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ELECTRIC ARCS IN TURBULENT FLOWS

GERHARD FRIND
GENERAL ELECTRIC COMPANY
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OFFICE OF AEROSPACE RESEARCH
United States Air Force

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AEROSPACE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
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FOREWORD

This interim report was prepared by the Engineering Research Section of the General Electric Company, Power Transmission Division, Philadelphia, Pennsylvania, on Contract AF33(657)-8206 S-1 for the Aerospace Research Laboratories, Office of Aerospace Research, United States Air Force. The work reported herein was accomplished on Task 7063-03 "Energy Exchange Phenomena in Electric Arc Discharges" of Project 7063 "Mechanics of Flight" under the technical cognizance of Mr. Charles A. Davies of the Thermo-Mechanics Research Laboratory of ARL.

The work was started in March, 1963 and the report manuscript was completed in April, 1964.

The author wishes to acknowledge the enthusiastic assistance of Messrs. J.J. Narbus and H.A. Smith. Mr. Narbus assisted in design and development of plasma generator and flow tube. Mr. Smith was responsible for design and operation of the electrical instrumentation and for the power supplies.

Many critical and stimulating discussions were conducted with the members of the Thermo-Mechanics Research Laboratory of ARL and the Engineering Research Section of General Electric Company.

ABSTRACT

Experiments are made with the aim to find characteristic differences between electrical arcs in laminar and turbulent flows. To start with the simplest conditions, it is attempted to burn arcs in the fully developed flow region of a flow tube. The tube is 37 cm long and has a 1 cm bore. It is made of electrically insulated copper discs (cascade-chamber) or of quartz glass and is operated with 25 amp DC for durations of 1/2 sec. Highly preheated carbon-dioxide gas of 3.1 atm. pressure from a plasma generator is injected into the tube to shorten the thermal entrance length.

Measurements of the electrical potential along the flow tube show that the electrical gradient reaches asymptotically constant values at the end of the flow tube, even for flow velocities as high as 250 m/sec. At these velocities the gradient is about twice as large as compared to gradients for arcs with speeds smaller than 20 m/sec. High speed photography with exposure times of 2 μsec. reveals that the low velocity arcs are in a quiet, apparently laminar mode, whereas the high velocity arcs are moving violently and with apparent randomness. The flow velocity of the high speed arcs still increases considerably at the end of the flow tube. This suggests that still larger ℓ/d values must be used to reach fully developed flow.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF SYMBOLS

C_p	Specific Heat at Constant Pressure
d	Tube Diameter
e	Electron Charge
$\vec{E}$	Voltage Gradient
h	Enthalpy
I	Current
$\vec{j}$	Current Density
κ	Thermal Conductivity by Molecular Diffusion
K	Thermal Conductivity by Turbulent Diffusion
ℓ	Length of Tube
m_e	Mass of Electron
n_e	Electron Density
p	Pressure
Q	Radial Heat Flux per cm Tube
r_1	Radius of Cylinder
r, θ, z	Cylindrical Coordinates
S	Radiation Energy (per Unit Volume)
T	Temperature
T_0	Temperature in Axis of Cylind. Arc
$\vec{v}$	Velocity
$\vec{v}_e$	Velocity of Electron
V	Volts
x	One Dimensional Coordinate
ϵ	2.718

LIST OF SYMBOLS (Cont'd)

λ	Wavelength
Λ	Mean Free Path of Electrons
ρ	Density
σ	Electrical Conductivity

1. INTRODUCTION

Understanding of phenomena occurring in the column of electric arcs has progressed considerably in the recent years. Of importance in this context were the various solutions of the conservation equations, including the energy balance equation of the arc. Most progress has been made for cylindrically-symmetrical arcs without flow and for flow arcs in the fully developed flow region. These arcs are often cooled by thermal conduction only. The energy balance in this case is:

$$\sigma E^2 + \frac{1}{r}\frac{d}{dr}\left[r\kappa\frac{dT}{dr}\right] = 0^* \qquad (1)$$

Several approximate analytical solutions for this equation have been presented(1,2,3,4). Also successful checks of the theory against detailed measurements have been made(6,7,3).

The energy balance equation of quiescent arcs is more complicated, when radiation cannot be neglected. No solutions of a general nature have as yet been presented but special cases have been treated(7,5,10).

A new degree of complexity arises, when a general flow field is imposed on an arc. In this case the conservation equations for energy, mass and momentum have to be solved simultaneously. Also, the energy balance equation is still more complicated by the additional terms of convection and expansion.

This complex non-linear set of equations has been solved numerically on a computer(8). But also analytical solutions have been reported upon(9,10). One finds, however, that all theoretical arc work is concerned with the laminar case only. Such restraint is understandable in view of the fact that the laminar situation is difficult enough and has not yet been treated exhaustively. In addition, it can be argued that practical plasma devices are often working in a density and temperature range, where turbulent effects are expected to be of minor importance.

The latter point, however, can be challenged. To do so, let us estimate the order of magnitude of Reynolds numbers in a hypothetical constant temperature air plasma with pressures between 1 and 30 atm. For this estimate tables of Hansen(11) and Burhorn(12) for viscosity and density were used and the tube diameter d = 1 cm was selected.

* A list of symbols is given at the beginning of the text.

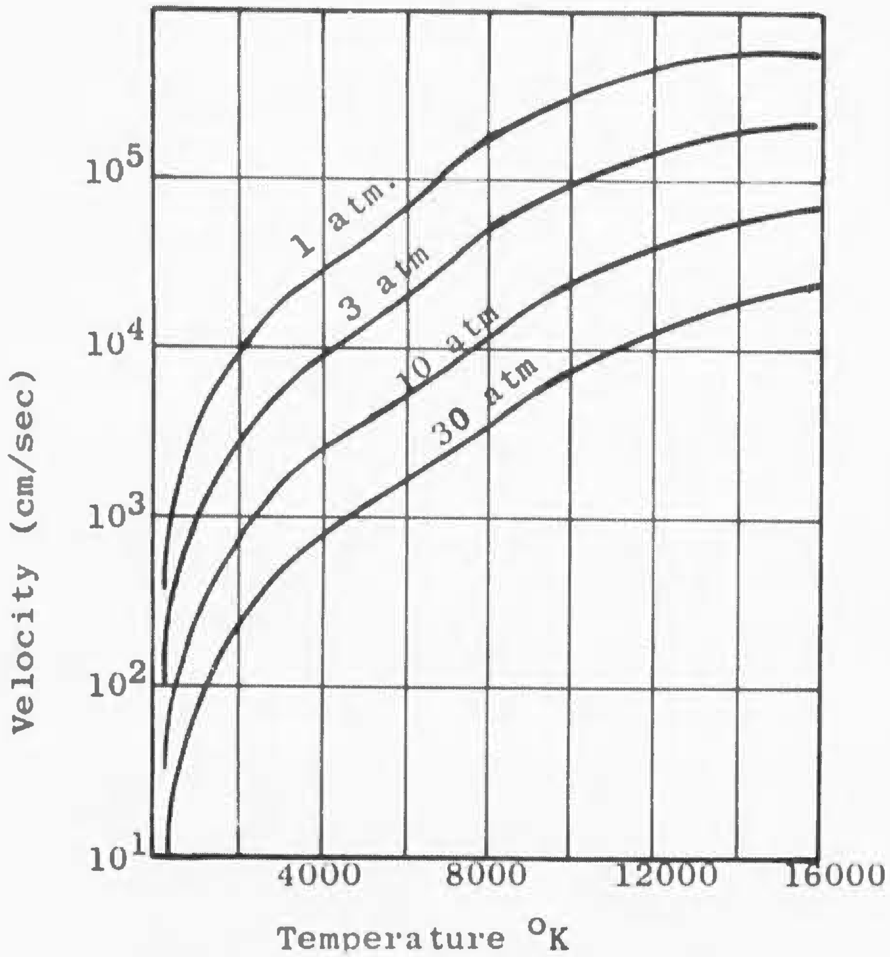

Figure 1 - Relationship between Gas Pressure, Temperature and Velocity to Satisfy the Critical Reynolds Number $R_e = 2000$, Required for Turbulent Flow

In Figure (1) velocity is plotted as a function of temperature, for which the Reynolds number R_e is equal to 2000. It is seen, that at the higher pressures Reynolds numbers substantially higher than 2000 can be reached with subsonic velocities even at temperatures between 10,000 and 15,000°K, that is in the core of high-current arcs. Still higher Reynolds numbers are indicated for plasmas of lower temperatures. If we now remember, that the electric arc has layers of widely different temperatures, it appears likely, that the outer cooler layers of an arc with their higher density and lower viscosity may show turbulent effects even at quite moderate pressures and flow velocities.

For these reasons, it seems interesting to study the influence of turbulence on arcs in high speed flow fields in more detail.

In this interim report, results of an experimental study of an electric arc burning in a long tube are presented. More specifically, the effect of a high speed flow field on the electrical gradient is determined and high speed motion pictures of the arcs are discussed.

2. METHODS

In this chapter reasoning is presented, which was of importance for the selection of the experiments. Also background information about the measuring methods is discussed.

2.1 Energy Balance

Of particular importance for the selection of the parameters of the experiments is an examination of a rather general energy - balance equation for flow arcs. This equation might be written:

$$\sigma \vec{E}^2 + \nabla.K\nabla.T + \nabla.K\nabla.T - \rho\vec{v}C_p\nabla.T + \left[1 - \rho\left(\frac{\partial h}{\partial p}\right)_T\right]\vec{v}\,\nabla.p - S(T,p) = 0 \qquad (2)$$

It includes terms for the electrical input, for molecular and turbulent* conduction, the so-called flow terms, namely convection and expansion, and the radiation term.

Within the scope of this investigation, we are mainly interested in the turbulent term. For this reason it is desirable to look for such arc conditions, in which as many of the other terms as possible are negligible or only small corrections. The radiation term and both flow terms are therefore discussed in more detail in the following section.

2.1.1 Radiation

Our quantitative knowledge of the radiative losses of plasmas is rather meager. It is known, however, that the continuous Bremsstrahlung is a powerful energy term in plasmas of both high temperature and high pressure(13,14,15,5). Maecker(7,6) has measured the total radiation of nitrogen arcs of 1 atm. for temperatures between 10,000 and 16,000°K. In these measurements, line radiation is included along with the continuous radiation. The data, which were taken for arcs in a 5 mm diameter tube, can be used for an estimate of the total radiation of arcs, which are burning at higher pressures and in tubes of larger diameter. For this estimate it has to be observed, that radiation is proportional to the plasma volume, if an optically-thin layer is assumed. The pressure dependency of radiation is somewhat more complicated, but at moderate temperatures a linear relationship between pressure and total radiation is likely (16).

Taking these points into account we find that radiation of an arc of 10 atm. which burns in a 1 cm diameter tube can be considered a minor term only if the axis temperature of the arc is lower than 8,000°K.

* The term for turbulent conduction is tentatively written employing the representation of Prandtl's mixing length theory.

2.1.2 Flow Terms

The flow terms, namely convection and expansion, are in a similar way as the Reynolds number, dependent on such important arc parameters as velocity and density. However, both flow terms are also, in contrast to the Reynolds number, proportional to the derivatives of temperature and pressure. It is because of these gradients, that one can hope to make the flow terms small and yet retain Reynolds numbers high enough for turbulent experiments. Such a condition with small temperature and pressure gradients may be found, as has also been pointed out by Emmons and Land(3), in the fully developed flow region of an arc in a long tube. But even in this region the flow terms do not vanish completely. A finite axial pressure gradient is necessary to maintain the flow. An axial temperature gradient is, by means of the pressure dependency of the electrical conductivity, coupled with this pressure gradient.

2.1.3 Flow Tube Experiment

Based on the foregoing discussion parameters for the arc apparatus have been selected. A practical set of these parameters is:

Tube Diameter	$d = 1$ cm
Tube Length	$\ell = 100$ cm
Gas Pressure	$p = 10$ atm.
Gas Velocity	$v = 3.10^4$ cm/sec.
Arc Current	$I = 20$A
Gas Kind	Air

There is, however, still one major inadequacy in the proposed set of parameters. Since an arc current of 20A is much too low to heat the full gas stream up to the desired temperatures within the limited length of the tube, the use of longer tubes was considered. But impractically long tubes and extremely high arc voltages in the order of 50,000 volts would be required. Therefore, it was decided to separate the operation of gas heating from the other functions of the flow tube and inject highly pre-heated gas from a plasma-generator into the tube. The pre-heated gas should be even somewhat hotter than required by the arc in the flow tube; then only a short entrance length will probably be required to reduce this temperature to that of the tube arc.

2.2 Methods of Measurement

Because in the fully developed flow region the flow terms and the radiative loss are negligible, a discussion of the measuring methods can be based on a somewhat simpler energy balance than Eq (1), namely:

$$\sigma \vec{E}^2 + \frac{1}{r}\frac{d}{dr}\left[rK\frac{dT}{dr}\right] + \frac{1}{r}\frac{d}{dr}\left[rK\frac{dT}{dr}\right] = 0 \tag{3}$$

which includes the terms for the electrical input and for the radial heat losses by thermal and by turbulent* conduction.

This equation has been thoroughly discussed for the laminar case, in which the turbulent term can also be neglected[2]. In this case, the heat transfer Q to the tube wall was found[2] to be per cm:

$$Q = I.E = 5\pi f \int_0^{T_0} K\, dT \tag{4}$$

In this equation the factor f varies only slowly with the axis temperature T_0. The heat transfer to the wall is hence for a gas with a given thermal conductivity $K(T)$ only a function of the axis temperature T_0 of the arc.

If the flow is turbulent, the heat transfer to the walls will be increased over the amount specified by Eq (4) for the laminar arc. This means, if both arc current and axis temperature of the arc are the same in the laminar and in the turbulent case, that the electrical gradient of the turbulent arc is bigger than that for the laminar arc. Hence, a comparison of the electrical gradient of arcs in both laminar and turbulent flows can serve as a measure for the significance of the term for turbulent mixing.

Whereas the measurement of the radial heat transport discussed above may give a picture of the overall significance of turbulent mixing in an arc, a closer examination of radial arc properties can show in which parts of the arc turbulent mixing is important. To illustrate this, let us consider a measurement of the turbulent thermal conductivity of an arc in the fully developed flow region.

For this purpose, it is useful first to remember again the laminar case[17]. The "laminar" energy balance is:

$$\sigma \vec{E}^2 + \frac{1}{r}\frac{d}{dr}\left[rK\frac{dT}{dr}\right] = 0$$

Integration over the radius r to r_1, yields:

$$2\pi E^2 \int_0^{r_1} \sigma(r)\, r\, dr + 2\pi\left[rK\frac{dT}{dr}\right]_{r_1} = 0 \tag{5}$$

* The term for turbulent conduction is tentatively written employing the representation of Prandtl's mixing length theory.

This equation states that the electrical power input into the plasma within a cylinder of radius r_1 is equal to the heat flux out of the surface of this cylinder. Solving this equation for the thermal conductivity κ gives:

$$[\kappa]_{r_1} = \frac{E^2 \int_0^{r_1} \sigma(r) r dr}{\left[r \frac{dT}{dr}\right]_{r_1}} \tag{6}$$

The molecular thermal conductivity κ can according to this equation be calculated, if the electrical gradient E, the local electrical conductivity $\sigma(r)$ and the temperature gradient $\frac{dT}{dr}$ are known. The required data can be obtained by measuring the radial temperature distribution $T(r)$, the electrical gradient and the arc current.

If we consider the well known expression for the electrical conductivity

$$\sigma = \frac{n_e e^2 \Lambda}{m_e v_e} \tag{7}$$

the measured temperature determines the electron velocity directly and the electron density with help of the Saha equation. The value for the mean free path Λ in Eq (7) can be taken from the literature. As to the latter point it may be interesting to observe, that we do not depend on the absolute value of Λ , because the measured total arc current permits a check on the calculated values of the electrical conductivity, if we integrate $\sigma(r)$ over the radius.

The effective thermal conductivity in the presence of turbulence can be measured in a similar manner. Starting with Eq (3) and going through the same formal derivation which led to Eq (6), we get:

$$(\kappa + K)_{r_1} = \frac{E^2 \int_0^{r_1} \sigma(r) r dr}{\left[r \frac{dT}{dr}\right]_{r_1}} \tag{8}$$

In this equation however, two properties are unknown, namely the "turbulent" values for the thermal and for the electrical conductivity. Fortunately however, as we have seen in the last section, only the radial distribution and not the absolute value of the electrical conductivity is of importance for the calculation of the thermal conductivity according to Eq (6) or Eq (8). It should therefore, be a reasonable approximation, to use, instead of the unknown turbulent, the known laminar electrical conductivity.

There are, however, some other more serious problems associated with a measurement of the turbulent thermal conductivity according to Eq (8). These arise from the very fact that the temperature fluctuates in turbulent flow. To understand the implications of these fluctuations, let us first consider that the temperatures are measured spectroscopically with a photographic technique. With such a technique the time average values of the brightness of spectral lines can be determined. Unfortunately, the brightness of spectral lines depends in general in a non-linear way on the temperature. For this reason, as can be seen, average brightness does not truly represent average temperature. The deviation depends on the amplitudes of the fluctuations and is small only for moderate fluctuations. There is, however, for all radiation from thermal plasmas, a certain limited temperature range in which brightness is proportional to temperature. In this range the time average of brightness can represent the average temperature.

3. APPARATUS

In order to perform the experiments, several pieces of equipment had to be developed. Some have unusual features and are therefore described in more detail.

3.1 Plasma Pre-Heater

As discussed in 2.1.3, a plasma pre-heater is required, which is capable of transferring a power of about 1 MW to a gas of 10 atm. pressure and to heat the gas to a temperature of the order of $10,000^{\circ}K$.

There are plasma generators known which can perform the required duty[18,19,20]; however, none of them were available for this investigation. Also, most plasma generators in use today are capable of performing for much longer periods of time than is necessary for these experiments. It is for this reason of long operational time, that the arcing chambers of the conventional plasma generators have water-cooled copper walls, a feature which makes the design elaborate and expensive. In contrast to this, other devices for the generation of high temperature, like shock tubes, do not need water-cooling, because they operate only for durations of a few milliseconds.

Our experiments can be performed in times of the order of 1 sec. For this reason water-cooling of the walls was dispensed with and a new, simple and inexpensive plasma generator was designed.

3.1.1 Design of Ablation Type Plasma Generator

The design of the plasma generator is schematically shown in Figure 2. The electric arc burns in a cylindrical duct of insulating material, which is evaporated and heated up to plasma temperature. A plasma jet, which consists entirely of the evaporated wall material leaves the arcing chamber through an exit nozzle half-way between the electrodes. The electrodes are hollow graphite cylinders which are mounted in copper heat sinks. The heat sinks serve several purposes. They separate the hot carbon electrodes from the arcing duct and keep the arcing chamber pressure tight. Also the connections for the electrical power are bolted to them.

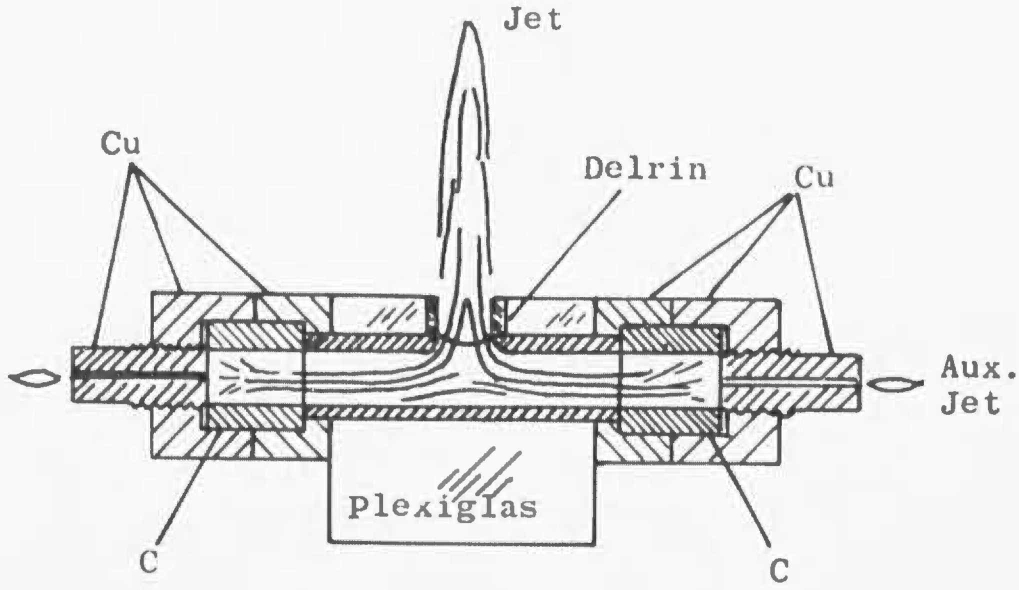

Figure 2 - Schematical Arrangement of the Ablation Type Plasma Generator

Besides the main nozzle there are two small auxiliary nozzles in the electrodes. They allow a small flow of plasma from the arc duct through the hollow electrodes to the ambient. This flow will in effect minimize the amount of electrode material in the main jet[21].

In Figure 3 an exploded view of a particular design is shown. The arcing duct is a readily exchangable cylinder of Delrin* which is slipped into a plexiglas block, to which the heat sinks are bolted. Other little exchangable ducts of Delrin and plexiglas form the main arcing nozzle and the two auxiliary nozzles. The generator is usually ignited by a thin metal wire, connecting the electrodes.

Figure 4 shows a still picture of a slightly modified version of the generator in action. Arc, main jet and the two auxiliary jets are readily recognized.

* Delrin is a Dupont plastic with the Brutto formula $(CH_2O)_n$.

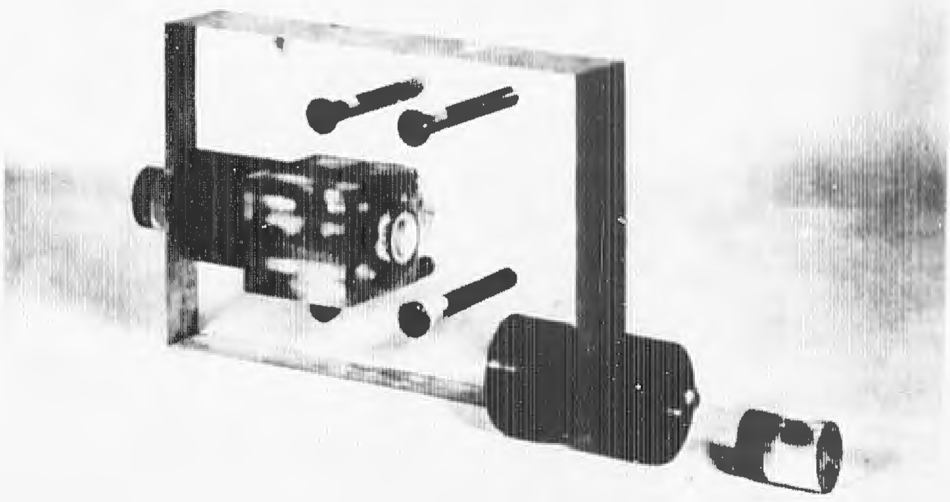

Figure 3 - Exploded View of 300 KW Ablation Type Plasma Generator. Plexiglas Choke has no Bore in this Particular Design

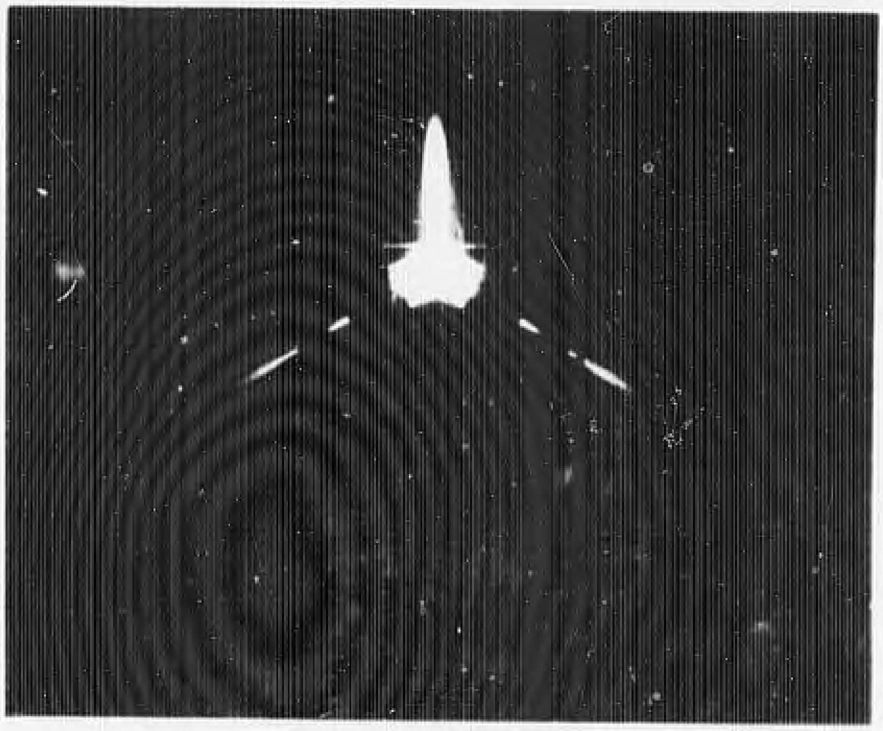

Figure 4 - Ablation Type Plasma Generator in Action. Design is Slightly Modified as Compared to Figure 2 and Figure 3. Arc, Main Jet and Two Auxiliary Jets are Readily Recognized.

3.2 Flow Tube and Associated Equipment

The flow tube is essentially a stack of copper plates with a central bore of 1 cm. The plates are electrically insulated from each other by polyethylene spacers. Such a "cascade arc" was first built by Maecker(23,24) and has since been utilized in the literature extensively.

As was mentioned earlier, only a duration of about 1 sec. is needed to perform the turbulent experiment. For this reason, the heat capacity of the copper plates can be used to absorb the radial heat flux from the arc and the elaborate water-cooling system for the plates can be eliminated. This simplicity of the flow tube also permits a high degree of flexibility in design. Copper plates can for instance be readily exchanged against new ones with other bores and also measuring equipment such as probes has a rather convenient access to the arc column. The copper plates are only 1 mm. thick; thinness of the plates has been found to be of importance for arcs with high electrical gradients(25).

Figure 5 shows details of the assembly of the copper discs in a 2" plexiglas tube, which is used to hold and center the stack. Fine alignment of the plates is made with a steel rod of precisely 1 cm. diameter, which is carefully pushed through the bore.

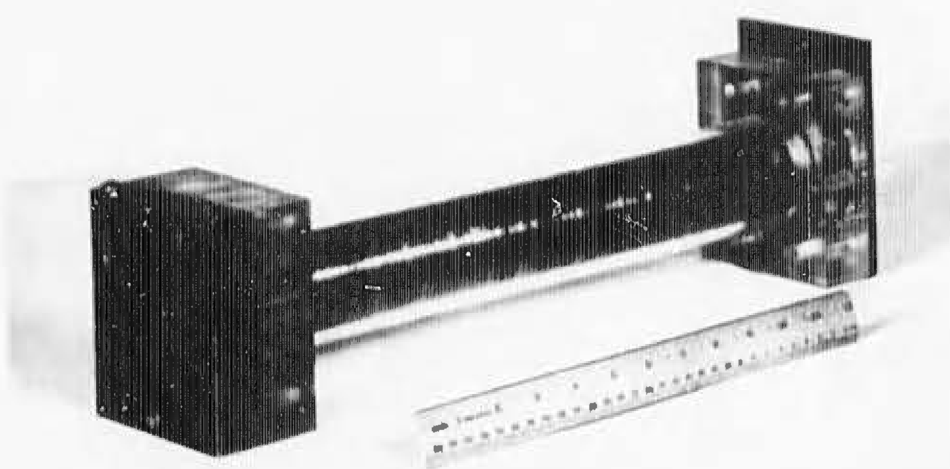

Figure 5 - Photograph of Flow Tube. Copper Discs are Held and Centered in a 2" Plexiglas Tube. Discs are 5 mm, Instead of 1 mm Thick in this Particular Design

The tube has end plates, one of which contains a hollow carbon electrode, whereas the other serves as a hold for a strong spring, which compresses the stack. The location of the electrodes and other details of the tube design can be recognized from the schematical Figure 6.

A picture of the total arc apparatus, which consists of the plasma generator, the flow tube and an exhaust tank is shown in Figure 7. The exhaust tank, into which the plasma is discharged after leaving the flow tube, has a volume of 18 feet^3 and can be used for pressures up to 300 p.s.i.

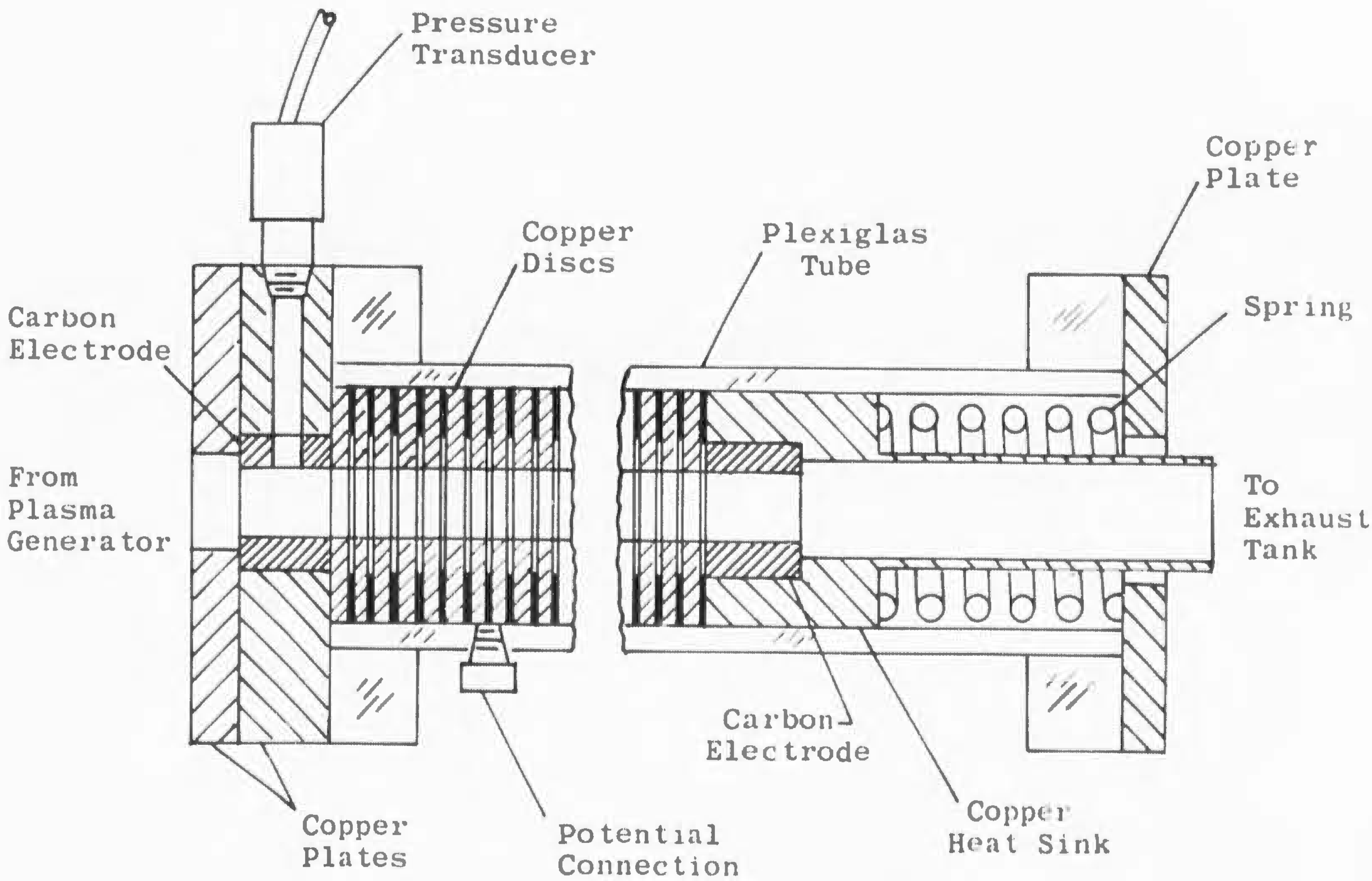

Figure 6 - Schematic Picture of Flow Tube, Showing Details of Design

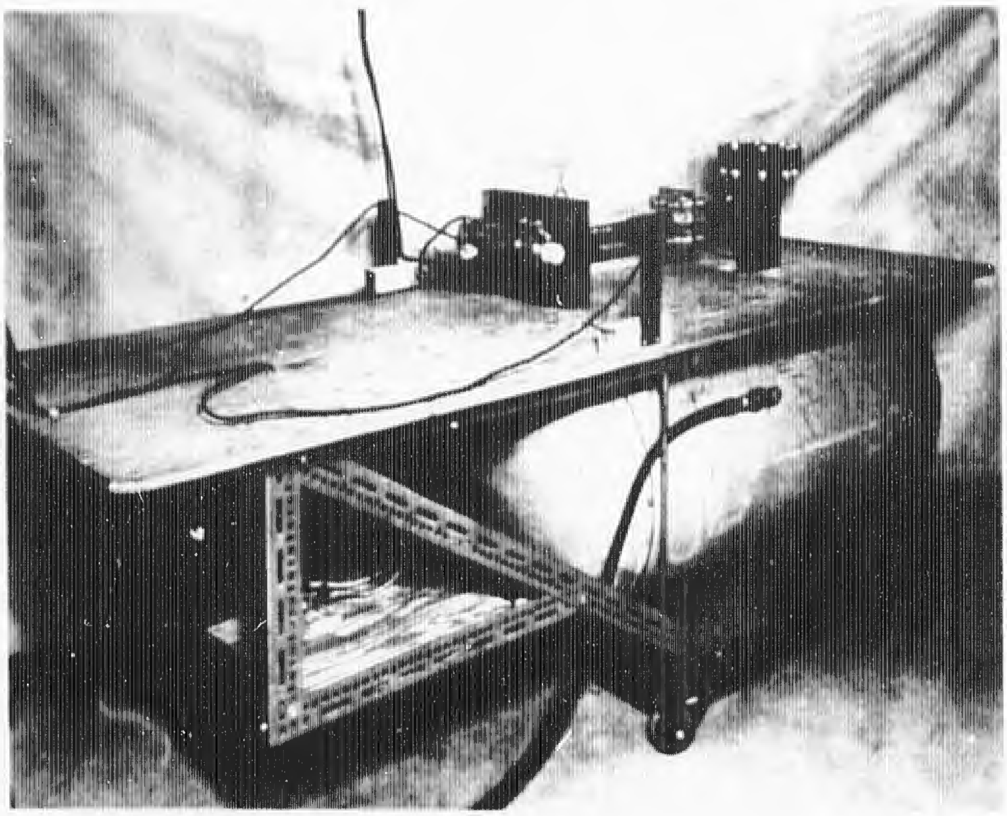

Figure 7 - Photograph of Assembled Flow Apparatus, Showing Plasma Generator, Flow Tube, and Exhaust Tank

3.3 Power Sources

The plasma generator and the flow tube arcs were operated on separate DC-power sources. For the plasma generator several supplies were used during the different phases of the work including a D-C generator delivering 20,000A at 1400 volts (for 1 sec.). For the flow tube a 3 Ø bridge rectifier was available, which delivers 50 amps at 10,000 volts.

3.4 Measuring Equipment

The plasma generator and the flow tube arc were electrically connected during operation, Figure 8. For this reason only the current in the flow tube arc was measured with a shunt. The plasma generator current was measured with a Hall probe, utilizing the magnetic field of a solenoid through which the generator current flows. Isolation of the solenoid, which is at high potential from the grounded Hall probe, was easily achieved. Care was taken to get a mechanically stable set-up of solenoid and Hall crystal. The probe was calibrated with a current of known value. The overall sensitivity was 1 mv/amp.

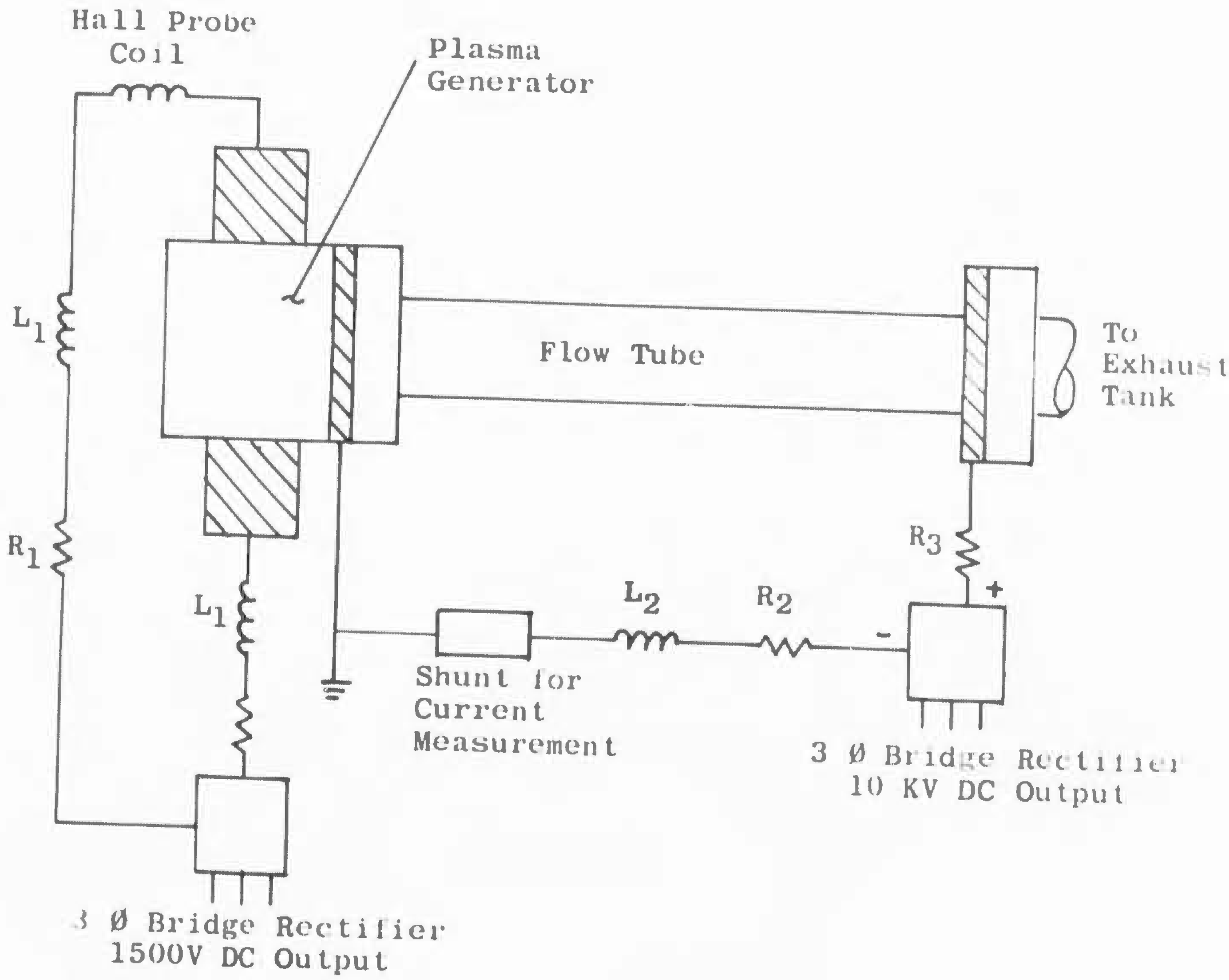

Figure 8 - Electrical Diagram of Power Supplies for Plasma Generator and Flow Tube Arc. The Circuits are Electrically Connected During Operation by the Plasma Jet of the Generator. R_1, R_2 and R_3 are Resistors; L_1 and L_2 are Reactors.

For the measurement of the voltages, a set of ten ohmic voltage dividers was built, each having a total resistance of 6 MΩ and a dividing ratio of 1000:1.

Pressures were measured with dynamic transducers* and charge amplifiers, which permit measurements of pressures as low as 1 p.s.i. with signals of 100 mv/psi.

All measuring signals were recorded with cathode ray oscilloscopes.

* Kistler Gage 601A and Amplifier 566.

4. EXPERIMENTS

4.1 Performance of Plasma Generator

For the ablation type plasma generator, which was described in 3.1, measurements of voltage current characteristics and erosion rate were performed. It was found that the voltage-current characteristics can readily be influenced by changes in:

duct diameter
duct length
duct material
operating pressure

In the following section, data are presented which have been made at an operating pressure of 1 atm. and with the duct materials, plexiglas and Delrin. Figure 9 shows, for example, the characteristics for generators with 4" long plexiglas ducts of 3/8" and 1/2" duct diameter. The current was varied from 50 to 650A. The arc voltage has a characteristic minimum around 250A for both ducts and rises markedly at higher currents. The voltage of the arc in the 3/8" duct is always higher than that of the arc in the 1/2" duct.

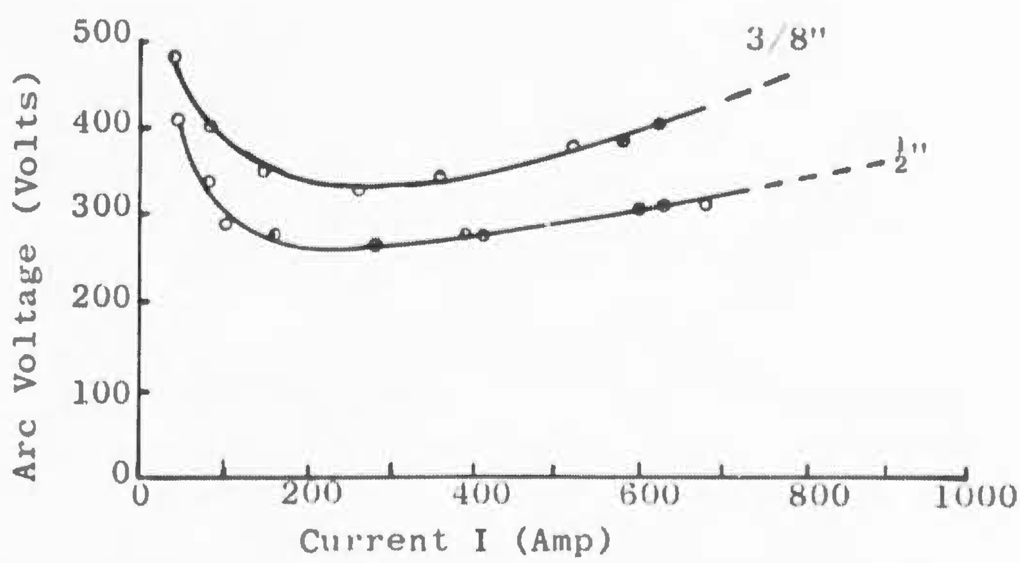

Figure 9 - Current Voltage Characteristic of Ablation Type Plasma Generator, Discharging into Atmosphere.
Duct Length 4"
Duct Diameter 3/8" and 1/2"
Material - Plexiglas

In Figure 10 results of measurements are plotted for a plexiglas duct of 6" length and 1" diameter. Also this curve has a falling and a rising part, the minimum however, is drastically shifted to higher currents around 1000A. Maximum power input into this generator was 2 MW at a current of 3000A.

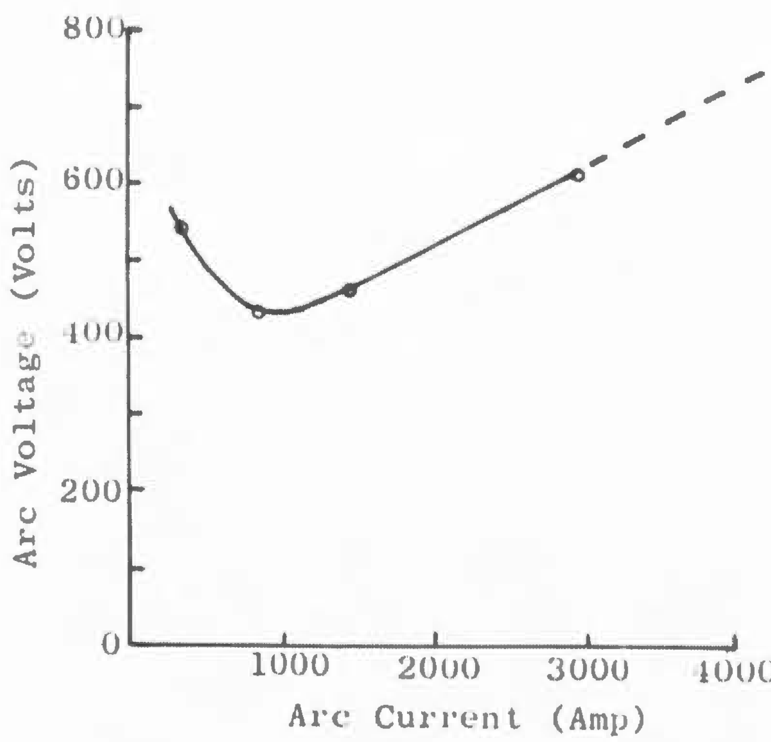

Figure 10 - Current Voltage Characteristic of Ablation Type Plasma Generator Discharging into Atmosphere
Duct Length 6"
Duct Diameter 1"
Material - Plexiglas

Besides the voltage-current characteristic, erosion rates were determined in a limited power range. Figure 11 and Figure 12 give the erosion versus arc energy for plexiglas and Delrin ducts. The curves indicate a linear increase of the erosion in the energy range of 20-120 KW sec. with deviations from this linearity both above and below this range.

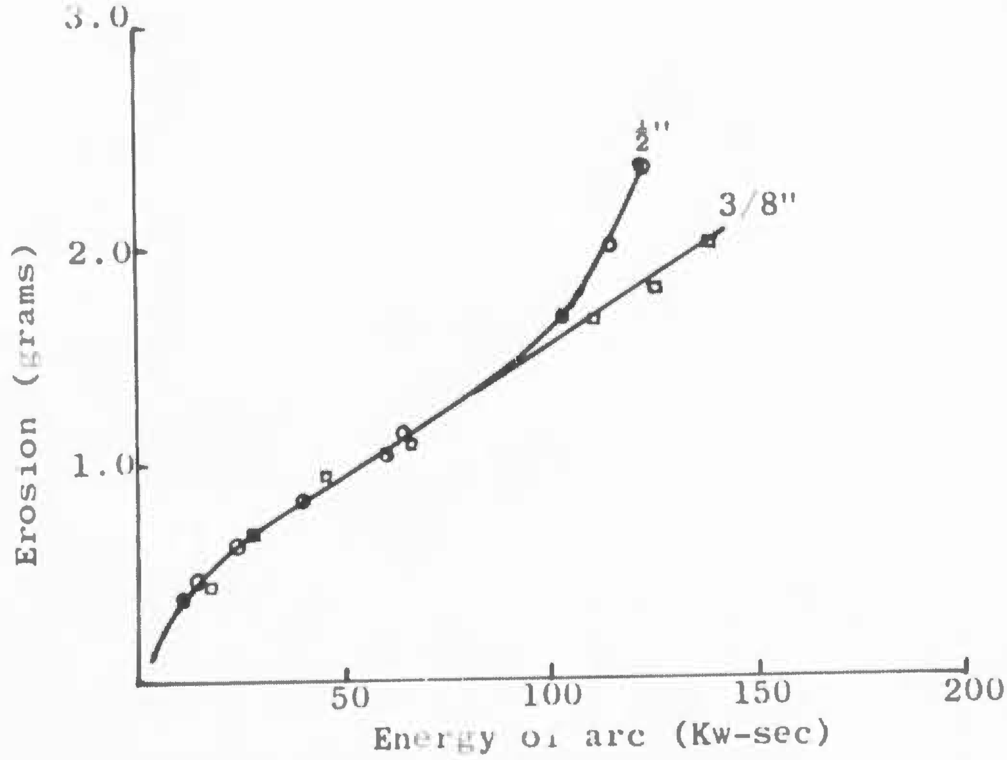

Figure 11 - Erosion of the Generator Insert as a Function of Arc Energy.

Material - Plexiglas
Duct Length 4"
Duct Diameter 3/8" and 1/2"

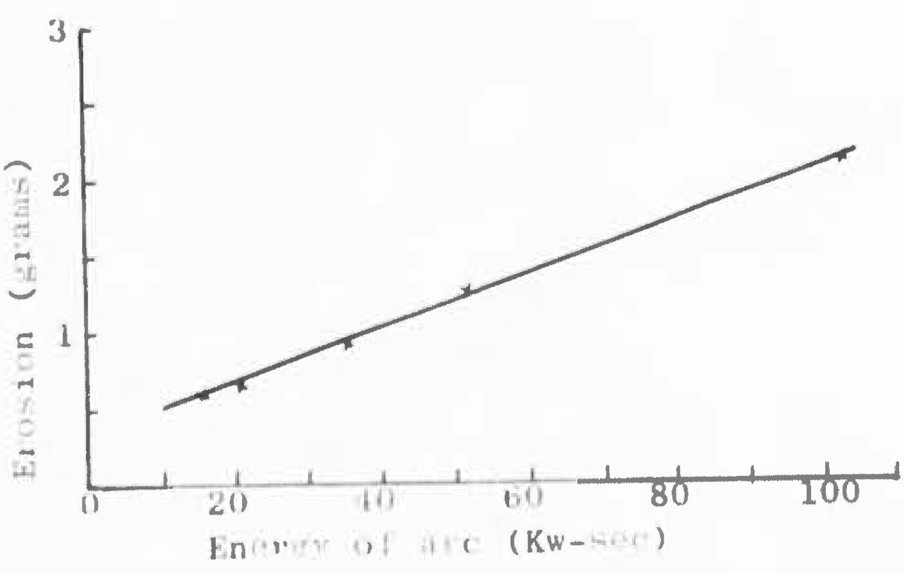

Figure 12 - Erosion of the Generator Insert as a Function of Arc Energy

Material - Delrin
Duct Length 4"
Duct Bore 1/2"

No temperature measurements of the arc or the jet of the plasma generator have yet been performed. An estimate of the arc temperature however, can be made, if we use an approximate formula[21] for the arc temperature as a function of arc current, electrical gradient and duct radius, namely:

$$T_0 = \left[\frac{3.36 \times 10^4 I}{\left(\frac{d}{2}\right)^2 E} \right]^{2/3} \tag{7}$$

This formula was derived from the current transport equation assuming a high degree of ionization and a parabolic temperature distribution. $d/2$ is the duct radius in cm, I is the current in amp., E the electrical gradient in V/cm and T the temperature in °Kelvin.

For a current of 500A, an electrical gradient of 40 V/cm and a duct-radius of 0.478 cm (3/8"), Eq (7) gives an axis temperature of:

$$T_0 = 15{,}000\,^\circ K \tag{8}$$

This value is plausible also for another reason. The voltage characteristic of the 3/8" generator rises markedly at high currents. This indicates, that the degree of ionization is high and the electrical conductivity increases only slowly with a further temperature increase. For this reason the electrical gradient has to increase if the current is to grow.

In this context it may be interesting to note that the minimums in the current-voltage characteristics of all the water stabilized arcs[21] also occur in the neighborhood of 15,000°K.

4.2 Voltage Gradients in Flow Arcs

As discussed in 2.2, the electrical gradient of arcs in the fully developed flow region can serve as a measure for the efficiency of turbulent mixing, if certain precautions are taken.

We therefore measured the arc potential along the axis of flow tube arcs of 37 cm length and 1 cm diameter. For these measurements several of the insulated copper discs, which comprise the flow tube, served as probes. All voltage measurements were made with identical voltage dividers of 6 MΩ resistance.

In Figure 13, results for measurements in carbon dioxide* at 3.1 atm. are plotted. The lower curve in Figure 13 represents the potential along an arc in a flow field with a velocity** smaller than 20 m/sec. The upper curve gives the data for an arc with a flow velocity of about 250 m/sec.

* The ablation type plasma generator had, in these measurement, inserts made of dry-ice.

** The method for measuring the flow velocities is described in 4.3.

Some results are immediately recognized. Firstly, the voltage gradient is considerably higher at high flow speeds than at low flow speeds. Secondly, the high speed flow arc reaches a condition of constant electrical gradient after a surprisingly short "entrance length". Thirdly, the voltage gradient of the arc with a low flow speed is constant all along the tube.

Figure 14 shows results for similar measurements of the arc potential in arcs burning in a stochiometric mixture of carbon monoxide and hydrogen*, the pressure being 1 atm. The flow velocities have not been determined for these arcs. It is known, however, that they are of the same order of magnitude as the velocities of the carbon dioxide arcs of Figure 13.

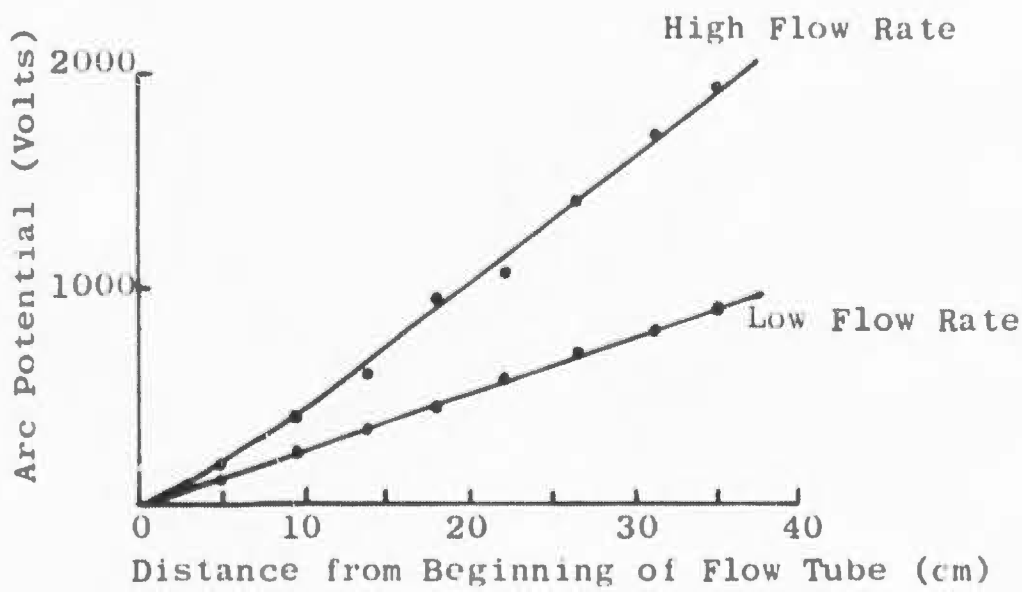

Figure 13 - Arc Potential Along Flow Tube for High and Low Flow Rates.

Tube Diameter:	10 mm
Tube Current:	25 Amp.
Tank Pressure:	3.1 Atm.
Gas:	CO_2

* These are the dissociation products of Delrin.

The qualitative character of the potential curves of the "Delrin" arcs is similar to that of the carbon dioxide arcs. The curve for the low flow velocity indicates a constant voltage-gradient all along the tube, whereas the curve for the high flow velocity shows this constancy only in its latter part. There is, however, one difference between the curves of Figure 13 and Figure 14. At the beginning of the flow tube the carbon dioxide arc has an increasing and the "Delrin" arc a decreasing voltage gradient.

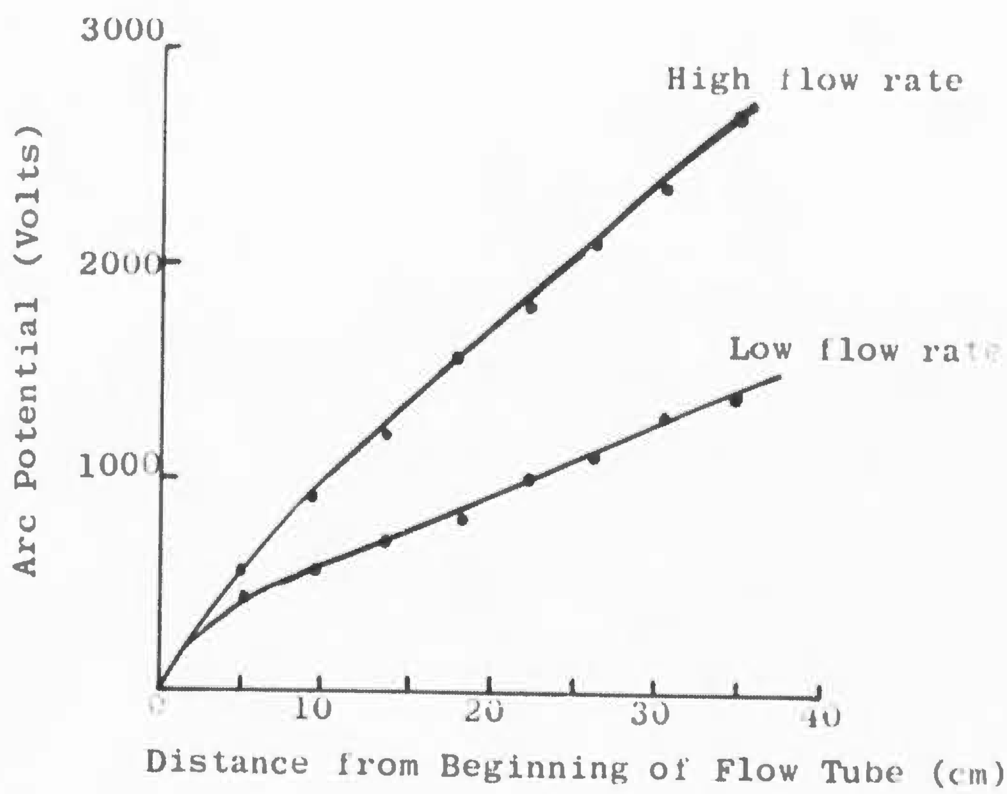

Figure 14 - Arc Potential Along Flow Tube for High and Low Flow Rates

Tube Diameter:	10 mm
Tube Current:	25 Amp.
Tank Pressure:	1 Atm.
Gas:	50% CO 50% H_2

Before we engage in a discussion of the curves of Figure 13 and Figure 14, some results of an optical study of these arcs shall be presented.

4.3 High Speed Motion Pictures of Slow Arcs

The flow tube, on which the data for Figure 13 and Figure 14 were taken, consisted essentially of a stack of copper discs, as described in more detail in 3.2. Such an arrangement is not suited for making high speed pictures of the arcs. Fortunately however, the flexibility of our flow tube design allowed a simple replacement of the stack of copper discs by a quartz tube. The quartz tube was 37 cm long with 10 mm inner and 12 mm outer diameter.

In this tube carbon dioxide arcs were burned under similar conditions as in Figure 13. The arcs were photographed with a Dynafax* camera, which can take 26,000 pictures per second with exposure times as short as 1 μ sec. Figure 15 shows on the left a sequence of arc pictures taken at low, and on the right another sequence taken at high flow velocity. The exposure time of each picture was 2.5 μ sec., with 100 μ sec. between exposures.

Flow Direction ↓

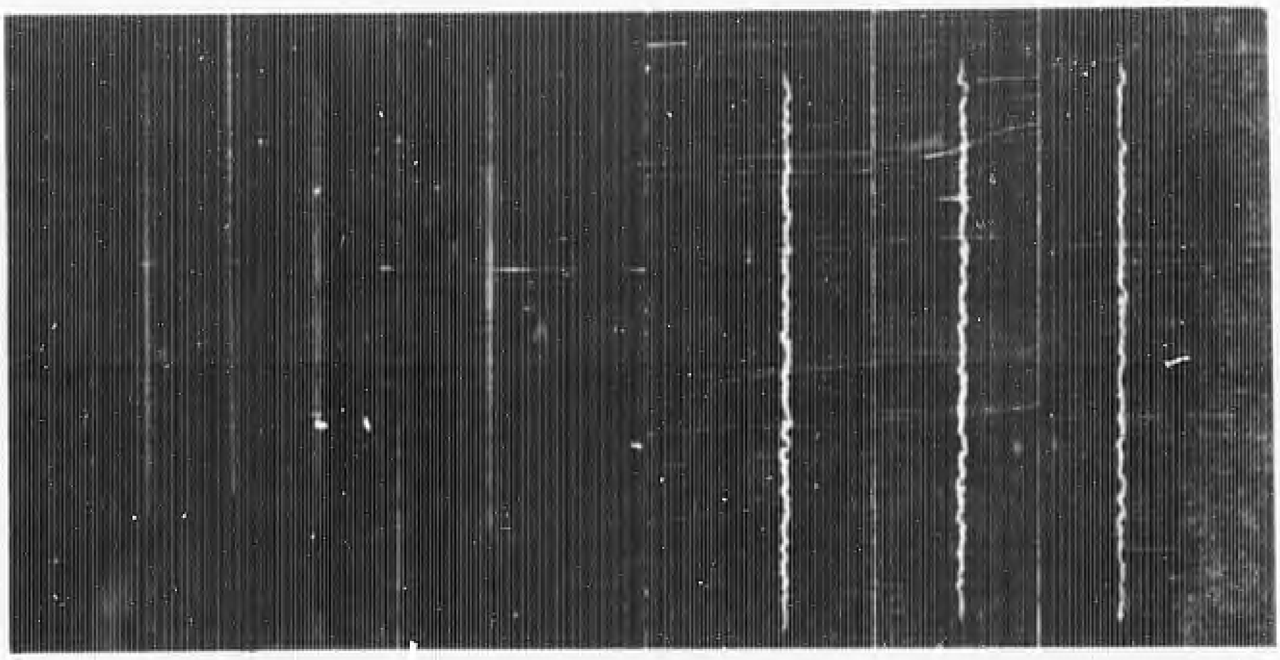

Figure 15 - High Speed Photographs of Long Arcs with Low and High Flow Velocities. Arcs were Confined within a Quartz Tube. Flow Direction is From Top to Bottom.
Left Group of Arcs: Flow Speed $<$ 20 m/sec.
Right Group of Arcs: Flow Speed $\approx$ 250 m/sec.
Current - 25 Amp.
Pressure - 3.1 Atm.
Gas - CO_2
The gaps in the three pictures on the left are not real, but are caused by optical obstructions.

* Trademark of the Beckman and Whitley Co., San Carlos, California

There is obviously a major difference in the appearance of the two arcs of Figure 15. For this reason it was decided to photograph also arcs with intermediate flow velocities. Figure 16 shows arcs with a wide range of different flow velocities; it appears, that "irregularities" originate at the beginning of the flow tube. They penetrate deeper into the tube for higher flow velocities. At a speed of 250 m/sec. the full length of the tube shows the violently moving arc-core. It is also noted, that the luminous core in the "irregular" moving mode is only about half as thick as in the quiet arc in the apparently laminar mode, which fills about 2/3 of the tube diameter.

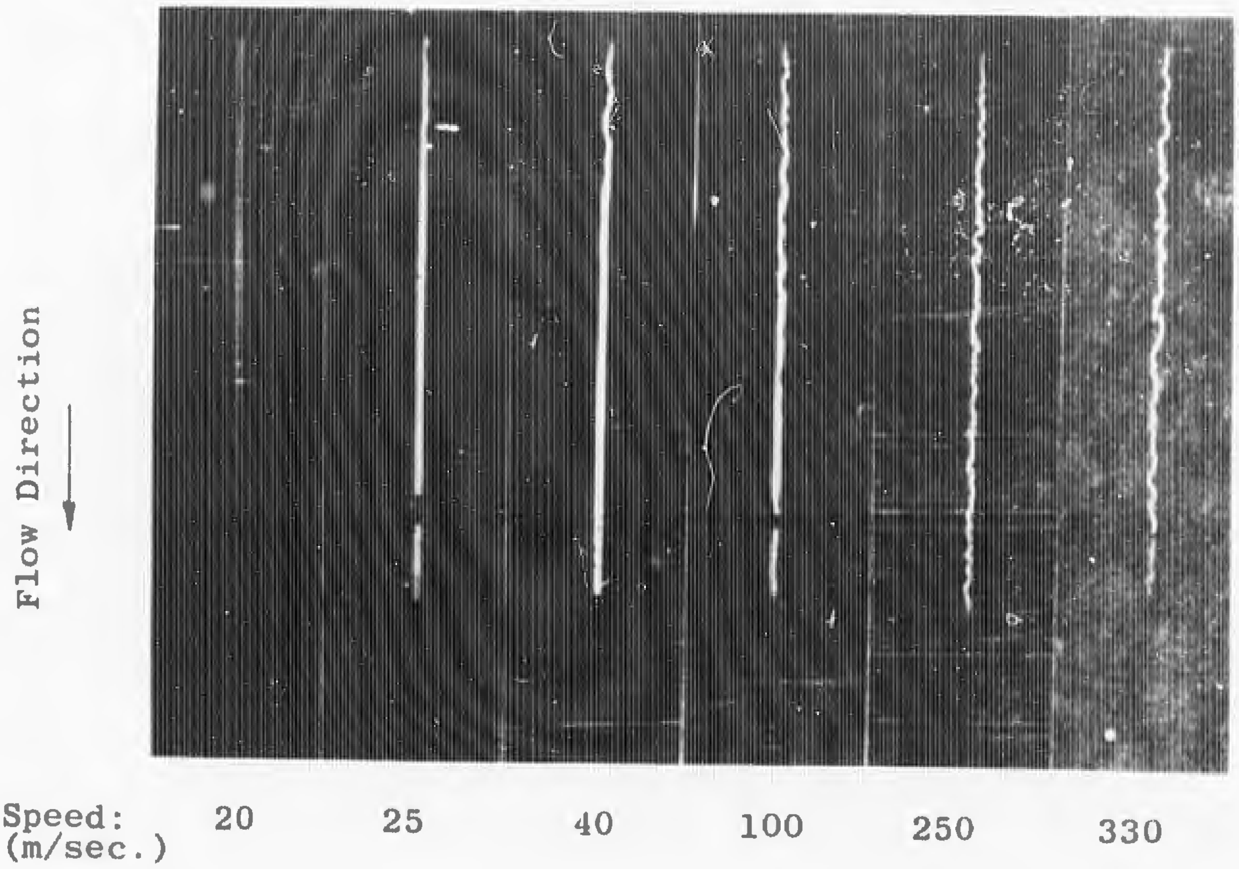

Figure 16 - High Speed Photographs of Arcs. Flow Speed Increases from Left to Right.

Current: 25 Amp.
Pressure: 3.1 Atm.
Gas: CO_2
Tube Diameter: 10 mm

The gaps in the pictures are caused by optical obstructions.

High speed pictures were also used to determine the flow velocities in the tubes. For these determinations it was assumed that at least some of the stronger kinks in the irregular arc shapes were not produced by a wave motion but by more or less irregular motions of the gas mass. Figure 17 shows, as an example, the flow velocity along the high-speed flow arc of Figure 15. The data are somewhat scattering. But in spite of this, it appears that the flow velocity does not reach constant values but is still growing even at the end of the flow tube; a point which is of importance for the discussion of the experiments in Section 5.

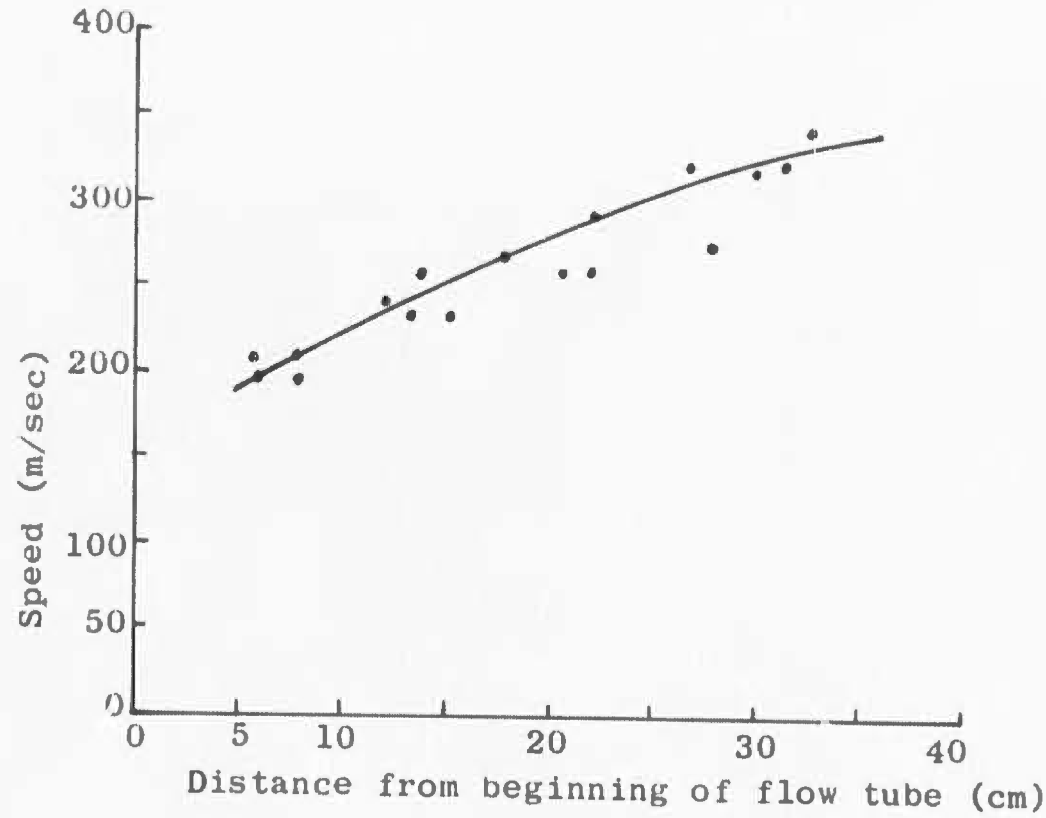

Figure 17 - Speed of Plasma Increases as a Function of the Distance from the Entrance of the Flow Tube

Current:	25 Amp.
Pressure:	3.1 Atm.
Gas:	CO_2
Tube Diameter:	10 mm

4.4 Estimate of Arc Temperatures

It was shown in Section 2.2, that the axis temperature should be kept constant, if laminar and "turbulent" arcs are compared. However, no temperature measurements have been performed in this investigation, except that an estimate of an upper limit for the axis temperature of the arcs of Figure 16 was made. This estimate is based on the spectroscopic observation, that these arcs had a band spectrum and no continuum. According to this, the arc temperatures were lower than 10,000^{o}K.

A hint regarding the desired constancy of the arc temperature in the laminar and "turbulent" mode can be taken from the fact that the arc brightness was about the same in both cases, whereas it changed considerably with the arc current.

For these reasons it was concluded, that there was no big difference in the axis temperatures of the laminar and the "turbulent" arcs.

5. DISCUSSION OF EXPERIMENTS

The performance of the plasma generator was reviewed in 4.1. We discuss therefore, here only the results concerning the flow tube experiments.

The pictures in Figures 15 and 16 give a clear impression, that the flow velocity, and this means the Reynolds number, has a major influence on arcs in a flow tube. At low flow velocities the arcs are very quiet and apparently in the laminar mode. This view is also supported by the low voltage gradient of this arc, (Figure 13), which is the same as without flow. At high flow velocities the luminous parts of the arcs exhibit violent motions, which appear to be irregular. However, pending the proof that these motions are really random, the phrase "turbulent" shall be avoided. It is in this context quite interesting, to observe how in the pictures of Figure 16 an initial irregular motion gets damped out on its way through the flow tube. The motions penetrate deeper into the tube with higher flow velocities. Such a behavior is to be expected from an initially turbulent motion in a flow field, which is still laminar but comes close to the transition to turbulent flow.

The high values for the electrical gradient of the high speed flow arcs in Figures 13 and 14 seem on the first view to be a consequence of the violent motions of these arcs. Moreover, the constant voltage gradient suggests that fully developed flow is reached. Figure 17 shows however, that a constant or at least a nearly constant flow velocity, which is one of the conditions of fully developed flow, is not yet reached. Therefore, it cannot be excluded that still major flow terms contribute to the energy balance. Hence, the difference between the energy input into the high and the low speed flow arc cannot be attributed to the arc motions alone.

6. SUGGESTIONS FOR FUTURE WORK

One obvious conclusion can be drawn from the discussion in the last section, namely, further measurements should be made on longer tubes to establish conditions of fully developed flow and further minimize the flow terms to a negligible magnitude. The radial heat flux to the tube walls should also independently be measured by a caloric technique.

Another important future project is temperature measurements. These are required to define the arc conditions for the radial heat flux measurements and also for more detailed studies of turbulent structure.

The application of Schlieren and shadowgraph techniques, in combination with high time resolution, may give qualitative information about the character of the flow field and possibly about eddy size. The use of these techniques is also being considered.

7. APPENDIX

7.1 Schlieren Light Source

Application of the Schlieren or shadowgraph technique to the investigation of high temperature plasmas requires the use of a light source which is much brighter than the plasma itself. For example, in a recent investigation(26) the light from a ruby laser was used. Also powerful sparks, exploding wires or certain types of flash lamps might be suited for that purpose. All these sources have a very short operational time. This is an advantage, if the light source is also used as time resolving element. We want, however, to use the light source in connection with a high speed camera. A longer operational time of the light source will then give a larger number of consecutive pictures.

For this purpose a high pressure argon lamp was built with an operational time of the order of 10^{-3} sec. One particular design is shown in Figure 18. The 1/4" tungsten electrodes are held by metal caps, which also keep the strong plexiglas tube pressure tight. A little "cascade" chamber can be slipped into the tube to further confine the arc. The cascade chamber is open on one side for the light.

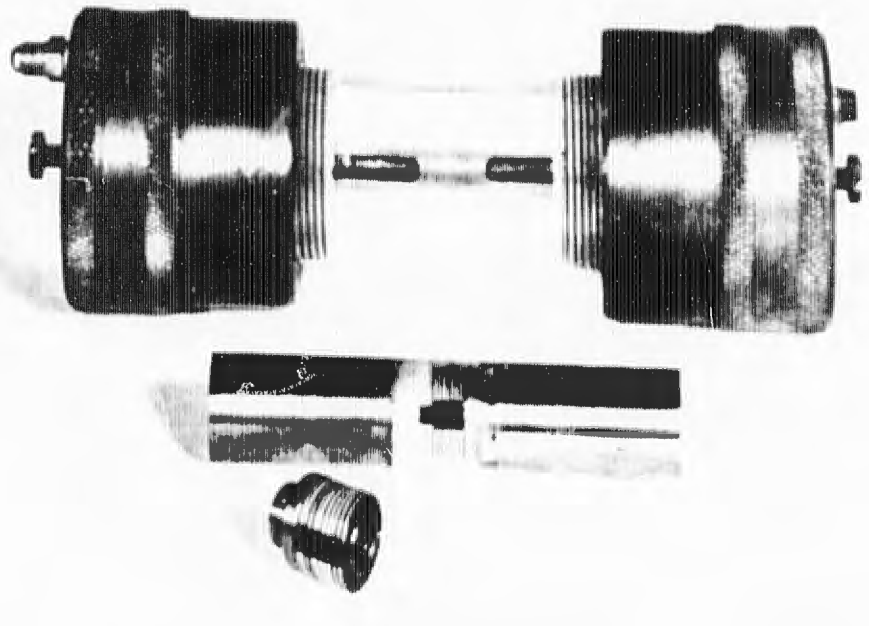

Figure 18 - Exploded View of High Pressure Argon Lamp, Showing Details of Cascade Chamber. Diameter of Electrodes 1/4"

Some experiments have been made with a slightly modified version of this lamp. The electrodes were graphite, and instead of the cascade chamber, a little plexiglas tube with an inner diameter of 5 mm was slipped between the electrodes. Other test data were:

argon pressure	p	=	70 Atm.
arc length	ℓ	=	10 mm
current	I	=	3000A

Using a half cycle pulse of current (equivalent 350 c.p.s.)from a capacitor bank, the brightness of this lamp was compared with that of the carbon crater of McPherson-Euler. Both light sources were photographed with a dynafax camera. Care was taken that the optical system was identical for all photographs and both light sources were photographed on the same film strip. Grey filters of known transmission were used for the intensity steps. The results of these tests showed that the argon lamp was 33 times brighter than the carbon crater as measured by the blackening of tri-X film. Also, the lamp had a useful duration of about 500 μ sec. It is believed, that these values of the brightness and duration are close to what we need for Schlieren experiments with our arcs. Moreover, it appears that the limits for this lamp in regard to brightness and duration have not yet been reached. It is thought, that the addition of the cascade chamber (Figure 18) will permit the use of longer half cycles and also higher currents.

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