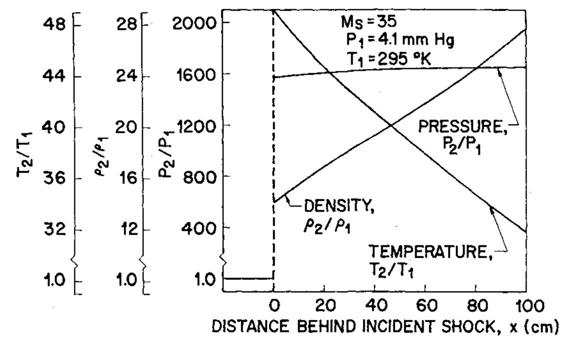


**Fig. 1 Driven-gas profiles with radiation loss**

equations reduce to the usual shock-wave equations and give the conditions immediately behind the shock.

In addition to Eqs. (1–3), the equation of state is required. This was used in the form of the large-scale Mollier diagram by Korobkin and Hastings.[1] All calculations were carried out for an initial temperature $T_1 = 295°K$.

The presently available information about the radiation properties of air has been summarized by Thomas,[2] who presents a curve fit for the emissivity which covers the ranges of temperature and density of interest here. This was used together with the assumption that all energy radiated is lost to the walls. The resulting expression is

$$dq/dt = 1.57 \times 10^4(\rho/\rho_0)^{1.28}(T/10^4)^{10.54} \text{ w-cm}^{-3} \qquad (4)$$

where $\rho/\rho_0$ is the density in Amagat and $T$ is in degrees Kelvin.

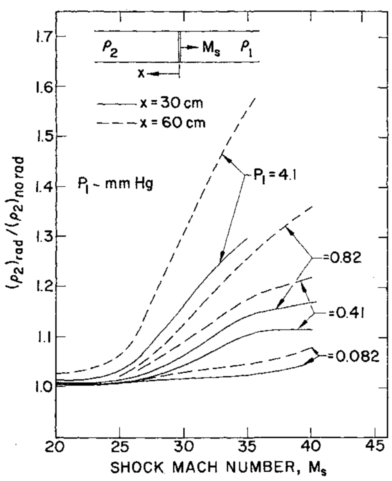


**Fig. 2 Effect of thermal radiation from the driven gas on driven-gas density**

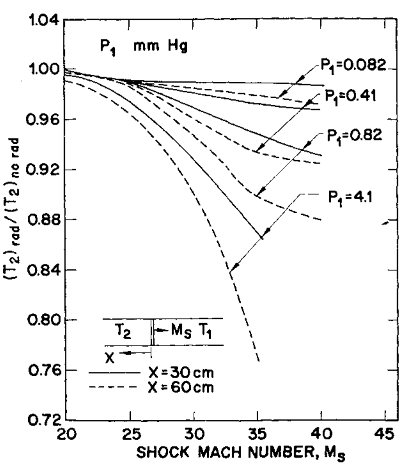


**Fig. 3 Effect of thermal radiation from the driven gas on driven-gas temperature**

The equations now can be solved for any choice of $\rho_1$ and $M_s$ (i.e., $v_1$). A point behind the shock wave is found by choosing a value of $\rho_2$ and finding $v_2$ aud $p_2$ from (1) and (2) and $h_2$ and $T_2$ from the Mollier diagram. Equation (3) then gives $q$. All variables behind the shock therefore can be plotted as functions of $q$. To transform to the $x$ coordinate, integrate

$$\Delta x = v\Delta t = v\Delta q/(dq/dt) \qquad (5)$$

As an example, Fig. 1 shows the variations of pressure density, and temperature behind a Mach number 35 shock wave traveling into air at a pressure of 4.1 mm Hg. This is an extreme case in which the effects on density and temperature are very large while the pressure remains essentially constant. Figures 2 and 3 show the effect on density and temperature, respectively, over the Mach number and pressure ranges covered in the calculations and at two stations, 30 and 60 cm behind the shock. It is apparent that calculations based on the presently available information about radiation from air suggest that, for high Mach number operation, the initial pressure shock be about 100 $\mu$ in order to limit nonuniformities in the test gas.

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# Instability of Arc Columns

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### Nomenclature

$I$ = arc current, amp
$\bar{I}$ = mean arc current, amp
$L$ = photo-diode output/output at reference temperature $T$
$\dot{m}$ = gas mass flow rate, lb/min
$T$ = Temperature, °K
$T_r$ = reference temperature, °K
$V$ = arc voltage
$\bar{V}$ = mean arc voltage

In a recent note,[1] the characteristics of a Gerdien-type plasma generator were described and an hypothesis proposed to explain the arc column's instability. Work of a similar nature has been carried out at Imperial College, some results of which are thought to be of current interest.

The tests to be described were performed using a Giannini vortex-stabilized arc-heater, equipped with a "constrictor" type of anode, shown schematically in Fig. 1. The arc chamber pressures range between 0.1 and 1 atm. Measurements were made of the instantaneous arc voltage, current, and the intensity of visible radiation of the plasma after it had been expanded to a supersonic velocity. The optical measurements were confined to a narrow plane normal to the

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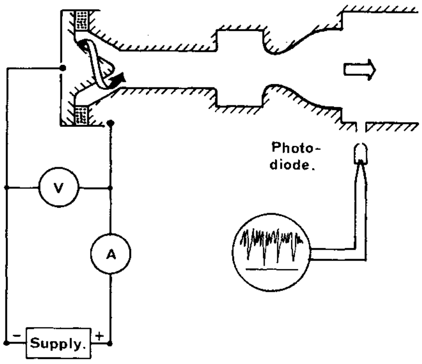



**Fig. 1 Schematic of the apparatus**

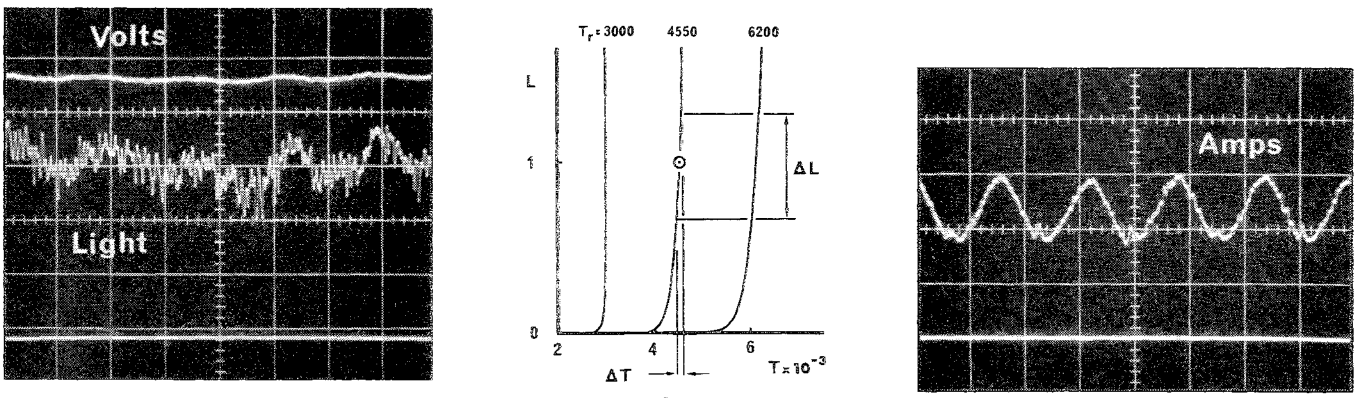
gas stream, thus enabling fluctuations of plasma intensity at frequencies in excess of 100-kc/sec to be resolved. In these investigations, both argon and nitrogen gases have been used.

The results show that two distinct modes of operation occurred: 1) a steadily burning arc, characterized by an almost constant voltage drop between the electrodes, and 2) an unstable arc, recognizable by large amplitude fluctuations in the voltage. When argon was being used as the test gas, both types of operation were observed, the unstable arc occurring only at low mass flow rates. In Fig. 2, traces of the arc voltage (Fig. 2a) and current (Fig. 2c) are shown for the stable arc column, the current trace reflecting a 300-cps ripple inherent in the power supply which uses three-phase rectification. Also in Fig. 2a is a trace of the photodiode output, which may be related to temperature fluctuations by reference to Fig. 2b. The curves shown in this figure have been derived from a knowledge of such transition probabilities as are currently available (see Ref. 2). For the nitrogen case discussed below, similar curves have been interpolated from data given by Keck et al.[3] considering the $N_2$ first and second positive bands and the $N_2^+$ first negative. These calculations have assumed the plasma to be in thermal equilibrium and optically thin, both of which conditions are, with other related matters, currently under investigation in the laboratory of the Imperial College of Science and Technology.§ The family of curves shown in Fig. 2b illustrates that the fluctuations in relative intensity recorded by the photodiode are indicative of only small changes in temperature. Spectroscopic measurements of the freestream temperature indicate a mean value of 4550°K (shown in Fig. 2b) for this operating condition, which leads to the conclusion that the gas temperature was fluctuating only by approximately ±50°K.

In passing, it should be noted that for argon at these temperatures a change of two orders of magnitude in the light intensity, i.e., the range normally covered by photographic materials, would indicate a temperature fluctuation of only about 15%. Although this is not an insignificant variation, when examining photographs of a jet care must be exercised to avoid concluding that unexposed regions on the film show the nonexistence of the plasma.

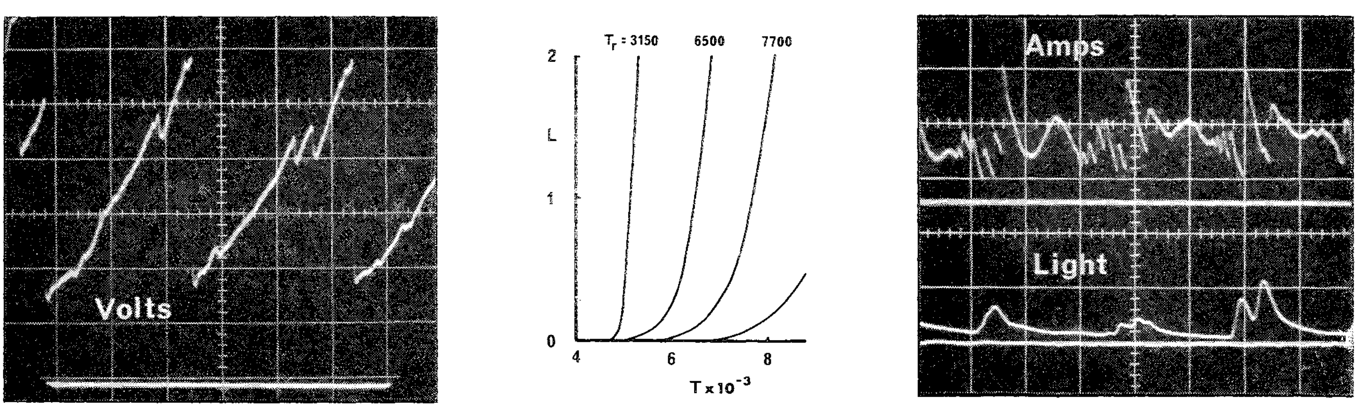
The curves of Fig. 3 illustrate the difference between the nitrogen operation and the stable argon characteristics discussed previously. The most striking point is the unsteadiness of the arc voltage, which oscillates at a frequency between 2 and 3 kc/sec. Figure 3a shows that the arc voltage increases from about 40 v to a peak value in excess of

§ "Excitation temperature measurements of gases in an arc heated wind tunnel at reduced pressures" (to be published).




a) b) c)

**Fig. 2 Observations of the arc behavior for argon; $\dot{m}$ = 0.154 lb/min, $\bar{V}$ = 24 v, $\bar{I}$ = 870 amp; sweep speed on oscilloscope traces is 2.0 msec/cm**




a) b) c)

**Fig. 3 Observations of the arc behavior for nitrogen; $\dot{m}$ = 0.180 lb/min, $\bar{V}$ = 81.0 v, $\bar{I}$ = 460 amp; sweep speed on oscilloscope traces is 0.2 msec/cm**

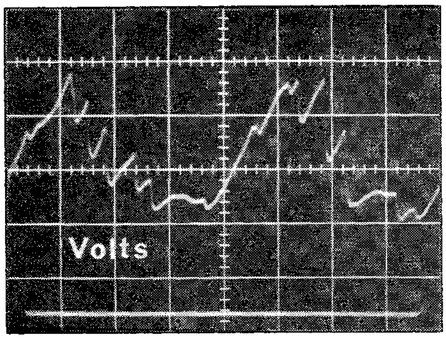



**Fig. 4 Another mode of the unstable nitrogen operation; $\dot{m}$ = 0.128 lb/min, $\bar{V}$ = 64 v; sweep speed is 0.1 msec/cm**

100 v and then falls very suddenly to the initial value; measurements of the decay time indicate values of the order of 1.0 μsec. This sudden drop in voltage is reflected as a peak in the arc current, seen in the upper trace of Fig. 3c. The lower trace of this figure shows the photodiode output, which indicates that a peak in the light intensity occurs in-phase with the current maxima, although the effects of diffusion appear to have broadened the intensity pulse. When operating with nitrogen, the test section becomes filled with a luminous gas, which probably accounts for the apparent shift of the intensity curve away from the zero.

It has been noticed that the nature of the voltage instability for nitrogen changes to that shown in Fig. 4 when the mass flow rate is reduced. Comparing Fig. 4 with Fig. 3a, it can be seen that the voltage follows a similar trend while increasing, but instead of falling suddenly from the peak value, it decreases in a series of steps. Despite the radical change in voltage characteristic, the frequency of the fluctuations remains almost unaltered.

It has been proposed that the arc instability results from a mechanism indicated in Fig. 5a. The arc initially strikes at position 1 and then moves down the anode through the subsequent positions. This movement results from both the downstream convection of the lower conductivity gas, initially at position 1, and the self-induced magnetic force caused by the curvature in the current path. For simplicity, any representation of the gas swirl has been omitted; however, the inherent stability of the vortex tends to localize the arc along the axis of the anode. When the arc reaches position 5, the voltage drop along it has increased to a value sufficiently high for breakdown to recur at position 1, so that the process is cyclic. Such a behavior is compatible with the voltage trace shown in Fig. 3a; however, it cannot explain the mode shown in Fig. 4. An explanation for this mode is that, before breakdown occurs, the arc column between C and B in Fig. 5a itself becomes unstable. This is possible because a radial perturbation of the column will produce an outward magnetic force, which under unfavorable conditions could overcome the inward aerodynamic force resulting from the gas swirl. This type of instability could lead to the column configuration shown in Fig. 5b. If the amplitude of the waves shown increases, the arc path will be shortened due to successive earlier contacts with the anode, and a voltage trace similar to that of Fig. 4 could be expected.

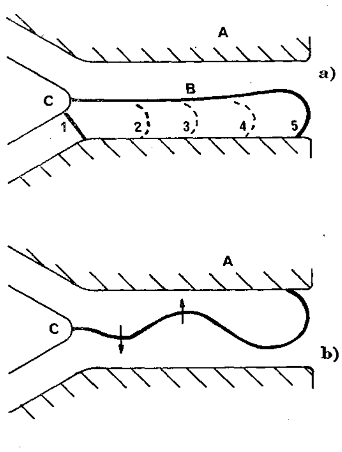



**Fig. 5 Proposed arc column configurations**

### Conclusions

The results of these investigations show that for this type of arc generator it is possible to have a stable arc column configuration for argon. This is contrary to the inference of Ref. 1, in which the gas being used was not stipulated.

Stable operation has not yet been achieved when running with nitrogen, even though the mass flow, open circuit voltage, and electrode geometry were varied. The measurements of the light intensity, taken downstream of the nozzle, indicate that the settling chamber and nozzle did not smooth the fluctuations. Thus, the interpretation of results taken in such a facility must be made with caution, since time-averaged measurements for the unsteady flow are not necessarily the same as those that would be measured in an equivalent steady flow.

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# Blast-Wave Correlation of Pressures on Blunt-Nosed Cylinders in Perfect- and Real-Gas Flows at Hypersonic Speeds

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**It is shown that the blast-wave parameter that includes a function of the isentropic exponent $\gamma$ offers the possibility of correlating blunt-nosed cylinder pressures obtained by theoretical solutions and experiment for both perfect and real gases. The result of the correlation is a single equation, in blast-wave form, which should approximate the pressures on blunted cylinders in both real and perfect gases for a wide range of nose drag and Mach number.**

THE blast-wave theory has been used in many investigations to correlate the surface pressures for blunted, stream-aligned cylinders. The parameter $(x/d)/M_\infty{}^2C_D{}^{1/2}$ has been used for both perfect and real gases (e.g., see Refs. 1 and 2). Pressures on cylinders with different nose-drag coefficients $C_D$ and freestream Mach numbers $M_\infty$ obtained by the method of characteristics are correlated in Ref. 1 for each of two perfect gases. The parameter worked very well for constant isentropic exponent $\gamma$ but is inadequate for correlating pressures for various values of $\gamma$.

The generalized first-order blast-wave theory for axisymmetric flow[2,3] contains a parameter for the effects of the isen-

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