flame growth for certain fuel/air ratios.

5.2. Experimental Results

It follows from the result in Chapter 2 that adding a liquid to the surface of a surface discharge igniter will lengthen the ignition kernel and that adding a magnetic field will shorten and rotate the discharge. Similarly, early work by Smiths Industries (1979) has shown the effect on the ignition envelope using a wetted surface discharge based pulsed plasma igniter. The effect of orifice size and length has also been studied.

Effect of igniter position

Initially, the effect of changing the igniter position, using both a dry and wetted (water or Avtur) igniter of either type, was examined. TAB. 1 and FIG. 2 show these results and the igniter positions used. It is clear that the best position is in the centre of the fuel/air stream and this was used for the rest of the experimental series. The effect of the liquid extending the ignition kernel becomes apparent as the igniter position is changed. For liquid additions, the surface discharge based pulsed plasma jet performs much better than the surface discharge igniter. This may be due to the confinement by the orifice, allowing dissociation and pressure build-up in the cavity, which then ejects the plasma further into the fuel/air stream. The benefit of adding liquid is especially relevant in position 5. It was impossible to achieve ignition at this point, with either plug dry but quite easy once wetted. As was to be expected, the Avtur

	Comment	position 0		position 1		position 2		position 3		position 4		position 5		position 6	
		Ign.	fl.h.	Ign.	fl.h.	Ign.	fl.h.	Ign.	fl.h.	Ign.	fl.h.	Ign.	fl.h.	Ign.	fl.h.
Dry	Surface discharge	2.0	2.6	2.4	2.8+	2.8		3.3		3.6		no ignition		no ignition	
	pulsed plasma	2.0	2.6	2.6	3.4	3.0	3.7	3.9		3.0	3.3	no ignition		4.3	
H_2O	Surface discharge	1.9		2.2		2.4		2.5		2.5		2.6		3.1	
	pulsed plasma	1.9		1.9		2.1		2.2		2.3		2.4		2.6	
Avtur	Surface discharge	1.8		2.0		2.2		2.2		2.4		2.5		2.7	
	pulsed plasma	1.8		1.7		1.7		1.9		2.0		2.1+		2.3	

TAB. 5.1. Ignition (Ign.) and flame holding (fl.h.) for various plug positions, igniters and liquids. Energy input 12J. Air velocity 15.8 m/s.

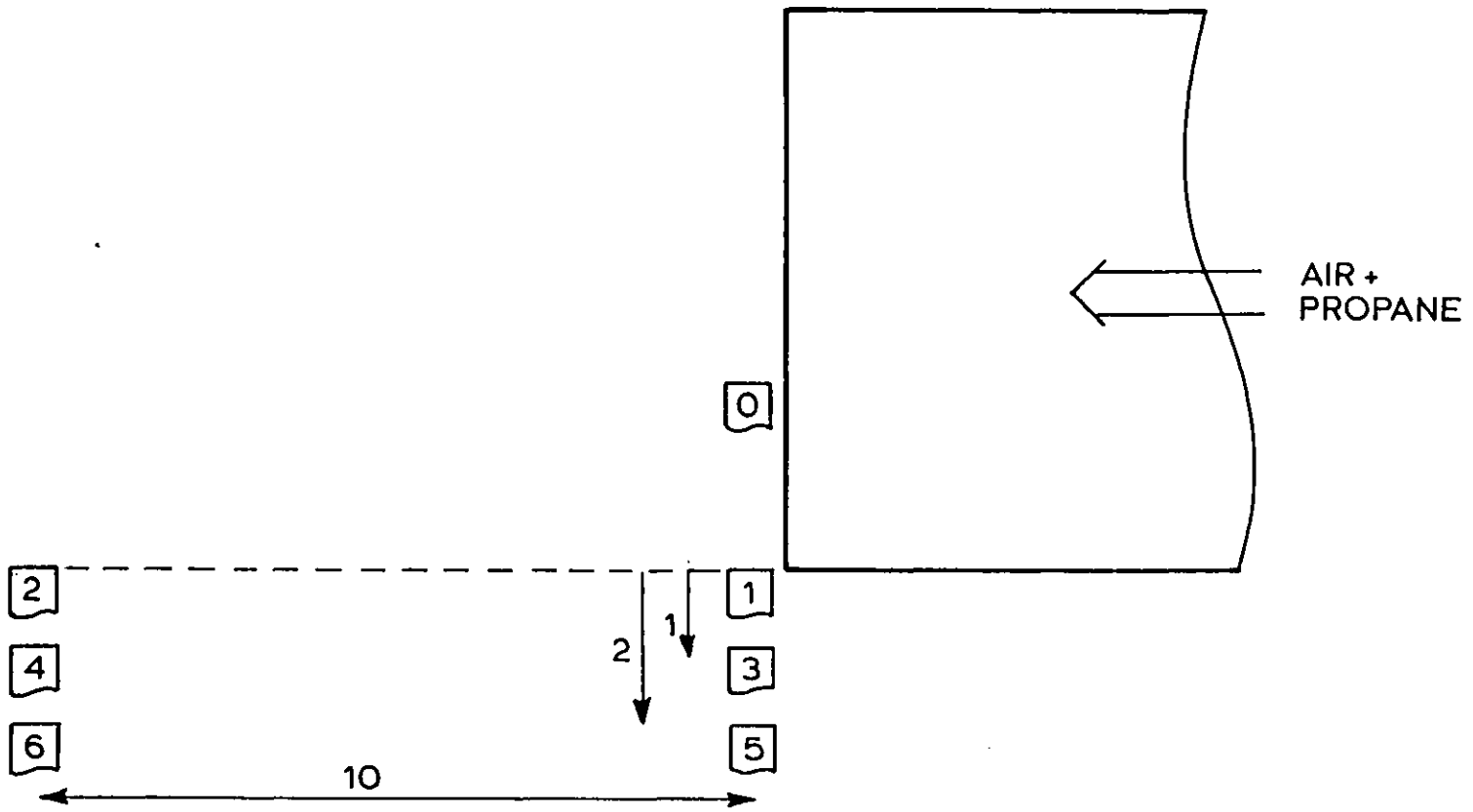


FIG. 5:2. Various igniter positions. Distances measured in centimetres.

performed better than water which, however, did better than a dry plug. The limits for wetted plugs are in some cases below the normal lean limit of flammability for propane/air.

Effect of number of firings on the remaining amount of liquid

Practical considerations for using these plugs in gas turbine engines and the initial experience of using the surface discharge based pulsed plasma igniter when wetted required the performance of the plug to be monitored for a sequence of shots. The effect of the number of firings for one wetting on the limit of propane/air was determined using the surface discharge based pulsed plasma jet. The cavity was filled with the appropriate liquid (water, dichloroethane or Avtur) and a large number of discharges fired into a propane/air stream flowing at 15 m/s. FIGS. 3, 4 and 5 show the results obtained.

The lowest value for propane in air, using a dry plug is $\emptyset$ min = 0.50. These graphs clearly show the amount of propane needed to achieve ignition decreasing. From the Avtur graph - FIG. 3 - it is clear that two effects play a role in this lowering of the fuel/air ratio. Initially, the plug expends all its energy on discharging the liquid as a droplet spray. After two shots, the surplus liquid no longer dissipates much of the discharge energy and the fuel is successfully evaporated, helping to increase the fuel/air ratio locally. This effect persists for approximately 10-20 shots. During this period, the cavity dries out slowly, though never completely, the input energy being used to break bonds in the Avtur and generating radicals. This effect persists

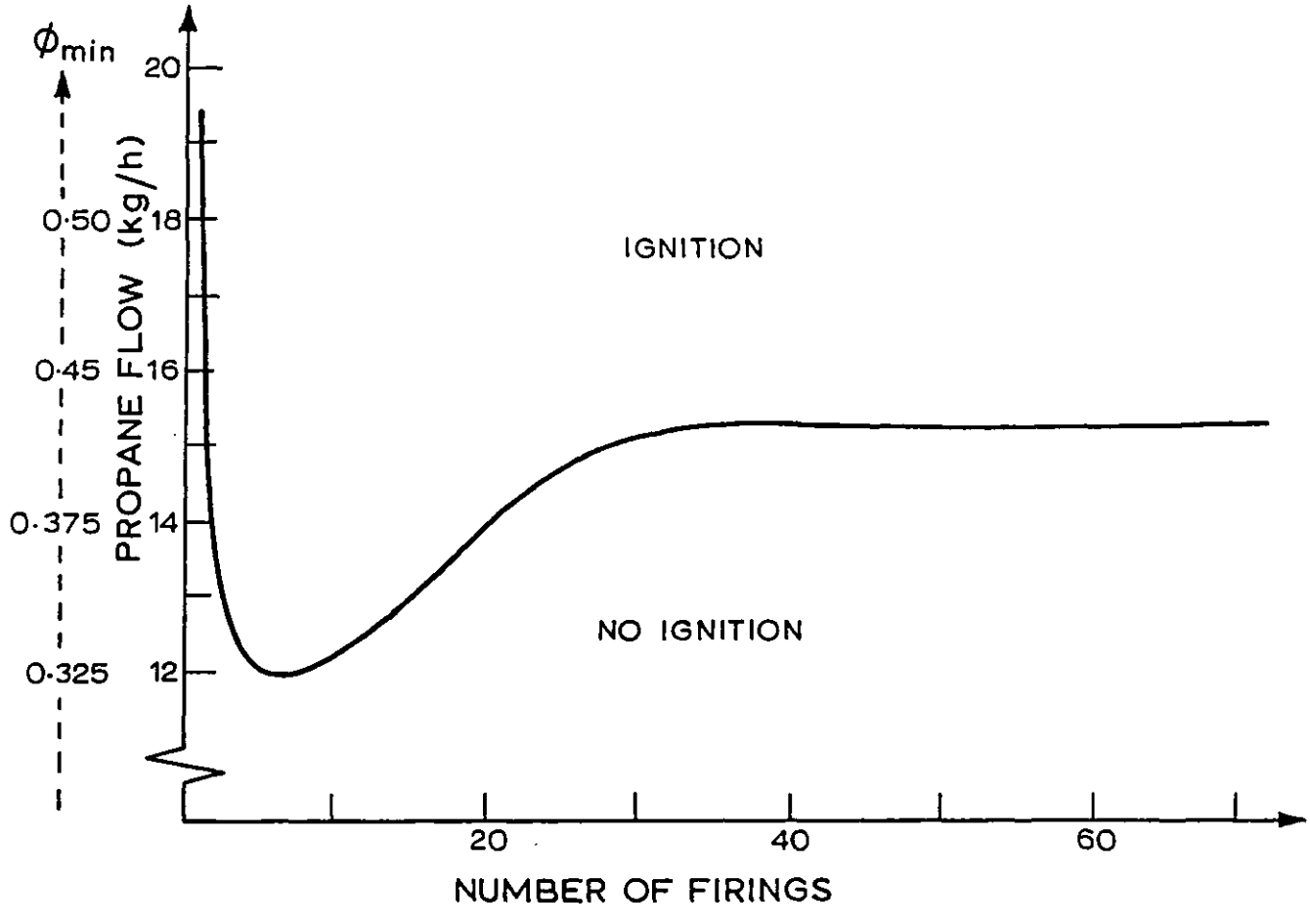


FIG. 5:3. Effect of number of firings on the amount of propane necessary to achieve ignition. Surface discharge based pulsed plasma jet wetted with Avtur. Air velocity 15.9m/s. Value for dry igniter = 18 kg/h propane.

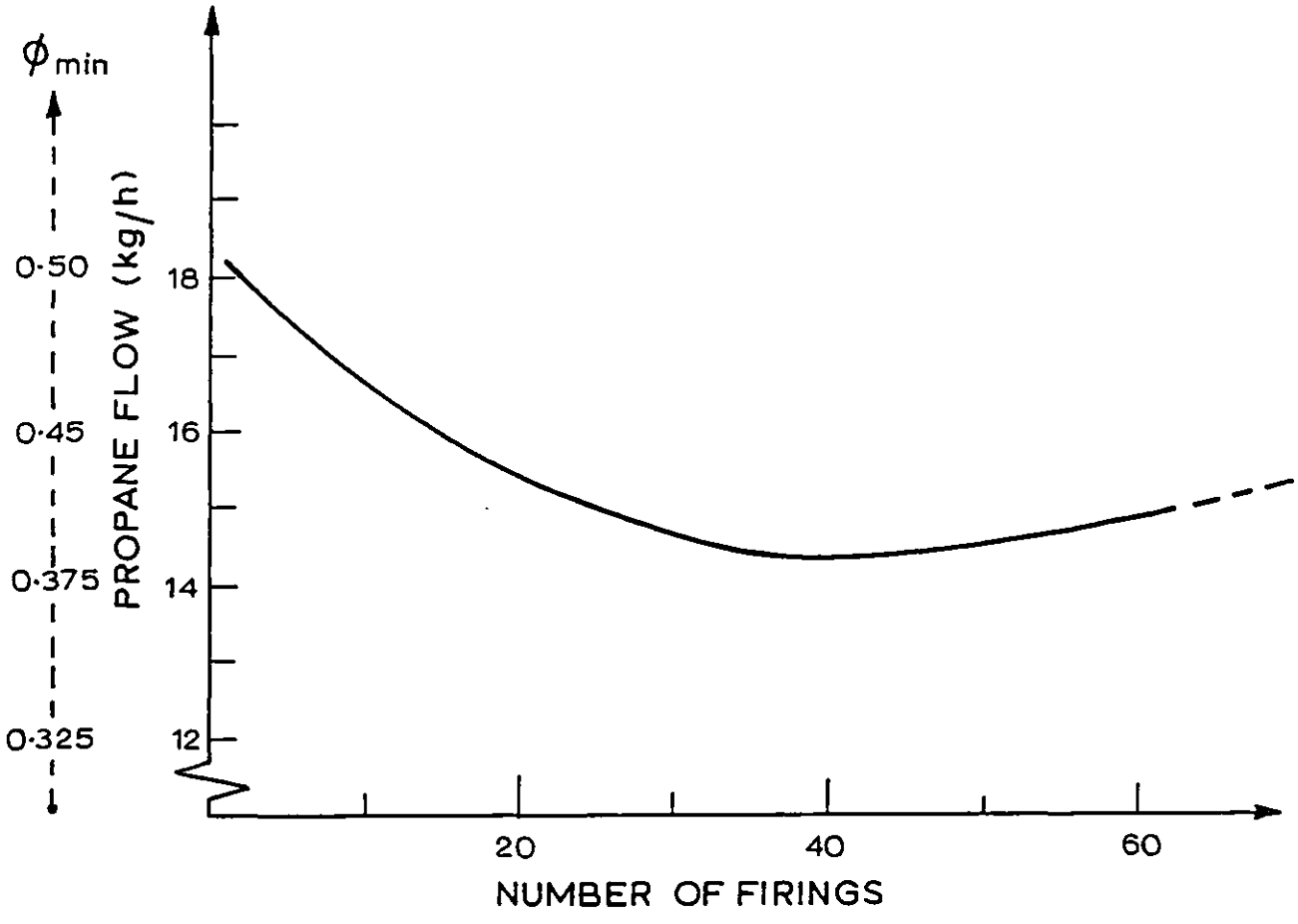


FIG. 5:4. Effect of number of firings on the amount of propane necessary to achieve ignition. Surface discharge based pulsed plasma jet wetted with water. Air velocity 15.9 m/s. Value for dry igniter = 18 kg/h propane.

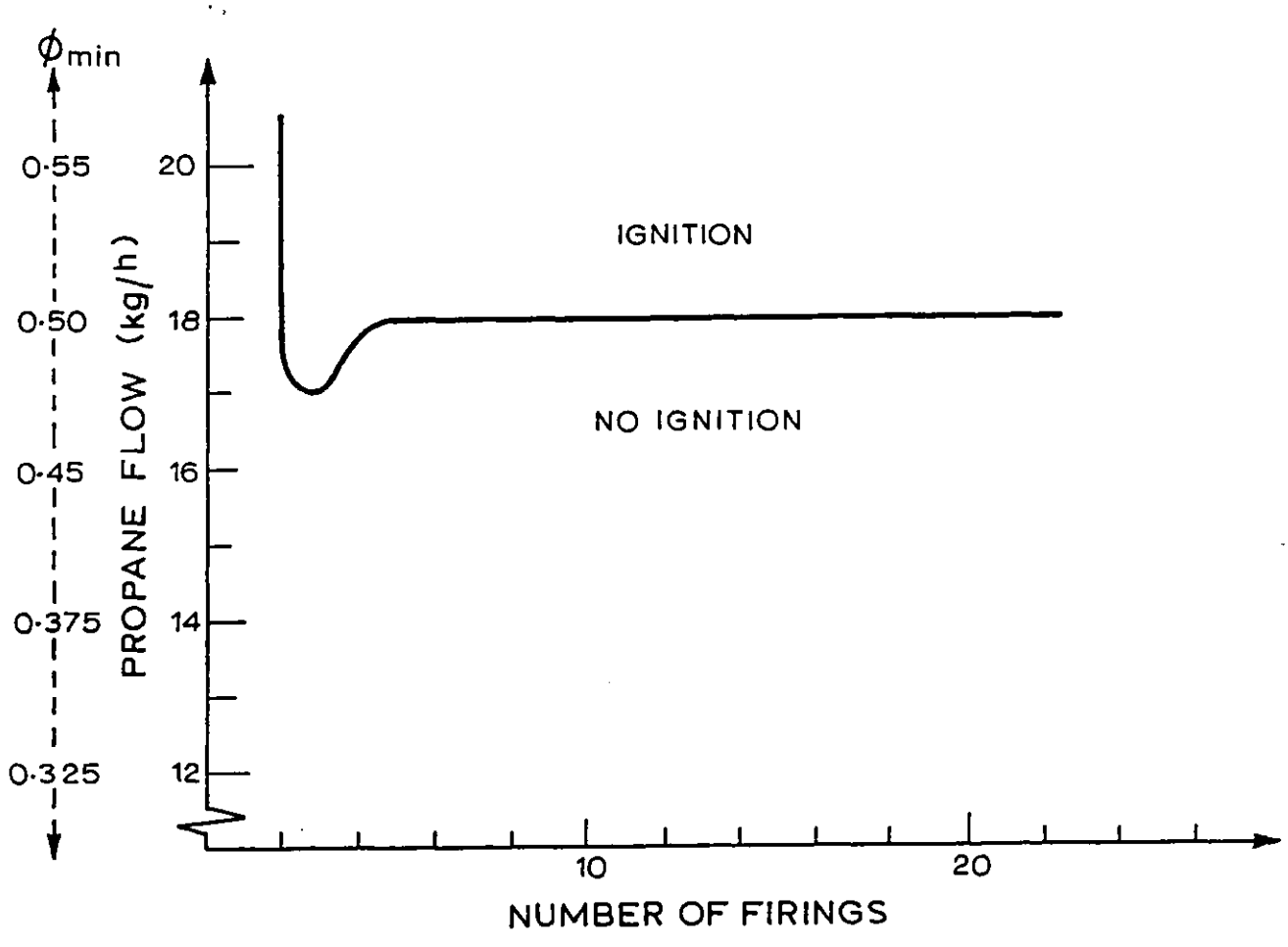


FIG. 5:5. Effect of number of firings on the amount of propane needed to achieve ignition. Surface discharge based pulsed plasma jet wetted with dichloroethane. Air velocity 15.9 m/s. Value for dry igniter = 18kg/h propane.

for over 200 shots at limits well below the fuel/air ratio achieved for a dry plug; Ø min = 0.45, as compared with 0.50. Avtur is an oil-based fuel and it is plausible to suppose that the oil has soaked into the ceramic and gradually evaporates during each discharge. On the basis of this curve, it was decided to use the value of Ømin = 0.45 for the following experiments. It was deemed necessary to use a value of Ø for propane, such that ignition would persist for over 50 shots. This allows the radicals generated to play a part in the ignition.

Water exhibits quite different properties, FIG. 4. Firstly, it is not a fuel, so that any lowering of the ignition value must be due to radicals,such as OH and H, formed in the discharge. Secondly, it is commonly used as a flame retardant, albeit in large quantities. Initially, just as for Avtur, the plug expends most of its energy on discharging the excess water as a droplet spray, before it starts igniting eventually. When ignition occurs, it depends on the propane/air ratio. The lower the amount of propane, the more firings are needed to achieve ignition, until eventually a limit is reached. As the number of shots increases, the possibility of achieving ignition declines to 50% and then 25%. However, for a Ømin value of 0.45, corresponding to the one achieved for Avtur, 90 shots are needed before ignition fails completely. Experimentally, a slightly higher Ømin value is desirable to achieve successive ignition for more than 15 to 20 shots.

Finally, dichloroethane showed the same initial droplet spray

as the two previous liquids, FIG. 5. Apart from this, the effect is to stop flame propagation after another two shots, except for one case where the Ømin is actually lowered below the value for a dry plug. However, this effect only persisted for two shots, presumably due to the bond breakage forming both CH- and Cl-radicals. Part of the molecule is a fuel. The value of Ømin for dichloroethane was chosen to achieve at least 20 successive shots.

Effect of air velocity on ignition by dry and wetted igniters

Varying the air velocity from 10 to 30 m/s while establishing the leanest fuel/air ratio for each and for the two types of igniter gave the results shown in FIGS. 6 and 7. For each igniter, dry or wetted with either water, methanol, dichloroethane or Avtur, the two limits of ignition and flame holding (as described in the Introduction) were determined. The values for the fuel/air ratio for each liquid were established using the criteria discussed in the previous section.

As was to be expected, the effect of wetting the plugs made no difference at all to the fuel/air ratio for flame holding. The radicals generated in the spark are far too short-lived to contribute to sustained flame stability for appreciable periods of time.

The ignition criteria yields the information that addition of any liquid, except dichloroethane, will lower the fuel/air ratio by varying amounts. Water,not being a fuel, can only contribute radicals, such as OH and H, and no heat of

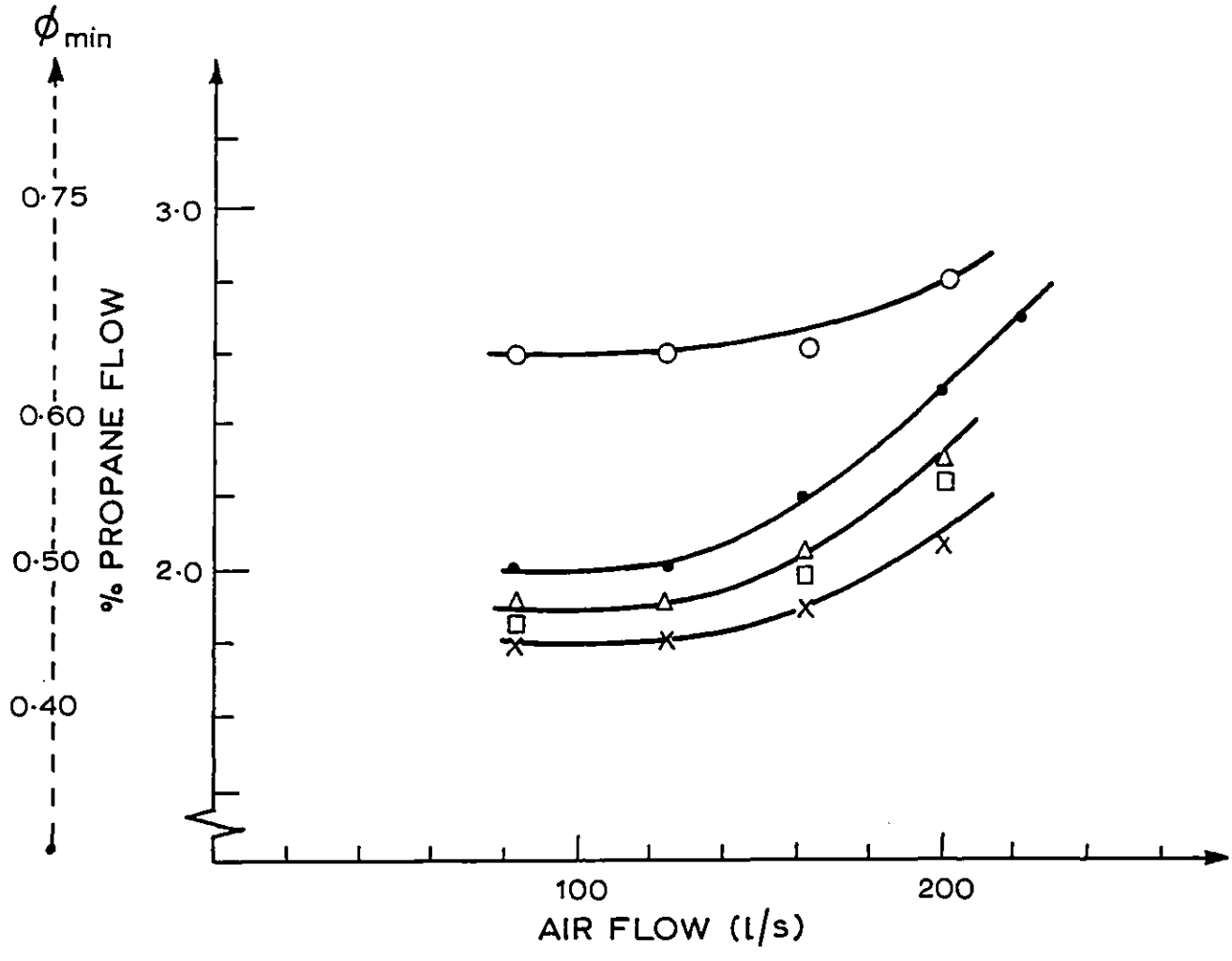


FIG. 5:6. Amount of propane necessary to achieve ignition and flame holding as a function of air flow. Surface discharge igniter. (12J).

• dry
△ wetted with water
□ wetted with methanol
x wetted with Avtur
o flame holding

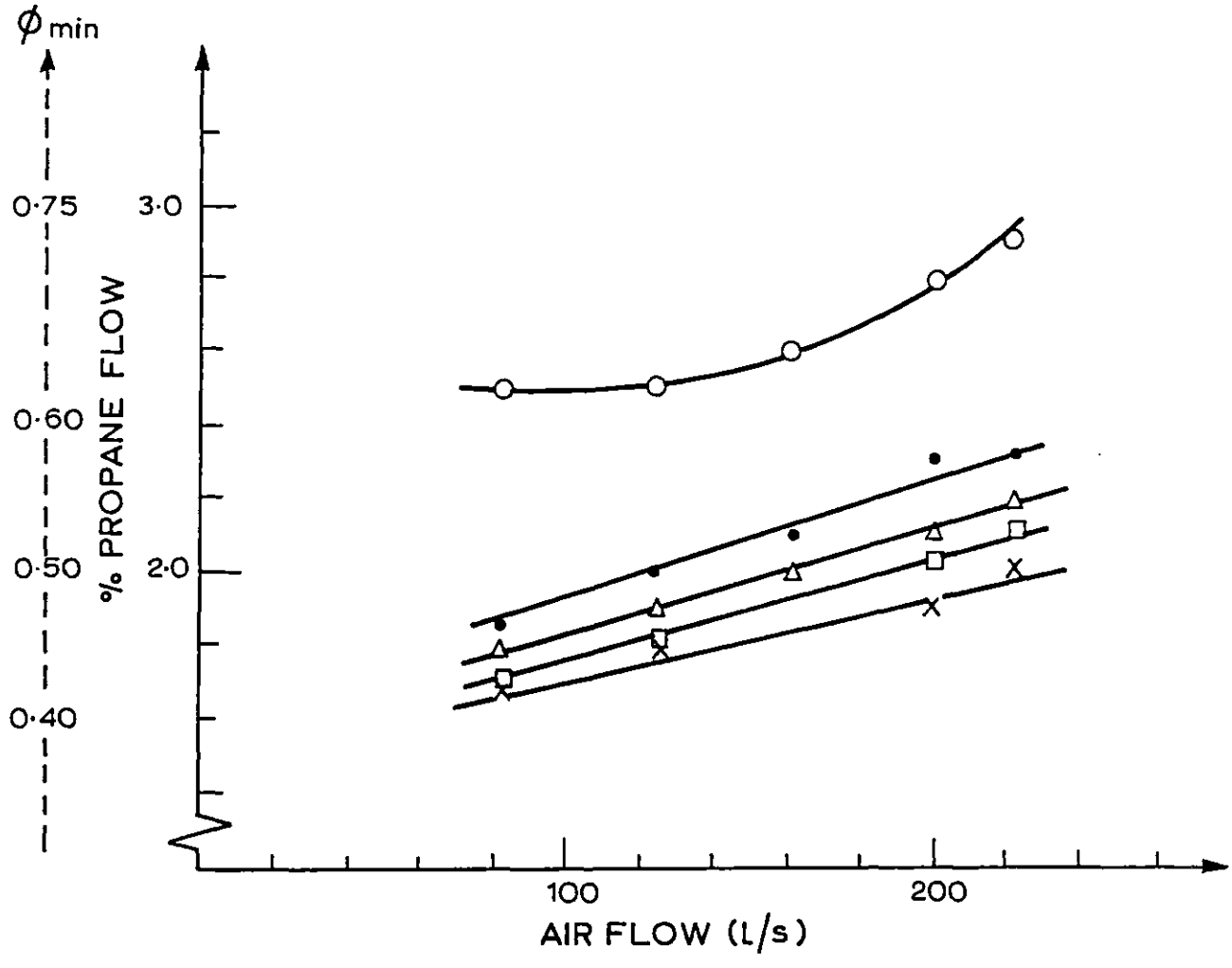


FIG. 5:7. Amount of propane necessary to achieve ignition and flame holding as a function of air flow. Surface discharge based pulsed plasma jet. (12J)

• dry
Δ wetted with water
□ wetted with methanol
x wetted with Avtur
o flame holding

combustion. Even so, the fuel/air ratio is lower than the limit for a dry plug. Although methanol is a fuel, the values for the fuel/air ratios were not determined until the fuel effect had worn off and the radical effect had taken over. Compare FIG. 3 for Avtur; all but a trace having been driven off by repeated discharges. However, for methanol, the possible radicals formed are increased to include active species, such as CH_3;H; CH· and OH: Which radicals are formed depend on energy transfer to the molecules and the bond energies involved. The value for methanol falls slightly below the value for water. As Avtur consists of higher hydrocarbons, a greater variety of hydrocarbon radicals may be formed. The limiting fuel/air ratio for Avtur wetted plugs is the lowest.

There is a marked difference between the two plugs. The surface discharge based pulsed plasma igniter performs better than the surface discharge igniter for the whole range of air velocities, whether dry or wetted. The pressure build-up in the cavity ejects the plasma further into the fuel/air stream. This also applies when the plug is dry. At high air velocities, the liquid applied to the surface discharge plug tends to blow off and the plug surface to dry out. A Reynolds number calculation reveals that the flow is turbulent for all flow velocities used.

$$Re = \frac{L.V}{\eta} \cdot \rho$$

L = characteristic length
V = fluid velocity
ρ = density
η = viscosity.

TAB. 2 shows the values obtained for this flow system.

Air Velocity (m/s)	Reynolds number x 10^4
5	3.76
10	7.53
15	11.29
20	15.06
25	18.83
30	22.59

TAB. 5.2. Reynolds number calculation for various air velocities. Smiths Industries flow rig with a diameter of 10cm.

Effect of magnetic field on dry and wetted igniters

From the conclusions of Chapter 2, it is clear that adding a magnetic field to the surface discharge igniter will shorten and rotate the spark kernel. This effect will diminish when a liquid is applied. The effect of a magnetic field applied to a surface discharge igniter on the fuel/air ratio necessary to obtain ignition was tested on the flow rig, using an air velocity of 10 m/s. The magnetic field was 1300 Gauss and applied as shown in FIG. 8. TAB. 3 lists the results obtained. As suggested in Chapter 2, the use of a magnetic field might have two effects. The rotation of the spark might lessen the erosion of the semi-conduction layer, extending the life of the igniter and the shortening of the spark kernel may increase the fuel/air ratio required to ignite and hold the flame. The use of liquid wetting will eventually remove this latter effect. However, only Avtur will completely overcome the effect of the kernel shortening and achieve a fuel/air ratio close to that obtained for a wetted igniter without a magnetic field. The vortex observed in Chapter 2 has apparently not enough energy to entrain the fuel/air mixture closer to the spark kernel.

Effect of varying the spark gap

The effect of the orifice diameter and length on the surface discharge based pulsed plasma jet performance has been studied at Smiths Industries (1979) and showed a length of 2.5mm and a diameter of 3mm to be the most successful. Initial experiments on the flow rig supported this conclusion and this configuration was, therefore, used. For the surface

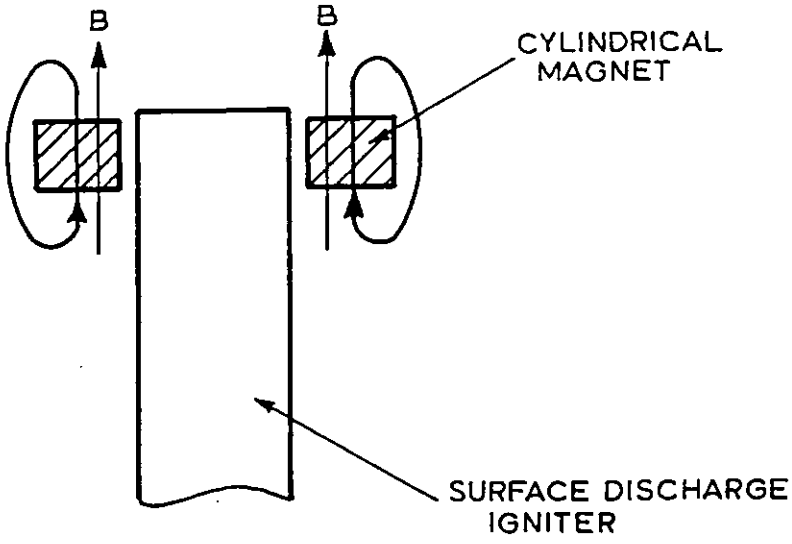


FIG. 5:8. The way a magnetic field was applied to the surface discharge igniter.

	% propane		Ø	
	Ign.	fl.h.	Ign.	fl.h.
NO magnetic field				
dry	2.0	2.6	0.50	0.65
water	1.9		0.48	
methanol	1.8+		0.45+	
Avtur	1.8		0.45	
1300 Gauss field				
dry	2.2	2.7	0.55	0.68
water	2.0		0.50	
methanol	2.0		0.50	
Avtur	1.9		0.48	

TAB. 5.3. Influence of a magnetic field on ignition (Ign.) and flame holding (fl.h) capabilities of a surface discharge igniter.
Input energy 12J. Air velocity 10.4 m/s.

discharge igniter, it is to be expected that the amount of energy released is affected by the electrode gap. TAB. 4 shows the result for two spark gaps, 1.52 and 1.27 mm., for a surface discharge igniter when dry and wetted. For a dry igniter, the difference in fuel/air ratio is marginal and within the error range of the fuel/air composition. However, when liquid is added, the ratio becomes appreciably different.

Effect of energy input

All previous results were for an energy input of 12J. One would expect a lowering of the energy input to affect the fuel/air ratio needed to achieve ignition. The effect of decreasing the energy input to a wetted plug would be to decrease the amount of liquid vaporized and, consequently, to increase the fuel/air ratio. TAB. 5 lists the results for a surface discharge igniter, using 6J and 12J. As the energy is decreased, the amount of propane necessary to obtain ignition is increased. For the surface discharge based pulsed plasma jet, the effect of a dry plug and one wetted with Avtur is illustrated in FIG. 9. The difference between a dry and an Avtur wetted plug increases as the input energy increases. It is, therefore, possible to deduce that a large proportion of the input energy is used for evaporating the liquid and generating radicals from the vapour. Mention should be made of the investigation by Mak (1979) showing that of a 12J discharge, only about 8%, i.e. 0.86J reaches the gas. For a 3J discharge, the corresponding figures are .9% and 0.26J.

Thus, for a lower energy input a large proportion of the energy reaches the gas. Even so, FIG. 9 shows that the

	% propane		Ø	
	Ign.	fl.h.	Ign.	fl.h.
gap = 1.27 mm.				
dry	2.0	2.6	0.50	0.65
water	1.9		0.48	
Avtur	1.8		0.45	
gap = 1.52 mm.				
dry	1.9+	2.5+	0.48+	0.63+
water	1.8		0.45	
Avtur	1.7		0.42	

TAB. 5.4. Influence of spark gap on ignition (Ign.) and flame holding (fl.h.) capabilities of a surface discharge plug.
Input energy 12J. Air velocity = 15.8m/s.

	% propane		Ø	
	Ign.	fl.h.	Ign.	fl.h.
Input 12J				
dry	2.0	2.6	0.50	0.65
water	1.9		0.48	
Avtur	1.8		0.45	
Input 6J				
dry	2.1	2.6	0.53	0.65
water	1.9+		0.48+	
Avtur	1.8+		0.45+	

TAB. 5.5. Influence of energy input on ignition (Ign.) and flame holding (fl.h.) capabilities of a surface discharge plug. Spark gap 1.27mm. Air velocity 15.8m/s

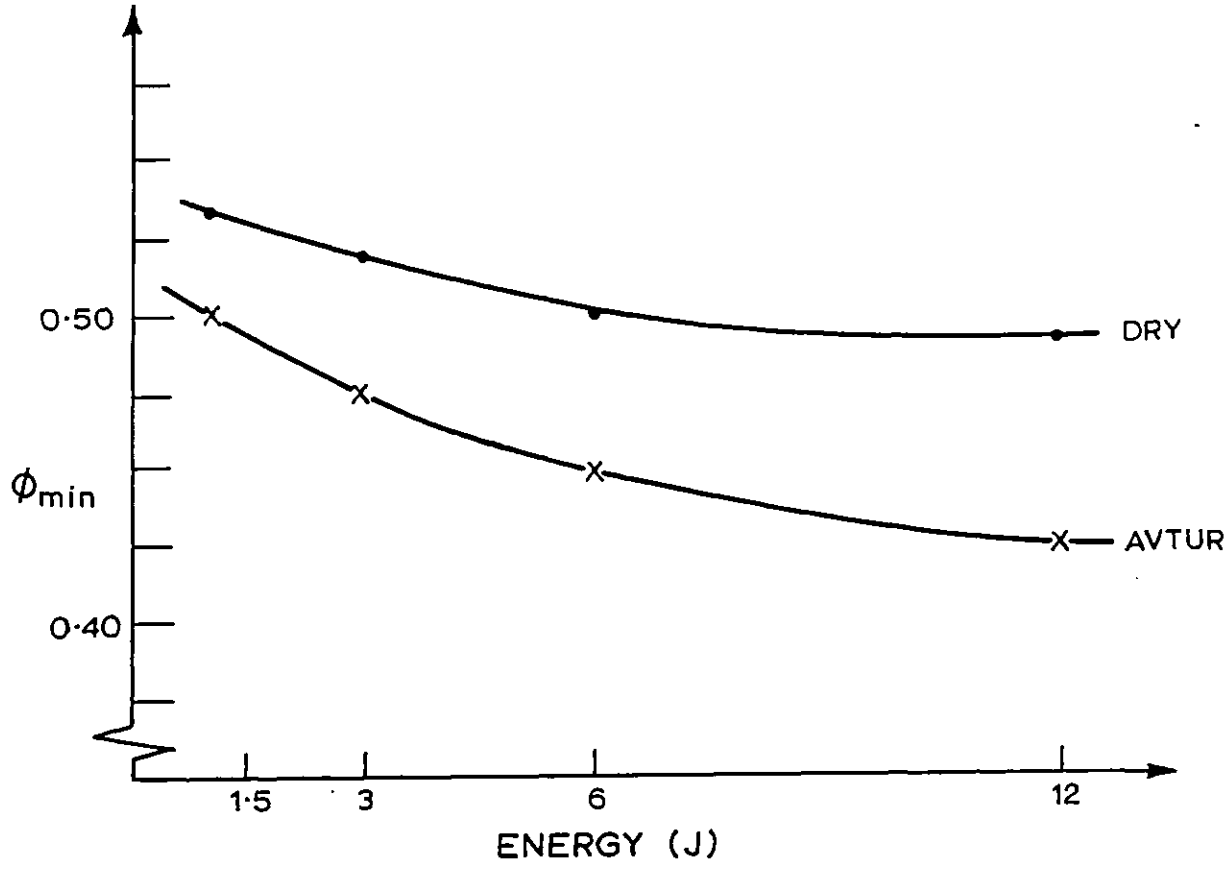


FIG. 5:9. Effect of energy input on the amount of propane needed to achieve ignition for the surface discharge based pulsed plasma jet.

larger the energy input, the better, although the difference between 12J and 6J is not large for a dry plug.

5.3 Discussion and Conclusions

Chemical effects (radicals and any fuel value of the plasma medium) and aerodynamic effects (momentum - i.e. kernel throw and turbulence) must be taken into consideration when discussing the effect these two igniters have on the ignition of a fast flowing fuel/air mixture. The practical conclusions of this research are also worth stressing, since it is hoped that a practical device will ultimately emerge from this work. For the surface discharge igniter, the main effects are chemical. For the surface discharge based pulsed plasma jet, both effects are important. The chemical effect will be considered first.

The effects of radical generation are well-known in plasma work. Weinberg et.al. (1978), Orrin et.al. (1980) demonstrated the effect of radicals on the flame growth and the extension of flammability limits, using a pulsed plasma plug similar to that of an internal combustion engine plug. They found that, for very lean mixtures, the larger the hydrogen content in the gaseous feed to the plasma plug, the faster the flame growth. Smiths Industries (1979) found an extended ignition envelope when using an igniter wetted with different liquids. Grant et.al. (1983) also report effects of radicals, whether initially in gaseous,liquid form or from a solid state source, on the limit of flammability. These investigations were done for stagnant mixtures. No demonstration has been found of the success of water as a radical source. Although it might be possible to arrange an igniter in a gas turbine, such

that water would condense on it or feed water to it, the use of water as a radical source is of more academic than practical interest. However, the results for water are of interest as it is possible to deduce that the decrease in the flammability limit for plugs wetted with water has to be due to radicals exclusively. Water cannot act as a fuel and it is more commonly used as a retardant. The OH and H radicals generated when splitting water molecules are of importance in the initiation stages of combustion. Lewis and von Elbe (1961) use the OH-radical to explain chain reaction and, particularly, the initiation of a chain reaction, taking place in hydrogen/oxygen reactions and hydrocarbon/oxygen reactions.

The effect of methanol and Avtur on the flammability limit is more complex, due to both liquids being fuels in their own right. From the graphs of number of firings for one wetting against fuel/air ratio it is clear that there is a fuel effect, a radical effect and, therefore, a combination of the two. The breaking of bonds in a hydrocarbon molecule requires differing amounts of energy, depending on the bond order and its location in the molecule. It is reasonable to assume that, for the first few firings, the fuel wetted plug uses most of its energy in ejecting the liquid from the cavity. Eventually, so little fuel is left that some of the energy remains available to break bonds and generate radicals. The radicals so generated will help propagate the chain reaction between propane and air, especially in the initiation stage. The cavity of a surface discharge based pulsed plasma jet has a volume of 14.7 µl. From the number of firings

required, it is clear that for Avtur even 200 shots do not succeed in drying the plug out. At this stage, so little liquid is left that radicals are generated from extremely small amounts of liquid, probably trapped in the semi-conducting ceramic. Very little fuel is necessary to achieve lowering of the ignition limit. This is thought to be due to the heavier fuel fractions and may be very important in practice.

Several methods of wetting the plug are possible. The plug can be subjected to occasional external fuel sprays from the fuel nozzle in the combustion chamber. Internal fuel feed through the plug is also a possibility. The use of some form of solid fuel (e.g. metal hydrides, Grant et. al., 1983) inside the cavity can also be envisaged. It would be necessary for a solid fuel supply to last between services on the gas turbine engine and, therefore, between replacements of igniters.

It is concluded that the effect of radicals on the ignition of a fast flowing fuel/air mixture is very significant and could be of great practical importance.

The aerodynamic effect of the design of a plasma cavity has been demonstrated and discussed by Orrin et. al. (1980), Cetegen et. al. (1980), Grant et. al. (1983). They found that the effect of pressure build-up inside a cavity and the subsequent ejection through a small nozzle was of importance in projection of the plasma plume and in the flame growth velocity. The orifice diameter must be such as to achieve maximum plume

length, whilst not quenching the radicals formed. For the surface discharge based pulsed plasma jet, this diameter was optimised at 3mm. The study on igniter position shows that the plasma kernel for a surface discharge based pulsed plasma jet is ejected much further while retaining sufficient energy to ignite than for a surface discharge plug. The spark kernel on a surface discharge plug is ejected away from the surface, due to the JXB force. Ahead of the spark kernel, there is a shockwave, Bradley et. al. (1974). Bradley (1977) has suggested that if the energy released is greater than 1J, the shockwave may raise the local temperature sufficiently to initiate combustion. However, it is expected that the shockwave formed when using a pulsed plasma plug should travel faster than the one associated with the surface discharge plug. The surface discharge based pulsed plasma igniter is more effective from the aerodynamic point of view than the surface discharge igniter.

Combining the two effects will give a most effective tool for achieving successful ignition. The surface discharge based pulsed plasma igniter, although similar to the surface discharge plug in design, offers the best potential for ignition. The plug should be wetted with a radical generating source; though water has been shown to improve the efficiency, it would be best, from a practical point of view, to use a heavy fuel. Avtur is favoured by its ready availability in a jet engine.

It is suggested that the surface discharge based pulsed plasma jet, fueled with Avtur, should be tested against a surface

discharge plug in a gas turbine engine. A solid fuel, such as a suitable metal hydride or a hydrocarbon vax, should be tested using a surface discharge based pulsed plasma jet and the present flow rig.

CHAPTER 6

FLAME HOLDING IN FAST GAS STREAMS USING CONTINUOUS PLASMA JETS

6.1. Introduction

The benefit of using perfectly stirred continuous magnetically rotated plasma jets for augmenting combustion rates and stabilizing flames was demonstrated by Harrison et.al. (1971). They found that, in a highly stirred system, an addition of 10% electrical power increased the throughput by almost 700% with nitrogen in the carrier gas, in spite of the inefficiency of the plasma jet. This compares with less than 100% to be expected from a perfectly stirred system. Although the effect of pure argon might be expected to be that of an inert diluent. It is clear from their results that argon increases the flame stability. The improvement in flame stability in supersonic air streams using plasma jets was demonstrated by Kimura et.al. (1981). They concluded that a nitrogen plasma is more effective than a hydrogen plasma in promoting combustion and stabilizing flames, when they took energy input into consideration.

The usual method of stabilizing flames in fast flowing turbulent gas streams is to use some form of bluff body. When an obstruction is placed in a gas stream, vortices are formed on the downstream side of the object. If the stream consists of a fuel/air mixture that is ignited, the flame so formed, which

would otherwise be carried away, often attaches itself to the eddy region behind the obstruction. The mechanism of flame stabilization on and flame propagation from bluff object in homogeneous mixtures of gaseous fuel and air flowing in a duct of constant cross-section was studied by Williams et. al. (1948). They found that varying the diameter and the type of stabilizer made no difference to the limit, except for very lean and very rich mixtures. This indicates that no vortex trail is shed from the stabilizer during combustion. They concluded that the effective flame velocity is increased over the laminar flame velocity by three different types of disturbances:

1. Turbulence due to velocity gradients across the flame front produced by the pressure drop resulting from the combustion process itself.

2. Turbulence generated in the region just downstream of the flame stabilizer by velocity gradients across the flame front.

3. Approach-stream turbulence; this effect is small.

Williams et.al. (1948) also stated that heating or cooling the stabilizer greatly influences the stability limits; heating extends them, cooling narrows them. Increasing turbulence intensity decreases the stability limits. Hottel et.al. (1952) used a liquid fuel for studying bluff body flame stabilization and found that:

1. Increasing velocity reduces the lean limit air/fuel ratio at blow out for gaseous fuels but increases it for liquid sprays.

2. With gaseous fuel, adding heat permits stable burning at leaner mixtures. With fuel sprays, added heat will eventually cause the flame to be extinguished.

3. The range of fuel/air ratios over which stable flames may be obtained in burning liquid sprays is very much wider than with gaseous fuel.

For liquid spray, the fuel/air ratio in the eddy region after the flame stabilizer is not necessarily the same as in the approach stream. This occurs because liquid fuel is collected by impingement on the obstacle and subsequently vaporized and mixed into the eddy zone, thereby increasing the fuel/air ratio. The collection of liquid fuel serves to limit the temperature of the obstacle, except when the lean limit blow out is approached. Very little or no liquid is collected on the bluff body, resulting in rapid temperature rise, increasing the heat transfer so the liquid starts to boil, forming a vapour film insulating further impinging liquid drops from heat transfer. The rod dries out and the flame extinguishes. Increasing the approach stream velocity increases the heat transfer from the flame, leading to larger evaporation rates for the fuel collected on the rod. Increased velocity also results in large quantities of fuel being deposited on the bluff body, so preventing the temperature from rising.

Moen et.al. (1980), using a range of obstacles placed in the way of a freely expanding cylindrical flame, found that flame speeds of up to 130 m/s could be achieved in stoichiometric methane/air. That is approximately 24 times the flame speed without obstacles. They also showed that this increased flame

speed could only be maintained by a sequence of obstacles extending throughout their reaction chamber.

The bluff body effects are of relevance to the present research, not only because it offers an alternative method of flame stabilization, but also because the body of the continuous plasma jet would inevitably also act as a bluff body when placed in the fuel/air stream.

The experimental system for the mixing of fuel/air is as described in Chapter 4. For this sequence of experiments, the use of flame detection methods proved unnecessary since the stabilized flames were clearly visible. The small aerodynamically spun plasma jet with a 1.5 mm diameter anode channel and a 45^{o} angle cut off cathode, FIG. 1, was used throughout.

A single phase rectified power supply, FIG. 2, was built for the continuous plasma jet, to be used at the Smiths Industries facility. This required capacitance smoothing to obtain a stable output and a bank of capacitors was, therefore, fitted. The ripple voltage was subsequently measured and turned out to be 2% of the input voltage. However, when the power supply was initially used, it would not stabilize the nitrogen arc. Argon presented no stability problem.

This power supply differed in various respects from that used at Imperial College and further investigation revealed that the protection coils, fitted on the output to the plasma jet, in the Imperial College unit,designed for a three phase supply,

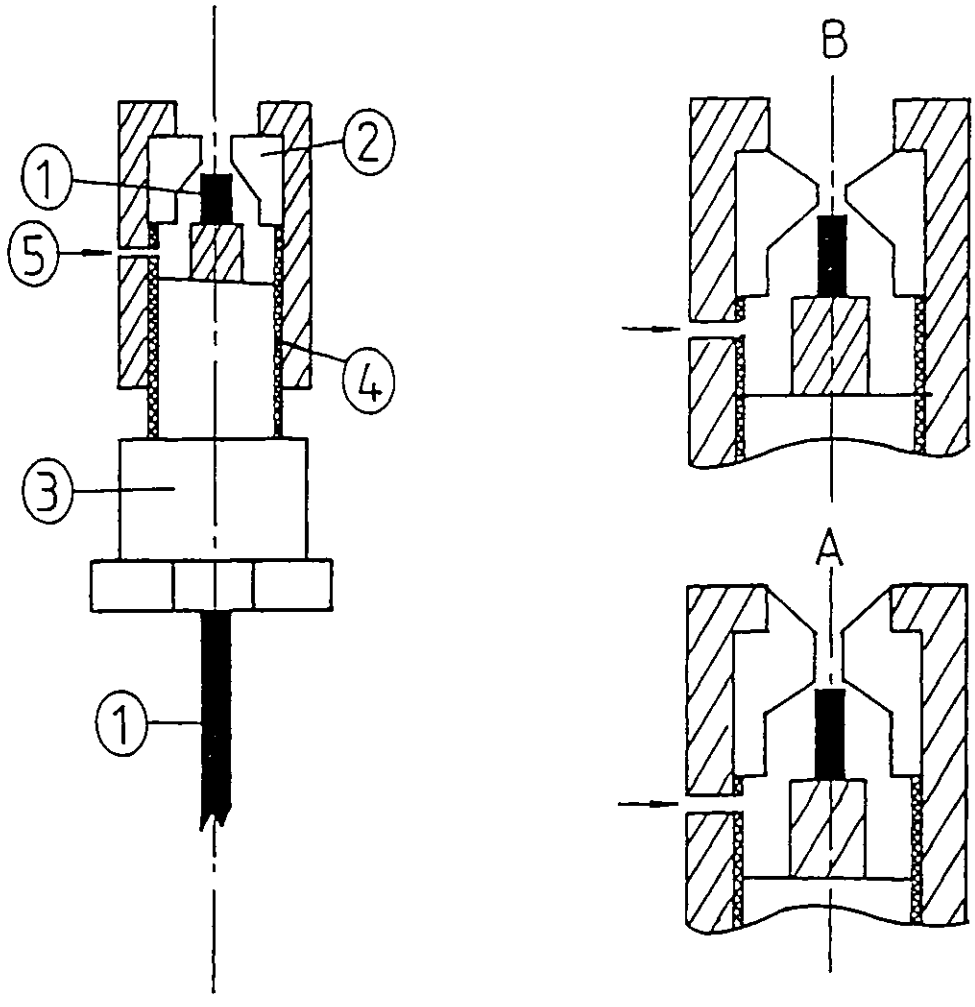


FIG. 6 :1. Initial aerodynamically spun plasma jet, various anode configurations.

1. Cathode
2. Anode
3. Spark plug body
4. Fine thread for gap adjustment
5. Tangential gas inlet

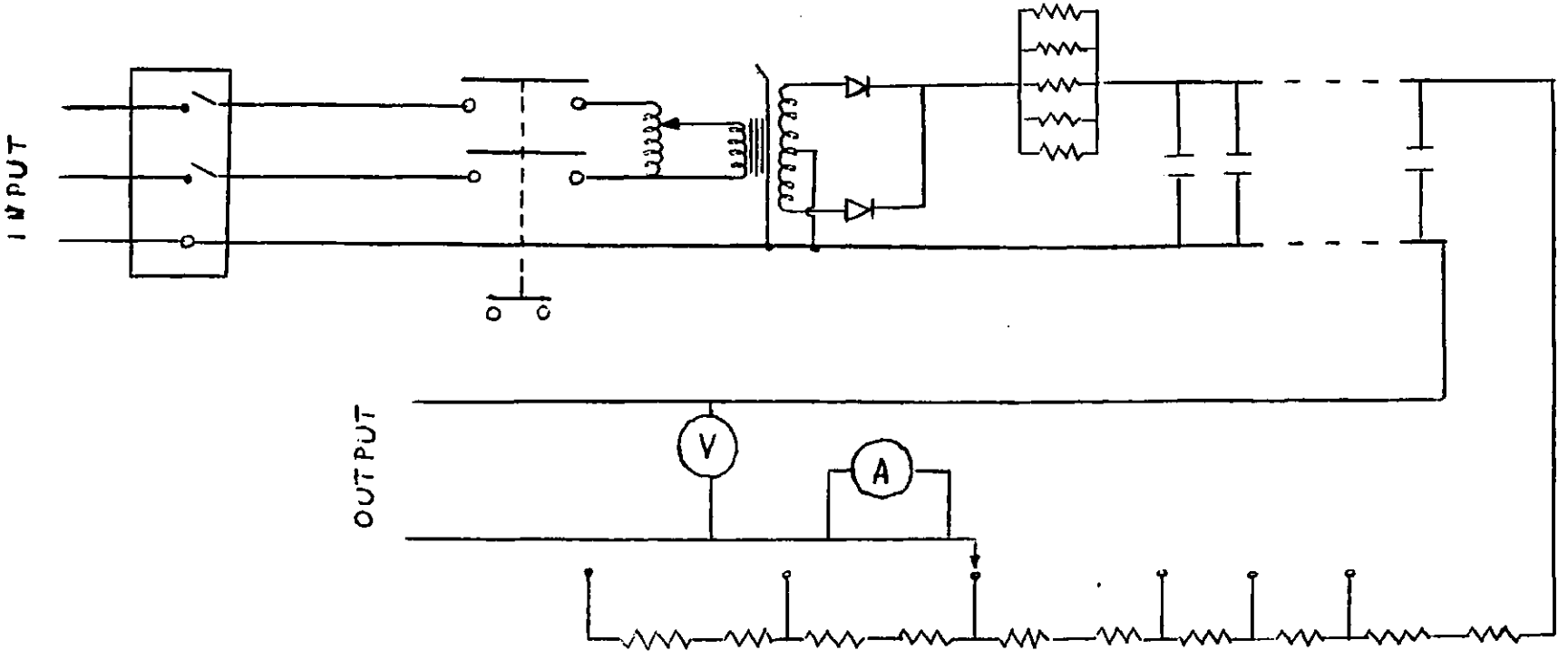


FIG. 6:2. Single phase power supply used at Smiths Industries for continuous plasma jet.

in fact served two purposes. They were initially designed only to prevent the high voltage spike, employed to initiate the arc, from damaging the rectifying diodes. However, they also proved to serve as an inductance which caused the arc to restrike whenever the current fell suddenly. The coils from the three phase supply were, therefore, fitted temporarily into the single phase power supply. It then became possible to stabilize and run a nitrogen arc. However, becasue of the limitations on the maximum current and voltage available from the single phase power supply, it was not possible to stabilize arcs in hydrocarbons, air, etc.

6.2. Experimental Results

Due to the effect of the plasma jet body as a bluff-body stabilizer, the values of fuel for a given air flow at which the flame would attach itself to the plasma jet were established first.

Bluff Body Stabilization

The plasma jet body was arranged either horizontally or vertically in the fuel/air stream. When placed horizontally, it was orientated with the anode exit hole facing downstream, approximately 15 cm. from the upstream end of the duct. In the vertical position, it was placed centrally, 10 cm. downstream of the upstream end of the fuel/air duct. The plasma jet discharge was upwards at right angles to the centre of the fuel/air stream. The fuel/air mixture was ignited using a surface discharge plug. The effect of the plasma medium when discharged as a cold diluent through the plasma jet nozzle was also established. FIG. 3 shows the different positions of the plasma jet.

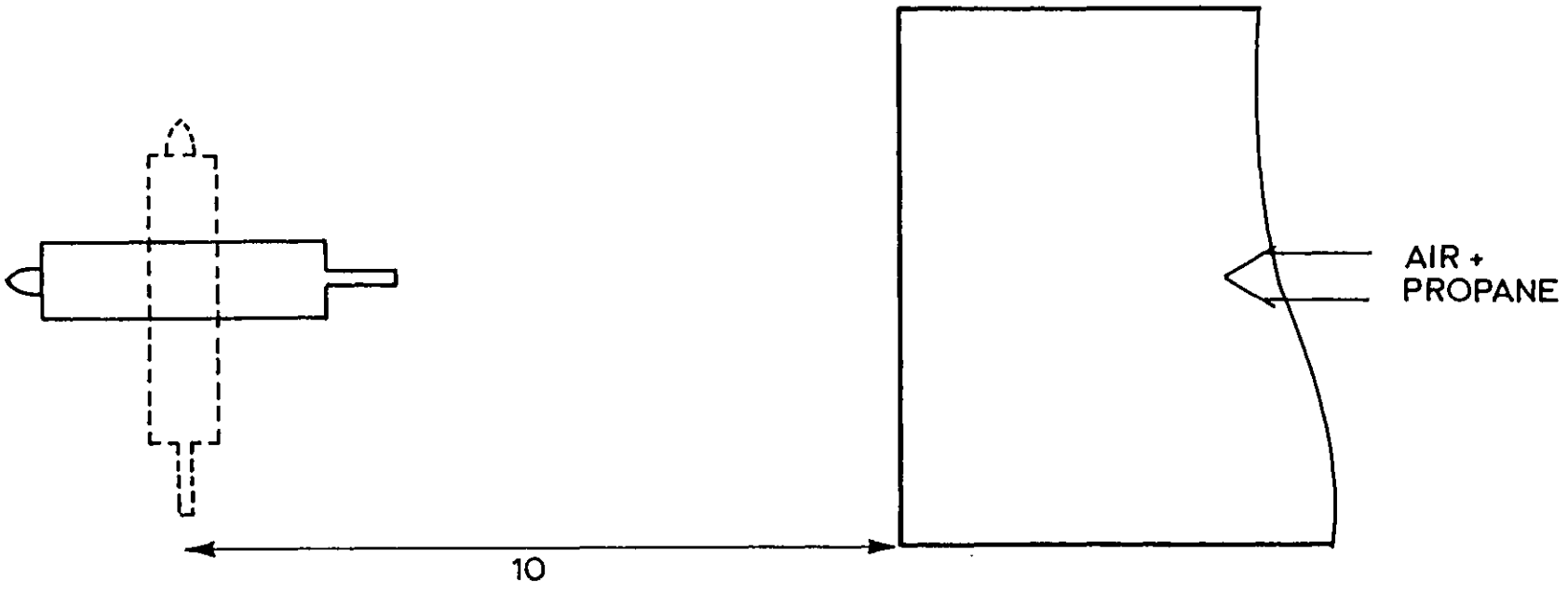


FIG. 6:3. Horizontal and vertical position of the continuous plasma jet in the flow system. Distance in centimetres.

The bluff body stabilization curves, FIG. 4, record the effect of changing velocities on blow off from the body of the plasma injector placed in the fuel/air stream. These results only deal with the lean limit blow off. As can be seen from these curves, there is no appreciable difference between the plasma jet with and without diluent flow through it. This is thought to be due to the flow of diluent only being 0.1% of the total flow of fuel/air. The vertical position gives a lower stability value, in terms of Ø min than the horizontal, FIG. 4, presumably because the recycling region behind the vertical plasma jet is much larger than for the horizontal one. This corresponds well with results from Williams et.al. (1948) who found that, for very lean or very rich mixtures, the flame width appeared to increase as the bluff body shapes were changed from gutters to rod to flat plate.

Argon Plasma Jet

Initial experiments, using an argon plasma jet, gave no indication of any flame initiation by the plasma. The argon plasma jet was, therefore, studied using a separate ignition source, as in the case of bluff body stabilization. The two positions used were the horizontal and vertical, as described earlier. FIGS. 5 and 6 show these results. As can be seen, there is no appreciable difference between the values for the argon plasma and the bluff body, in terms of flame stability. This was also the case when the argon flowrate or the energy input was increased. The anode configuration was subsequently changed to allow the fuel/air mixture to come in contact with the whole of the hot plasma. In the original design, the

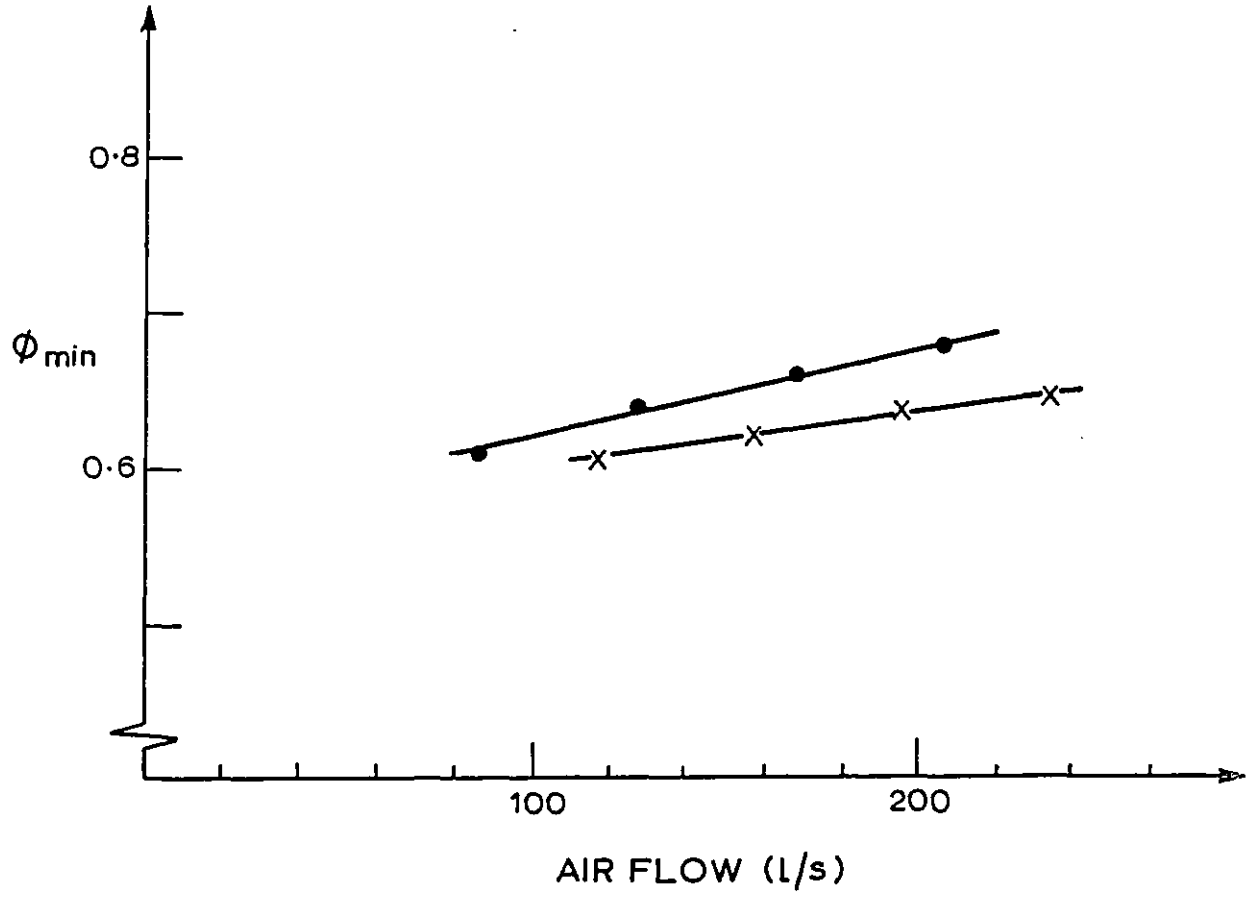


FIG. 6:4. Ømin as a function of air flow. Bluff body stabilization for the continuous plasma jet, no flow through the plasma jet.

x vertical position

• horizontal position

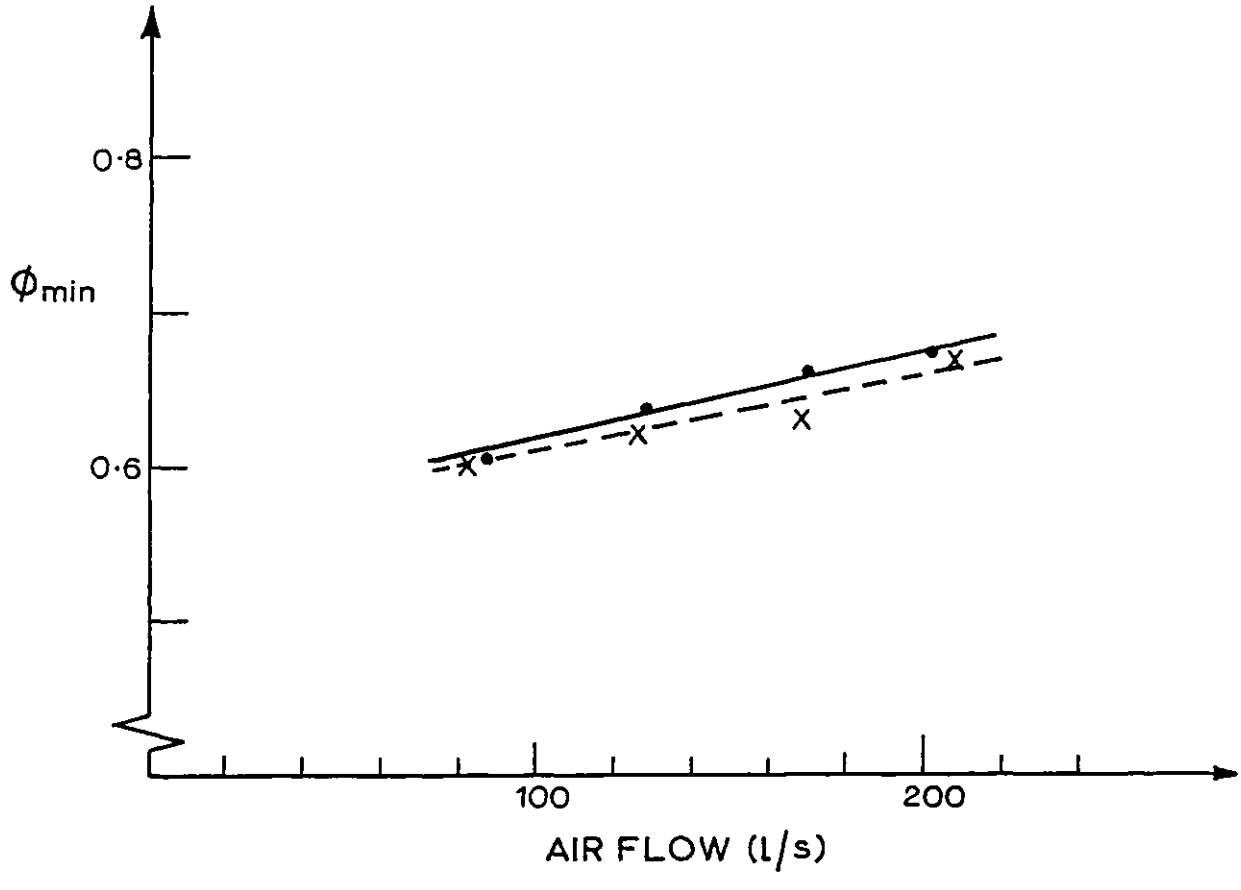


FIG. 6:5. Ømin as a function of air flow. Bluff body stabilization with and without an argon plasma (300W). Horizontal position.

- • Bluff body, no flow
- x Argon arc

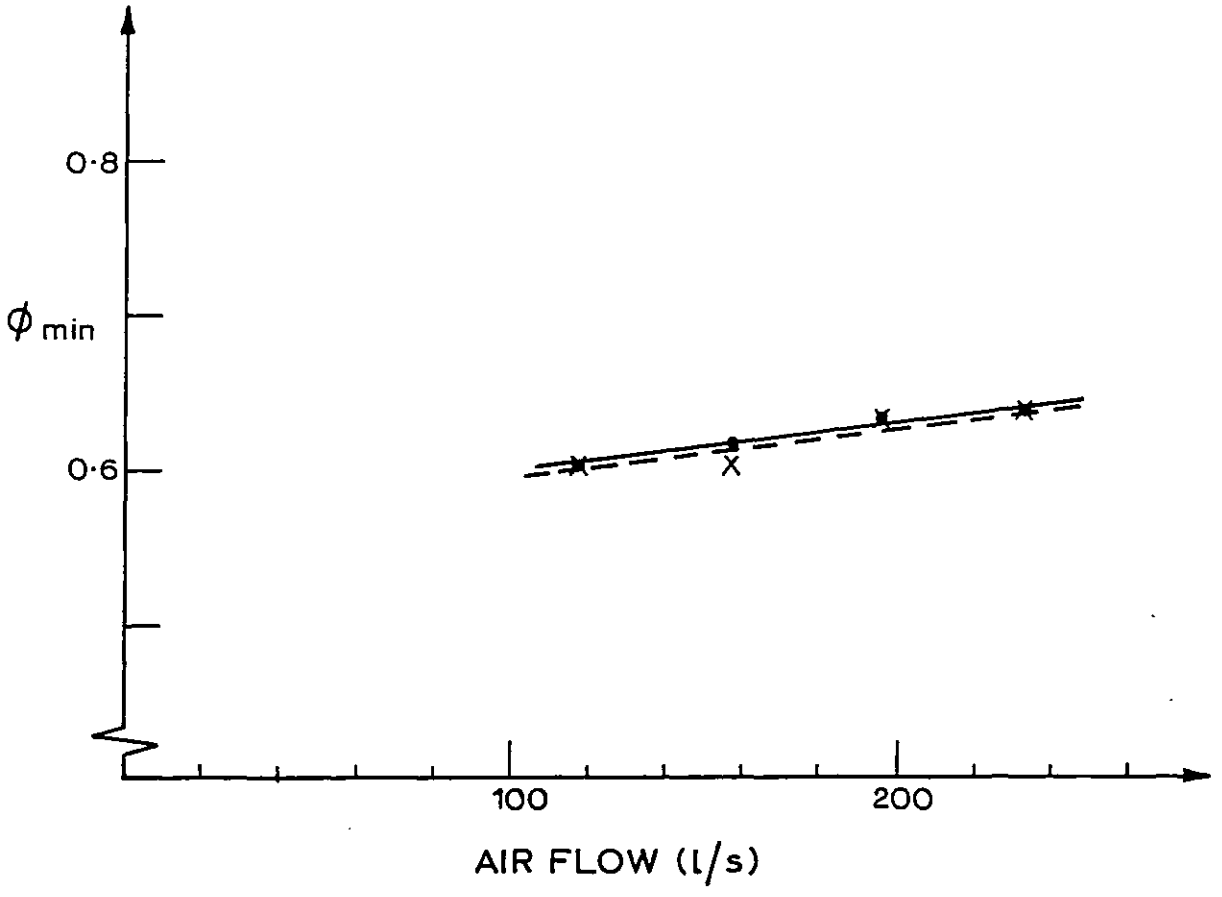


FIG. 6:6. Ømin as a function of airflow. Bluff body stabilization with and without an argon arc (300W). Vertical position.

- • Bluff body, no flow
- x Argon arc

first 3 mm. of the plasma plume was shielded from the gases by the top of the steel cap. The argon plasma has a short cone, approximately 5 mm. high, extending out of the anode channel; FIG. 9 shows an argon arc in the flow system. This change in anode design did not alter the values given in FIGS. 5 and 6. The reason for this behaviour will be discussed later.

Nitrogen Plasma Jet

The positions used to test the flame holding capabilities of a continuous nitrogen plasma again were the horizontal and vertical geometries described previously. A second vertical position was also used where the plasma jet body was placed outside the fuel/air stream with the hot plasma just protruding into it, corresponding to position 3 used in the previous Chapter.

This was done to eliminate any bluff body effect and to study flame holding with the luminous jet barely reaching the fuel/air mixture.

From initial experiments, it was clear that the nitrogen plasma entrained some of the fuel/air stream. When small amounts (less than 1% of the total flow) were added, the plasma cone became longer and its boundaries hazier. Three different flame holding criteria were defined for use during this work, as follows:

"Initial flame" : The luminous plasma jet cone is lengthened to 10cm (from its usual 2-3cm) by the flame reaction in the surrounding propane/air mixture. This looks like a bright, small flame; FIG. 7a

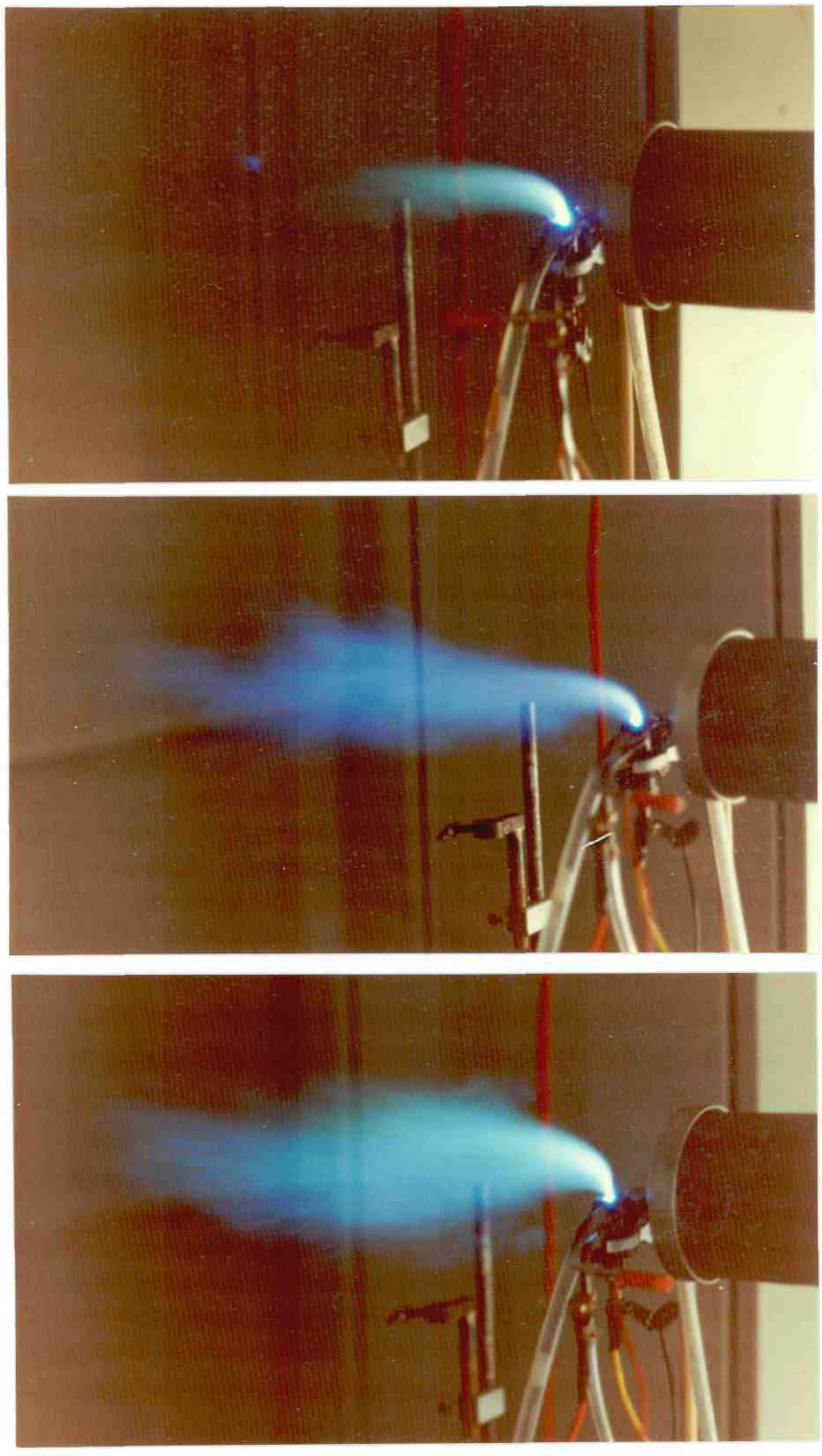


FIG. 6:7 : Nitrogen plasma jet in a propane/air stream.

a. "Initial Flame"

b. "Flame"

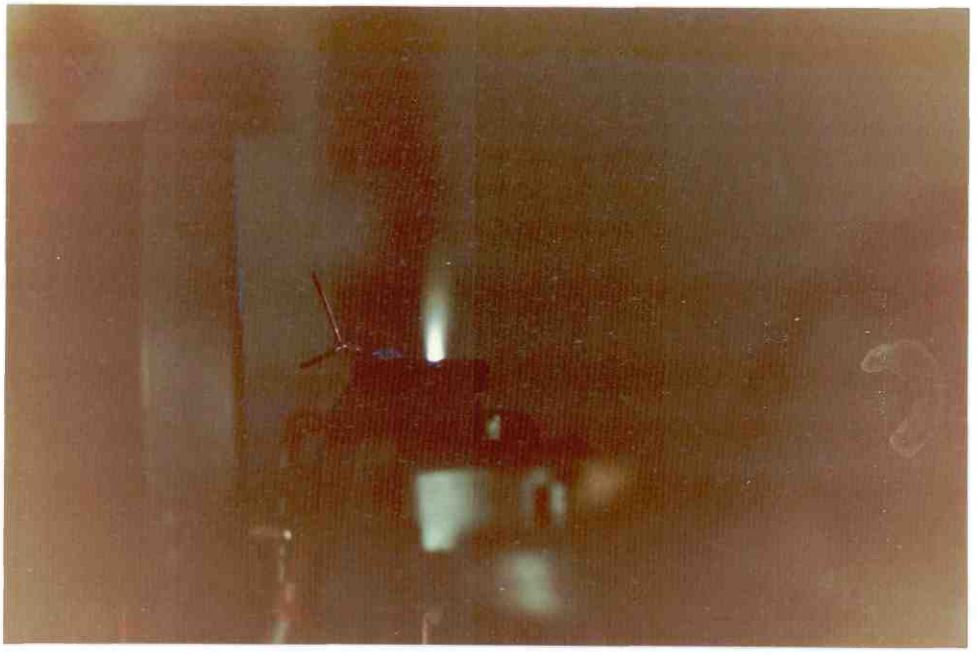
c. "Fully developed flame"

"Flame" : The plasma + flame extends 50 cm downstream from the plasma jet body; FIG. 7b.

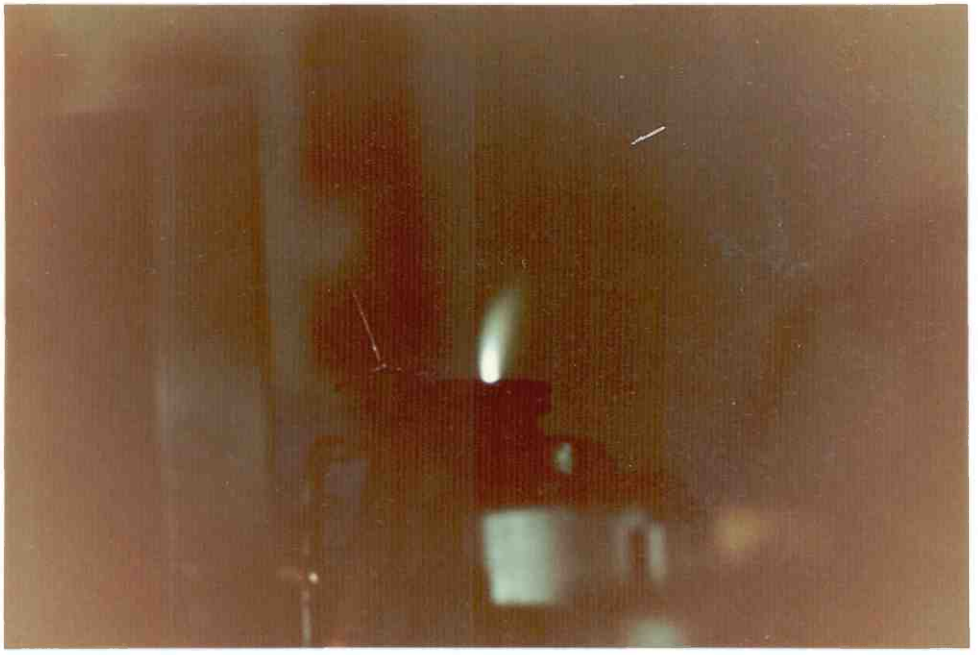
"Fully developed flame" : The flame width has expanded to 10cm (i.e. it essentially fills the part of the duct diameter that contains mixture of desired Ø.) and it is about 50 cm. long; FIG. 7c.

When the plasma jet was in either of the vertical positions and the air flow through the duct was started, the plasma cone bent over, FIG.8a and b. From the photographs, one can approximately deduce the local velocity of the luminous plasma. This has slowed to less than 15 m/s at a distance of 20 mm from the exit. The exit velocity of the nitrogen plasma, assuming cold gas, is approximately 200 m/s. The plasma deflects, of course, even when air alone flows in the duct. However, the deflection of an argon plasma in the air flow is almost imperceptible. This is at least partly due to the distance downstream at which the plasma is observed. The argon plasma has a short cone, approximately 5 mm high, whereas the nitrogen plasma has an outer and an inner cone with a total height of close to 30 mm. FIG. 9 shows an argon arc in the flow system.

The air velocities were varied between 10 m/s and 30 m/s and the amount of propane required to achieve each of the three flame stabilization stages determined for each air velocity and for each plasma jet position. The results can be seen in FIG. 10 (horizontal), 11 (vertical) and 12 (vertical II) The curve for bluff body stabilization has been added for comparison in FIGS. 10 and 11. In FIG. 12, the value for a pulsed plasma jet filled with either water or Avtur and located in the same



a.



b.

FIG. 6:8 : Effect of external air flow on a nitrogen plasma jet, flowrate 290 cm^3/s.

a. No external flow.

b. 15 m/s external airflow.



FIG. 6:9 : Argon plasma in the external flow system, air velocity 20 m/s.

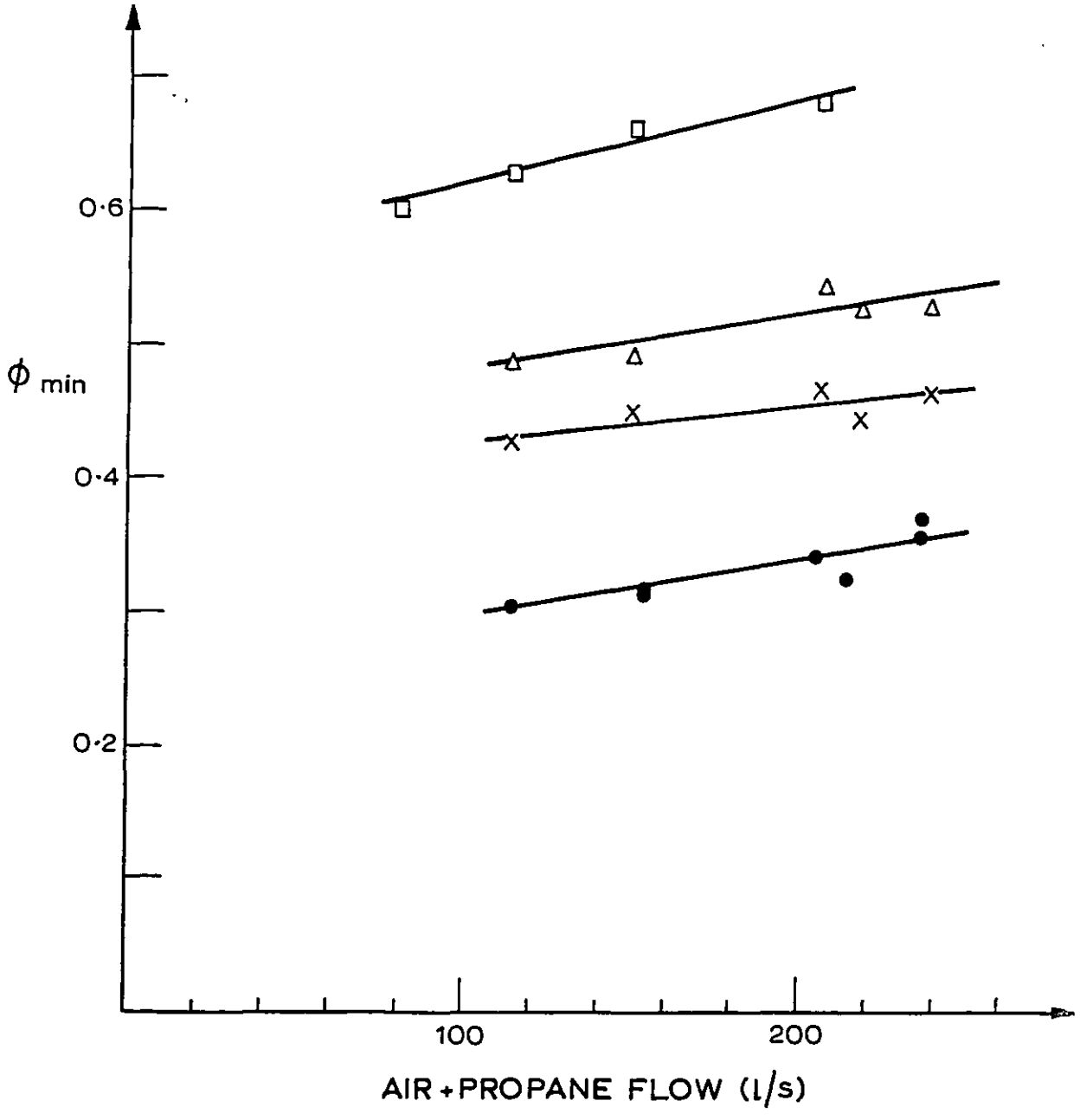


FIG. 6:10. The flame stabilizing effect of a nitrogen arc (flowrate 290-355 cm^3/s; power 1200W) in the horizontal position. Ømin as a function of total flowrate.

• "Initial flame"

Δ "Fully developed flame"

x "Flame"

❑ Horizontal bluff body stabilization

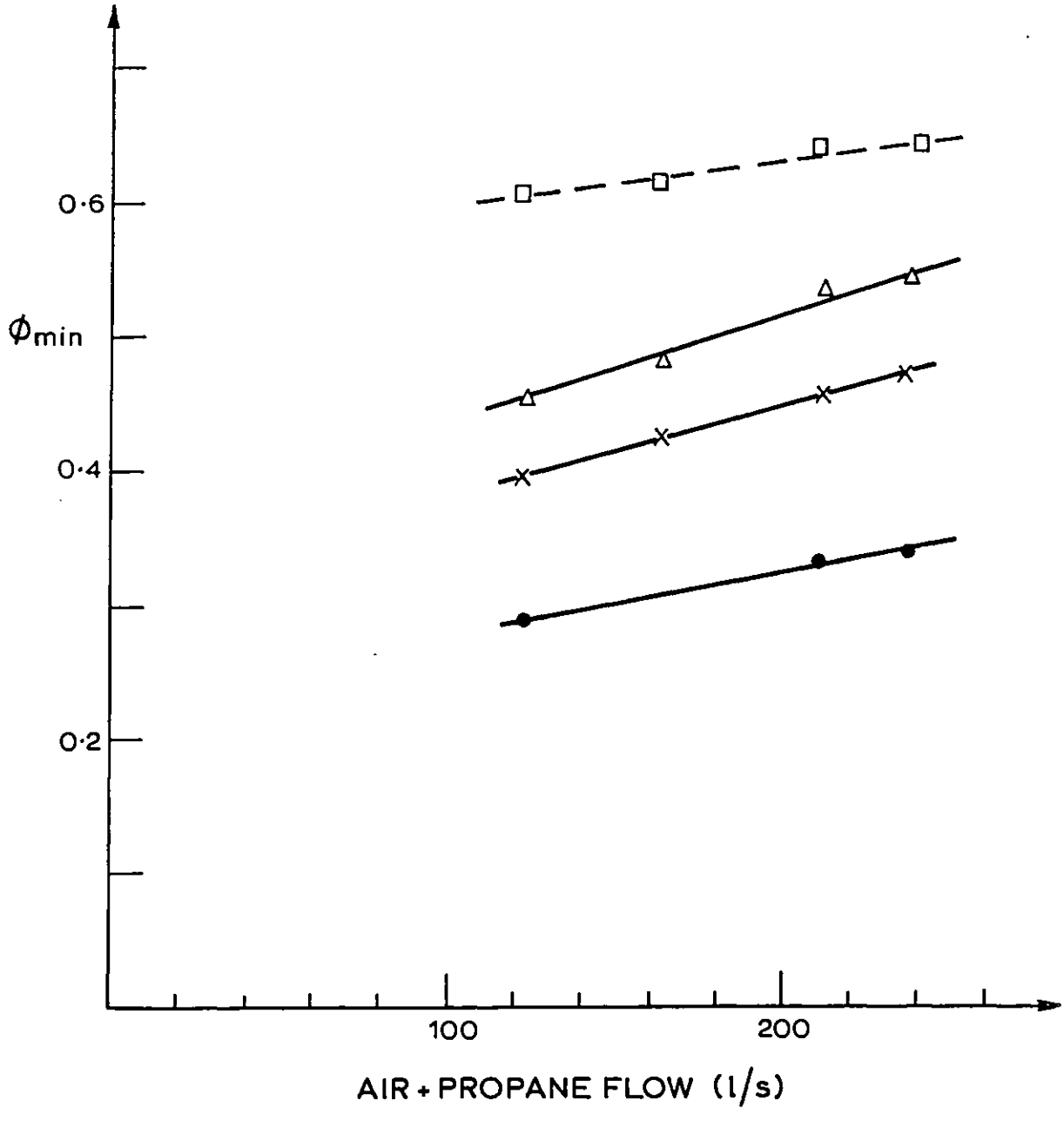


FIG. 6:11. The flame stabilizing effect of a nitrogen arc (flowrate 355 cm^3/s; Power 1300W). Vertical position. Ømin as a function of total flowrate.

• "Initial flame"
Δ "Fully developed flame"
x "Flame"
□ Vertical bluff body stabilization

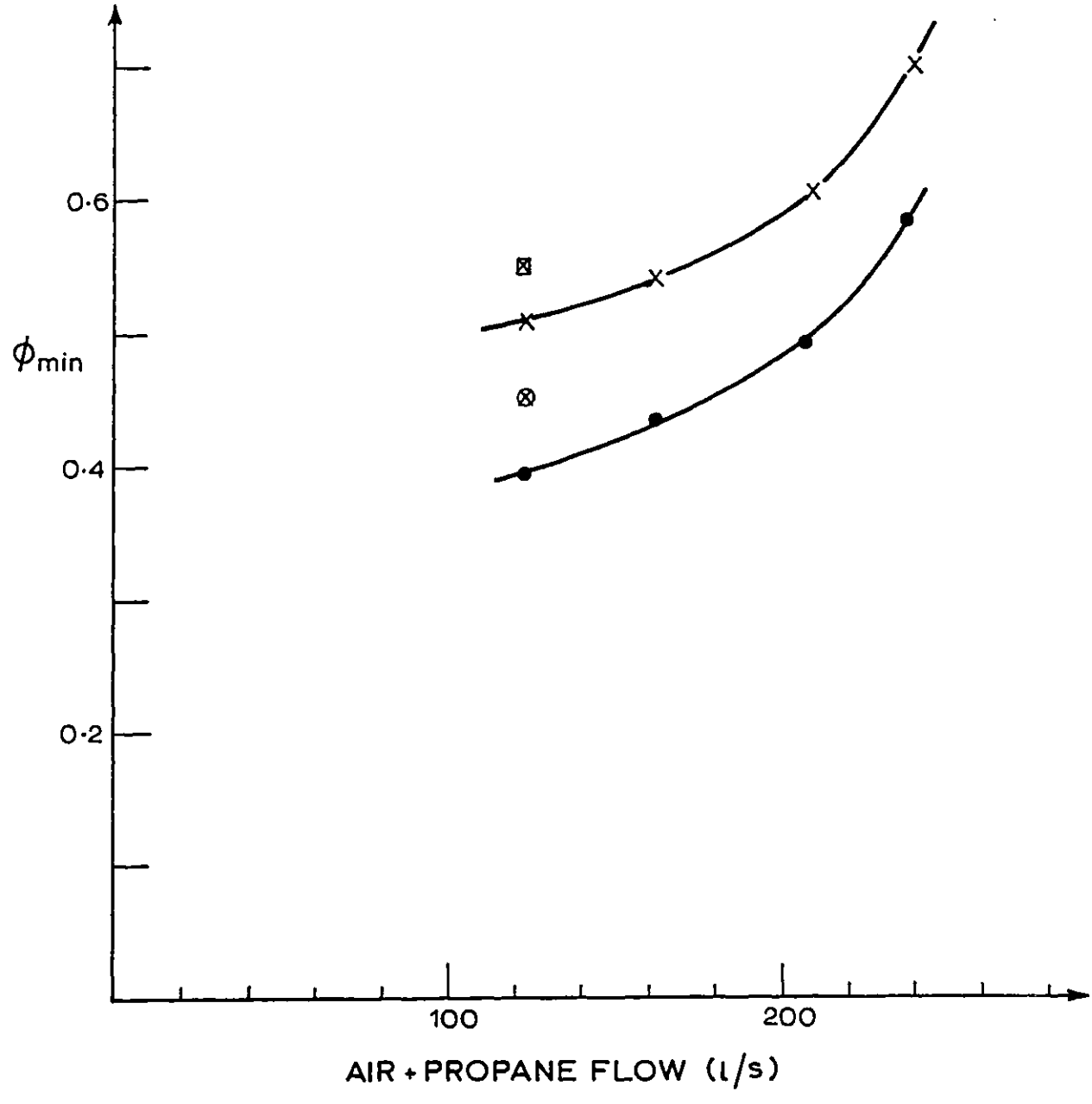


FIG. 6:12. The flame stabilizing effect of a nitrogen arc (flowrate 355 cm^3/s; power 1100W). Vertical II position. Ømin as a function of total flowrate.

• "Initial flame"
x "Flame"

Pulsed plasma jet ignition for

⊠ water; ⊠ Avtur

position is marked.

The nitrogen flow rate was varied from 355 cm^3/s to 290 cm^3/s, assuming cold gas, for the horizontal position but this had no effect on flame stabilization, i.e. gave no variation in the amount of propane necessary to achieve the different flame criteria. The single phase power supply used did not allow any large variation in power input, as the nitrogen arc operated close to the maximum output of the power supply.

The results clearly show the great extension of range resulting from the use of a continuous nitrogen plasma to initiate and stabilize flames in fast gas streams. The graphs for the various flame stages turn out to be straight lines and there is little difference between the horizontal and vertical case. The gradient changes slightly in going from horizontal to vertical positions. The fact that the lines are straight indicates that the total flow velocity has much less bearing on the flame stability than the fuel/air ratio. The nitrogen plasma jet performs better than the bluff body of its own dimensions for all the flame criteria. With the plasma jet in the vertical position, if larger amounts of propane are added to the air stream than are needed to achieve fully developed flame, the flame will eventually settle on the plasma jet body. Initially, this occurs only on the top part, close to the plasma, FIG. 13. This section is hotter than the rest of the plasma jet, as well as being closer to the plasma jet.

The vertical II position shows the distinct influence of flow velocity on the flame stability. The larger the velocity, the

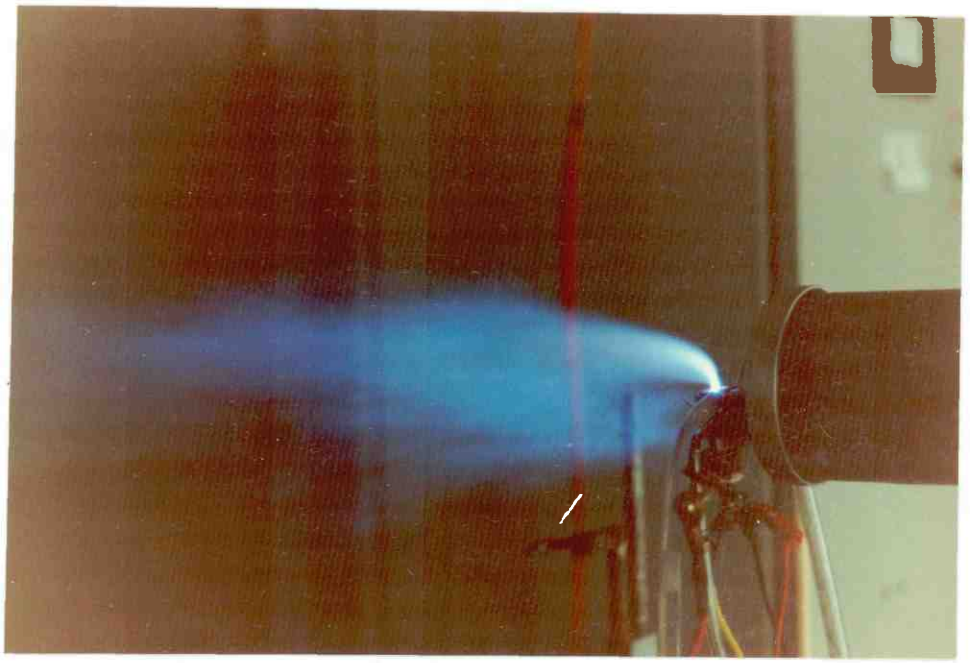


FIG. 6:13 : Initial stage of a flame settling on the plasma jet body.
Nitrogen arc (flowrate 355 cm^3/s; power 1300 W)
Air velocity 20 m/s,
Ø min = 0.505.

larger the amount of propane needed to achieve a flame. In this case, it was difficult to separate the two final flame criteria, so only two are used here: the initial and the fully developed. The Ø min. values for the pulsed plasma jet marked on the graph are for flame travel and are, therefore, more comparable with the initial flame criterion. It is clear that the continuous plasma jet with nitrogen performs better than a pulsed plasma jet fueled with Avtur.

These results for the continuous nitrogen plasma in the horizontal and vertical position- except for some of vertical II position- are well below the lean limit of flammability for propane as determined in a quiescent mixture. This is all the more striking since the lower limit of flammability increases under turbulent conditions and the flow in this case is turbulent (see the Reynolds number calculation in Chapter 5).

6.3. Current and Future Work

The work of Harrison et. al. (1971) and Kimura et. al. (1981) clearly show the great increase in stability resulting from the use of a nitrogen fed continuous plasma jet for flame stability. Although nitrogen is a diluent and hydrogen a fuel, Kimura et al. (1981) demonstrate that nitrogen plasmas perform better than hydrogen plasmas, especially when the energy input is taken into consideration.

The present work further demonstrates the efficiency of a nitrogen plasma jet for initiating and stabilizing flames in fast flowing fuel/air streams. Nevertheless, it would be desirable to test hydrogen or hydrocarbon plasmas to compare

the results. Unfortunately, the power supply at Smiths Industries could not deliver the power necessary to run and test a hydrogen plasma or hydrocarbon plasma on the flow system. Tests are, therefore, continuing at Imperial College, in association with another project.

The author is engaged in using plasmæ to stabilize a pulverized coal flame. Since there is a need for reliable ignition and stabilization of flames in pulverized coal combustion chambers. Failure to ignite during early stages of injection or flame blow out later, could lead to devastating coal dust explosion following subsequent ignition. To obviate this hazard, current practice is to mix pulverized coal with oil which costs Britain £300 million in the electricity generating industry alone. There are also great difficulties in turning a pulverized coal furnace down when demand diminishes and the furnace is often run at full or $\frac{3}{4}$ load even if less would be desirable. It is thought, however, that the radicals generated in a plasma jet would have little effect on the solid cold coal particles. They could promote combustion and increase flame stability most effectively once the coal particles had started giving off their volatiles. This suggests the use of some form of auxiliary flame.

Together, these reasons suggest the need for some form of gas flame surrounding the plasma jet. The current design is a circumferential anular duct, approximately 20 mm long. It has tangential gas inlets to allow easier entrainment of the gas into the plasma jet. The exit anulus diameter can be varied between 10 and 30 mm, allowing for exit flow velocities of up

to 30 m/s. The contribution of the plasma flow would be approximately 2.5% of the total flow. Using lean mixtures of methane and air, the blow off characteristics and flame stability of this surrounding flame can be tested for various plasma media. The combination of the plasma jet and the surrounding flame fueled with hydrocarbons, hydrogen and various flammable mixtures should help in generating sufficient heat to drive volatiles out of the coal particles and to ignite and stabilize a flame. It may be possible to do away with the separate fuel/air feed once a flame is established in the furnace.

Work is in progress to test this suggestion. The results will be reported elsewhere.

6.4. Discussion and Conclusions

These experiments clearly show the large improvements resulting from the use of a nitrogen plasma jet for flame stabilization, even though nitrogen is a diluent and does not contribute any active radicals normally associated with hydrocarbon combustion.

It is interesting to speculate why nitrogen succeeds where argon fails. Both gases act as diluents. Argon is a monatomic gas and, therefore, cannot dissociate to form atoms. This means the plasma temperature rises quickly with energy input. Nitrogen is a diatomic gas and has a large dissociation energy. This will affect the temperature versus energy input graph and generate very energetic labile species. An enthalpy calculation for an argon and a nitrogen plasma reveals that the enthalpy for a nitrogen arc is much higher than for an argon arc because a nitrogen arc requires a higher energy in-

put to stabilize it. TABS. 1 and 2 list the various results depending on energy input and and flow through the plasma jet. Under typical operating conditions, an argon plasma (200 cm^3/s and 300W) gives an enthalpy of 33.6 kJ/mole and a corresponding temperature of approximately 2000 K. The adiabatic flame temperature for stoichiometric propane/air is approximately 2000 K. For nitrogen, typical running conditions of 1200W at 200 cm^3/s give an enthalpy of 134.4 kJ/mole and an approximate temperature of 3500 K. So, the nitrogen arc runs much hotter than the argon arc. This does not take into account the variation in temperature due to the arc not heating the gas uniformly. Because of the temperature discrepancies, the nitrogen arc will remain hotter further downstream than for an argon arc. The amount of external gas entrained into the nitrogen arc will also be larger, due to the larger temperature difference between the emerging plasma and the surrounding gas. The nitrogen atoms generated in the plasma are highly reactive due to their electron-configuration. It appears that nitrogen works better than argon because it generates highly reactive radicals and runs at a higher average temperature.

Apart from the difference in enthalpy, there are two other reasons why the nitrogen arc differs from the argon arc. One is physical and one chemical. The physical is due to the entrainment of fuel/air into the plasma jet. A simple calculation of the emerging velocities and amounts entrained reveals that during the first 5 mm. the argon arc entrains approximately 72% of the propane/air mixture, whereas the nitrogen arc entrains roughly 78% of the propane/air. The percentage is the amount entrained divided by the total mass of the jet at

Energy (W)	200	300	500	625
Flowrate (cm^3/s)				
50	89.6	134.4	224.0	280.0
150	29.9	44.8	74.7	93.3
200	22.4	33.6	56.0	70.0
300	14.9	22.4	37.3	46.7
400	11.2	16.8	28.0	35.0

TAB. 6.1. Enthalpy (kJ/mole) for an argon plasma as a function of flowrate and energy.

Energy (W)	700	900	1000	1200	1500
Flowrate (cm^3/s)					
50	313.6	403.2	448.0	537.6	672.0
100	156.8	201.6	224.0	268.8	336.0
150	104.5	134.4	149.3	179.2	224.0
200	78.4	100.8	112.0	134.4	168.0
300	52.3	67.2	74.7	89.6	112.0

TAB. 6.2. Enthalpy (kJ/mole) for a nitrogen plasma as a function of energy and flowrate.

that height. This calculation does not take temperature into consideration, so the real amount entrained is actually higher and varies more, due to the temperature difference between the two arcs. According to Coward et. al. (1952), the effect of nitrogen diluent on the lean flammability limit of propane/air is negligible, as long as the amount of nitrogen added to the original fuel/air mixture is less than 33%. So, for a nitrogen plasma, the amount of fuel/air entrained is sufficient to overcome the effect of nitrogen as a diluent.

Although the emerging argon arc is hot, as can be observed from the UV-radiation and sensed from the ozone generation, most of the gas is cold, 99.5% according to Behbahani (1981). So, the chances of the fuel/air mixture encountering any hot argon is small and, as the fuel/air mixture is diluted with the cold argon while being entrained, the fuel/air/argon ratio becomes close to or outside the lean limit of flammability.

The chemical reason why the nitrogen arc differs from the argon arc is due to the generation of nitrogen atoms. Harrison et. al. (1971) showed that nitrogen performs much better than water, fuel or fuel/air mixtures. They suggested that this was because nitrogen atoms would react with oxygen to form NO and free oxygen atoms, as follows:

$$N + O_2 \longrightarrow NO + O$$

They concluded that generating highly reactive nitrogen atoms to store the arc energy was useful as whatever molecules the nitrogen atom would hit subsequently (except another nitrogen atom) would produce radicals. Another possible reaction mechanism was briefly investigated by Hilliard (1981). He

suggested that the reaction of hydrocarbon fragments with nitrogen atoms would generate HCN and a hydrogen atom. The HCN would then react with the oxygen present to form NO. Using a nitrogen plasma jet in a hydrocarbon/air system, he found that slightly more HCN was formed than NO_x.

Both the oxygen and the hydrogen atoms are of importance in the combustion reaction system. The generation of either or both of these atoms in the fuel/air/nitrogen atoms system is advantageous, especially as the nitrogen atoms can carry the arc energy downstream of the plasma jet and, therefore, carry the combustion reaction into a larger volume than that of the central plasma cone. The chemical effect must be considered to be the most important reason for the efficiency of the nitrogen arc in stabilizing a flame in correlation with the argon plasma.

There are several reasons why a nitrogen arc performs better than an argon plasma. It produces highly reactive nitrogen atoms in the hot pockets that can travel up to 2 cm. downstream. The nitrogen atom, although not present in normal flames, would react with the entrained fuel and air generating radicals normally associated with hydrocarbon combustion. The average running temperature of a nitrogen plasma is higher than for an argon arc. (3500 K as compared with 2000 K). Finally, a nitrogen arc entrains more of the surrounding fuel/air mixture than argon arc, resulting in less dilution by the cold nitrogen compared to the argon case.

For all the present experimental conditions, it is not possible

to blow off the plasma using the external flow system. Previous designs of plasma jet could be blown off by velocities high enough in the surrounding gas. This important difference is due to the sonic velocity in the anode channel of the present design, which makes it impossible for conditions downstream to feed back into the arc region.

CHAPTER 7

CONCLUSIONS

The development of a pulsed plasma jet based on a surface discharge igniter and the optimization of the continuous plasma jet for use with various feedstocks was one of the objectives of this research. The other aim was to do research into the use of both devices for ignition and flame stabilization in fast gas streams, with special reference to gas turbine engines.

Regarding the development of a pulsed plasma jet, Chapter 2 concludes that the use of a wetted surface discharge igniter will contribute to extending the length of the discharge plume by up to 100%, as compared with a dry igniter. Addition of a magnetic field will spin the discharge on the surface of the igniter while shortening it. This led to suggestions for new plug designs.

The continuous plasma jet was found to contain hot and cold volume stratifications. This observation led to a new design using aerodynamic swirl to rotate the arc. The aerodynamically spun plasma jet is smaller, more compact and performs better than the magnetically spun plasma jet. Entrainment pattern studies of the plasma jet led to the suggestion that feedstocks other than hydrogen and hydrocarbons could be used, because

the plasma jet would entrain the external gas close to the emerging jet,so generating radicals from the external stream. This led to the development of an air plasma.

The surface discharge igniter, the surface discharge based plasma jet and the continuous plasma jet were tested in a fast flowing fuel/air system. These results clearly show the advantages of using either a surface discharge based plasma jet wetted with Avtur or a continuous nitrogen plasma jet for ignition and flame stabilization. The fuel/air mixture is turbulent, which generally narrows the limit of flammability and increases the minimum ignition energy. Even so, ignition and flame stabilization for these two devices occur below or close to the normal (quiescent atmosphere) lean limit of flammability. The effect of specific radicals is clearly of importance when the igniter is wetted. It was shown that even water successfully lowers the ignition limit and this can only be due to the additional radicals generated. In the case of the continuous plasma jet, radicals generated by nitrogen atoms are again the main reason why it performs so well. The other reasons are the large energy of nitrogen atoms at quite a low average temperature of the nitrogen plasma and the plasma jet's strong entrainment of the fuel/air mixture.

The pulsed plasma jet and the continuous plasma jet are not directly comparable. They have different work modes; one acts as an ignition source and the other as a flame holding device. Two different strategies as regards flame out are involved. The pulsed plasma jet allows the flame to extinguish and then relights it, whereas the continuous plasma

jet never allows the flame to go out. One could, therefore, envisage the use of both of them in a gas turbine engine. However, it is unlikely that both of them would be used together and, therefore, it might be instructive to look at some criteria comparing their performance. Before doing so, it is worth stressing that it is hoped that a practical device will emerge from this research. The continuous plasma jet gave lower values for $\emptyset$ min than the Avtur wetted igniter. However, it requires a more complicated experimental rig, power supply, etc. and consumes more power than the surface discharge based plasma jet. This igniter so closely resembles a surface discharge plug that to adapt one in a gas turbine engine should present minimal problems.

It is hoped that during the future development of the continuous plasma jet, greater versatility will be achieved and, therefore, a more practical device for ignition and flame stabilization will emerge. This is the long-term objective. Meanwhile, it is of relevance to test and develop both the surface discharge based plasma jet wetted with Avtur and the continuous plasma jet for use in a gas turbine engine. This should quickly lead to practical igniter with enhanced ignition and flame stabilizing effects.

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A P P E N D I X

A.S.L. 16083 - Analysis of unknown deposit from electrode.

Summary.

X-ray diffraction analysis revealed the major phase of the sample to be graphite (J.C.P.D.S. file No. 23-64) and a classical analysis for total carbon yielded (98±5)%.

A qualitative analysis by X-ray fluorescence showed no significant components in the elemental range Si → U.

The vast majority of the sample,it is concluded, is therefore graphite.

Experimental

A Debye-Scherrer diffraction pattern was produced from the untreated sample (photograph 1). To clarify the analysis of the pattern, the sample was ground and mounted in a glass capillary tube. Two further diffraction photographs were produced of different exposure times to account for variations in line intensities (photographs 2 & 3).

Conditions used to produce these patterns are indicated below.

Photograph No.	Sample Preparation	Radiation	X-ray tube Conditions	Exposure time (mins)
1.	Sample removed from electrode No further treatment	Ni filtered Cu K_α λ=1·542A	40kV 20mA	130
2.)	Sample ground and mounted in glass capillary tube	"	"	8
3.)		"	"	100

In each case the camera diameter was 114·83M.M. with the film loaded in the Straumanis position.

Report

No single phase could be found to account for all the diffraction lines obtained so a qualitative analysis by X-ray fluorescence was made. This covered all elements of atomic number greater, than 14 (Silicon) and revealed no significant components. The sample is therefore composed of one or more light elements.

Most of the diffraction lines are consistent with the graphite phase listed in J.C.P.D.S. file No. 23-64, however, preferential orientation of the crystal planes has occurred which obviates strict comparison of relative intensities.

The diffraction pattern produced by the sample along with the graphite lines from file No. 23-64 are detailed below.

SAMPLE			GRAPHITE 23-64		
2θ	d(A)	Intensity	d(A)	Plane	RELATIVE INTENSITY
19·4	4·57	w			
22·0	4·04	w			
24·5	3·63	w			
26·5	3·36	vs	3·36	002	100
31·0	2·88	w			
34·0	2·63	mw			
42·5	2·13	ms	2·03	101	50
			2·13	100	10
54·5	1·68	s	1·678	004	80
77·5	1·23	m	1·232	110	30
86·0	1·13	mw	1·158	112	50
			1·138	105	5
			1·120	006	20
93·5	1·058	w	0·994	114,116	40
			1·054	201	5
129·0	0·85	vw	0·829	116	40
			0·841	008	10
147·0	0·803	mw	0·801	211	5
	Not detected		1·80	102	5
	"		1·544	103	10

Key:- S. Strong m: Medium w: weak v: very

Taking preferential orientation into consideration a sufficiently good correlation exists between the diffraction patterns produced by the sample and that of J.C.P.D.S. file No. 23-64

to confirm the major phase of the sample to be graphite.

The remaining five lines unaccounted for, may be due to another graphite phase or to an unidentified light element compound or organic, but these lines are likely to represent only a minor part of the sample.

As a final confirmation of the analysis, a carbon determination was carried out on the sample by a classical combustion method. This gave a total carbon content of (98±5)%.

Analysts:

Mr. R. Sweeney	X-ray analysis
Mr. M.J.L. Haddon	Classical analysis

M. J. L. Haddon.

14-3-84

ERRATA

page

2 - line 15, . Gas vortex should read , gas vortex

31 - add in air

48 - line 7, cobolt should read cobalt

52 - line 1, should read $NO + N \rightarrow N_2 + O$

53 - line 3, anulus should read annulus

61 - Number 5 should read 4

96 - add $N_2 + O \rightarrow NO + N$

97 - line 23, aircrafts should read aircraft

99 - ari should read air

103 - line 5, jets should read jet

103 - line 26, cobolt should read cobalt

113 - line 19, remove full stop.

131 - line 17, photodiod should read photodiode

137 - add as a function of % propane

147 - line 9, depend should read depends

161 - line 8, add ... perfectly stirred system, using Longwell kinetics.

167 - line 8, becasue should read because