THE MASS TRANSIENT AND PLASMA ARC INSTABILITY

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Early in the development of plasma arc heaters the criteria for stable arc operation were only poorly understood. The result was that many arc runs were attempted under unstable conditions, with arc blowouts frequently resulting. Many of these failures we now know would have been successful except for the adverse effect on the arc of the starting-pressure transient caused by the initial excess of gas in the chamber. The author discusses this problem and the incorporation in the APL arc of a vent valve to overcome it.

Visitors who come to the Propulsion Research Laboratory to observe the APL-developed split-ring plasma arc[1,2] functioning as a gas heater for a hypersonic propulsion or material ablation test are almost certain to see a successful operation. It will be carried out without incident by a test engineer who knows beforehand whether or not the arc will operate under the established conditions. This was not always so, however. We recall the early stages of arc development when the erratic operation of experimental arc units, sometimes igniting successfully and sometimes blowing out under seemingly identical conditions, or failing from insulation breakdown, cooling-water leaks, etc., caused much discouragement. It has only been within the past two years that a clear, quantitative picture of the factors governing arc stability has begun to emerge.[3]

In the case of the present split-ring, DC, high-pressure, plasma-arc unit whose basic elements are diagrammed in Fig. 1, the control parameters are: no-load supply potential E; total circuit resistance external to the arc (battery, ballast, and lines) r; exit-nozzle area A; and mass flow of carrier gas $\dot{m}$; most recently an additional parameter—electrode spacing d—has been added. The dependent variables are chamber pressure P, emergent gas enthalpy H, arc voltage V, and current i. What is required for a working knowledge of the confined gas-fed arc is a series of equations of the form

$$\begin{aligned} V &= V\,(E, r, \dot{m}, A, d), \\ i &= i\,(E, r, \dot{m}, A, d), \\ P &= P\,(E, r, \dot{m}, A, d), \\ \text{and } H &= H\,(E, r, \dot{m}, A, d). \end{aligned} \tag{1}$$

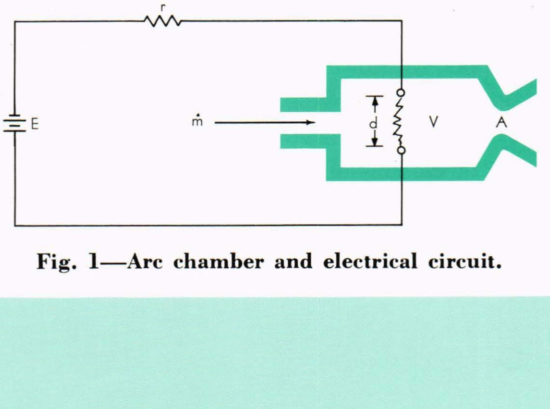

Fig. 1—Arc chamber and electrical circuit.

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[1] S. D. Raezer, E. A. Bunt, and H. L. Olsen, "Applications of D.C. Plasma Arc Heating to Hypersonic Propulsion Testing," *J. Spacecraft and Rockets,* 1, Mar.–Apr. 1964, 155–160.

[2] E. A. Bunt and H. L. Olsen, "Plasma Arc Heating for Hypersonic Wind Tunnels," *APL Technical Digest,* 1, Nov.–Dec. 1961, 16–18.

[3] S. D. Raezer, "Operating Points and Stability Limits of a High Pressure Direct Current Plasma Arc," CM-1043, The Johns Hopkins University, Applied Physics Laboratory, Mar. 1964.

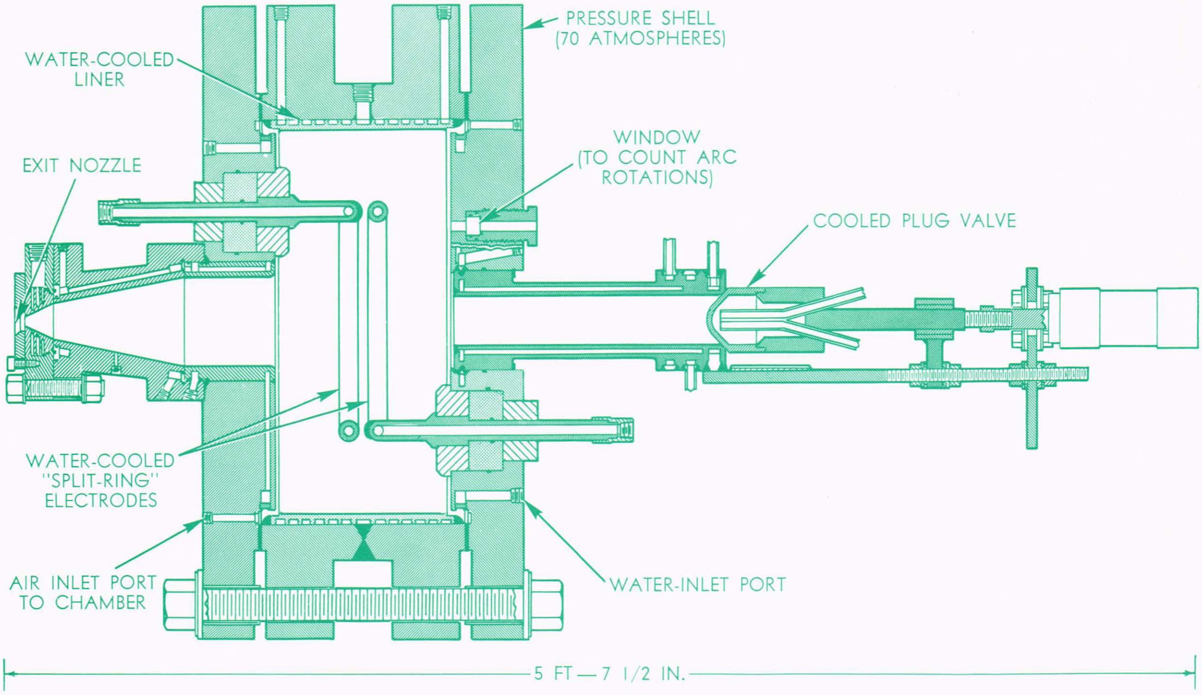

Fig. 2—APL split-ring plasma arc.

From the number of variables involved, one may obtain a rough idea of the complexity of the problem. In an effort to solve it we may apply certain well-established principles such as continuity of mass and conservation of energy. We have an essentially complete knowledge of the electrical power circuit and the equations governing the state of the gas (air), and a far less thorough knowledge of the various mechanisms of heat transfer between arc, gas, and walls. Finally, we do not understand completely how the current, pressure, and mass flow affect the arc voltage, but have obtained reliable approximations over certain ranges of these variables. (The equation expressing this relationship is generally referred to as the arc characteristic.) In principle the foregoing analysis should allow a synthesis of the set of Eqs. (1); $P, H, V,$ and i are not usually uniquely determined by these steady-state solutions since they are, in general, multi-valued. In addition, some understanding of the dynamics is therefore required to allow the selection of stable solutions.

Assurance that unique solutions of the form of Eqs. (1) exist can come only from experience gained by working with the arc. For a given setting of the control parameters, one hopes for a unique set of conditions (P, H, V, i). However, confidence in this belief was for some time shaken by apparent uncertainties in the response of the arc resulting from factors easily overlooked.

One such factor was the mass transient. The mass flow of gas (which is held fixed and independent of conditions in the chamber by the choked orifice in the supply line) is established and the arc ignited by passage of current through a wire wrapped around both electrodes. The resultant explosion of the wire creates an ionized high-temperature region of gas and metal vapor that starts the arc avalanche. If the proper settings have been made, the starting discharge should grow into an arc, stable under the final conditions; if the settings are improper the arc will be quickly extinguished.

After the steady-state conditions for stable operation began to be understood, it became evident that many of the unsuccessful runs should have been stable and that starting conditions must therefore be particularly adverse for arc stability. Therefore, it was decided to reduce pressure at the beginning of the run by incorporating a water-cooled plug-type valve in the arc, as shown in Fig. 2. This valve, kept open at the start of each run and closed upon attainment of arc equilibrium, ended the starting difficulty.

The primary cause of this difficulty is simple to understand, but it was initially obscured by the complexity of the overall system. It results from the fact that under normal conditions of arc operation, the initial mass of gas in the chamber before firing is greater than the final mass; this excess must, therefore, be ejected from the chamber in the process of equilibration, resulting in an initially higher pressure (Fig. 3). This acts to force the voltage up, which, it can be shown, reduces arc stability. The peak of the pressure pulse $P_t(o)$ on the instant of firing (assuming a step change in the temperature and no moles change) is, from the ideal gas law,

$$P_t(o) = \frac{T_f}{T_o} P_o, \qquad (2)$$

where P_o refers to the initial pressure, T_o the initial temperature, and T_f the temperature after firing (which for all practical purposes is identical with the final equilibrium temperature). This can be compared to the final equilibrium pressure P_f which, for choked inlet and exit nozzles is roughly

$$P_f = \left(\frac{T_f}{T_o}\right)^{1/2} P_o. \qquad (3)$$

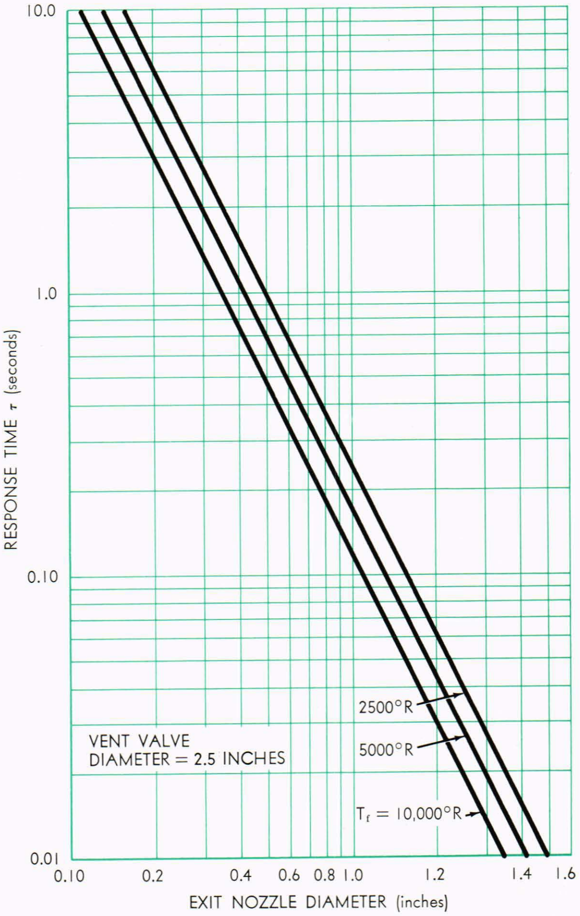

Fig. 4—Pneumatic response time as a function of nozzle diameter for various values of final equilibrium temperature. Chamber volume V is 2.0 cu ft; γ is assumed to be 1.4.

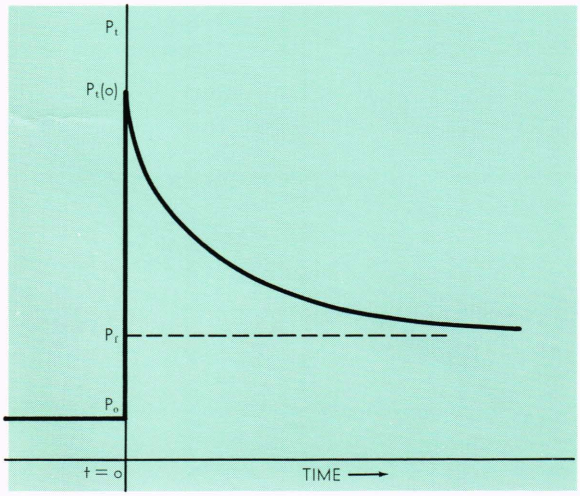

Fig. 3—Theoretical pressure peak resulting from an excess of gas in the arc chamber prior to firing. Time scale depends on the geometry of the apparatus.

More important still is the duration of the pulse, since a long-maintained increase in the pressure may outlast the decay of initial conditions favorable to the maintenance of stable arc operation—the presence of metal vapor from the explosion of the wire, for example. The time dependence of P_t is given by

$$P_t - P_f = [P_t(o) - P_f]\, e^{-t/\tau}, \qquad (4)$$

where

$$\tau = \frac{V}{AC_f}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}.$$

Here C_f, the speed of sound, $= \sqrt{\gamma R T_f}$, V is the volume of the chamber, and A is the exhaust-nozzle throat area. It is thus seen that for a large-volume arc chamber with small nozzle-throat area, the time required for the excess mass to be expelled from the chamber will be large. This is the case with the present APL arc whose response time is shown as a function of nozzle diameter in Fig. 4. This does not mean that the starting problem is necessarily any greater than with a smaller-sized unit, since in general, available voltage and power-handling capability that improves stability *during* the starting phase increases with the size of the arc unit.