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COAXIAL-FLOW STABILIZATION OF AN ALTERNATING-CURRENT PLASMA ARC

by Chester D. Lanzo
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TECHNICAL PAPER proposed for presentation at Fluid and Plasma Dynamics Conference sponsored by the American Institute of Aeronautics and Astronautics Los Angeles, California, June 24-26, 1968

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Abstract

Experimental results are presented for a coaxial-flow-stabilized, ac, 12- to 22-cps (12- to 22-Hz) electric arc. The arc is maintained along the centerline of an argon jet. Coflowing streams of either helium or nitrogen surround the central argon jet. The arc is stabilized by the flow field of the two gases. General characteristics of arc behavior are described for various operating conditions. Arc voltage-current curves are shown. Arc length is varied from 1 to 12 inches (2.54 to 30.5 cm). Photographs of the arc at maximum intensity are shown.

Introduction

Most of the major effort of previous investigations on arcs has been associated with dc operation. Recently, ac arcs have been utilized for high-power, arc-heated, heat-transfer devices because of the availability of large amounts of power at a frequency of 60 cps (60 Hz). Interest in the use of arc-heated, heat-transfer devices has greatly increased, and in the past few years these devices have been utilized by modern technology so that the state of the art is advanced to where large, high-power-level installations are being used.

Various arc configurations have been investigated in the past. The primary problems associated with arc devices are the methods used to maintain and stabilize the arcing region and the hot plasma gases that are created. The term stabilize means to maintain a steady-state, or continuous, plasma flame. Stabilization is generally accomplished by a constriction or compression of the arc column by some method outside of the arc itself. The usual methods of stabilization have utilized liquid and gas vortexes or magnetic fields. A Gerdien arc type of electrode configuration uses a water vortex for stabilization. A Gerdien arc is characterized by a circular orifice anode and an inner electrode positioned on the centerline of the orifice and enclosed in a chamber. A Gerdien arc was first operated about 1922. The arc region was projected through a narrow nozzle in order to increase the current density and temperature. Modern versions of the Gerdien type plasma generator which use a nonswirling gas flow are described in reference 1.

Experimental results obtained from an investigation of a vortex-stabilized arc which operates at 1 atmosphere (1.013×10^5 N/m^2) of nitrogen and uses either alternating or direct current are reported in reference 2. Vortex-stabilized arcs several feet in length were used extensively in the investigation of reference 2.

Experiments described in reference 3 showed that an electric arc contained in a quartz tube is a useful tool for radiation heat-transfer studies, but that the arc gas temperature is limited by the melting temperature of the quartz-tube enclosure. Studies of a free burning arc with no solid surface near the arc[4] have shown the arc is extinguished or "blown off" at low transverse gas velocities of approximately 3 feet per second (0.91 m/sec). Instability is produced by convective flow in the vicinity of the arc column.

This paper describes an experiment on the feasibility of using coaxial jets of dissimilar gases maintained at uniform parallel and horizontal flow through concentric nozzles to achieve arc stabilization. Such a configuration has been developed, and it uses low-frequency ac power with current from 500 to 1000 amperes. The system is evaluated as an experimental arc facility to study radiant heat-transfer processes. The arc is maintained in a center jet of axially flowing argon, between an upstream and a downstream water-cooled electrode. An outer stream of gas flows coaxially around the center jet. Both nitrogen and helium were used in the outer stream. Tests were conducted to determine qualitatively the effect of varying the relative velocities of the inner and outer gas streams on arc stability. The tests were conducted at chamber pressures from 8 to 25 psia (55×10^3 to 172×10^3 N/m^2 abs) with arc lengths of 1 to 12 inches (2.54 to 30.5 cm). Visual observations were made by means of high-speed motion pictures, and voltages and currents were measured.

Experimental System

Arc Source

A schematic diagram of the experimental apparatus and the primary instrumentation for the arc system of this investigation is shown in figure 1. A photograph of the arc apparatus is shown in figure 2. In regard to the power supply and ballast resistor, this system is quite similar to that described in reference 3.

The arc chamber consists of a welded and bolted, stainless-steel, gas-tight system designed to operate at pressures from 0 to 60 psia (0 to 415×10^3 N/m^2 abs). The arc is contained in a test chamber that has a cross section of 7 by 7 inches (17.8 by 17.8 cm). In each of two opposite sides there is a window for observing the electrodes and the arc during operation. The windows are made of 7/8-inch-thick (2.2-cm) fused quartz and are 6 by 14 inches (15.25 by 36 cm) in area. Cooling of

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the windows is accomplished by natural convection on the outside of the windows. The arc is maintained between fixed-upstream and movable-downstream, water-cooled, copper electrodes that have tungsten tips.

Argon was chosen as the central jet gas because it does not require any dissociation energy and is, therefore, relatively easy to ionize, and it produces a highly radiant plasma. The arc is held within a jet of metered argon gas that is introduced through an upstream plenum chamber and flow-straightening screens. The argon gas flows coaxially past the fixed electrode in the inlet duct to the arc chamber in a laminar flow mode. Argon is supplied from a high-pressure bottle farm. As the gas passes through a pressure regulator, the pressure is dropped to 100 psi (689×10^3 N/m^2) near the arc inlet control valve.

Gas is accelerated past the upstream electrode by a long converging nozzle to produce a uniform and parallel stream around the upstream electrode. In the arc region the gas velocity is approximately 2 to 50 feet per second (0.61 to 15.3 m/sec). This velocity is high compared to the upward velocity of the gas due to free convection.

The grounded downstream electrode is mounted on a movable carriage. When all gas flow rates are set, the arc is initiated by a pneumatic-electric servosystem that drives the downstream electrode into the pressure vessel until contact is made with the fixed electrode. Then the movable electrode is withdrawn to a position about 1 to 12 inches (2.54 to 30.5 cm) from the upstream electrode. This entire sequence is accomplished in 5 seconds.

The electrodes are identical in design and construction. They are cooled by water with a flow rate of 10 gallons per minute (0.04 m^3/min), a temperature of 65° F (292° K), and an inlet pressure of 275 psi (1900×10^3 N/m^2). The design of the electrodes allows for their easy removal and replacement. They usually are replaced after about 15 minutes of running time. This frequent replacement is more of a convenience than a necessity since some electrodes have been run as long as $1\frac{1}{2}$ hours.

Power Supply

The electrical energy used to supply the power for the arc discharge is obtained from variable-frequency ac rotating machinery that generates 66 volts per cycle per second (66 V/Hz) at 16 cps (16 Hz) and operates in the range from 10 to 60 cps (10 to 60 Hz). A characteristic curve of voltage as a function of frequency for the power supply is shown in figure 3. All runs were made at arc frequencies from 12 to 22 cps (12 to 22 Hz). A maximum power of 7 megawatts was available at the limiting current of 1125 amperes. The frequency of the applied voltage to the arc can be varied (while the arc is in operation) from 10 to 60 cps (10 to 60 Hz).

A bank of water-cooled, stainless-steel tubing is used as a 1.6-ohm pure resistance. This ballast resistor is connected in series with the arc to give the necessary voltage drop to stabilize against changes in arc discharge voltages and to match the power-supply output to arc characteristics.

Instrumentation

The primary measurements made during a test run were as follows:

(1) Argon and helium or nitrogen flow rates

(2) Outlet gas temperature

(3) Arc voltage and arc current

(4) Ballast voltage and current

Argon and helium or nitrogen flow rates were measured with an orifice assembly in each flow system. The argon and helium or nitrogen mixture outlet temperature for all runs was measured with a high-stagnation, aspirated, radiation-shielded thermocouple. The cooling coils surrounding the arc chamber and its piping dropped the outlet gas temperature to a low value so it could be measured directly without thermocouple burnout.

The electrical power delivered to the arc was determined from measured values of arc current and voltage. Actual measurements were made on the secondaries of current and voltage transformers.

A dual-beam oscilloscope was used to obtain instantaneous voltage and current waveforms. Waveforms for a 20-cps (20-Hz) arc are shown in figure 4.

The voltage waveform is typically nonsinusoidal. The indicated voltmeter reading was checked for one run and was found to be within ±3 percent of the value given by a true rms meter.

Graphic integration of the instantaneous power curve from the curves of figure 4 gave an average power within ±7 percent of the product of rms voltage and rms current. Because of the close agreement between the two measurements it was considered to be satisfactory to obtain arc power directly from the panel meters.

Flow Field

Because of the possibility that the flow in the outer jet annulus would have an effect on the stability of the arc contained in the center jet, cold flow field velocity was measured.

Figure 5 shows a typical velocity profile taken with hot wire device when nitrogen was used in the jets. Mean velocity measurements were made of the axial velocity component only. Velocity fluctuations due to turbulence were averaged out by visual observation of the meter fluctuations. The velocity profiles indicate a relatively small velocity defect behind the upstream electrodes. The velocity ratio of the two concentric jets does have an effect on the center jet profile. Although no measurements were made of gas velocity with the arc ignited, the velocity field would certainly be affected by the addition of heat.

Experimental Procedure

During operation, the arc facility is controlled from an adjoining control room adjacent to the test area with all of the data being remotely indicated and recorded. The arc is visually observed by a mirror system through a window. The window is composed of 1/4-inch-thick (0.64-cm) number 8 welding glass. The glass decreases the ultraviolet and visible radiation to a tolerable level.

Prior to ignition of the arc, the power supply is set at 12 cps (12 Hz). The electrodes, the ballast cooling water, and the concentric argon and nitrogen or helium gas jet flows are set for starting conditions. The pressure in the containment tank is set by adjusting one or both of the inlet gas flows to a predetermined flow rate in the test section area; it is then necessary to adjust the exhaust control valve to throttle the total gas flow in order to maintain a fixed static pressure. A pneumatic starting device inserts the downstream electrode into the pressure vessel and causes this electrode to contact the fixed upstream electrode. After contact, the downstream electrode is withdrawn (by the pneumatic device) to a preset position of 1 to 12 inches (2.54 to 30.5 cm) from the upstream electrode.

The desired power level is reached by adjusting the voltage generated by the variable-frequency power supply. After steady-state conditions are observed, the motion-picture cameras are started. The arc-chamber pressure is held constant during a run by adjusting the opening of the downstream valve in the gas exhaust system. The pressure was held constant within ±1/2 psia ($\pm 3.45 \times 10^3$ N/m^2) during all the runs.

The velocities of the center jet of argon and of the outer jet of nitrogen were varied up to 50 feet per second (15 m/sec). Most of the runs were made with nitrogen as the outer gas; however, some runs were made with helium as the outer gas. The center gas was argon for all runs.

Discussion of Results

Electrode Design and Life

For a long time it was generally thought to be impossible to operate low-frequency ac arcs between cooled metallic electrodes because the rapid cooling of the electrodes would prevent the reignition of the arc after the extinction period when the voltage and current were at zero. However, Engel and Steenbeck[5] were able to operate an ac arc with a short arc length of 0.12 inch (3 mm) at 10 amperes, between water-cooled electrodes, with inductive stabilization. The reignition voltage was more than eight times the rms arc voltage.

For the tests reported herein, a series of preliminary runs was conducted with cold metallic electrodes to determine feasibility of operation. Figure 6 is a photograph of a set of water-cooled, pure-copper electrodes that were used in some initial tests of the present ac arc. The upstream electrode is shown mounted between the two concentric gas nozzles, and the downstream electrode is shown in the normal run (after-contact) position, about 4 inches (10.2 cm) downstream. The copper electrodes melted very rapidly. They generally failed after about 30 seconds or less of running time at normal power operations. As can be seen in figure 7, large beads of melted copper would form at the tips. These beads would then drip off as the run progressed until, ultimately, the high-pressure cooling water would leak out and extinguish the arc. No combination of jet flow rates used had any significant effect on the short lifetime of these cooled copper electrodes or on the stability of the arc column. To eliminate this melting problem tungsten-tipped electrodes were used.

Figure 7 shows the final electrode configuration used in the concentric-jet arc system. A tungsten plug about 3/8 inch (0.95 cm) in diameter and 1/4 inch (0.64 cm) thick used in the preliminary tests was inserted into the copper tip and silver soldered to reduce contact resistance to the high current flow and to improve heat-transfer rates. Tungsten was used because of its high melting temperature (3500° C).

Because the electrode tip operates at sufficiently high temperatures to guarantee adequate electron emission without cooling off during the extinguished period of an ac arc, sufficient electrons are supplied by thermal emission for arc reignition. All runs discussed in this paper were made with tungsten inserts in the water-cooled electrodes. Short runs of 15 minutes duration were possible at all arc conditions with the tungsten tip insert shown in figure 7(a) before complete disappearance of the tungsten tip occurred.

A new set of electrodes was constructed with tungsten tipped inserts that were extended 1 inch (2.54 cm) from the end of the copper water-cooled electrodes (fig. 7(b)). This extension of length allowed the tungsten tips to operate while in the liquid state. Greatly prolonged electrode life and arc running times were realized. Runs have been made up to 1 hour with no appreciable change in electrode diameter or length.

Figure 8 is a photograph of these same electrodes after 1 hour of operation at 600 amperes at 60 volts with coflowing argon and nitrogen gases. This was a typical operating condition.

The tips are bright after 1 hour of operation at liquid-tungsten temperature. This appearance is to be expected, since no oxygen was present to contaminate the tungsten. The bright, shiny, meniscus-shaped appearance of the electrode tip indicates that the tungsten was molten during operation. The presence of molten tungsten probably contributes significantly to stable arc behavior.

Effect of Coaxial Gas Stream Velocities

Figure 9 shows the coaxial-flow-stabilized arc in operation with argon gas in the center jet flowing at a velocity of 30 feet per second (9.1 m/sec) and nitrogen gas in the outer jet flowing at 15 feet per second (4.57 m/sec).

Figure 10 shows the argon arc with a center velocity of 30 feet per second (9.1 m/sec) and an outer nitrogen velocity also of 30 feet per second (9.1 m/sec). The change in shape of the plasma region with this increased velocity and velocity ratio is almost undetectable when compared with the shape in figure 9. Both of these photographs were taken at camera speeds of 4000 frames per second and were selected from the region where the light intensity emitted is the highest in the ac cycle. Figures 9 and 10 indicate that cooling of the arc by increasing the velocity of the concentric gases does not produce a significant reduction of the average plasma-column diameter in a free-jet arc.

Plotted in figure 11 is the arc voltage as a function of the rms arc current. These were taken at a fixed electrode gap of $3\frac{1}{2}$ inches (8.9 cm) with argon gas flowing at 30 feet per second (9.1 m/sec) under a pressure of 8 psia (55×10^3 N/m^2 abs). (Note that the arc has a positive characteristic.)

Figure 12 shows the effect on arc voltage of increasing the gas static pressure with the electrode gap spacing held at 3 inches (7.6 cm) and the arc current held constant at 550 amperes.

Figure 13 shows the effect on arc voltage of increasing the electrode gap from 1 to 12 inches (2.54 to 30.5 cm). The arc current was held constant at 500 amperes, and the gas pressure was held constant at 8 psia (55×10^3 N/m^2 abs).

Also shown in figure 13 is the effect on the arc voltage of increasing the arc gap from 1 to 12 inches (2.54 to 30.5 cm) for a constant gas chamber pressure of 8 psia (55×10^3 N/m^2 abs) but with the arc current now held constant at 700 amperes. A slightly different curve results, but both voltages approach 70 volts at 11 inches (28 cm) arc length.

High-Speed Motion-Picture Results

The high-speed motion pictures taken at 400 to 4000 frames per second indicated that increasing the flow rate of the concentric gases did not produce a significant reduction of the plasma diameter. The expected result of a reduction in the diameter of the outer plasma was not discernible. Decreasing the gas flow rates did increase plasma stability and improve starting at constant pressure.

High-speed motion pictures of the downstream electrode with the short tungsten tip (shown in fig. 7(a)) disclosed that the arc attached itself to the tungsten tips initially. Then, as the cycle proceeded, the arc attached to small regions of the copper portion of the electrode immediately behind the tungsten. This instability was corrected by the use of the longer tungsten tips which had molten ends during operation.

Conclusions

An ac arc stabilized by coflowing annular jets of two gases flowing parallel to the arc discharge was designed and built. Velocity profiles of the coflowing gases were measured for cold-flow conditions. The outer nitrogen jet velocity was varied from zero up to a value greater than that of the inner argon jet velocity. The arc column diameter did not change with increasing flow rate of either of the two coflowing gases. (This "thermal pinch" effect normally occurs as the external cooling of the gas jets decreases the column diameter and increases the plasma intensity.) When helium was used as the outer-stream gas, the arc was quite unstable, and arc startup was difficult.

A water-cooled copper electrode with tungsten inserts of different lengths was built and tested. This electrode, as compared to an electrode of just copper, added considerably to ac arc stability and greatly increased electrode life.

The general conclusion of these tests is that it is possible to maintain a stable, steady-state ac electric arc in the central region of two coflowing streams of gases such as argon and nitrogen. It is presumed that the primary constraining force is the result of a difference in the ionization potentials of the two streams. It was found that arc behavior is quite insensitive to changes in the velocity of either the inner or the outer gas stream. The experimental arc facility of this investigation is considered a useful tool for the study of radiant heat-transfer processes at high temperatures.

References

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[2]Schreiber, P. W., "Radiation from an Alternating Current Nitrogen Arc." Rep. No. ARL 65-105, Aerospace Research Labs., May 1965. (Available from DDC as AD-620043.)

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[4]Thiene, Paul G., Chambers, James E., and Jaskowsky, Woldemar V., "An Experimental Investigation of the Behavior of an Arc Positive Column in the Presence of Forced Convection." Rep. No. T-4TN031-334 (AFOSR-682), Plasmadyne Corp., Apr. 29, 1961.

[5]Engel, Alfred V., Steenbeck, Max, "Measurement of the Time Variation of the Temperature in the Column of an Alternating Current Arc Light." Wiss Veroff. Siemes. Konzern., vol. 12, 1933, pp. 74-89.

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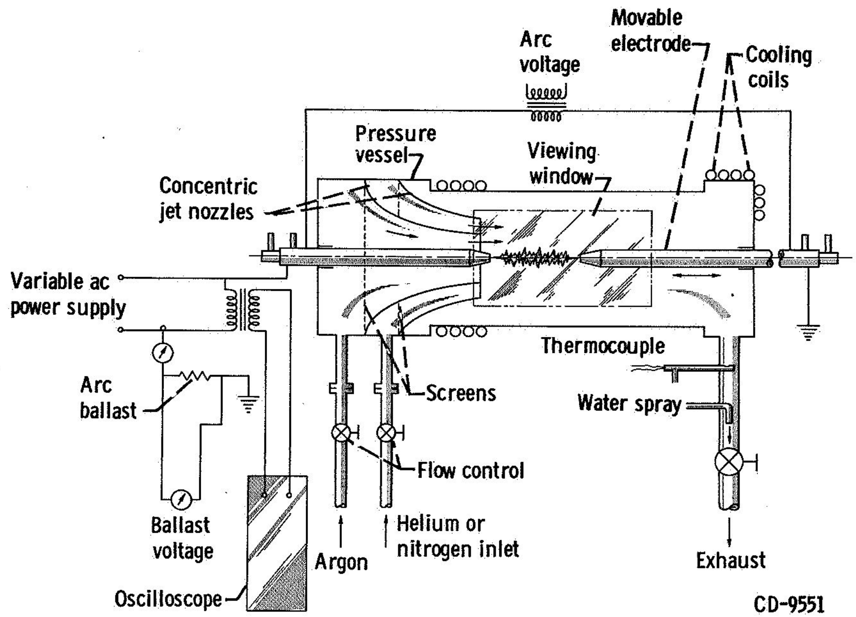

Figure 1. - Schematic diagram of experimental arc system.

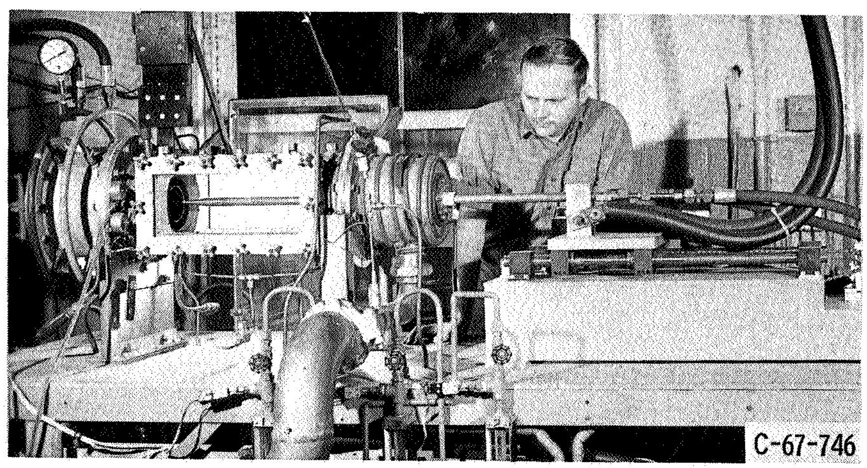

Figure 2. - Experimental arc apparatus.

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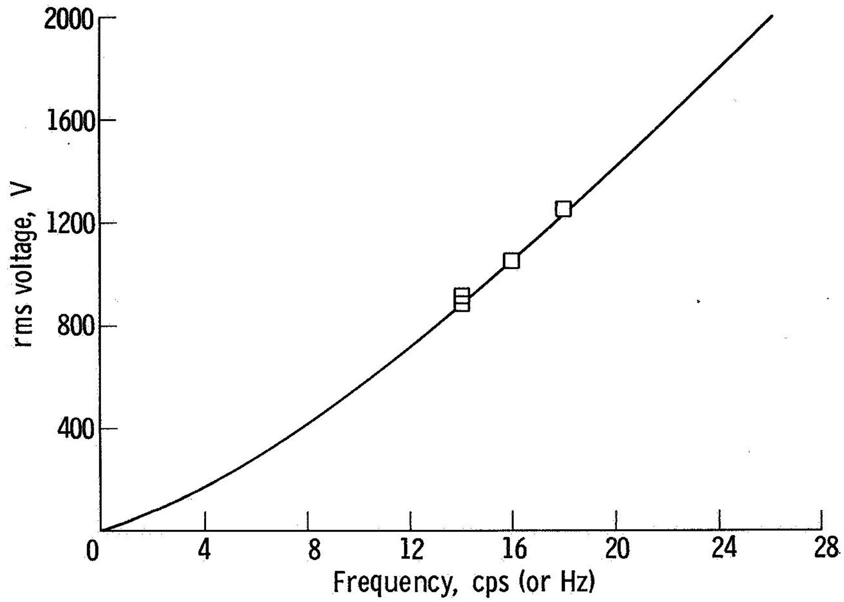

Figure 3. - Power-supply voltage characteristics under load. Current, 500 to 800 amperes.

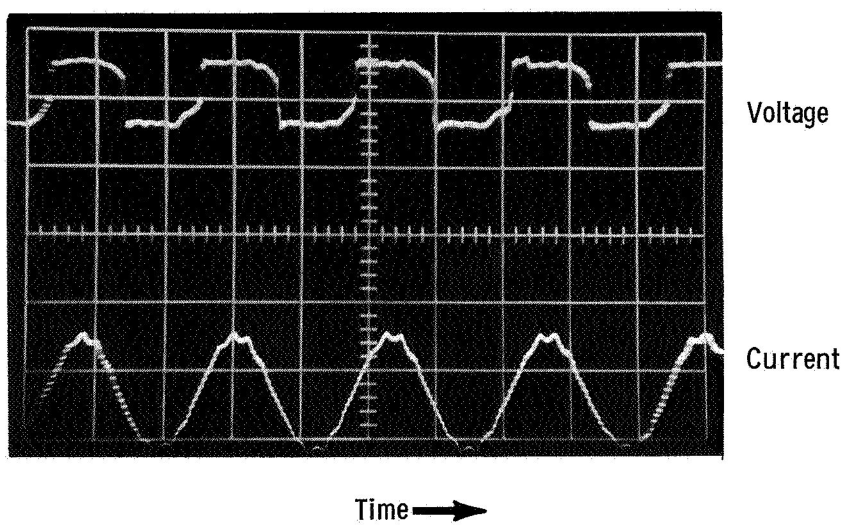

Figure 4. - Current and voltage cycles of arc. Power factor, 0.93; current, 800 amperes; arc gap, 3-1/2 inches (8.9 cm); frequency, 20 cps (20 Hz).

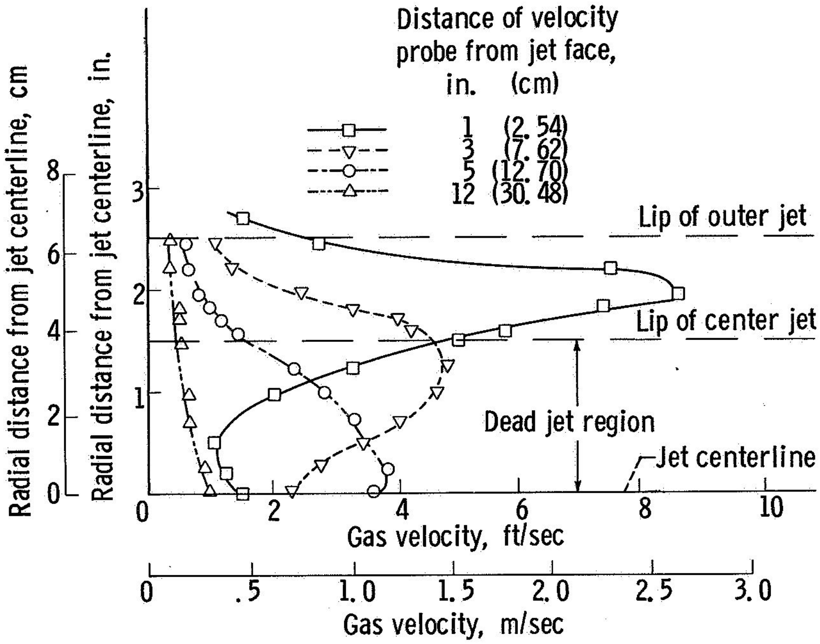

Figure 5. - Velocity profiles for two concentric jets. No gas flow in center jet; nitrogen gas flow in outer jet; 7/8-inch- (2.2-cm-) diameter electrode at center of jets.

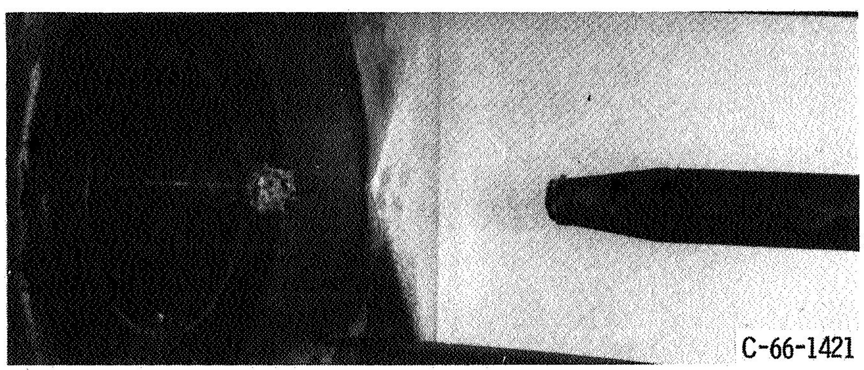

Figure 6. - Water-cooled copper electrodes after 30 seconds of arc operation.

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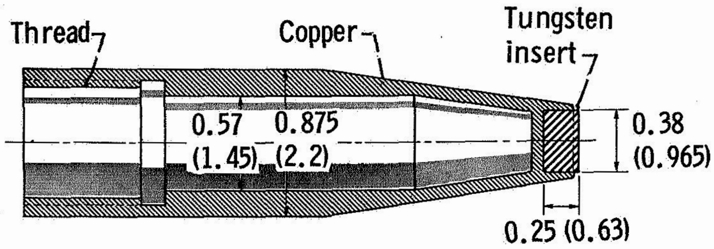
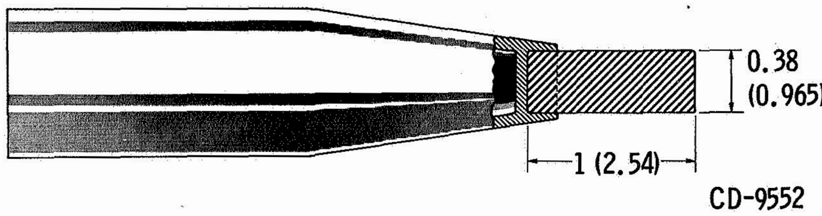


(a) Length of tungsten insert, 1/4 inch (0.63 cm).



(b) Length of tungsten insert, 1 inch (2.54 cm).

Figure 7. - Tungsten-tipped copper electrodes. Dimensions given in inches (cm).

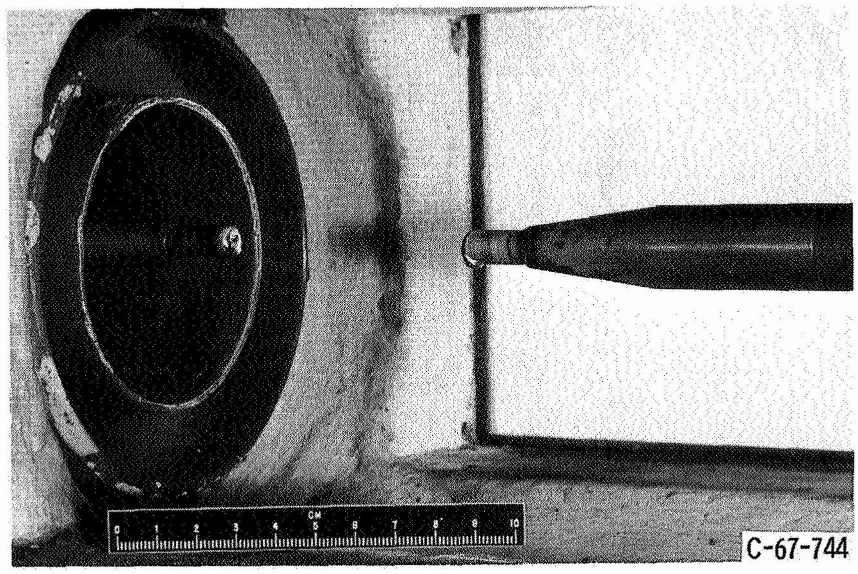


Figure 8. - Tungsten-tipped electrodes after 1 hour of arc operation.

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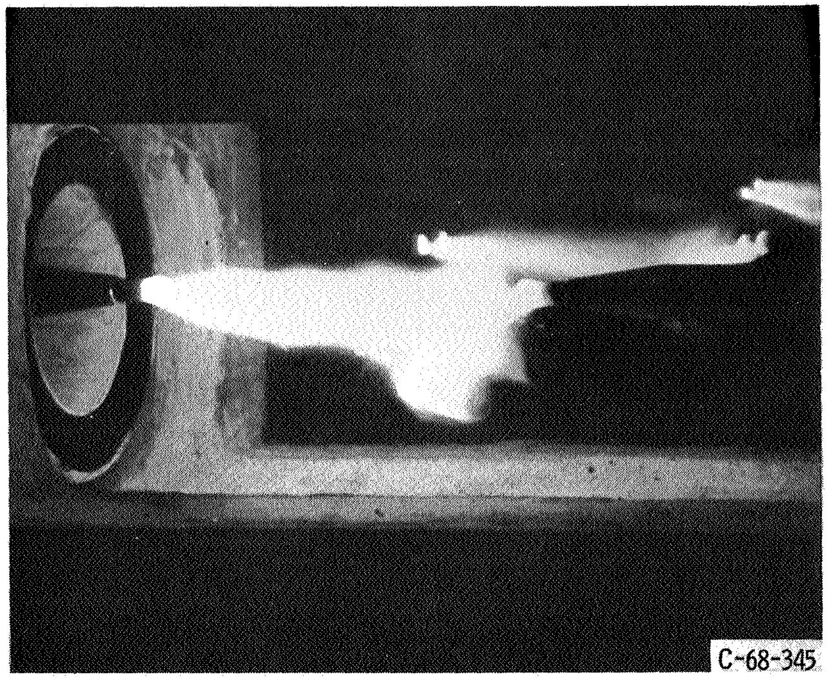

Figure 9. - High-speed photograph of arc in operation. Outer nitrogen jet velocity, 15 feet per second (4.57 m/sec); center argon jet velocity, 30 feet per second (9.1 m/sec); arc length, 6 inches (15.2 cm); camera speed, 4000 frames per second; pressure 8 psia ($55x10^3$ N/m^2 abs); voltage, 47 volts; current, 540 amperes; power 236 kilowatts.

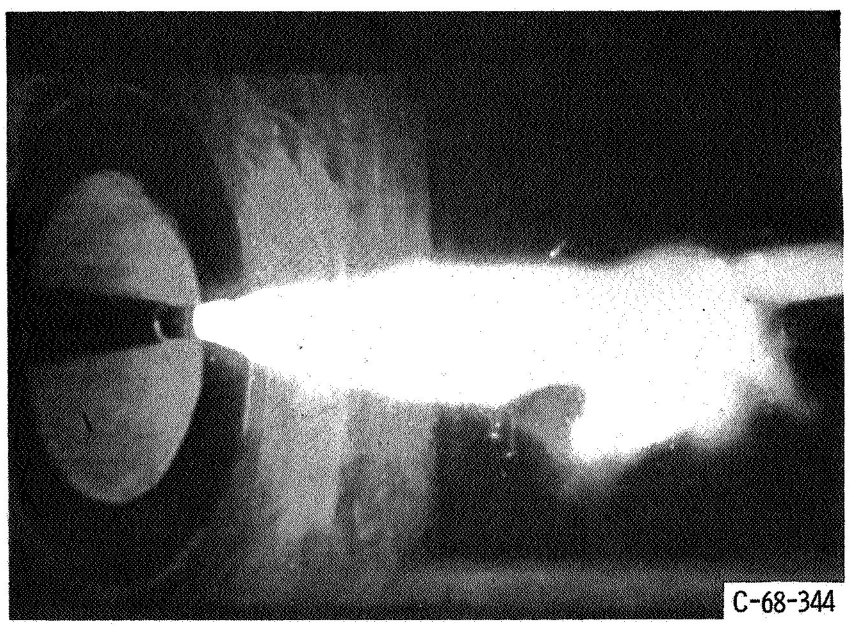

Figure 10. - High-speed photograph of arc in operation. Outer nitrogen jet velocity, 30 feet per second (9.1 m/sec); center argon jet velocity, 30 feet per second (9.1 m/sec); arc length, 6 inches (15.2 cm); camera speed, 4000 frames per second; pressure 8 psia ($55x10^3$ N/m^2 abs); voltage, 65 volts; current, 700 amperes; power, 426 kilowatts.

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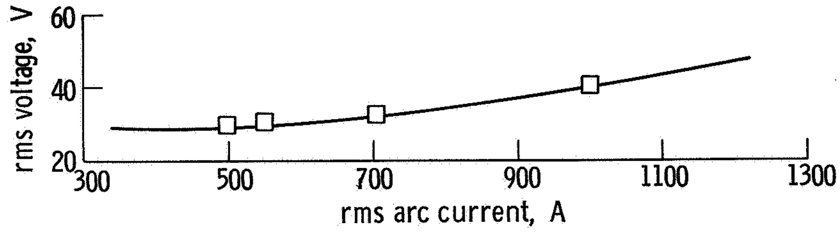

Figure 11. - Arc voltage-current characteristics at constant arc gap, pressure, and gas flow rate. Arc gap, $3\frac{1}{2}$ inches (8.9 cm); pressure, 8 psia ($55x10^3$ N/m^2 abs); argon gas flow rate, 30 feet per second (9.1 m/sec).

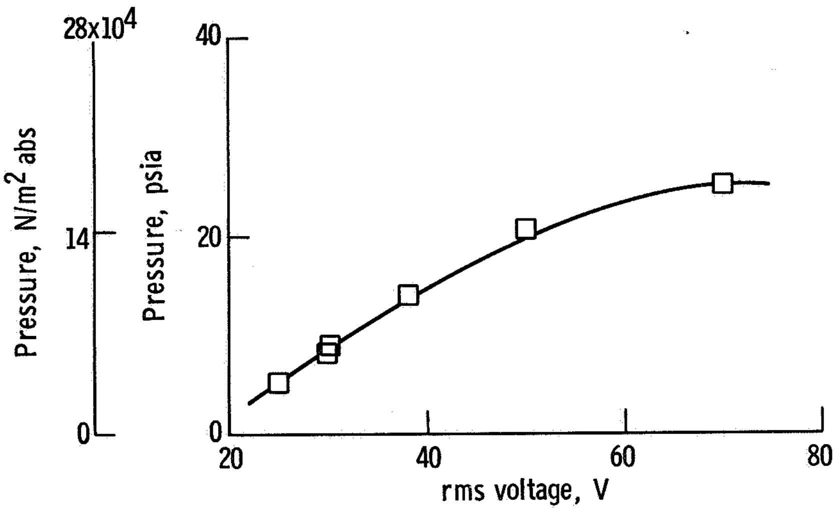

Figure 12. - Arc voltage at various static pressures. Arc gap, 3 inches (7.62 cm); current, 550 amperes.

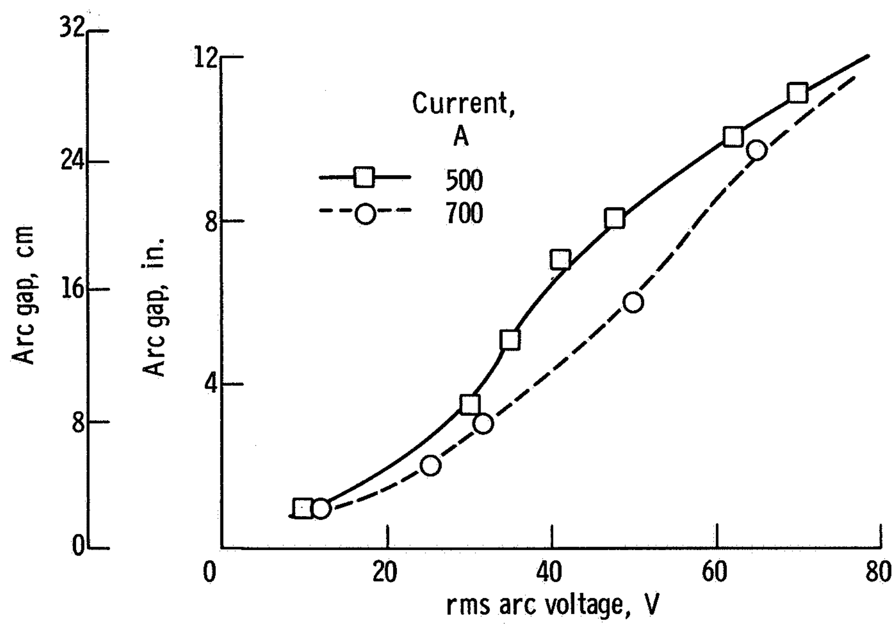

Figure 13. - Arc voltage as function of arc gap. Pressure, 8 psia ($55x10^3$ N/m^2 abs).