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ELECTRIC ARCS IN TURBULENT FLOWS, II

GERHARD FRIND
GENERAL ELECTRIC COMPANY
PHILADELPHIA, PENNSYLVANIA

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Contract AF 33(657)-8206
Project 7063

AEROSPACE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This interim report was prepared by the Engineering Research Section of the General Electric Company, Power Transmission Division, Philadelphia, Penna. 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, 1964 and the report manuscript was completed in June, 1965.

The author wishes to acknowledge the very able assistance of Messrs. J.J. Narbus and H.A. Smith. Mr. Smith designed the electrical power supplies, the control system for the experiments and also the electronic switch. Mr. Narbus assisted in design and development of arc apparatus and measuring equipment. He also conducted the experiments and collected most of the data.

The author also thanks Mr. W.D. Breingan for mathematical assistance, Dr. P. Barkan for stimulating discussions of the aerodynamic aspects of this paper, and Dr. T.H. Lee for continued support and enccuragement.

Critical discussions were also conducted with members of the Thermo-Mechanics Research Laboratory of ARL and the author likes, in particular, to thank Drs. J.G. Skifstad and H.O. Schrade for their help in focussing of problems.

ABSTRACT

Turbulent heat transfer in axial flow electrical arcs has been experimentally studied. The arcs were operated with argon in the current range of 10 to 100 amps, with pressures of 1 to 10 atm., and with flow rates of 0.02 to 35 grams/sec. The flow tubes employed were 75 cm long and had inner diameters of 0.5 and 1.0 cm.

It was found that the arc potential increased linearly along most of the tube length for all flow rates. Also, calorimetric measurements at the end of a flow tube with 0.5 cm diameter showed close agreement between wall heat flux and electrical input per cm for all flow rates. This, together with a careful estimate of the remaining flow terms, showed that a fully developed temperature profile had been achieved.

The arcs at high flow rates showed considerably larger electrical gradients than the arcs at low flow rates. In addition to this, high speed photographs revealed that increased electrical gradients were accompanied by the onset of disturbances of the plasma column. At conditions of the highest flow rates and electrical gradients achieved, the arcs appeared to be strongly turbulent, with the arc column "broken up" into plasma globules of irregular shapes and sizes.

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LIST OF SYMBOLS

C_p	Specific Heat at Constant Pressure
d	Tube Diameter
E	Voltage Gradient
h	Enthalpy
I	Current
ℓ	Length of Tube
N_{conv}	Convection Term per cm Arc Length
N_{exp}	Expansion Term per cm Arc Length
N_{visc}	Viscous Heating Term per cm Arc Length
p	Pressure
Q_r	Radial Heat Flux to Wall per cm Arc Length
r_o	Radius of Tube
S	Radiation Term per cm^3
Δt	Time Duration
T	Temperature
T_o	Temperature in Axis of Cylindrical Arc
ΔT	Temperature Difference
$\vec{v}$	Velocity
V	Volts
v_z	Z - Component of Velocity
w	Flow Rate (gr/sec.)
z	One Dimensional Coordinate
z_r	Relative Arc Length

LIST OF SYMBOLS (Cont'd)

ϑ	Arc Radius
κ	Thermal Conductivity by Molecular Diffusion
κ_t	Thermal Conductivity by Turbulent Diffusion
μ	Viscosity
ρ	Density
σ	Electrical Conductivity
ϕ	Viscous Heating Term per cm^3

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1. INTRODUCTION

1.1 General Remarks

At present there are many groups working with electrical arcs in laminar flow fields[1,2,3,4,5,6], but information pertaining to arcs in turbulent flows is rather meager. Turbulent effects however, must be expected to occur in certain types of high speed flow arcs, particularly if the pressure of the arcs is considerably higher than atmospheric[7].

Therefore, an experimental investigation was initiated to study electrical arcs under conditions of axially symmetric, turbulent flow fields. The axial flow arc configuration in its so-called fully developed flow section, is today fairly well understood for laminar flow fields, and can therefore serve as a basis for the study of additional turbulent effects.

Our objectives in this investigation are:

a) To learn in which range of the following parameters namely gas pressure, flow velocity, tube diameter, and arc current, turbulent effects are significant.

b) To measure the radial turbulent heat transfer to the tube walls as compared to laminar heat transfer, and

c) To study the structure of turbulent arcs.

Up to the present time most work has been done towards objectives a) and b), with some first results on c), the turbulent structure.

1.2 Review of Work from Last Year

Part of our work on turbulent arcs has been reported earlier[7]. In this phase, electrical arcs with a current of 25 amps and with a pressure of 3.1 atm. of CO_2 gas were investigated in flow tubes of 37 cm length and 1 cm diameter.

Essentially, two different conditions of the flow field were chosen. One was an arc with a low flow velocity of 20 m/sec., and the other an arc with a high but still subsonic flow velocity of 250 m/sec. In both arcs the distribution of the electrical potential along the tube was measured and high speed motion pictures of the arcs were taken.

Both arcs commonly exhibited a linear increase of the electrical potential along most of the tube. Furthermore, the arcs differed dramatically in two other observations. First, the voltage gradient of the high speed arc was substantially larger than that of the low speed arc. Secondly, the high speed pictures revealed that the low speed arc had a laminar, very stable arc column, whereas the high speed arc column fluctuated violently in the tube. Therefore, one might be inclined to attribute the higher electrical gradients of the high speed arcs to a higher heat transfer to the tube wall due to the wildly fluctuating column.

However, in a subsequent measurement, the flow velocity of the high speed arcs was found to be still increasing considerably at the end of the tube. This observation indicates that fully developed flow was not achieved and prohibits quantitative conclusions as to the amount of radial heat transfer.

1.3 Definition of Work Reported Here

In the following sections we will report on subsequent further work, the aim of which was to measure radial heat transfer independently by a calorimetric method, and to decide on this basis whether the temperature profile was really fully developed. Also, new high speed photographic studies are discussed which, with a high time and spatial resolution, show details of the respective laminar or turbulent structure of the arcs.

In addition to this, the investigated range of arc parameters has been greatly extended to currents between 10 and 100 amps; to gas pressures of 1 - 10 atm; to the tube diameters 5 and 10 mm, and also to argon-plasma, which permits a better comparison of our results with those of other contributors.

2. METHODS

2.1 The Energy Balance

One of our main objectives is a quantitative measurement of radial turbulent heat transfer from an electric arc in axial flow to the surrounding tube wall. It is therefore appropriate to study a rather general energy balance for arcs in some detail. The energy balance* can be written:

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

or

Electrical Input + Laminar Thermal Conduction + Turbulent Thermal Conduction** + Convection + Expansion + Radiation + Viscous Dissipation = 0

As we, within the scope of this investigation, are mainly interested in the turbulent term, it is desirable to look for arc conditions in which as many as possible of the other terms are negligible or only small corrections. As pointed out earlier by Emmons and Land(2), such a situation, with a considerably simpler energy balance, is found in the so-called fully developed flow area of a cylindrical arc in axial flow. If, in a fully developed flow arc, radiation is kept small by the use of moderate arc temperatures and pressures, and if also the flow terms are diminished by avoiding flow velocities and pressure gradients which are too big, the energy balance reduces to the simple Eleenbaas equation, to which only the turbulent term is added(7). This equation is then amenable to a further study of turbulent effects.

However, typical plasma devices, such as plasma generators, are not in general restricted to low values of temperature, flow velocity, and pressure gradient. Also, turbulent effects will increase considerably with higher pressures and flow velocities.

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

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

It is therefore useful to extend the investigation of turbulent effects to values of higher velocities, pressures, and arc currents. Under such conditions some of the other energy terms of eq (1) will no longer be negligible even in the fully developed regime. We will therefore discuss them here in more detail. This discussion is simplified, if the achievement of fully developed flow can be assumed. Therefore, let us first see under which conditions of tube length, tube diameter, and flow rate, fully developed flow can be expected.

2.2 Conditions for Fully Developed Flow

The problem of the developing column in the entrance section of a laminar axial flow arc has been treated theoretically by several authors(1,5,6). We will follow here the work of Weber*(5) and use his results for an estimate of the highest flow rate for which fully developed flow conditions can still be expected.

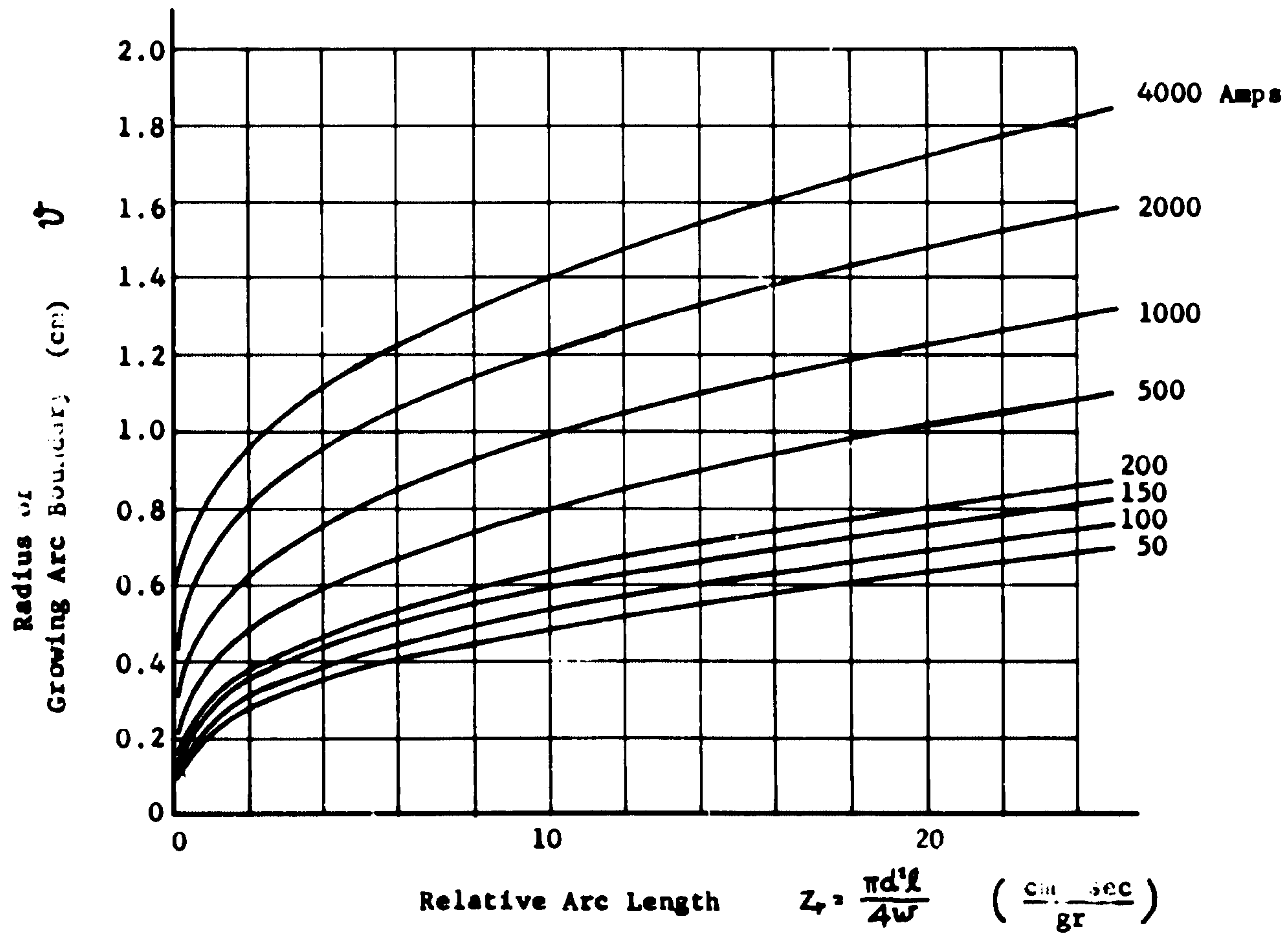

Figure 1 - Weber's(5) Result for the Column Growth in the Entrance Regime of an Axial Flow Arc

* We thank Dr. H. Weber for the additional calculations at small currents below 500 amps.

Figure 1 shows Weber's result for the radius ϑ of the growing arc column as a function of the relative arc length z_r:

$$z_r = \frac{\pi d^2 \ell}{4 w} \tag{2}$$

where ℓ is the arc length, w the flow rate, and d the tube diameter.

If we now, as Weber does, assume that the flow is fully developed when the arc radius ϑ is equal to the tube radius $\frac{d}{2}$, the desired maximal flow rates w can easily be calculated with:

$$w = \frac{\pi d^2 \ell}{4 z} \tag{3}$$

For tubes with a length of 75 cm and with diameters of 0.5 cm and 1.0 cm, the maximum flow rates were calculated for currents between 50 and 200 amps, and the results were plotted in Figure 2.

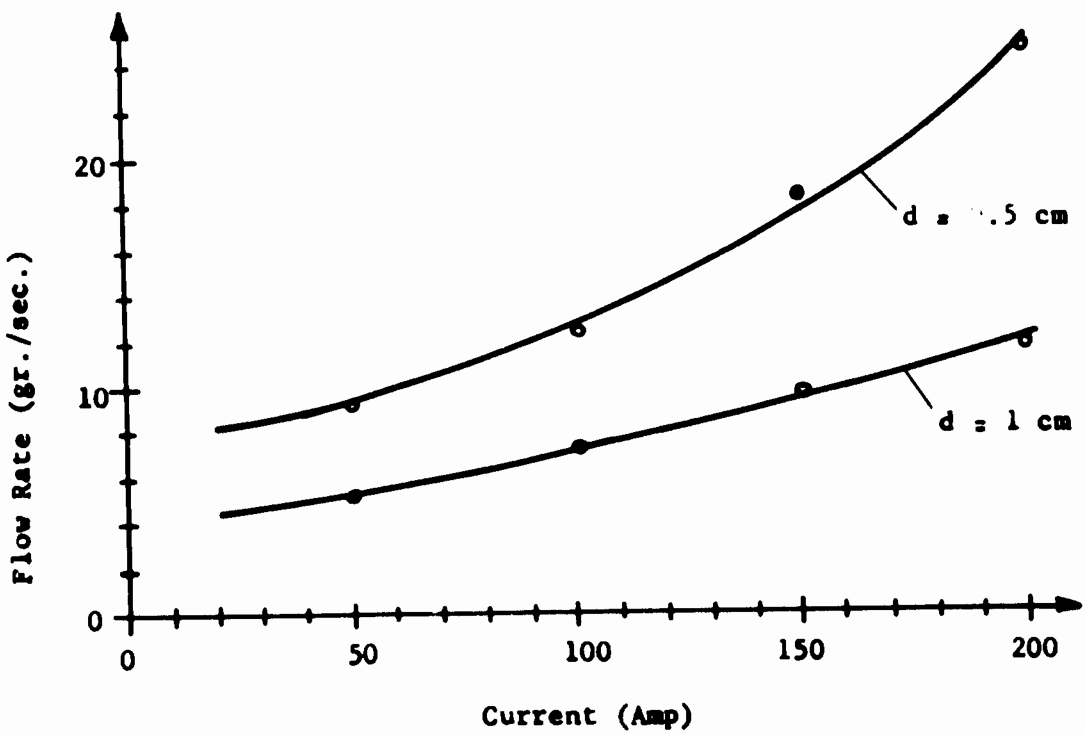

Figure 2 - Maximum Flow Rate for which Fully Developed Conditions are Maintained in an Axial Flow Air Arc

It is seen that the tube with a diameter of 0.5 cm will, according to these calculations, attain fully developed flow for flow rates smaller than 8 gr/sec., whereas the maximum flow rate of the 1 cm tube is slightly more than 4 gr/sec. at small currents.

However, this estimate contains a flaw. The data of Figure 1 are calculated for air and we wish to apply them in this paper to argon. The parameter which describes the influence of the particular gas on column growth is $\frac{C_p}{K}$, the quotient of specific heat C_p and thermal conductivity K. This only slightly pressure dependent quotient is calculated for argon and air of one atm. pressure by using data of (3,8,9,10) and plotted in Figure 3.

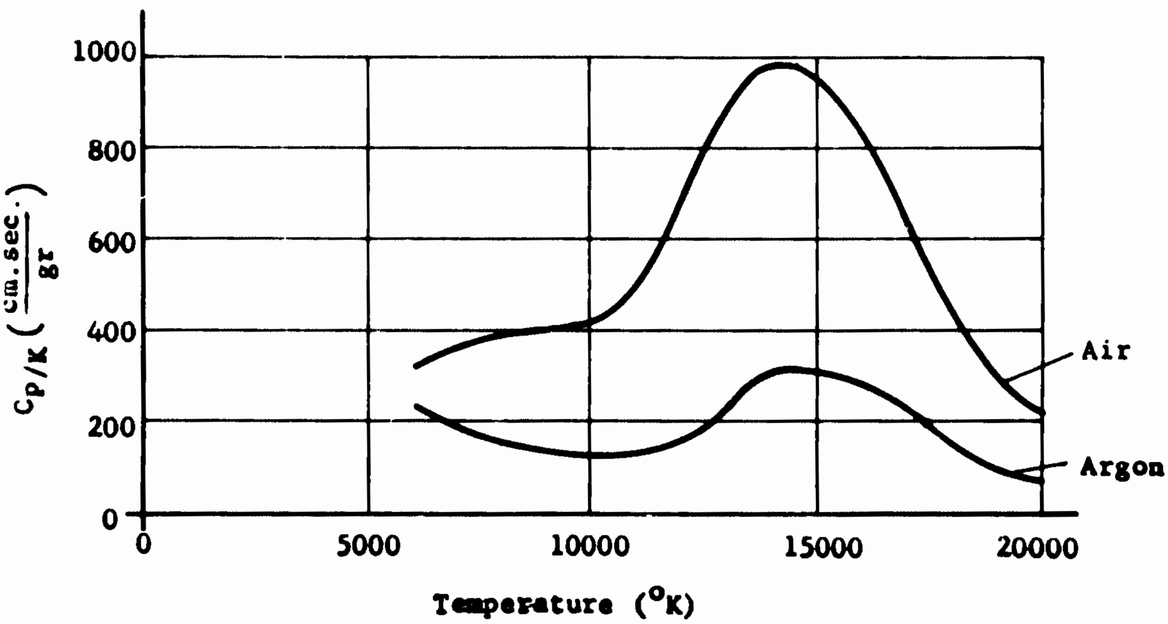

Figure 3 - Quotient of Specific Heat C_p and Thermal Conductivity K, for Air and Argon, as a Function of Temperature, (7,8,9), Pressure 1 Atm.

It is seen that for argon this quotient is considerably smaller than for air. Therefore, in argon, fully developed flow can be expected at even higher flow rates than indicated by Figure 2.

Under conditions of turbulence, radial heat transfer (effective K value) increases markedly. Therefore, considerably higher flow rates than indicated in Figure 2 will still lead to fully developed conditions in turbulent arcs.

2.3 Viscous Heating

In the following sections it will be assumed that fully developed flow is achieved. With this assumption, estimates will be made for the size of the terms for viscous heating, expansion, convection, and radiation in Eq (1).

For an estimate of an upper limit of the viscous heating term, let us additionally assume:

a) A parabolic velocity distribution

$$v_z(r) = v_z(0)\left[1-\left(\frac{r}{r_0}\right)^2\right] \tag{4}$$

b) A laminar arc

c) A constant value of the viscosity, namely

$$\mu = 3.2 \times 10^{-3} \text{ poise}$$

This value is, according to Yos[3], an upper limit for the viscosity of nitrogen plasma, and it is also larger than the maximum of the argon viscosity[9,10]. Now, integrating the viscous heating term over the arc radius,

$$N_{visc} = \int_0^{r_0} \mu \left(\frac{\partial v_z}{\partial r}\right)^2 2\pi r dr \tag{5}$$

where N_{visc} is the total viscous heating per cm arc length, and using assumptions a) to c) made above, the integral can be evaluated to obtain:

$$N_{visc} = 2\pi\mu v_z(0)^2 \tag{6}$$

Viscous heating is therefore, in this estimate, only dependent on the viscosity and the axial velocity $v_z(0)$, and it is independent of the tube radius r_0. Choosing the highest axial flow velocity found in our arcs:

$$v_z(0) = 10^5 \text{ cm/sec}$$

Eq (6) can be numerically evaluated to obtain:

$$N_{visc} = 20.2 \text{ watt per cm arc} \tag{7}$$

This value is, in view of our choice of the values for the viscosity and the flow velocity, an upper limit for the laminar arcs in our experiments. However, under conditions of turbulent flow, even larger values than (7) might be found depending on the value of the effective turbulent viscosity.

By way of departure it may be noted that viscous heating can be of more importance in arcs in hydrogen and helium, because of the higher sound velocities in these gases.

2.4 Expansion Term

The expansion term $\left[1 - \rho\left(\frac{\partial h}{\partial p}\right)_T\right]\vec{v}\nabla p$, because of its dependency on the pressure gradient, cannot be completely avoided even in the fully developed flow section of arcs. Let us therefore estimate its magnitude for a nitrogen arc. For nitrogen, Yos[3] has calculated enthalpy and density for the pressures 1,3,10 and 30 atm. From these values the derivative $\left(\frac{\partial h}{\partial p}\right)_T$ can be obtained by graphical differentiation. This differentiation process is not very accurate, but may suffice for the purpose of this estimate. The thus obtained $\left(\frac{\partial h}{\partial p}\right)_T$ values are multiplied with the densities and listed in the following Table 1.

Table 1

P \ T	4000	6000	8000	10,000	12,000	14,000	°K
1 Atm.	-0.004	-1.22	-1.40	-0.25	-1.23	-1.18	-
3 "	-0.08	-0.28	-1.78	-0.36	-0.58	-0.85	-
10 "	-0.30	+1.32	-1.80	-0.55	-0.57	-0.82	-
30 "	+1.53	-2.8	-1.63	-1.14	-0.33	-0.65	-

It is seen that in the temperature range from 4000 - 6000°K, and for pressures up to 10 atm, $-\rho\left(\frac{\partial h}{\partial p}\right)_T$ is always smaller than 2. The 10 atm. values, which are of most importance for this estimate, may even be approximated by an average value of $-\rho\left(\frac{\partial h}{\partial p}\right)_T = 1$. As for the velocity in the expansion term, a parabolic distribution shall again be assumed:

$$v_z(r) = v_z(0)\left[1 - \left(\frac{r}{r_0}\right)^2\right] \tag{8}$$

This leads to the average flow velocity:

$$\overline{v_z(r)} = \frac{v_z(0)}{2}$$

Then, selecting again the highest axial velocity observed in our experiments, namely

$$v_z(0) = 1 \times 10^5 \ \text{cm/sec}$$

and also the highest pressure gradient:

$$\frac{3 \text{ atm.}}{75 \text{ cm}} = \frac{3 \times 92 \times 10^4}{} \ \frac{\text{dyne}}{\text{cm}^3}$$

an upper limit for the expansion term is obtained:

$$\left[1 - \rho\left(\frac{\partial h}{\partial p}\right)_T\right]\vec{v}\nabla p \leq 392 \ \text{watt/cm}^3 \tag{9}$$

This is a substantial value. It is therefore fortunate that, as the expansion term is proportional to the volume, its integral over the arc cross section can be minimized by the use of small tube diameters, as shown in the following Table 2. It may also be recalled that the radial heat loss of 1 cm arc by thermal conduction is, in contrast to this, independent of the tube diameter, if the axis temperature of the arc is kept constant.

Table 2

$\pi r_0^2 \left[1 - \rho\left(\frac{\partial h}{\partial p}\right)_T\right] \vec{v} \nabla p \leq$	27.7	77	306	1220	$\frac{\text{watt}}{\text{cm}}$
Tube Diameter d	0.3	0.5	1.0	2.0	cm

By the use of tubes with inside diameters as small as 0.5 or even 0.3 cm, the expansion term per cm arc length can therefore be made reasonably small, as compared to the heat loss by thermal conduction. By the same token, arcs with diameters of 2.0 cm or more, and particularly under conditions of high pressure gradients, will have a considerable expansion term even in the fully developed flow section. Therefore, in some types of plasma generators the expansion term should not be neglected.

2.5 Convection Term

One might suppose that the convection term can be neglected in the fully developed flow region of an axial flow arc. However, in deviation to what happens in a flow tube without an electrical arc, the flow of an electrical current can cause an axial temperature gradient, and with this a convection term.

To understand this, let us remember that there is always a pressure gradient along a flow tube and that, in general, the electrical conductivity of a plasma depends on temperature and pressure. The arc can therefore compensate for the change of the electrical conductivity caused by the decreasing pressure along the flow tube by a simultaneous temperature change. Of course, the arc still has the other possibility of changing the electrical gradient, leave the temperature constant, and thus enforce the flow of a constant current. Without a deeper investigation, it cannot be decided which of the two changes, the temperature change or the change in electrical gradient, will happen. Probably, they both happen to some degree.

For the purpose of estimating the size of the convection term in fully developed flow, it is useful to assume that the electrical gradient remains constant and only the temperature changes along the tube. With this assumption an upper limit for the convection term can be obtained.

Values for the dependency of the electrical conductivity on pressure and temperature can be taken from the Yos[3] tables. We select here nitrogen instead of argon, but no major differences between them as to the ΔT effect is to be expected.

In our estimate, by graphical interpolation, the temperature difference which is necessary to compensate for a relative pressure drop of 30% is determined. 30% is the highest relative pressure drop in our experiments. This calculation is made for a number of temperatures between 6000 and 14,000°K and for pressures of 1,3,10 and 30 atm. The ΔT values computed in this manner are plotted in the following Table 3.

Table 3

P \ T	6000	8000	10,000	12,000	14,000	°K
1 Atm.	-80	-90	-22	≈ 0	+110	°K
3 Atm.	-100	-75	-65	≈ 0	+ 95	°K
10 Atm.	-60	-50	-100	≈ 0	+ 55	°K
30 Atm.	-90	-75	-100	≈ 0	+ 40	°K

It is seen that below 12,000°K negative ΔT values are found as compared to positive ΔT values above 12,000°K. This, of course, reflects the fact that at low temperatures the electrical conductivity rises with decreasing pressure, whereas the effect is opposite at high temperatures. Therefore, the convection term will add energy to the plasma volume at very high arc temperatures, and will take energy out of it at arc temperatures below 12,000°K.

For the purpose of our estimate let us choose $\Delta T = 100°K$ as an upper limit for arcs with an axis temperature below 12,000°K. With this value for ΔT and with a tube length of 75 cm, and a velocity of 1×10^5 cm/sec., the convection term $\rho C_p \vec{v} \nabla T$ for the different temperatures can be calculated. The results are shown in the following Table 4.

Table 4

P \ T	6000	8000	10,000	12,000	°K
1 Atm.	-58	-35	-11	≈ 0	watt/cm^3
3 Atm.	-112	-146	-32	≈ 0	watt/cm^3
10 Atm.	-250	-520	-140	≈ 0	watt/cm^3
30 Atm.	-560	-1300	-655	≈ 0	watt/cm^3

This table may convey an impression of the possible order of magnitude of the convection term under conditions of our experiments. Due to the manner in which these numbers were derived they are high limits.

In the case of our experiments with rather low currents and low temperatures, the expansion and the convection terms fortunately have opposite signs and cancel partially out. Also, the convection term is, as is the expansion term, proportional to the volume and can be further diminished by the use of small diameter flow tubes.

2.6 Radiation Term

At elevated pressures and simultaneously high plasma temperatures, radiation is a very powerful term in the energy balance. The order of magnitude of this term can be recognized from the following Table 5, which contains calculated values of the total radiation(3) of nitrogen. At higher temperatures the radiation consists largely of Brems-Strahlung, and because the intensity of Brems-Strahlung is proportional to , the square of the electron density, other gases with values of the ionization potential similar to nitrogen, such as argon, will radiate comparable amounts of energy.

Table 5

P \ T	8000	10,000	12,000	16,000	20,000	^oK
1 Atm.	2.77	8.2×10^1	1.1×10^3	8.2×10^3	7.7×10^3	watt/cm^3
3 Atm.	12.8	3.0×10^2	4.5×10^3	5.5×10^4	6.8×10^4	watt/cm^3
10 Atm.	60.6	1.3×10^3	1.9×10^4	3.5×10^5	6.5×10^5	watt/cm^3
30 Atm.	255	5.1×10^3	7.2×10^4	1.7×10^6	4.7×10^6	watt/cm

Radiation, in general, can therefore only be neglected at moderate pressures, and temperatures below 8,000°K. At temperatures of 12,000°K and higher, and at pressures of 10 atm. and higher, radiation will, in many discharges, be the dominant energy loss term. Under these conditions radiation must be carefully measured if a proper treatment of the energy balance is desired.

In our experiments, under conditions of 10 atm. pressure and currents above 50 amps, the regime of strong radiation is reached. The implications of this point shall be discussed in more detail in Section 6, where the results of our electrical and caloric measurements are evaluated.

3. APPARATUS

The arc apparatus used in these experiments was described in some detail earlier(7). However, it has been modified considerably and therefore shall now be shortly discussed in the following sequence: flow tube, plasma pre-heater, power supply and gas flow system.

3. Flow Tube

The axial flow tube permits the measurement of several arc properties such as electrical gradient and radial heat transfer in laminar and turbulent flows. The length of the tubes was increased from 37 cm to 75 cm. Tube diameters of 1.0, 0.7, 0.5 and 0.3 cm were employed, but most measurements were made on the 0.5 cm tube.

The principal design of the flow tubes remained the same as reported in (7), namely:

a) 1 mm thick copper discs with a hole in the center were stacked in a plexiglass tube and insulated from each other by thin polyethylene spacers (Maecker Arc).

b) Quartz tubes were used for the high speed photographic studies of the arcs.

Neither the copper discs nor the quartz tubes were water-cooled. This was done mainly to produce an economic and flexible design. In these tubes, the heat capacity of the walls was used to absorb the heat flux from the arcs for durations of the order of 1 sec. This duration was long enough to establish steady state conditions and to record the measurements.

3.2 Plasma Pre-Heater

At small currents and large tube diameters, the establishment of a fully developed temperature profile can be assisted by the use of a plasma generator which injects preheated plasma into the flow tube.

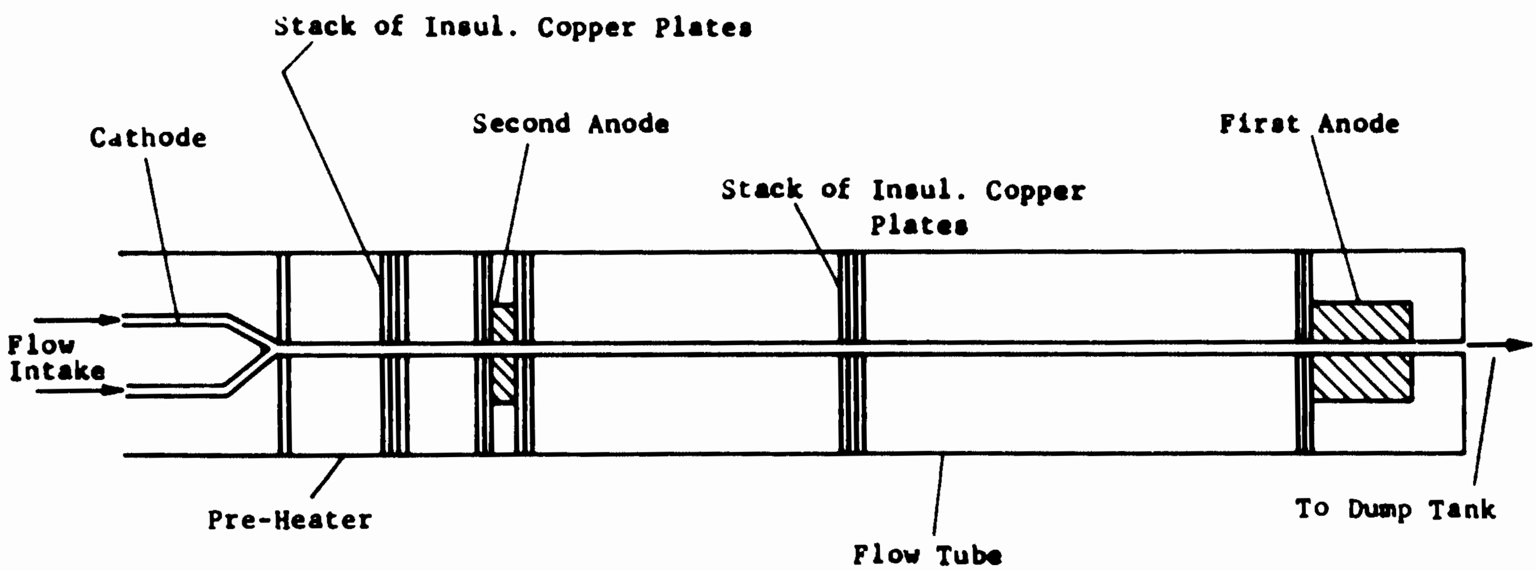

Figure 4 - New Arc Apparatus, Schematic. Pre-Heater and Flow Tube are Closely Integrated

Length of Pre-Heater:	18.5 cm
Length of Flow Tube:	37 or 75 cm
Inner Diameter of Tube:	0.5 cm or 1.0 cm

The pre-heater previously used was an ablation type generator (7), working with somewhat unconventional plasmas like CO_2 or a mixture of 50% H_2 and 50% CO. For the purpose of a better comparability with the results of other authors, a new pre-heater was built which can heat the conventional gases. The new generator is of the axial flow type and consists, like the flow tube, of a stack of uncooled, insulated copper discs. This design can be closely integrated into that of the flow tube and the two arc chambers can actually be considered as one long axial arc heater which has an additional anode in its initial part, Figure 4.

3.3 Power Supply

The use of longer arcs required the design of a power supply with a substantially higher voltage. Therefore, a new three-phase bridge rectifier was built (Figure 5), which delivers for 1 sec. 100 amps at 17,000 volts. In the design of this device, decisive advantage has been taken of the short time overload capability of the small semiconductor diodes. The steady state current of this rectifier is much smaller, namely only 15 amps.

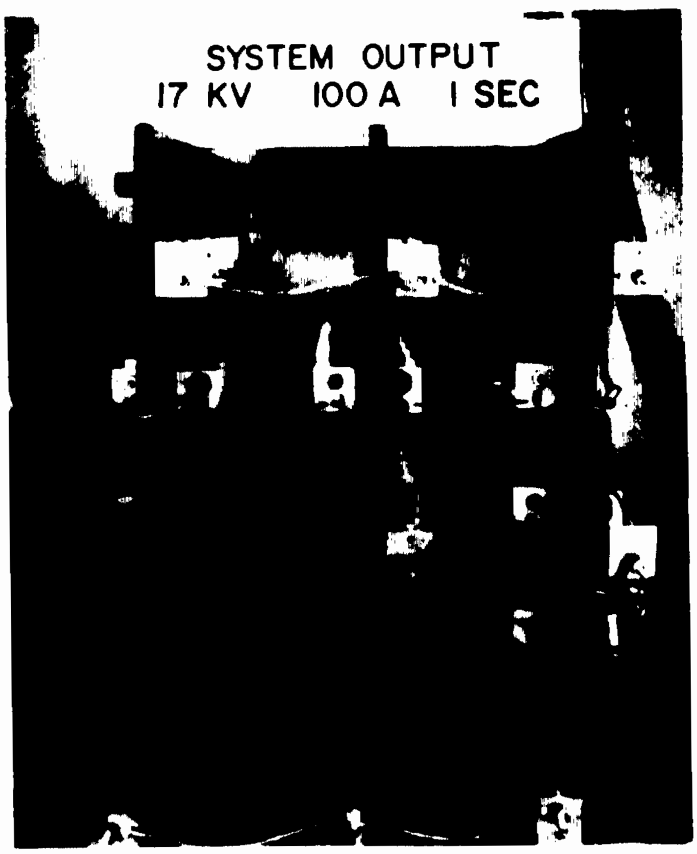

Figure 5 - Three-Phase Bridge Rectifier. Delivers 100 Amps at 17,000 Volts for One Second. Consists of Silicon Diodes. Steady-State Capability 15 Amps.

The electrical power supply shows even more clearly than the arc apparatus, the economic advantage of short-time test with durations of the order of 1 sec. The cost of a steady-state rectifier and even more so a steady-state power source of 2-3 MW would have been many times the cost of those which were used here.

3.4 Flow System

The flow system, which controls the gas input into the new axial flow pre-heater is shown in Figure 6. Two or more bottles B pressurize the manifold M. The flow is established very quickly by an electrically actuated valve V. Critical orifices O determine the flow rate. The valve V is mounted very close to the arc heater and "dead volume" between valve and heater is carefully avoided. These measures help to establish steady flow conditions quickly during an arc operation.

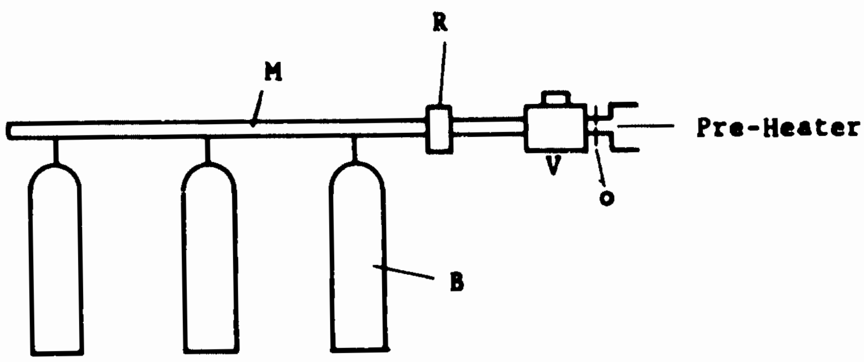

Figure 6 - Flow System, Schematic, with Gas Bottles B, Manifold M, Pressure Regulator R, Valve V and Critical Orifice O

A picture of the complete new arc apparatus, showing the plasma pre-heater, flow tube, flow system, power supplies for pre-heater and flow tube, and also some of the wiring used for the measurements, is shown in Figure 7.

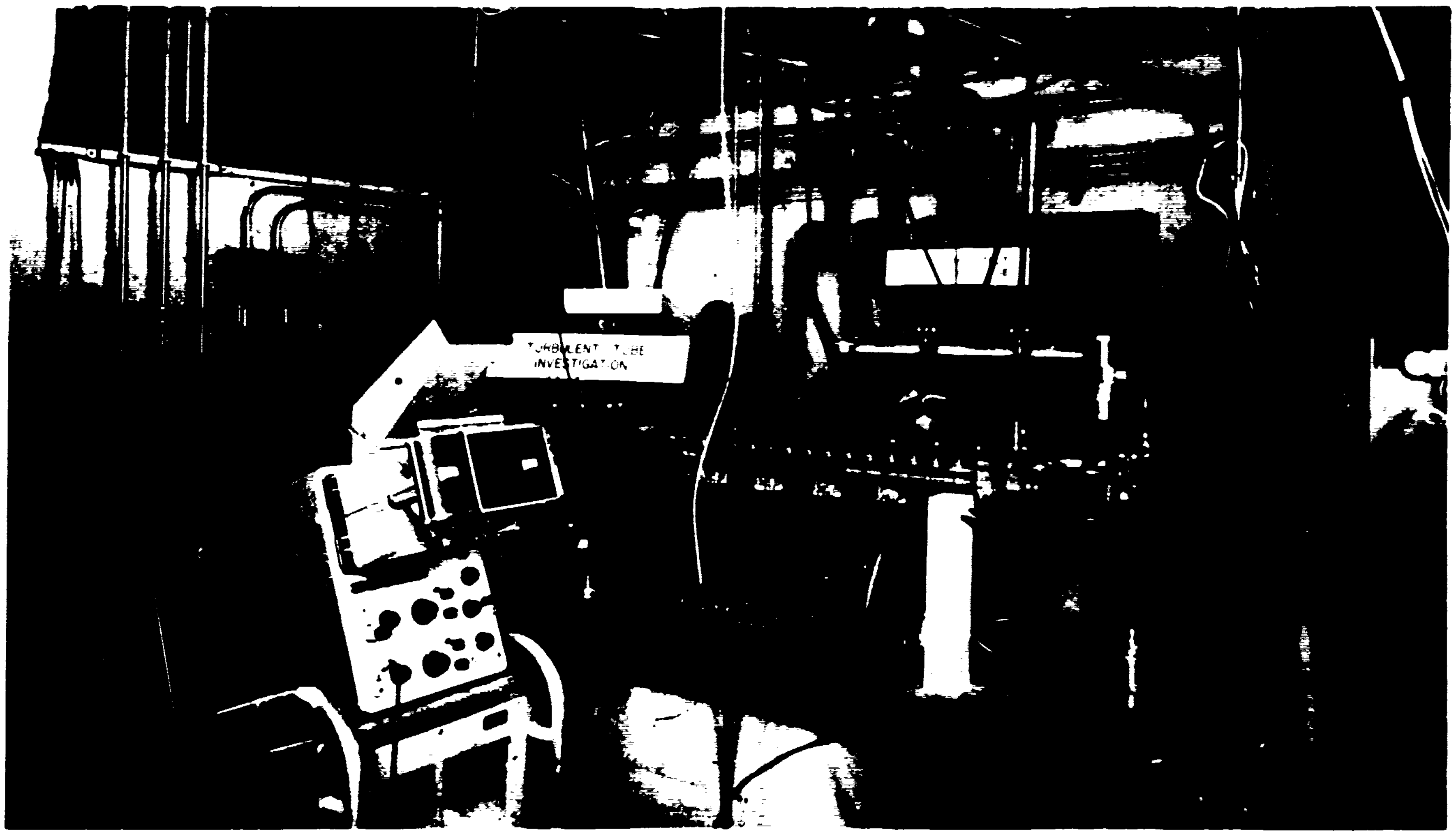

Figure 7 - Photograph of Complete Arc Apparatus. Photo Shows Plasma Pre-Heater and Flow Tube (Both shown as Copper-Cascade Chambers) Flow System, Power Supplies for Pre-Heater, Flow Tube and Some of the Measuring Installations.

4. MEASURING EQUIPMENT AND MEASURING METHODS

Electrical, optical and caloric measurements were made. Since the arcs were operated for durations of ½ - 1 sec., time resolved measuring technique was necessary. Therefore, most signals were recorded with Tektronix 532, 545B and 502A cathode ray oscilloscopes.

4.1 Electrical Equipment

Arc currents were measured by non-inductive shunts, arc voltages by ohmic voltage dividers with an impedance of 6 MΩ . The electrical potential along the tube was determined by using a number of the copper discs which comprise the flow tube, as potential probes. The arc potential was recorded simultaneously at eight positions along the flow tube. An electronic switch, which was designed and built by our group, was used to display all eight potential signals on two beams of an oscilloscope. The pressure drop along the flow tube was measured by dynamic transducers* and displayed on an oscilloscope. Reasonably clear signals could be recorded for pressures as low as 2 psi. This limited the range of quantitative pressure measurements to the higher flow rates employed in this investigation.

Typical signals of arc current, arc voltage,for pressure and electrical potentials, which were recorded with this equipment, are shown in Figures 8-10.

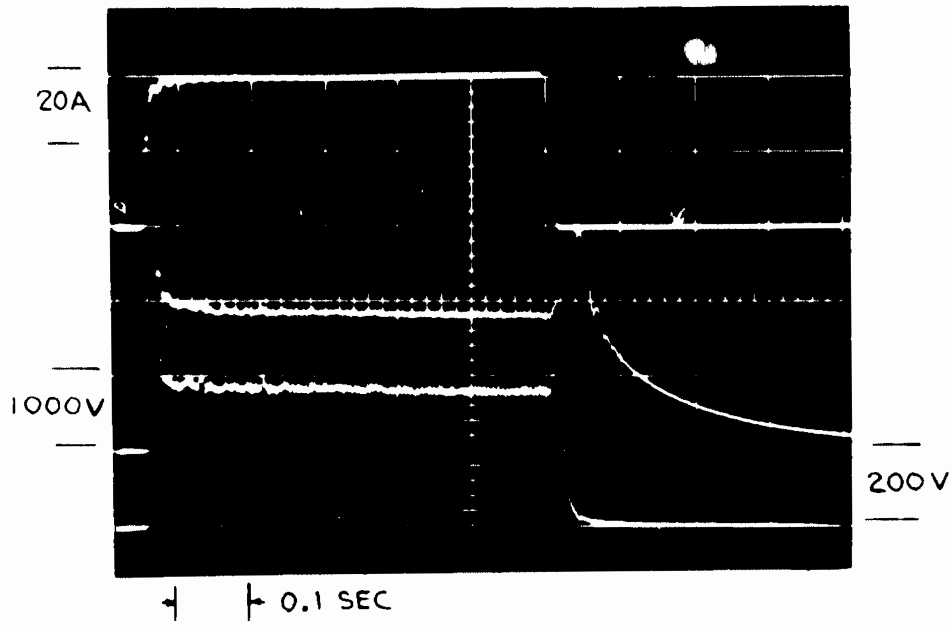

Figure 8 - Typical Oscillograms of a Measurement of Tube Current, Tube Voltage, and Pre-Heater Voltage.

* Kistler gages 601A and amplifier 566

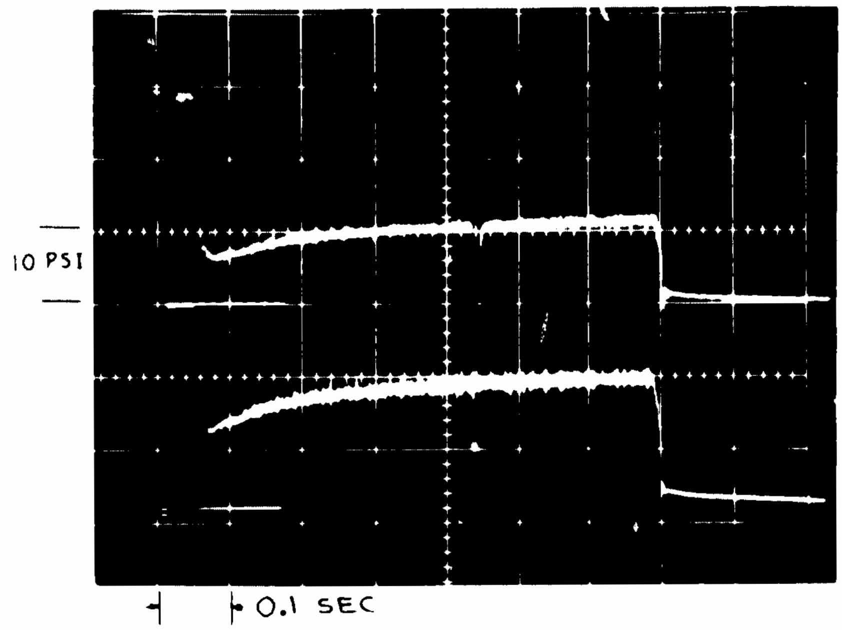

Figure 9 - Typical Oscillogram of Pressure Measurements Taken at Two Different Positions Along the Arc Apparatus.

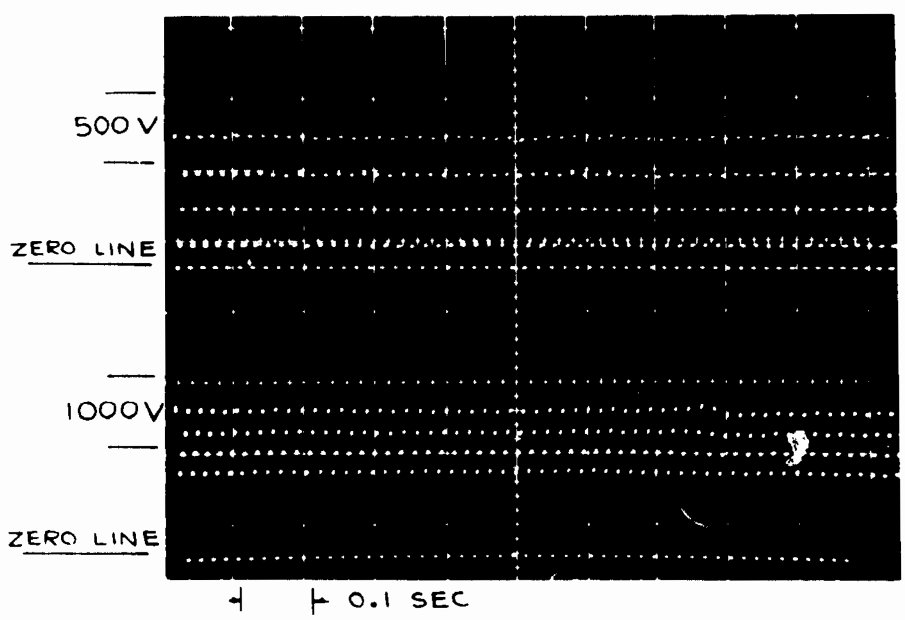

Figure 10 - Typical Oscillogram of Potential Measurements Taken at Different Positions Along Flow Tube. Oscillogram is Taken 0.1 Sec. Before Arc Extinguishes

4.2 Heat Flux Probe

To measure the heat flux from the arc to the tube walls one of the copper discs of the cascade chamber was used as a calorimeter. However, in order to increase the signal sensitivity, the mass of the disc had to be reduced to 1/5 or 1/2 of the mass of the full disc. Therefore, the outside diameter of the disc was reduced and the resulting smaller disc was pressed into a plexiglass ring (Figure 11). Then, into the outer edge of the copper disc a copper constantan thermocouple was soldered. Also, the two next neighbor discs on each side of the calorimeter disc were cut to the same smaller diameter. By this measure it was hoped to insure identical temperature distribution in the calorimeter disc and its neighboring discs and to exclude heat exchange between them.

Figure 11 - Photograph of Heat Flux Probe Showing Copper Disc, into which Thermocouple is Soldered, and Plexiglass Ring, into which Copper Disc is later Mounted.

A steady-state check on the quality of the calorimeter was made by measuring the thermocouple voltage, when the calorimeter was immersed into a water bath of a known and constant temperature. This voltage was measured by a General Electric thermocouple bridge. Agreement between measured voltages and those tabulated by Leeds and Northrup[11] was found to be of the order of 1%.

In addition to this, the calorimeter was tested under conditions of transient heat transfer from a laminar arc with a very low flow rate. For such an arc it can be safely assumed that all electrical energy put into one cm of arc length will flow from the arc volume radially into the surrounding walls. In this measurement, the calorimeter is used as an integrating instrument, which samples the heat flux during a current pulse of ½ sec. duration. This, as will be shown shortly, can be done because the time constant of the temperature rise of this calorimeter is short as compared to the time constant of its temperature decay due to the heat losses.

To understand this, let us look at a signal from a thermocouple as recorded by a Tektronix 502A oscilloscope which was operated at a sensitivity of 0.5 mV/cm and a deflection of 5 sec/cm (Figure 12). One sees that the thermocouple signal rises quickly to a maximum and then falls off slowly with a much longer time constant. Further, it can be seen that the trace of the thermocouple signal is interrupted in regular intervals. During these interruptions the signal was short-circuited by an automatic switch. Thus the temperature measurement and the zero line could be recorded simultaneously. This measure was necessary to recognize a possible drift of the zero line at this extremely sensitive position of the oscilloscope

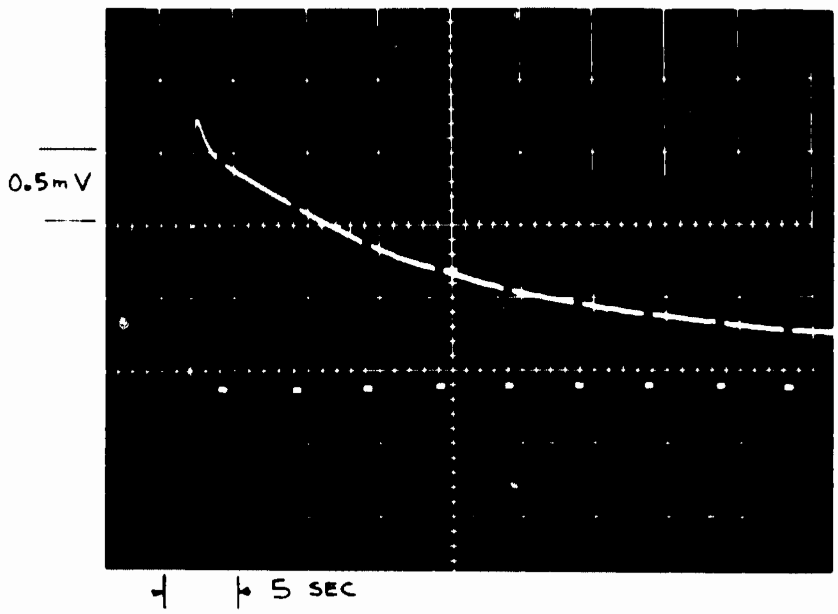

Figure 12 - Typical Oscillograms of Signal from Heat Flux Probe, Showing Rapid Temperature Rise and Slow Temperature Decay. Zero Line Trace is Simultaneously Taken by Short-Circuiting Signal Periodically.

The thus measured temperature rise of the calorimeter can, by means of the known values for the specific heat and the mass of the copper disc, be evaluated in terms of wall heat flux per cm arc. This value of the heat flux should then agree with the integrated electrical input E.I. Δt.

It was found that the electrical input and the heat flux agreed in the case of the low flow rate laminar test arc to within less than 5%. This agreement was better than could be expected in view of the unavoidable inaccuracies of the oscilloscopes and the calorimetric method as such. Therefore, we had confidence in using this simple calorimeter to also measure the wall heat flux from arcs which were operated with high flow rates.

4.3 High Speed Photography

High speed photographic studies were made of arcs burning in quartz tubes. The quartz tubes were of a high quality without wave surfaces. However, it was not attempted to achieve an optical quality in these tubes comparable to that of a true optical surface. This would have been too costly and was also not necessary for the present investigation. An impression of the quality of the surface of the quartz tube may be gained from Figure 13, which shows a file inserted into one end of a tube.

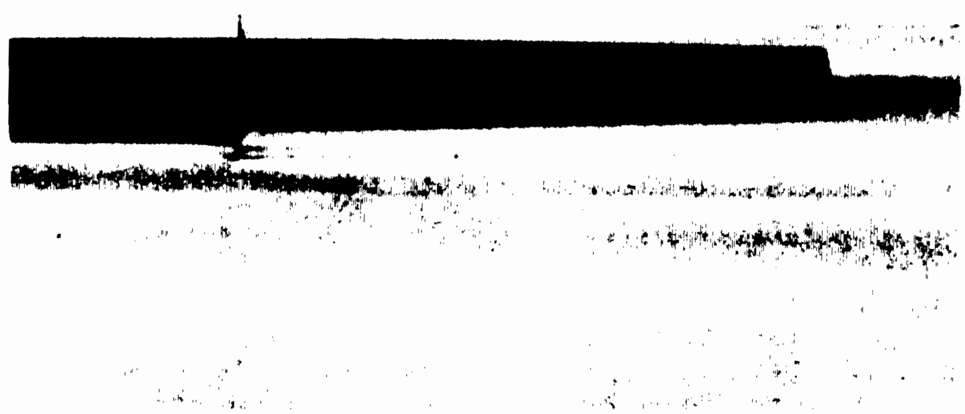

Figure 13 - Photograph of Quartz Tube, Demonstrating Quality of Surface

The high speed pictures for this investigation were taken with a Dynafax camera, usually with an exposure time of 1.35 μsec. Within this short exposure time even very rapidly moving plasma can be "stopped". For instance, a typical flow velocity of 5×10^4 cm/sec. causes a blurr Δz of:

$$\Delta z = 5 \times 10^4 \times 1.35 \times 10^{-6} = 6.75 \times 10^{-2} \text{ cm.} \tag{17}$$

This is then the smallest plasma object we can resolve in the longitudinal direction of the flow tube. Of course, the total resolution in lines per mm of the system, including film and optics, can limit the smallest discernable object still further, particularly if the chosen "field" is too large. Therefore, the best results with respect to resolution are achieved with close-up photographs of a limited field.

Very sensitive film had to be chosen for the photographs and a very "high contrast" developing technique was employed. The new Kodak recording film 2475 was primarily used, and it was developed for durations of 5 or even 10 minutes in a 1:1 solution of Kodak Dektol.

5. MEASUREMENTS

5.1 Electrical Measurements

5.11 Potential Distribution Along Argon Arcs in 0.5 cm Tubes

The distribution of the electrical potential along a flow tube of 0.5 cm diameter, which was operated with argon arcs, was measured for a great number of currents, pressure and flow rates, namely:

Current: 10-100 amp.

Pressure: 1-10 atm.

Flow Rate: 0.02 - 2.95 gr/sec.

Also, the argon plasma was pre-heated in the above described pre-heater of 18.5 cm length. The pre-heater was operated at the same current level as the respective flow tube arc.

Typical examples of potential distributions found in these experiments are shown in Figure 14. The potential rises linearly along the tubes with the exception of the first two measuring points, which lie 5 cm and 15 cm from the beginning of the tube. These points show a larger stray and lie often high at the high flow rates. The other points also show some stray, particularly at high flow rates, but a straight line does, for all the arcs mentioned in the table above, represent the measured points very well.

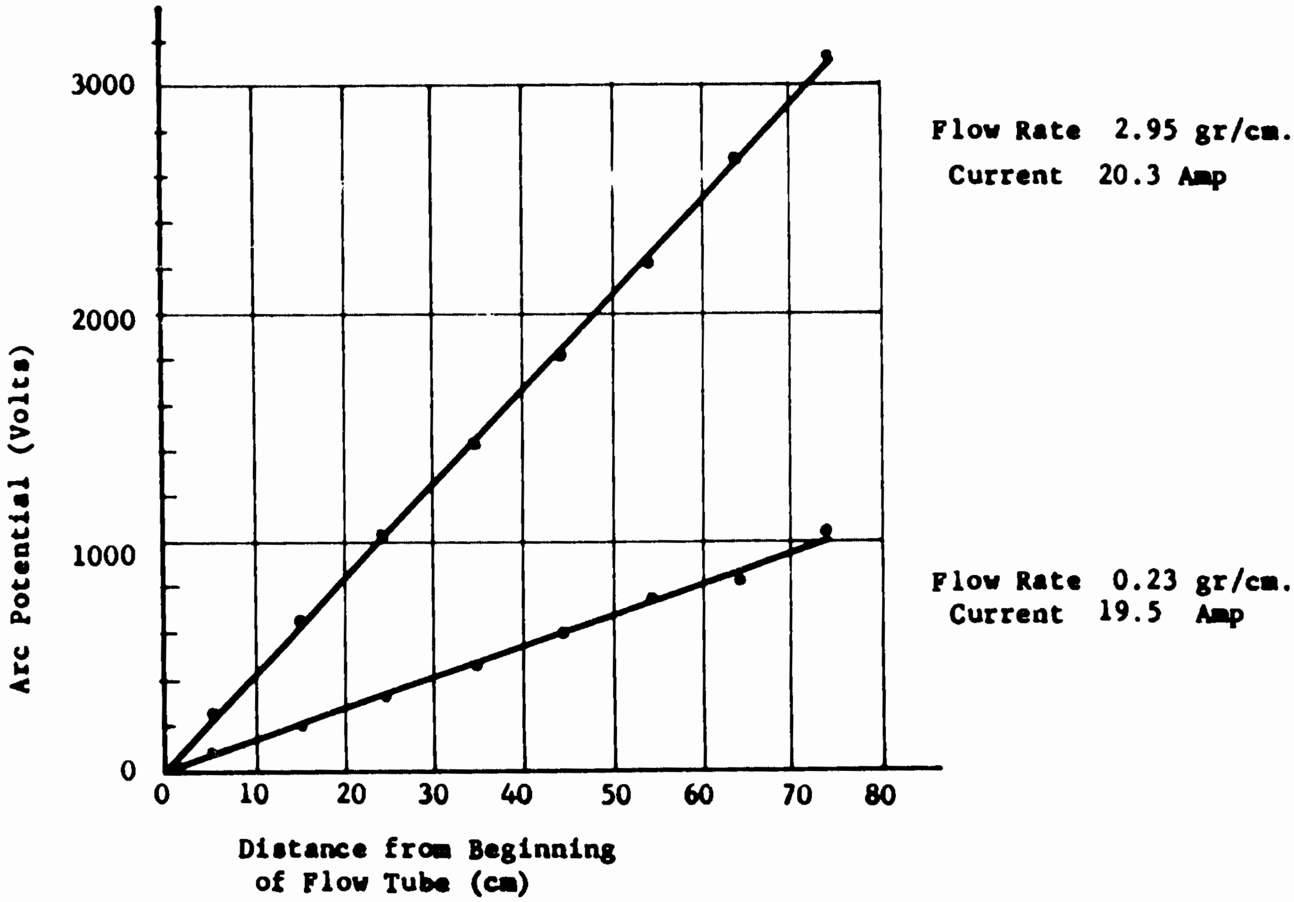

Figure 14 - Potential Distribution Along Argon Arcs.

Pressure: 10 atm
Tube Length: 75 cm
Tube Diameter: 0.5 cm

5.12 Characteristics of Argon Arcs in 0.5 cm Tubes

The linear voltage rise along the argon arcs, which was reported upon in the last paragraph, defines a constant value of the electrical gradient for each arc. Therefore, the potential measurements were evaluated in terms of their arc gradients and these were plotted in Figures 15-17 for the pressures of 1,3 and 10 atm. At each pressure level two arc characteristics are shown, one for a low and one for a high flow rate. The characteristic at the high flow rate lies at all pressures higher than that for the low flow rate. There is also a strong influence of the pressure level on the shape of the curves and on their separation in the E-I diagram.

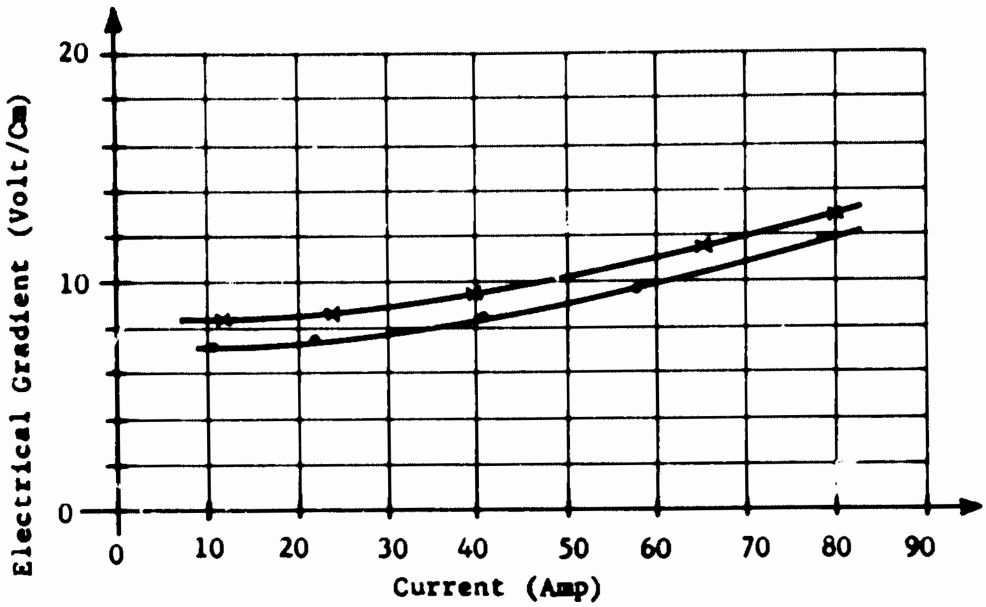

Figure 15 - Characteristics of Argon Arcs at 1 Atm. Pressure

Tube Diameter: 0.5 cm
Tube Length: 75 cm
Flow Rates: XXX 0.29 gr/sec.
... 0.02 gr/sec.

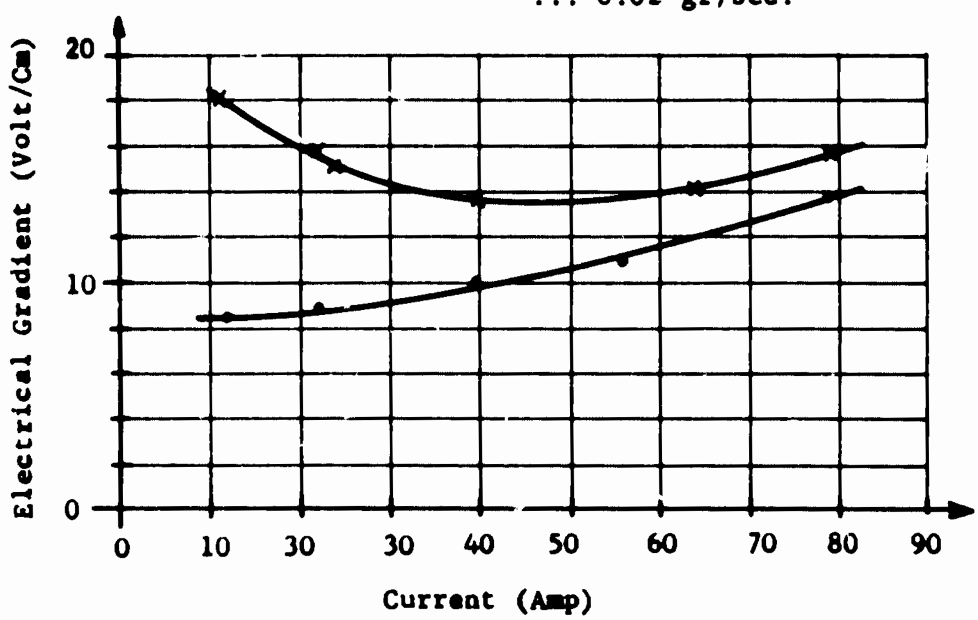

Figure 16 - Characteristics of Argon Arcs at 3 Atm. Pressure

Tube Diameter: 0.5 cm
Tube Length: 75 cm
Flow Rates: XXX 0.88 gr/sec.
... 0.069 gr/sec.

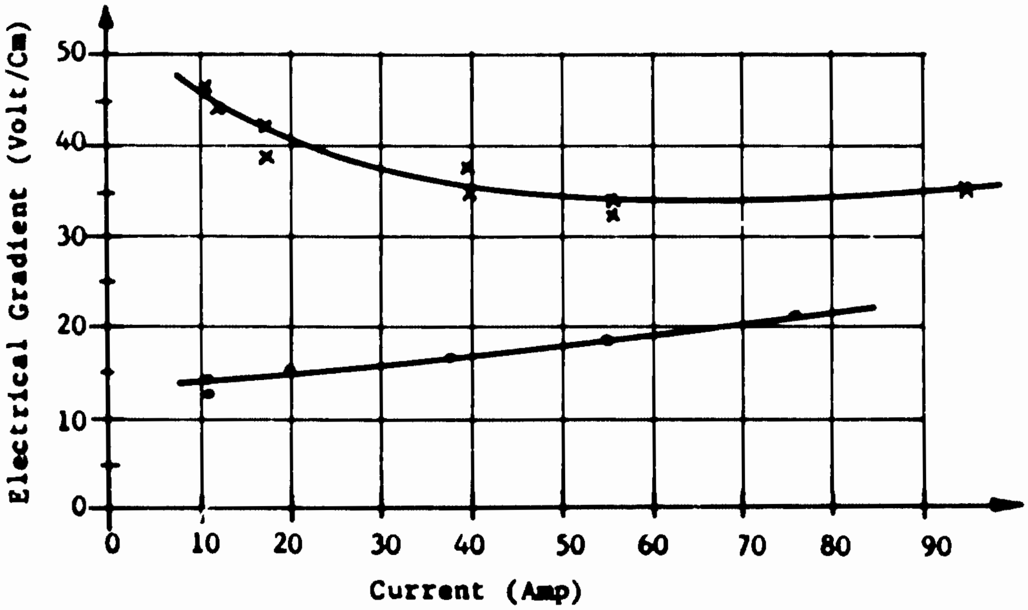

Figure 17 - Characteristics of Argon Arcs
at 10 Atm. Pressure

Tube Diameter: 0.5 cm
Tube Length: 75 cm
Flow Rates: XXX 2.95 gr/sec.
... 0.23 gr/sec.

At 1 atm., Figure 15, both arc characteristics lie quite close to each other and are both rising in the current range shown. At 10 atm., however, Figure 17, the curves lie far apart and whereas the curve for the low rate of mass flow rises, the other characteristic falls at low currents and rises only at the high current end. At three atm. the high flow rate curve shows an intermediate behavior, Figure 16. It falls as the 10 atm. curve does, at small currents, but the minimum is reached earlier. At high currents it finally approaches rather closely the curve for the low flow rate.

5.13 Potential Distribution and Characteristics of Argon Arcs in 1.0 cm Tubes

Some potential distributions were also determined for argon arcs in 1.0 cm tubes. These arcs were operated with a current of 22 amps and a pressure of 10 atm. The plasma was pre-heated with a current of 100 amps in the above described plasma generator, and flow rates of 0.25 and 35 gr/sec. were employed.

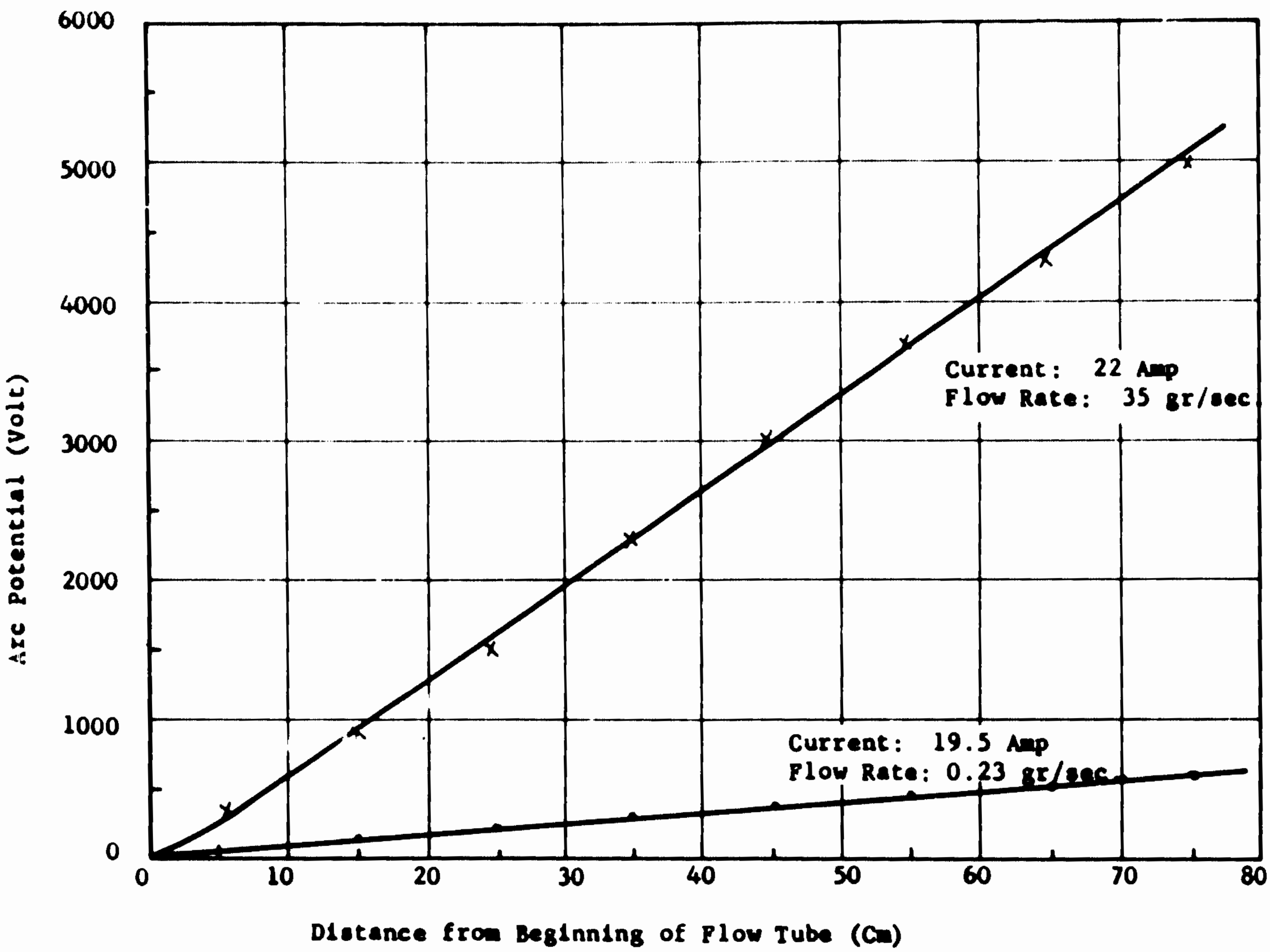

Figure 18 - Potential Distribution Along 1.0 cm Argon Arcs

Pressure:	10 Atm.
Tube Length:	75 cm
Tube Diameter:	1.0 cm
Current:	19.5 and 22 amp
Flow Rates:	0.25 and 35 gr/sec.

The electrical potential increased linearly along the tube for both the low and the high flow rate, Figure 18, and for the high flow rate was nearly one order of magnitude larger than for the low flow rate. The values for the respective electrical gradients were 66.5 and 8.3 volt/cm. This was the largest relative increase in electrical gradient observed so far in our experiments.

For the 1.0 cm argon arcs, no further electrical gradients were measured. However, total arc voltages were determined at a pressure of 10 atm., for currents between 10 and 100 amp. and for different flow rates. Figure 19 shows the result. It can be seen that the arc voltages for the high flow rates are considerably larger than for the low ones. This increase in arc voltage is still more pronounced as that earlier observed for the 0.5 cm tubes. Also the characteristics for the high flow rate are falling over the whole current range while they are rising for the low ones.

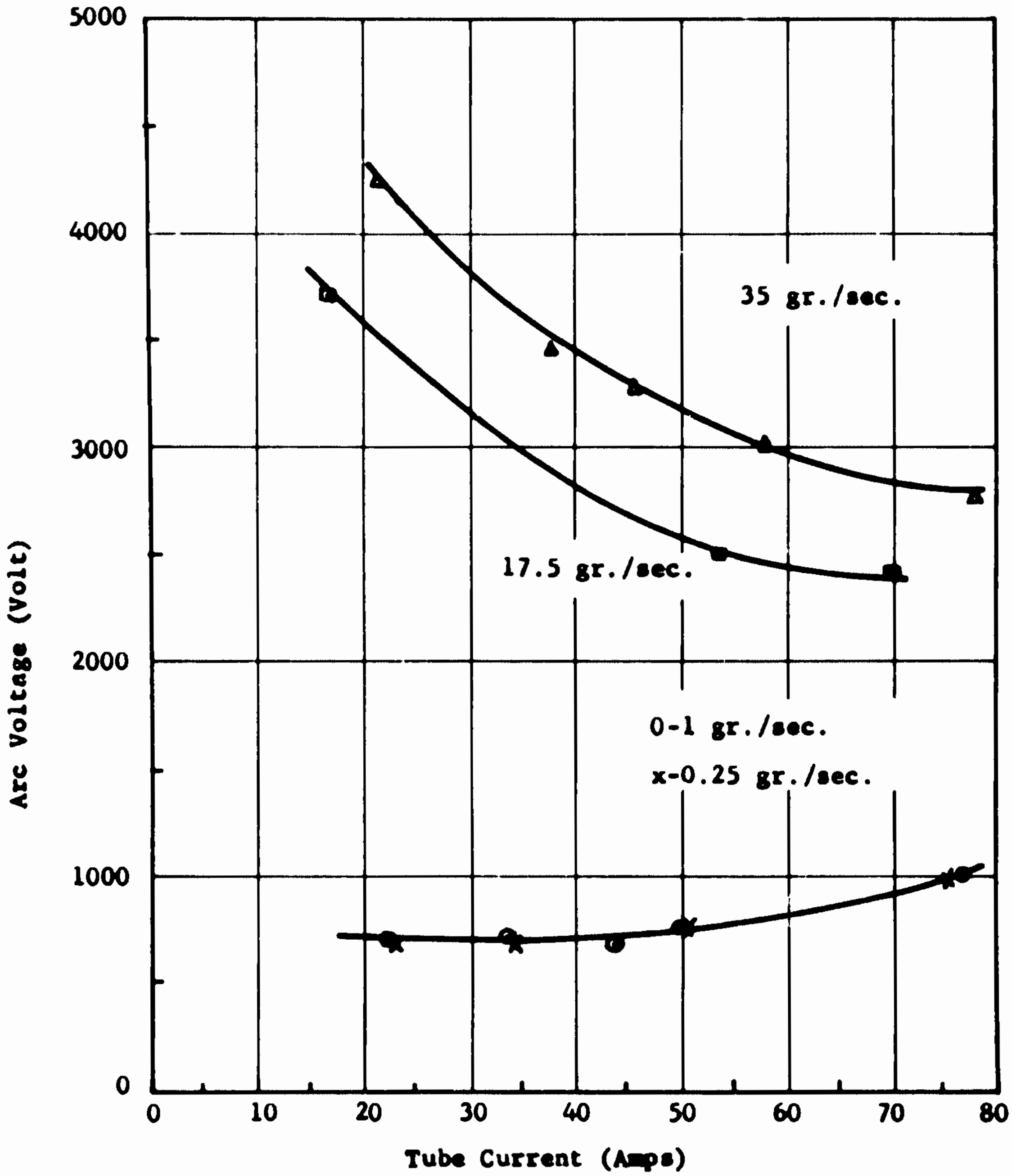

Figure 19 - Characteristics of Argon Arcs at 10 Atm. Pressure
Tube Length: 74 cm
Tube Diameter: 1.0 cm

5.2 Caloric Measurements

5.21 Radial Heat Flux of 0.5 cm Argon Arcs

In addition to the before described measurements of the electrical gradients in 0.5 cm argon arcs, also radial heat fluxes to the tube walls were measured. This was accomplished by means of the above described calorimeter, which was mounted downstream in a position 5 cm before the end of the tube.

Measurements were performed for the following conditions:

Gas: Argon
Pressure: 10 atm.
Tube Length: 75 cm
Tube Diameter: 0.5 cm
Current: 20 and 60 amp.
Flow Rates: 0.23 and 2.95 gr/sec.

The pre-heater was 18.5 cm long and carried the same current as the flow tube arc. The heat fluxes Q_r from 1 cm arc length to the surrounding cylindrical walls were determined from the calorimeter readings, and, in addition, the total electrical input per cm arc, $EI\Delta t$, with Δt the duration of current flow, was determined.

The values of the quotient $\frac{Q_r}{N}$ received for the two currents and flow rates are listed in Table 6.

I \ W	0.23	2.95	gr/sec.
20A	-	1.21	--
60A	0.98	1.12	--

Whereas the experiment with the 60 amp arc at the low flow rate 0.23 gr/sec. can be considered as a further calibration of the calorimeter, the Q_r/N values at the high flow rates are close to, but measurably larger than unity. This means that the measured heat flux to the wall was, at the position of the calorimeter, somewhat larger than the electrical energy released in the respective arc length.

5.22 Radial Heat Flux of 10 mm Argon Arcs

Also for the 1.0 cm arcs, measurements of the radial heat flux to the wall were made. Here the current 22 amps was chosen and the flow rate varied from 2 to 35 gr/sec. The resulting Q_r/N values are shown in Figure 20. Again at low flow rates Q_r/N values close to 1 are reached. At high flow rates, however, in these wide tubes Q_r/N falls down to about 0.70.

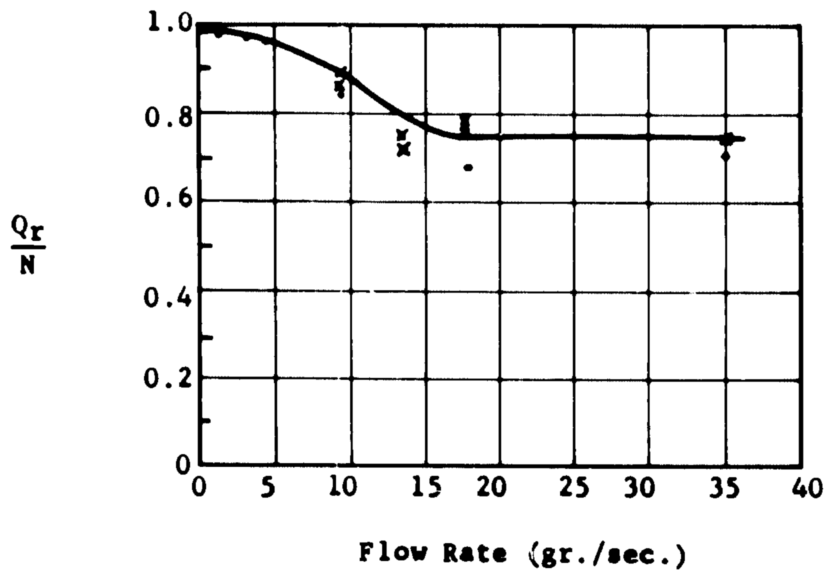

Figure 20 - Quotient of Radial Heat Flux Q_r and Electrical Input N, as a Function of the Flow Rate

Gas:	Argon
Pressure:	10 Atm.
Current:	22 Amp.
Tube Diameter:	1.0 cm
Tube Length:	75 cm
... Pre-Heater:	90 - 120 Amp.
xxx Pre-Heater:	200 - 220 Amp.

5.3 High Speed Photographic Studies

5.31 Argon Arcs with 0.5 cm Diameter

A very characteristic arc behavior can be recognized from Figure 21. In this series 10 atm., 40 amp. argon arcs are operated in a 0.5 cm quartz tube with flow rates from 1.5 to 4.5 gr/sec. Whereas the arcs at the lowest flow rate are in a very quiet state, increasing flow rate causes disturbances. These appear first, see picture 2 of Figure 21, at the outer periphery, in the cooler parts of the arcs. With further increasing flow rate, picture 3, the disturbances penetrate deeper into the column and cause finally, picture 4, the column to be strongly modulated in light intensity and in shape, even to such a point that the column appears to be "broken up" into plasma globules.

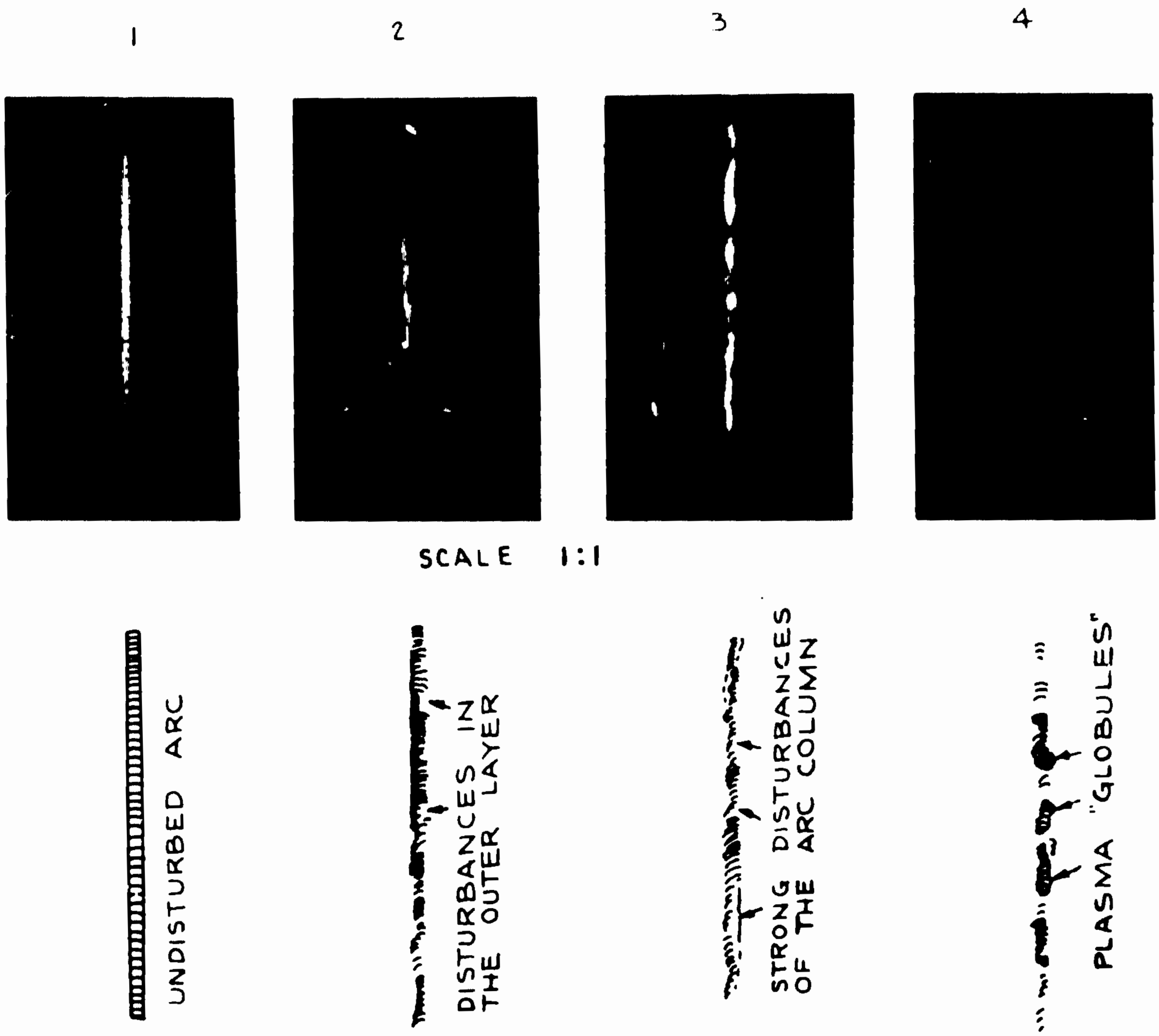

Figure 21 - High Speed Photographs of Arcs in a Long Quartz Tube. Flow Rate Increases from Left to Right.

Exposure Time:	**1.35 μ sec.**
Gas:	**Argon**
Pressure:	**10 atm.**
Current:	**40 amp.**
Tube Diameter:	**0.5 cm**
Tube Length:	**37 cm**

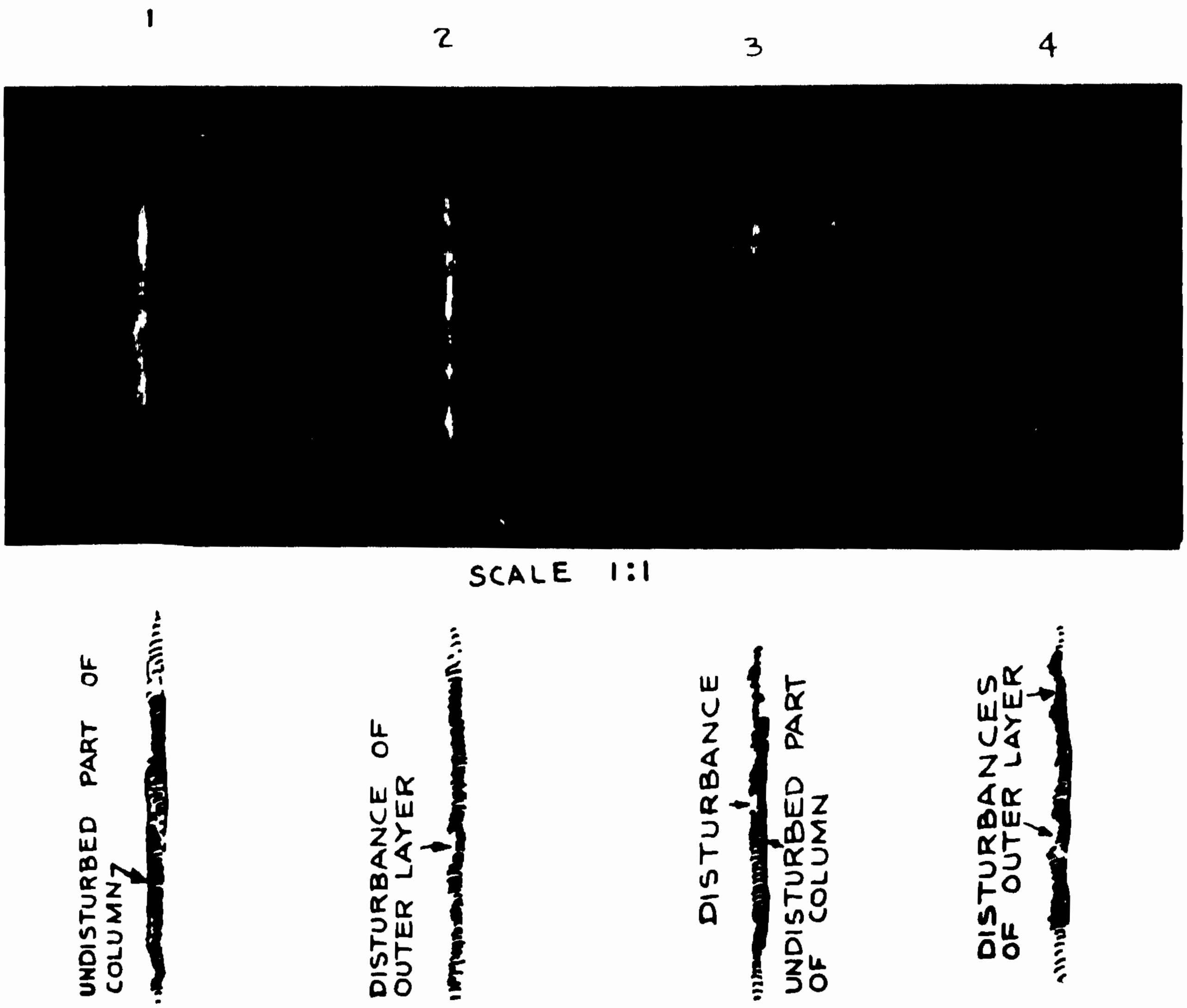

Figure 22 - Sequence of High Speed Photographs of Arcs with a Low Flow Rate, Showing that Disturbances Occur Intermittently

Frame Distance:	100 μ sec.
Exposure Time:	1.35 μ sec.
Gas:	Argon
Pressure:	10 atm.
Current:	40 amps
Tube Diameter:	0.5 cm
Tube Length:	37 cm
Flow Rate:	2 gr/sec.

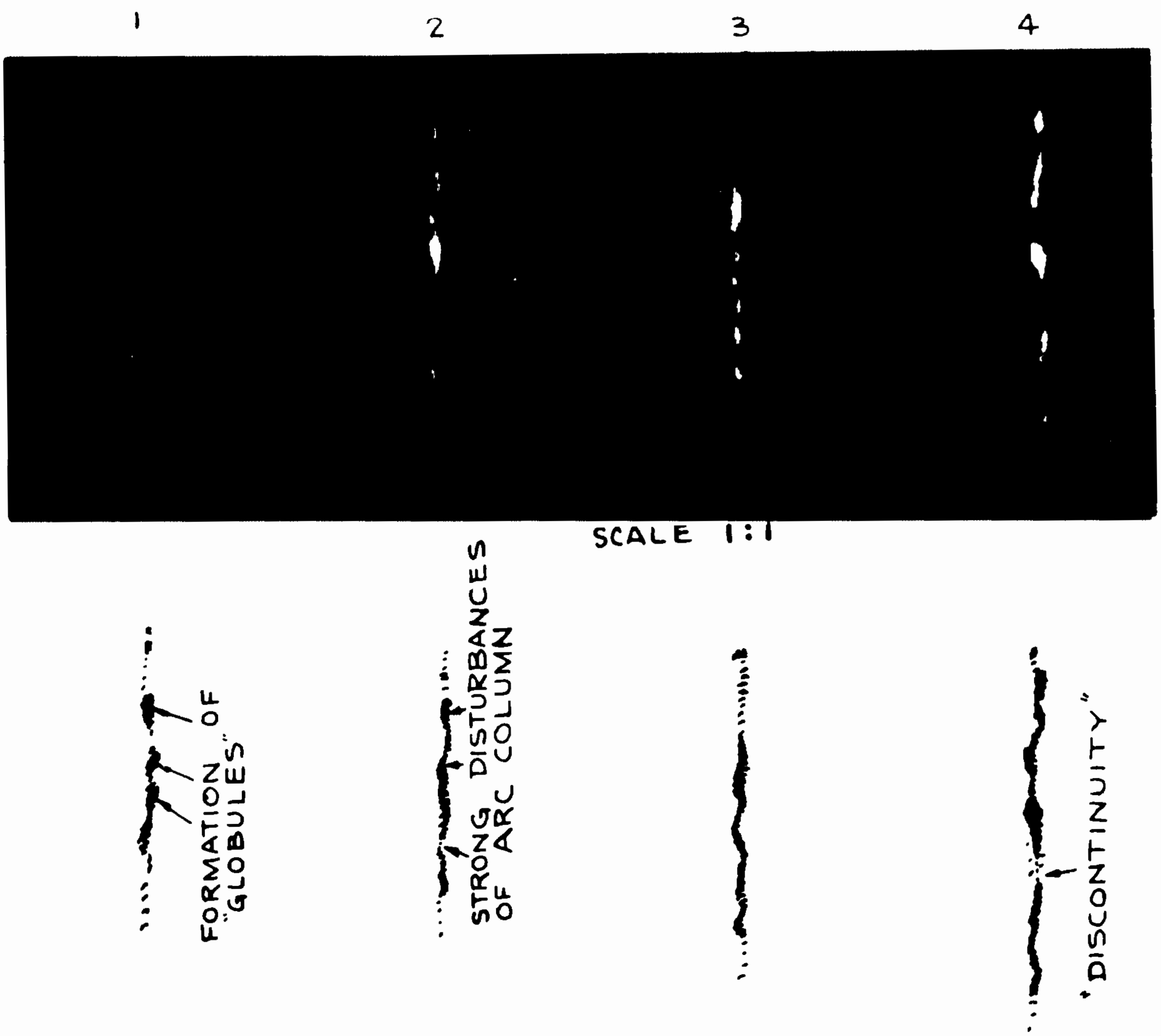

Figure 23 - Sequence of High Speed Photographs of Arcs with High Flow Rate, Showing Strong Disturbances Without Intermittence

Frame Distance:	100 μ sec.
Exposure Time:	1.35 μ sec.
Gas:	Argon
Pressure:	10 atm.
Current:	40 amp.
Tube Diameter:	0.5 cm
Tube Length:	37 cm
Flow Rate:	4.55 gr/sec.

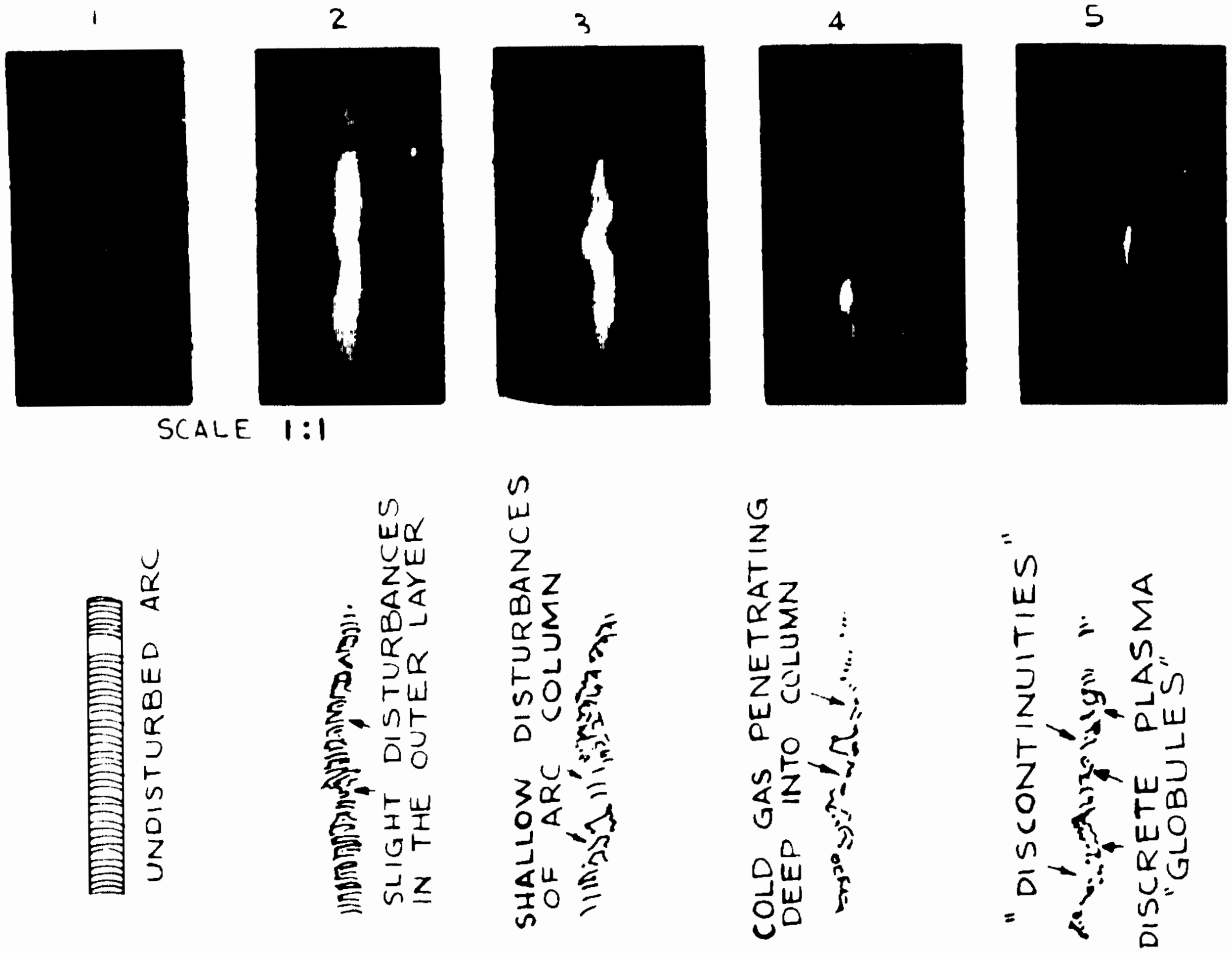

Figure 24 - High Speed Photographs of Arcs Burning in a Wide Quartz Tube and with a High Current. Flow Rate Increases from Left to Right

Exposure Time:	1.35 μ sec.
Gas:	Argon
Pressure:	10 atm.
Current:	80 amp.
Tube Diameter:	1.0 cm
Tube Length:	75 cm

Anotner aspect of the behavior of arcs in axial flow fields can be recognized from Figure 22. Here a sequence of 6 high speed photographs of an arc with 2.0 gr/sec. flow rate is shown. These photographs are from the same movie as is picture 2 from Figure 21, and are made with an exposure time of 1.35 μsec. and a frame distance of 100 μsec. It is seen that short lengths of a quiet column alternate with disturbed parts. The disturbances seem therefore to be intermittent at that low flow rate.

The behavior regarding intermittence is different at the higher flow rate of 2.95 gr/sec., for which Figure 23 displays a series of 6 consecutive pictures, again with a time distance of 100 μsec. against each other. All pictures show strong variations in light intensity and geometrical structure of the plasma body, but no quiet pieces of undisturbed plasma column can any more be recognized.

5.32 Argon Arcs with 1.0 cm Diameter

The behavior of argon arcs in a 1.0 cm quartz tube is rather similar to tha of the arcs in a 0.5 cm tube. This can be recognized from Figure 24, which shows 10 atm. arcs with currents of 80 amps and with flow rates of 1 to 35 gr/sec. At the lowest flow rate 1 gr/sec., the arcs are completely quiet. At 4.5 gr/sec., small disturbances appear in the outer parts of the arcs. At higher flow rates, the disturbances penetrate deeper into the arc column, picture 3, flow rate 9.5 gr/sec., and then finally seem to "break" the column apart in different locations, picture 5, flow rate 35 gr/sec.

5.33 Measurement of Flow Velocity

Flow velocity was measured from high speed photographs of the turbulent plasma column. The position of characteristical disturbances can namely be identified on several consecutive pictures[7]. The displacement of the disturbances and the framing rate of the movie give then directly the flow velocity. No extensive series of flow velocity measurements were made. However, flow velocities of 100 m/sec. were measured for argon arcs in the 1 cm tube. These arcs were operated with a current of 80 amps and a flow rate of 4.5 gr/sec. The measured value of 100 m/sec. was then used to estimate the flow velocities of arcs with higher flow rates. For this estimate the assumption was made that the flow velocity is proportional to the flow rate.

These estimated value of the flow velocity were used only to determine the order of magnitude of the flow terms in Section 2.3 to 2.5, and the inaccuracy introduced by using the above assumption does not significantly affect the results of this paper.

6. DISCUSSION

In this section the results of the measurements will be discussed. Of particular importance for this discussion is the question of whether or not the experiments were made under conditions of fully developed flow. Therefore, we will first try to decide this question on the basis of the various results which we have obtained so far.

6.1 Fully Developed Flow

Stine and Watson's[1] approximative theory describes arc behavior in the entrance region and also in fully developed flow. According to this theory electrical gradient and radial heat flux vary strongly in this area and reach then constant values in fully developed flow. Also, in fully developed flow, radial heat flux and electrical input per cm arc are numerically equal.

These results of the theory are of great importance for the discussion of our measurements. Therefore, before they are used, they shall be critically reviewed.

Let us begin with the electrical gradient. In recent experiments (12,13), contrary to the prediction of the theory, rather constant values of the electrical gradient were found also in a large part of the entrance region of the arc. The reasons for this disagreement of theory and experiment have not yet been discussed in the literature. However, because of the relative simplicity of the gradient measurements, they should be found in the present state of the theory which uses a strongly idealized arc model. In view of this situation, it must be concluded that the measured constancy of the electrical gradient in our experiments cannot serve as a criterion for the establishment of fully developed flow conditions.

Let us therefore turn to the other predictions of the theory (1) and see if these can be used as criteria for fully developed flow conditions. Theory states that electrical input and radial heat flux balance each other in fully developed flow. This result was obtained with the assumption that the energy terms for convection, expansion, and viscous heating can be neglected in the fully developed region. However, as was demonstrated in Section 2 of this report, the general validity of this assumption must be doubted. But there is still the possibility that the before mentioned terms are small under the specific conditions of our experiments , as for an instance, the small arc diameter. Therefore, in the following, by using the results of the estimates of Section 2, the size of the disputed terms will be numerically estimated for the two interesting cases, namely the 0.5 cm and the 1.0 cm arc.

6.11 Arcs in 0.5 cm Tubes

As an estimate of the energy terms for viscous heating, convection, and expansion in the fully developed section, the results of Section 2 can be applied to the 0.5 cm tube with the modification that the velocity in this tube was only 5×10^4 cm/sec. and not 1×10^5 cm/sec., the value chosen in Section 2.

For this relatively low flow velocity the term for viscous heating turns out to be one order of magnitude smaller than the flow terms; therefore it is neglected.

The flow terms are estimated for the two arcs in which radial heat flux was measured, namely the 60 amp and the 20 amp arcs, and at a flow rate of 2.95 gr/sec. (see Table 6). Relating the flow terms per cm of arc to the electrical input per cm of arc, one obtains:

For the 60 amp arc of Table 6

$$\frac{N_{conv.}}{I \times E} = \frac{51}{1950} = -0.026$$

$$\frac{N_{exp.}}{I \times E} = \frac{38.5}{1950} = 0.020$$

and for the 20 amp arc:

$$\frac{N_{conv.}}{I \times E} = \frac{-51}{800} = -0.064$$

$$\frac{N_{exp.}}{I \times E} = \frac{38.5}{800} = 0.048$$

It can be seen for the 60 amp and 20 amp arcs which were burned in the 0.5 cm tube, that the flow terms will be small if the arcs are fully developed. Therefore, under the specific condition of such a small arc diameter and if the flow is fully developed, radial heat flux is closely equal to the electrical input.

It also is obvious that radial heat flux is not equal to the electrical input in the entrance section of the flow tube, because part of the arc energy in this section is used to heat the plasma stream.

Therefore, numerical equality of electrical input and radial heat flux can, under these conditions, be used as a criterion for the achievement of fully developed flow.

Turning to the experimental results reported in Table 6, it is found that the measured values of radial heat flux and electrical input were indeed equal to within 12% in one case and 21% in the other. This agreement is, in view of the difficulty of the caloric measurement, considered close enough to prove that fully developed conditions were found in the 0.5 cm arcs. This result is also in agreement with the prediction of Weber's theory, Figure 2, according to which arcs in tubes of 0.5 cm diameter and 75 cm length will be fully developed for flow rates as high as 8 gr/sec.

6.12 Arcs in 1.0 cm Tubes

The flow terms in the fully developed section of the 1.0 cm tube are because of the higher flow velocity of 1×10^5 cm/sec. and the four times larger arc cross section, eight times larger than those estimated for the 0.5 cm tube.

Such large energy terms cannot be neglected. Therefore, a balance of the electrical input and the radial heat flux cannot be expected in these tubes even in the fully developed section. The decision as to whether fully developed flow prevails is to be based upon the heat flux measurements. Therefore, the size of the flow terms must be accurately known. However, our present estimates of these terms are not good enough for this purpose. Therefore, we have no choice but to leave the question of fully developed flow in the 1.0 cm tubes open at this time.

6.2 Characteristics of the Observed Radial Heat Flux

In the last section it was concluded that, under the conditions of the experiments, the argon arcs in a 0.5 cm flow tube had a fully developed temperature profile. In addition to this, the flow terms were of a negligible size in these tubes. Therefore, all measurements plotted in Figure 15 to 17 can also be interpreted in terms of radial heat flux and not only in terms of electrical gradients. Figures 15 and 17 represent the measured dependency of electrical gradient on gas density, gas temperature and flow velocity. Therefore, they also show the dependency of the radial heat flux on these parameters. This will be discussed in more detail in the following.

6.21 Influence of Gas Density

At a gas pressure of 1 atm., Figure 15, the radial heat flux is, at high flow rates, only slightly larger than at low flow rates. At 10 atm., however, Figure 17, radial heat flux is considerably higher for the high flow rate. An intermediate behavior is shown in Figure 16 by the 3 atm. characteristics.

Therefore, it can be said that within the limited range investigated here, radial energy transfer at high flow rates is a monotonic function of the gas density.

6.22 Influence of Gas Temperature (Viscosity)

The influence of the gas temperature can indirectly be taken from the current dependency of the radial heat flux because gas temperature will rise with rising current.

Figure 16 and 17 then show that the relative increase in radial heat transfer decreases with rising arc temperature. The reason for this behavior may be found in the fact that in the current range of Figures 16 and 17, with increasing arc temperatures, the viscosity of the plasma also increases. This, of course, would tend to inhibit irregular motions in the plasma and decrease heat transfer.

6.23 Influence of Gas Velocity

The influence of the gas velocity is so obvious from the results of this investigation that it need not be discussed in detail. It can therefore be concluded that radial heat transfer is also a monotonic function of the flow velocity.

From the results of the last three subsections, it can be inferred that the radial heat flux in the 0.5 cm tubes seems to be monotonicly dependent on the variables ρ, $\frac{1}{\mu}$ and v. Therefore, it can be suspected that the radial heat flux is also a monotonic function of the Reynolds number $R_e = \frac{v d \rho}{\mu}$ of the arc.

With the limited amount of data available, it cannot be inferred for which part of the arc column the Reynolds number should be defined. A decision to this question and, of course, to the possible form of the before mentioned function must await further and more quantitative results.

6.24 The Radiative Heat Flux

Even at 1 atm. pressure(2), argon arcs in 0.5 cm tubes are strong radiators. At higher pressures radiation increases rapidly, Table 5. Therefore, for the 10 atm. arcs in Figures 15-17, the radiative component of the radial heat flux will be for the low flow rate of the same order of magnitude as the component due to thermal conduction.

Therefore, it may be suspected that the increased radial transfer at the high flow rates is due to an increase in radiation. However, the opposite effect has been observed. It was found by high speed photographs, that the arcs at high flow rates were less bright than those at the low flow rates. Also, the radiating volume was smaller at high flow rates, as can be seen from Figures 22 and 24. Therefore, total radiation decreases with increasing flow rate in these experiments, and the increase in the total radial heat transfer must be attributed to an increase of the conductive component of that transfer process.

6.3 The High Speed Photographic Studies

The high speed photographic studies showed the reason for the increased radial heat transfer in the 0.5 cm argon arcs. As soon as radial heat transfer increases, Figure 21, disturbances are observed which are first of an intermittent nature, Figure 22, and later have a continuous character, Figure 23. Also, the disturbances penetrate deeper into the column proper with increasing flow rates. Finally, at the highest flow rate, it appears that the disturbances penetrate the column completely and "break" the plasma up into single globules, Figure 21 and 24. Actually, what we call "breaking up" will be equivalent to a modulation of the arc column temperature in axial direction, showing brighter and less bright spots.

Whereas on the basis of the high speed photographs of Figures 21-24, it cannot be decided what kind of a turbulent motion is found in these arcs, the turbulence of the plasma stream is obvious. It also seems understandable that irregular motions of such violence can transport considerable amounts of energy from the plasma column proper to the tube walls.

7. CONCLUSIONS

Electrical arcs have been operated under conditions of both laminar and of turbulent flow in the fully developed region of a flow tube with an ℓ/d value of 150. Considerably greater heat transfer to the walls of the tube was observed in the turbulent mode as compared to the laminar mode. It was also found that within the range of the parameters investigated, the relative increase in radial heat transfer varied monotonicly with gas density, gas velocity and arc current.

In future experiments, measuring methods will be refined so as to permit a sharpening of the conclusions reached in this paper. For instance, radial heat flux will be measured at several positions along the tube to determine quantitatively the entrance length of the arcs. Also, the accuracy of the heat flux measurements will be improved.

Other projects are measurements of arc temperature and a better measurement of flow velocity.

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13 ABSTRACT Turbulent heat transfer in axial flow electrical arcs has been experimentally studies. The arcs were operated with argon in the current range of 10 to 100 amps, with pressures of 1 to 10 atm., and with flow rates of 0.02 to 35 grams/sec. The flow tubes employed were 75 cm long and had inner diameters of 0.5 and 1.0 cm. It was found that the arc potential increased linearly along most of the tube length for all flow rates. Also, calorimetric measurements at the end of a flow tube with 0.5 cm diameter showed close agreement between wall heat flux and electrical input cm for all flow rates. This, together with a careful estimate of the remaining flow terms, showed that a fully developed temperature profile had been achieved. The arcs at high flow rates showed considerably larger electrical gradients than the arcs at low flow rates. In addition to this, high speed photographs revealed that increased electrical gradients were accompanied by the onset of disturbances of the plasma column. At conditions of the highest flow rates and electrical gradients achieved, the arcs appeared to be strongly turbulent, with the arc column "broken up" into plasma globules of irregular shapes and sizes.

14 KEY WORDS	LINK A		LINK B		LINK C	
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