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ELECTRICAL CHARACTERISTICS OF A FREE-BURNING DIRECT-CURRENT ARGON ARC OPERATING BETWEEN 90 AND 563 KILOWATTS WITH TWO TYPES OF CATHODES

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16. Abstract

The electrical characteristics of a high-power, long-lived, free-burning dc argon arc are presented. Empirical formulas relating voltage to current, electrode separation, and operating pressure are given for two types of cathodes: a typical point tip cathode and a cathode with a 1.27-cm- (0.5-in.-) diameter crater in the tip. Power was varied from 90 to 563 kW. A discussion of the cathode with the crater tip is given.

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ELECTRICAL CHARACTERISTICS OF A FREE-BURNING DIRECT-CURRENT ARGON ARC OPERATING BETWEEN 90 AND 563 KILOWATTS WITH TWO TYPES OF CATHODES

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SUMMARY

The electrical characteristics at high power of a long-lived, free-burning dc argon arc were measured for two types of cathodes: a cathode with a pencil tip was used in the 90- to 367-kilowatt power range, and a cathode with a crater machined in the tip was used in the 102- to 563-kilowatt power range. The characteristics changed little when the arc chamber volume was changed from 0.028 to 2.1 cubic meters. The characteristics are summarized by the following formulas:

Cathode with pointed tip:

For pressure p in newtons per square meter,

$$V = 3.34\times10^{-3}(Lp)^{2/3} + 2.14\times10^{-4}I(Lp)^{2/3} - 7.31\times10^{-4}Ip^{2/3} + 8.50I + 13.03$$

For pressure in atmospheres,

$$V = 7.25(Lp)^{2/3} + 0.46I(Lp)^{2/3} - 1.59Ip^{2/3} + 8.50I + 13.03$$

Cathode with crater in tip:

For pressure in newtons per square meter,

$$V = 2.98\times10^{-3}(Lp)^{2/3} + 3.78\times10^{-4}I(Lp)^{2/3} - 1.05\times10^{-3}Ip^{2/3} + 5.79I + 12.88$$

For pressure in atmospheres,

$$V = 6.47(Lp)^{2/3} + 0.82I(Lp)^{2/3} - 2.27Ip^{2/3} + 5.79I + 12.88$$

where V is the arc voltage in volts, I the arc current in kiloamperes, p the arc chamber operating pressure in newtons per square meter (or atm where noted), and L the electrode separation in centimeters.

For cathodes with a crater tip, the arc switches from attachment at a single point to uniform attachment over the entire crater at a certain transition current. This transition current is independent of pressure and electrode separation but it is dependent on cathode condition. A typical transition current is 3000 amperes. The cathode with a

crater has shown a life of more than 100 hours at 400 kilowatts when operated above the transition current.

INTRODUCTION

A set of electrodes has been developed at the Lewis Research Center for a 400-kilowatt argon arc lamp. The arc lamp is the radiation source for a solar simulator. One lamp is designed to produce one solar constant (135 mW/cm^2) on a test area 4.6 meters by 9.2 meters when used with a collimating mirror.

The electrodes, the arc, and the solar simulator are described in references 1 to 5. References 1 and 2 describe the arc electrodes. Reference 3 presents the arc spectra while burning in argon, krypton, and xenon. Reference 4 describes the arc lamp and the solar simulator and summarizes the design of the electrodes. Reference 5 describes the process for bonding tungsten to copper during the fabrication of the cathode.

When used to support a free-burning arc, the electrodes have demonstrated a long life at a high arc power. An arc has been operated for more than 100 hours at 400 kilowatts. Although designed for use in a solar simulator, the electrodes and the arc can be used whenever a long-lived source of several hundred kilowatts of radiation is needed.

A set of electrical characteristics is needed to choose operating conditions for the arc and a power supply. These characteristics are arc voltage as a function of electrode separation, arc chamber pressure, and current.

Two different cathodes were used to obtain the electrical characteristics. The first was the pencil tip (point cathode) cathode normally used in a free-burning arc intended for producing radiation. The second cathode is designed so that the arc burns from inside a cone-shaped crater (annular cathode).

The annular cathode permits operation at higher power and much longer electrode life than is possible with a point cathode. However, the point cathode has some advantages. A large part of the radiation output comes from a small ball of bright plasma at the cathode tip. Optical systems which can collect from only a small source find this feature desirable. Also, a point cathode is easier to make.

This report presents measurements of the electrical characteristics of the arc in argon. For the annular cathode, 160 separate measurements were taken covering a range of arc power from 102 to 563 kilowatts. The electrode separation ranged from 3.8 to 8.9 centimeters (1.5 to 3.5 in.) and the operating pressure ranged from 1.5×10^5 to 4.1×10^5 newtons per square meter (1.5 to 4.0 atm). For the point cathode 90 measurements were taken in the power range from 90 to 367 kilowatts. The electrode separation ranged from 3.8 to 7.6 centimeters (1.5 to 3.0 in.), and the operating pressure ranged from 1.5×10^5 to 3.0×10^5 newtons per square meter (1.5 to 3.0 atm). An earlier report (ref. 6) presented characteristics for the point cathode at much lower power;

however, the pressure was as high as 10.1×10^{5} newtons per square meter (10 atom).

When the arc is operating with the annular cathode, it does not cover the entire crater at all currents. At low currents the arc is constricted to a point on or near the rim of the crater of the annular cathode. As the current is increased, the arc changes fairly abruptly to cover the whole crater. This change (transition) in operating modes is marked by a sudden decrease in voltage and a change in the appearance of the arc from unstable to stable.

If the current is decreased enough the arc will change back to operating on the rim of the crater. This change may be abrupt, but it frequently is marked by arc instability. The transition as the current is reduced occurs at a lower current than does the transition when the current is increased.

The transition and its control are important to a user of the electrodes in the large argon arc lamp. Before the current increasing transition the arc is most likely to be destructive to the electrodes. During either transition the arc can throw off particulate matter that will contaminate the optics. A starting technique is outlined that allows the quickest transition and the least destructive start.

APPARATUS AND STARTING PROCEDURE

The data in this report were taken using parts of a 400-kilowatt argon arc solar simulator. Full details of the entire simulator are given in reference 4. For this set of data we used the arc chamber without optics, an anode and cathode, a high pressure water system, a power supply for the electrodes, and high purity argon gas.

Arc Chamber

A sketch showing a cross section of the arc chamber is shown in figure 1. The chamber consists of a tapered main section 2 meters in diameter. A top plate and a collector complete the enclosure. The overall height is 1.5 meters, and volume is 2.1 cubic meters (75 ft^3). The chamber is held together by a 2-meter-diameter ring. The outside supports are attached to this ring. Four struts, each 3.8 centimeters wide, run from the ring to a center hub. This hub holds the anode, and the struts provide electrical ground and anode cooling water passages. The movable cathode is inserted through a seal in the bottom of the collector and is insulated from the chamber.

Electrodes

A sectional drawing of the copper anode is shown in figure 2. The anode diameter is 8.9 centimeters (3.5 in.) and has a removable spherical cap. The cap, which has a 5.1-centimeter (2.0-in.) radius of curvature, has rectangular passages for the high pressure cooling water. The cooling water enters the anode at 5.1×10^{6} newtons per square meter (750 psig) and exits at 1.7×10^{6} newtons per square meter (250 psig). The flow rate is 0.01 cubic meter per second (160 gal/min.).

The cathode is a 5.1-centimeter (2.0-in.) diameter copper pipe with a 2 percent thoriated tungsten cap. Figures 3(a) and (b) show the cathode with annular and point caps. The diameter of the crater in the annular cathode is 1.3 centimeters (0.5 in.). There is a flow divider for the cooling water concentric in the cathode pipe. The inlet pressure is 5.1 newtons per square meter (750 psig), and the outlet pressure is 1.4 newtons per square meter (200 psig). The flow rate is 6.3×10^{-3} cubic meter per second (100 gal/min).

The electrodes are shown in an electrical schematic (fig. 4) which also shows the power supply and variable arc ballast. The power supply is a dc generator, 0 to 250 volts and 0 to 5000 amperes. The electrical schematic also shows the current measuring shunt and the meters for arc voltage and generator voltage.

Starting Procedure

The following starting procedure was developed to ignite the arc with a minimum degradation effect on the electrodes. At start, a ballast of 0.1 ohm is in series with the electrodes. (The switch in fig. 4 is open.) The argon fill pressure is 1.3×10^{5} newtons per square meter (1.3 atm). The cathode is moved up to touch the anode, the power is turned on, and the short circuit current is adjusted to 350 amperes. The arc is then ignited by moving the cathode down at a rate of about 0.5 centimeter per second. When the electrode separation reaches 1.3 centimeters the ballast is reduced to 0.017 ohm by closing the switch and the current is adjusted to 1200 amperes. The current is maintained at 1200 amperes until the electrode separation reaches 5.1 centimeters. Then the current and electrode separation gap are increased until the desired initial operating conditions are reached (usually 7.6 cm and ~3000 A). When starting with the annular cathode, the arc at first is attached only to a spot on the crater rim. As the current is increased the arc suddenly changes to cover the entire crater of the annular cathode. This transition generally occurs after the final electrode separation is established (usually 7.6 cm) but before the initial operating current (3000 A) is reached. Occasionally, the arc attachment has not changed to cover the entire crater by the time the current is raised to 3000 amperes. In this case, the current is further increased until the arc attachment changes; when it does, the current is lowered back to the initial operating current.

TEST PROCEDURE

Arc voltages were measured over a range of currents, pressures, and electrode separations. The ranges were as follows: current, 1800 to 4800 amperes; pressure, 1.5×10^5 to 4.1×10^5 newtons per square meter (1.5 to 4.0 atm); electrode separation, 3.8 to 8.9 centimeters. Tables I and II give measurements of arc voltage for various conditions for the two types of cathodes. Table I is for the annular cathode, and table II is for the point cathode. In general, the pressure was varied in steps of 0.5×10^5 newtons per square meter (0.5 atm), electrode separation was varied in steps of 1.3 centimeters (0.5 in.), and current was varied in steps of 200 to 400 amperes (200 A for the shorter electrode separations). Voltages were measured only at conditions where a stable arc existed.

The general procedure for taking data was first to set the electrode separation. Next, the pressure and current were set to obtain a stable arc. After the voltage measurement, the current was changed to a new setting. This required a small pressure adjustment to maintain a constant pressure. At each pressure-electrode separation setting, the current was varied in steps upward until electrode melting or excessive arc instability was observed. The lower current limit for the annular cathode was set above that current at which the arc cathode attachment no longer covers the crater. The lower current limit with the point cathode was arbitrarily set at 1800 amperes.

The estimated random error in the measurements are as follows:

Current, A	±40
Pressure, N/m^2 (atm)	$\pm0.1\times10^5$ (0.10)
Electrode separation, cm	±0.08
Voltage, V	±0.5

DATA AND ANALYSIS

Arc Voltage

Figures 5 to 9 show voltage as a function of current for various pressures and electrode separations. The subscript a denotes the annular cathode while b denotes the point cathode. The voltage dependence on current is linear. This agrees with the earlier, lower current data of reference 1. Figure 10(a) shows voltage as a function of (pressure)$^{2/3}$ for different electrode separations and for a current of 3600 amperes for the annular cathode. Figure 10(b) is the same type of graph for a current of 2400 amperes with the point cathode. Figures 11(a) and (b) show voltage as a function of (electrode separation)$^{2/3}$ at various pressures and currents for the annular and point cathodes.

From a study of the data in tables I and II and the graphs of that data, it was determined that a least-squares fit to the equation

$$V = a(Lp)^{2/3} + bI(Lp)^{2/3} + cIp^{2/3} + dI + e$$

would give an excellent empirical representation of the data. The results are as follows:

Cathode with pointed tip:

For pressure p in newtons per square meter,

$$V = 3.34\times10^{-3}(Lp)^{2/3} + 2.14\times10^{-4}I(Lp)^{2/3} - 7.31\times10^{-4}Ip^{2/3} + 8.50I + 13.03$$

For pressure in atmospheres,

$$V = 7.25(Lp)^{2/3} + 0.46I(Lp)^{2/3} - 1.59Ip^{2/3} + 8.50I + 13.03$$

Cathode with crater in tip:

For pressure in newtons per square meter,

$$V = 2.98\times10^{-3}(Lp)^{2/3} + 3.78\times10^{-4}I(Lp)^{2/3} - 1.05\times10^{-3}Ip^{2/3} + 5.79I + 12.88$$

For pressure in atmospheres,

$$V = 6.47(Lp)^{2/3} + 0.82I(Lp)^{2/3} - 2.27Ip^{2/3} + 5.79I + 12.88$$

where V is in volts, L the electrode separation in centimeters, p the operating pressure in newtons per square meter (or atm as indicated); and I the current in kiloamperes. The solid lines in figures 5 to 11 are calculated from the previous formula. The rms deviations between measured voltage and formula voltage are 0.7 volt for both the annular cathode and the point cathode. These values agree with the estimated uncertainties in the measurements of current, pressure, electrode separation, and voltage. Typical voltage differences between different cathodes of the same design were of the order of 1 to 2 percent.

The empirical formulas were developed from measurements made in an arc chamber with a volume of 2.1 cubic meters. The formula for the point cathode agrees within 1 or 2 volts of previous measurements made in a much smaller arc chamber volume (0.028 m^3) (ref. 6). The geometry of the smaller tank is that of a 60-centimeter-long cylinder, whereas the geometry of the arc chamber (fig. 1) is quite different. The two tank sizes (volume ratio, ~75) require different fill pressures to reach the same operating conditions after arc ignition. Hence, the two tanks have different average gas densities when operating at the same conditions. The smaller tank has less than two-thirds the gas density of the larger one. The conclusion is that at a given operating pressure the voltage is not sensitive to the average density of argon in the arc chamber. To reach a given operating pressure the average density of argon (fill pressure) must be increased as the volume of the arc chamber is increased.

The average density of the argon fill primarily influences heat transfer in the outer part of the arc column (convective stabilization). The lack of sensitivity of voltage to density implies that the voltage and stabilization of the arc are determined mainly by radiation and by rejection of heat to the electrodes (electrode stabilization). (See refs. 7 and 8 for a discussion of arc stabilization.) Surprisingly, the lifetime of the annular cathode seems to be sensitive to the size of the chamber in which the arc is run. The lifetime increases as volume increases. This effect has not yet been explained since the arc operates with the same gas purity and the same electrical behavior in both the large and the small volumes.

Voltage Differences Between Point and Annular Cathodes

There is a substantial difference in measured voltage between the point and annular cathodes under identical operating conditions. The point cathode operates at about a 15 percent higher voltage than the annular cathode. Figure 12 shows the voltage difference (point minus annular) as a function of the current for different pressures and one electrode separation of 6.4 centimeters. For the figure, voltage differences were calculated using the empirical voltage formulas. Note that the slope of the voltage difference as a function of current curves are nearly independent of pressure. The curves are plotted at an electrode separation of 6.4 centimeters only because the dependence on electrode separation is very weak. The largest spread in voltage difference at a given current and pressure due to different electrode separations is only 0.5 volt.

Transition Between Spot and Annular Modes

When starting the arc with an annular cathode, the arc first attaches to a spot on the cathode crater. When the current is raised to the transition current, the cathode attachment spreads to cover the entire crater. Several tests were made to determine the effect of starting pressure and electrode separation on this transition current.

With starting pressures of 1.27×10^5 and 2×10^5 newtons per square meter (1.25 and 2 atm) and electrode separations of 5.1, 6.4, 7.6, and 8.9 centimeters, the transition current is nearly constant at 3000±200 amperes. After the transition, the current was decreased until the cathode attachment collapsed back into a spot. This downward transition current was also independent of pressure and electrode separation. However, the downward transition occurred at a lower current, approximately 1200±400 amperes.

Even though both transition currents are independent of pressure and electrode separation, they are dependent on the physical condition of the cathode. The transition currents typically decreased somewhat with age. There is no correlation between the current at which the transition occurs and the pressure or the electrode separation. The transition current does depend on the purity of the gas. The presence of water vapor in the argon reduces the current at which the transition will occur. Indeed, a small amount of water vapor in the argon (10 to 20 ppm) results in a more stable arc. Water vapor concentrations of over 100 ppm hasten the destruction of the cathode.

CONCLUDING REMARKS

The practical interest in the transition is because the arc operating from a spot is more destructive to both the anode and the cathode. Therefore, a starting procedure should minimize the time spent in the spot mode.

There are many interesting and unanswered questions associated with the transition. Among them are these:

(1) What properties of the cathode determine the transition current so definitely that pressure and electrode separation have no effect?

(2) How does the transition occur when the self-magnetic field of the arc and natural convection work to contract the arc column?

(3) Why is the transition current "up" different from the transition current "down?"

(4) What causes the presence of a small quantity of water vapor to reduce the transition current?

(5) How does the electrode crystal structure change the transition current?

If these questions can be answered, perhaps a mathematical model can be constructed which will predict the transition for other cathode designs.

Lewis Research Center,
National Aeronautics and Space Administration,
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TABLE I. - RECORDED DATA FOR ANNULAR CATHODE

Separation, cm	Pressure, N/m²	Pressure, atm	Current, A	Voltage, V
3.8	1.52×10^5	1.50	2200	46.6
	1.53	1.51	2400	47.0
	1.51	1.49	2600	47.6
	1.53	1.51	2800	48.7
	1.53	1.51	3000	49.8
	1.52	1.50	3205	50.5
	1.51	1.49	3400	51.8
	1.51	1.49	3600	52.5
	1.52	1.50	3800	53.6
			4000	54.3
			4200	55.3
			4400	56.2
	1.53	1.51	4600	57.4
	1.51	1.49	4800	58.1
	2.03	2.00	2400	50.1
	2.03	2.00	2600	51.9
	2.02	1.99	2805	52.6
	2.03	2.00	3000	53.8
	2.02	1.99	3200	55.1
	2.03	2.00	3400	56.3
	2.02	1.99	3600	57.4
	2.02	1.99	3800	58.2
	2.03	2.00	4000	59.8
	2.04	2.01	4200	60.4
	2.03	2.00	4400	61.2
	2.02	1.99	4600	61.8
	2.53	2.50	2600	55.1
	2.54	2.51	2800	56.6
	2.53	2.50	3000	57.8
	2.53	2.50	3200	59.1
	2.54	2.51	3400	60.7
	2.53	2.50	3600	61.8
	2.53	2.50	3800	62.9
	2.54	2.51	4000	63.8
	2.53	2.50	4200	64.8
	2.54	2.51	4400	65.6
	3.04	3.00	2600	58.1
	3.04	3.00	2800	59.7
	3.03	2.99	3000	61.2
	3.06	3.02	3195	62.7
	3.04	3.00	3400	64.5
	3.03	2.99	3600	65.6
	3.05	3.01	3795	66.5
5.1	1.52×10^5	1.50	2200	51.3
			2400	52.3
			2600	53.6
			2800	54.7
	1.53	1.51	3000	56.0
	1.52	1.50	3200	57.1
			3400	58.4
			3600	59.7
			3800	61.0
			4000	62.1
	1.53	1.51	4200	63.1
	1.52	1.50	4400	64.2
	1.52	1.50	4600	65.2
	1.52	1.50	4800	66.1
	2.03	2.00	2400	57.6
	2.04	2.01	2600	58.8
	2.03	2.00	2800	60.0
	2.03	2.00	3000	61.3
	2.03	2.00	3200	62.8
	2.04	2.01	3400	64.5
	2.04	2.01	3600	65.7
	2.03	2.00	3800	67.2
	2.03	2.00	4000	68.6
	2.04	2.01	4200	69.6
	2.04	2.01	4400	70.7
	2.03	2.00	4600	71.4
	2.53	2.50	2200	61.3
	2.52	2.49	2400	62.9
	2.52	2.49	2600	63.3
	2.53	2.50	2800	64.2
	2.53	2.50	3000	65.7
	2.52	2.49	3200	67.2
	2.53	2.50	3400	68.8
	2.53	2.50	3600	70.3
	2.52	2.49	3800	71.6
	2.52	2.49	4000	72.9
	2.53	2.50	4200	74.2
5.1	2.53×10^5	2.50	4400	75.2
	3.04	3.00	2600	67.1
	3.05	3.01	2800	68.0
	3.04	3.00	3000	69.4
	3.04	3.00	3200	71.3
	3.05	3.01	3300	72.2
			3400	73.0
			3600	74.5
			3800	76.1
6.4	2.04×10^5	2.01	2100	61.8
	2.04	2.01	2400	64.0
	2.02	1.99	2700	66.0
	2.03	2.00	3000	68.2
	2.03	2.00	3300	70.3
	2.04	2.01	3600	72.6
			3900	74.4
			4200	75.9
			4500	77.6
	2.01	1.98	4800	79.6
	2.53	2.50	2400	70.2
			2700	71.3
			3000	73.8
			3300	75.9
			3600	78.3
			3900	80.7
			4200	82.6
	3.05	3.01	3000	79.1
	3.04	3.00	3310	81.6
	3.04	3.00	3605	83.8
	3.05	3.01	3900	85.7
	3.04	3.00	4200	87.9
	3.54	3.49	3300	86.5
	3.54	3.49	3600	90.7
	3.55	3.50	3900	92.9
	3.55	3.50	4200	94.6
	3.56	3.51	4500	96.5
	3.55	3.50	4800	98.1
7.6	2.01×10^5	1.98	2400	71.8
	2.03	2.00	2700	74.2
	2.01	1.98	3000	75.3
	2.04	2.01	3300	77.4
	2.03	2.00	3600	79.2
	2.03	2.00	3940	81.0
	2.04	2.01	4200	83.6
	2.08	2.05	4500	86.5
	2.54	2.51	2700	79.6
	2.53	2.50	3000	81.7
	2.53	2.50	3300	85.1
	2.53	2.50	3600	87.6
	2.54	2.51	3900	88.9
	2.54	2.51	4200	91.2
	2.53	2.50	4500	93.0
	2.53	2.50	4800	94.9
	3.04	3.00	2700	85.5
	3.03	2.99	3000	87.4
	3.03	2.99	3300	90.0
	3.04	3.00	3600	93.4
	3.05	3.01	3900	96.0
	3.05	3.01	4200	98.4
	3.04	3.00	4500	100.0
	3.05	3.01	4800	102.0
	3.54	3.49	3000	93.4
	3.55	3.50	3300	96.3
	3.54	3.49	3600	99.2
	3.55	3.50	3900	101.8
	3.56	3.51	4200	104.0
	3.56	3.51	4500	106.2
	3.55	3.50	4800	107.9
	4.04	3.99	3600	104.6
	4.06	4.01	3900	107.9
	4.06	4.01	4200	110.0
	4.04	3.99	4500	112.0
8.9	3.04×10^5	3.00	3600	101.0
	3.04	3.00	3900	102.8
	3.04	3.00	4200	105.5
	3.03	2.99	4500	107.4
	3.03	2.99	4800	109.7
	3.55	3.50	4190	112.5
	3.58	3.53	4500	115.4
	3.55	3.50	4800	117.2

TABLE II. - RECORDED DATA FOR POINT CATHODE

Separation, cm	Pressure, N/m^2	Pressure, atm	Current, A	Voltage, V
3.8	1.52×10^5	1.50	1800	49.9
	1.52	1.50	2000	51.2
	1.53	1.51	2205	52.7
	1.52	1.50	2400	54.0
	1.53	1.51	2600	55.4
	1.53	1.51	2800	56.7
	2.04	2.01	1800	54.5
	2.04	2.01	2000	56.2
	2.03	2.00	2200	57.8
			2400	59.4
			2600	60.8
			2800	62.2
	2.53	2.50	1800	59.0
			2000	60.8
			2215	62.5
			2400	64.1
			2600	65.6
	3.04	3.00	1800	63.3
	3.05	3.01	2000	65.1
	3.04	3.00	2200	66.6
	3.05	3.01	2400	68.2
5.1	1.52×10^5	1.50	1800	55.7
			2000	57.4
			2200	59.0
			2400	60.7
			2600	62.2
	1.51	1.49	2800	64.0
	1.52	1.50	3000	65.1
	1.52	1.50	3200	65.8
	2.01	1.98	1800	62.3
	2.03	2.00	2000	64.3
			2200	66.0
			2400	67.6
			2600	69.0
			2800	70.4
	2.53	2.50	1800	67.2
	2.53	2.50	2000	69.4
	2.53	2.50	2200	71.2
		2.51	2400	73.2
		2.50	2600	74.6
		2.51	2800	76.0
		2.51	3000	77.4
		2.93	1800	71.4
		2.99	2000	74.1
		3.00	2200	76.1
5.1	3.04×10^5	3.00	2400	78.0
	3.05	3.01	2600	79.4
	3.03	2.99	2800	80.7
6.4	1.52×10^5	1.50	1800	61.3
	1.51	1.49	2100	64.0
	1.52	1.50	2400	66.7
	1.52	1.50	2700	69.0
	1.53	1.51	3000	71.4
	2.03	2.00	1800	68.4
	2.04	2.01	2130	70.5
	2.02	1.99	2400	72.4
	2.05	2.02	2700	76.2
	2.04	2.01	3000	78.5
	2.54	2.51	1800	73.4
	2.53	2.50	2100	76.6
			2400	79.8
			2700	82.4
			3000	84.8
	3.03	2.99	1810	78.8
	3.03	2.99	2100	82.0
	3.03	2.99	2400	85.2
	3.06	3.02	2700	87.6
	3.03	2.99	3000	90.4
7.6	1.53×10^5	1.51	1800	65.9
	1.54	1.52	2100	69.1
	1.52	1.50	2400	71.9
	1.51	1.49	2700	74.5
	1.52	1.50	3000	76.7
	2.03	2.00	1800	72.5
	2.04	2.01	2100	77.3
	2.03	2.00	2400	80.1
	2.04	2.01	2700	82.7
	2.04	2.01	3000	84.7
	2.03	2.00	3300	86.8
	2.53	2.50	1810	79.5
			2100	82.8
			2400	85.9
			2700	88.7
			3000	91.2
	3.04	3.00	2095	88.5
	3.04	3.00	2400	92.0
	3.06	3.02	2705	95.0
	3.04	3.00	3000	97.7
	3.03	2.99	3300	100.0
	3.04	3.00	3595	102.0

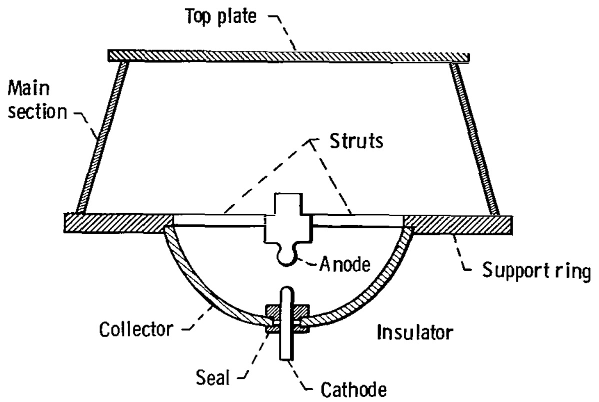


Figure 1. - Arc chamber cross section.

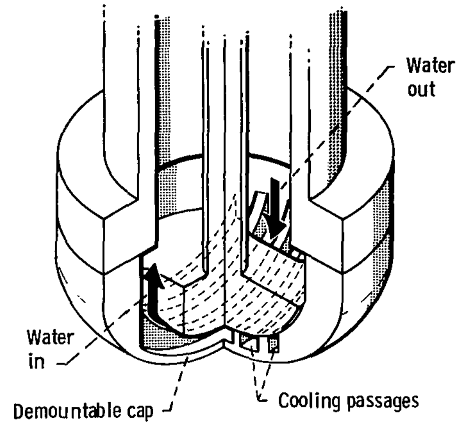
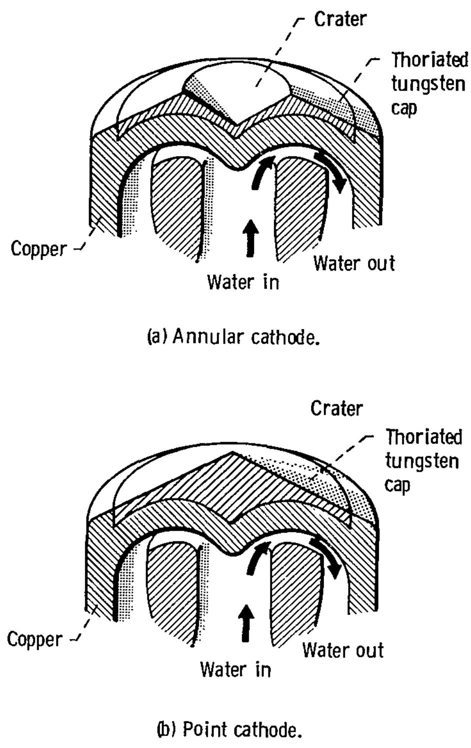


Figure 2. - Sectioned diagram of anode.



(a) Annular cathode.

(b) Point cathode.

Figure 3. - Sectioned diagrams of cathodes.

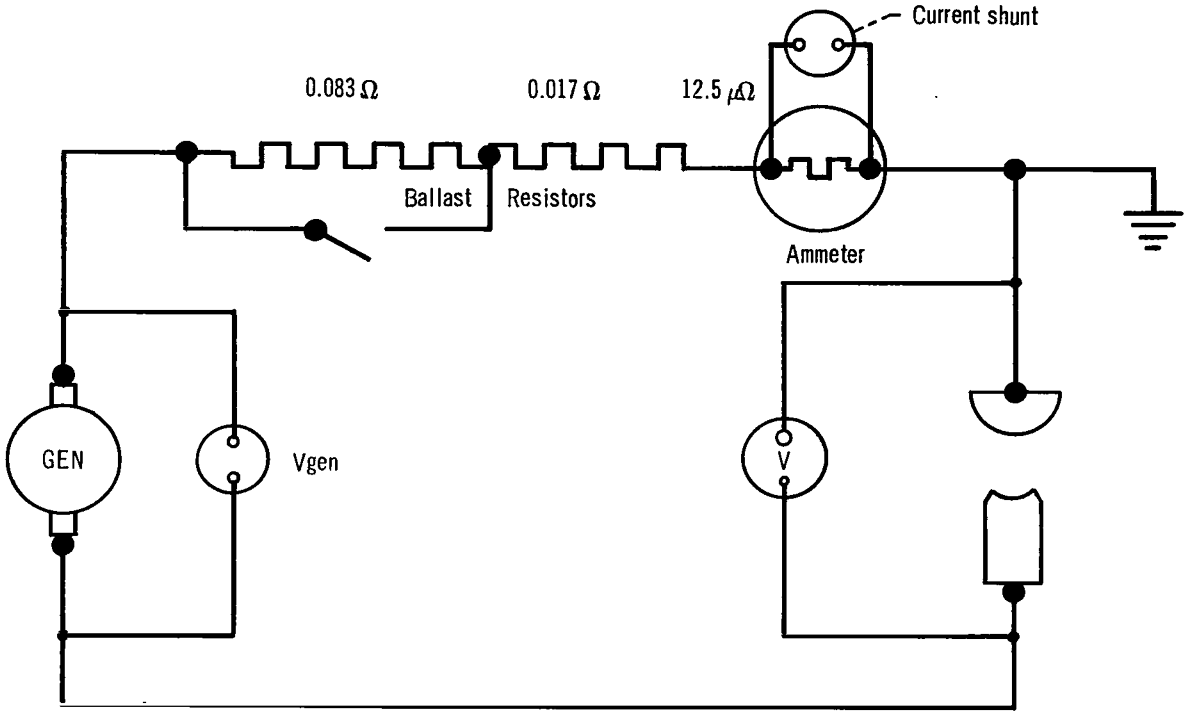


Figure 4. - Electrical schematic of arc circuit.

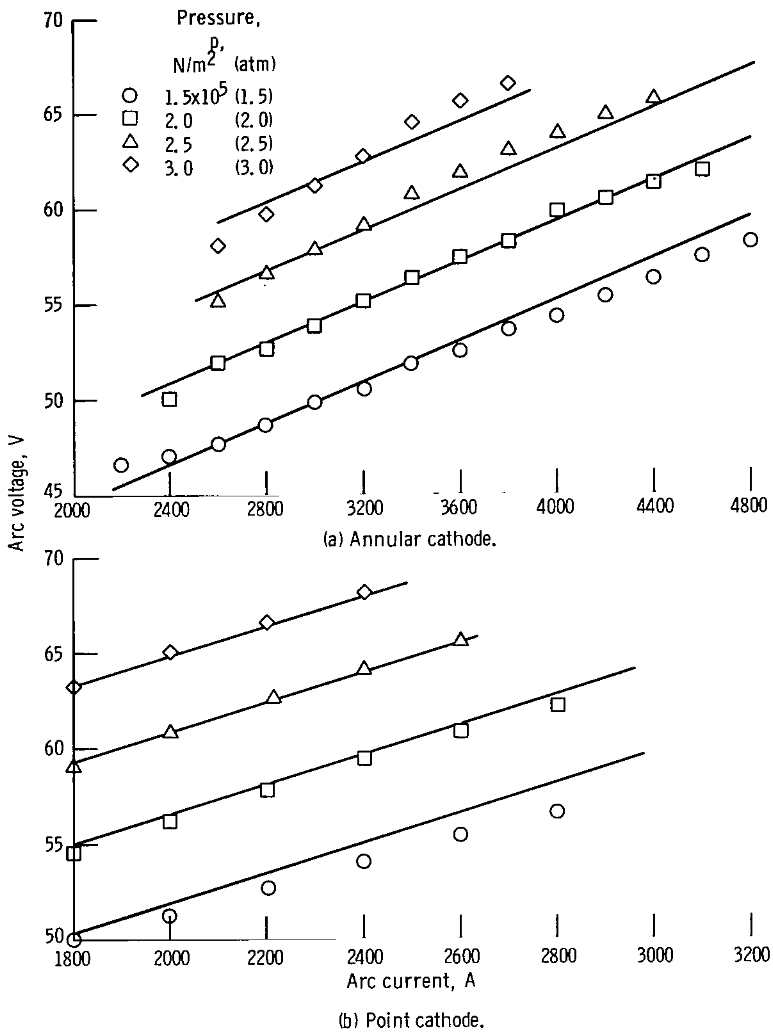


Figure 5. - Arc voltage as function of arc current. Separation, 3.8 centimeters (1.5 in.).

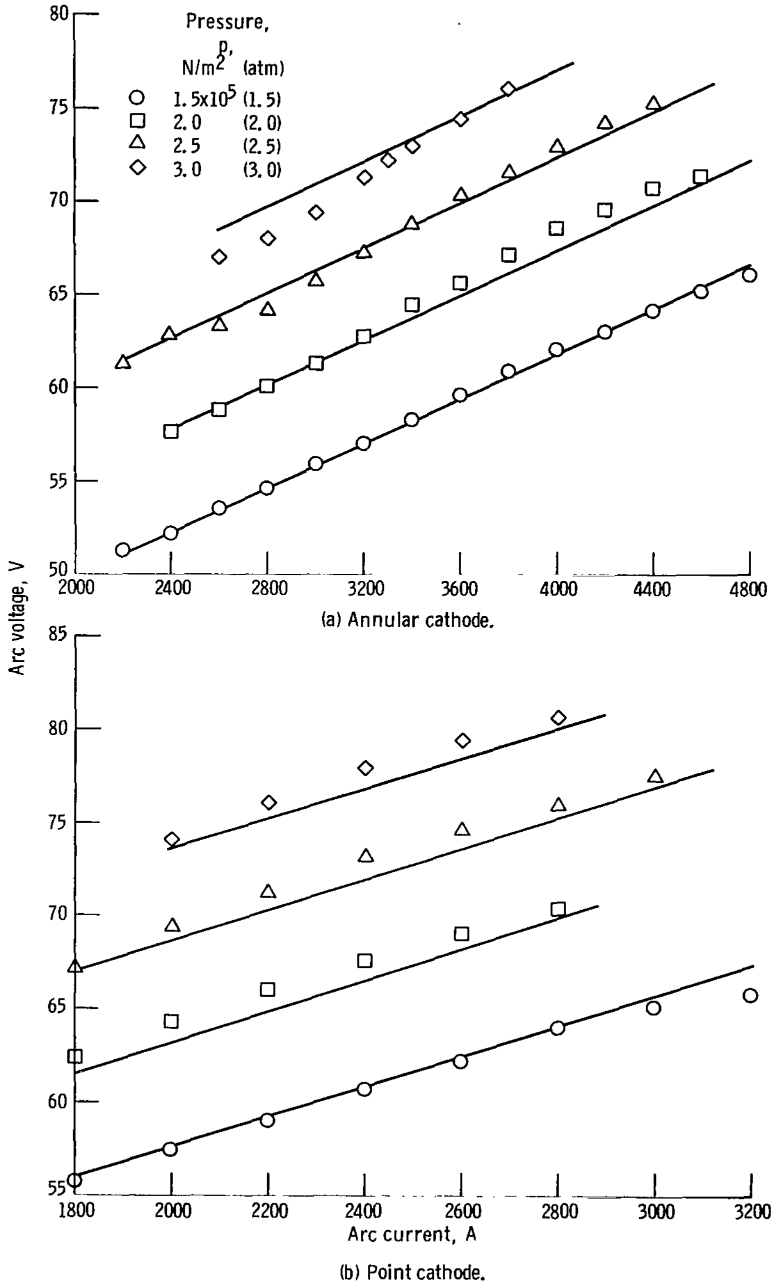
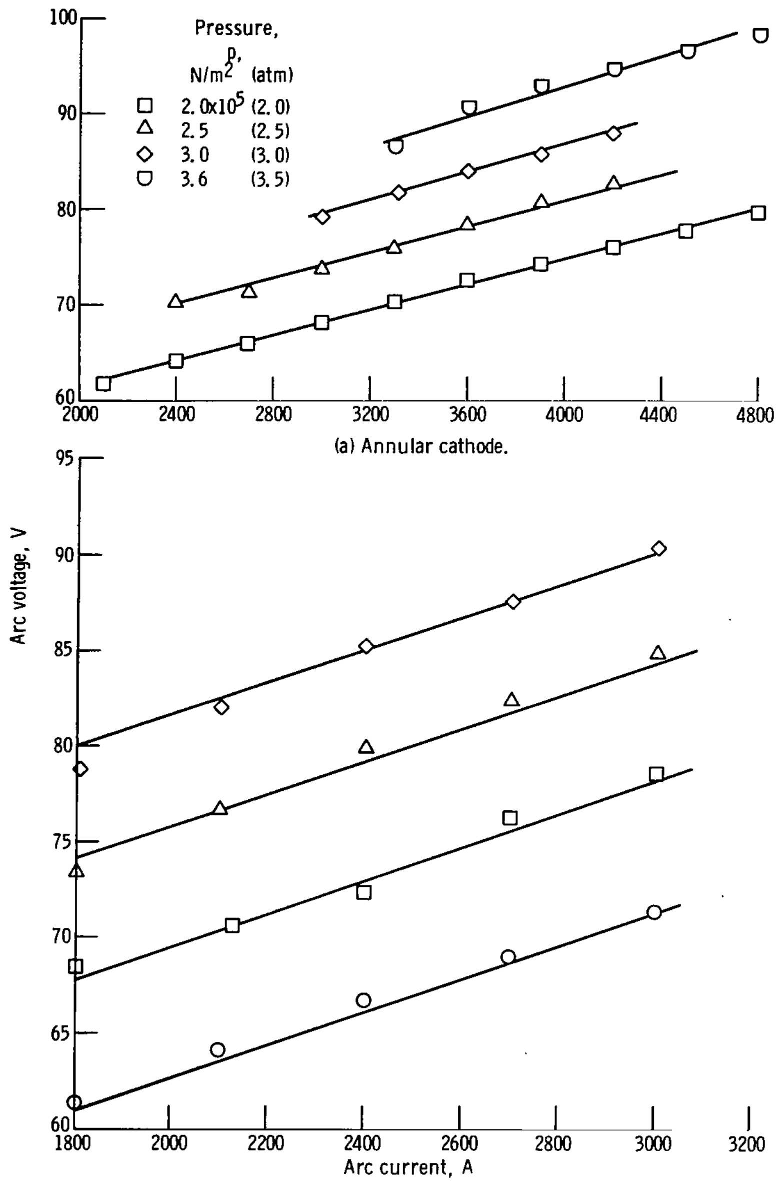


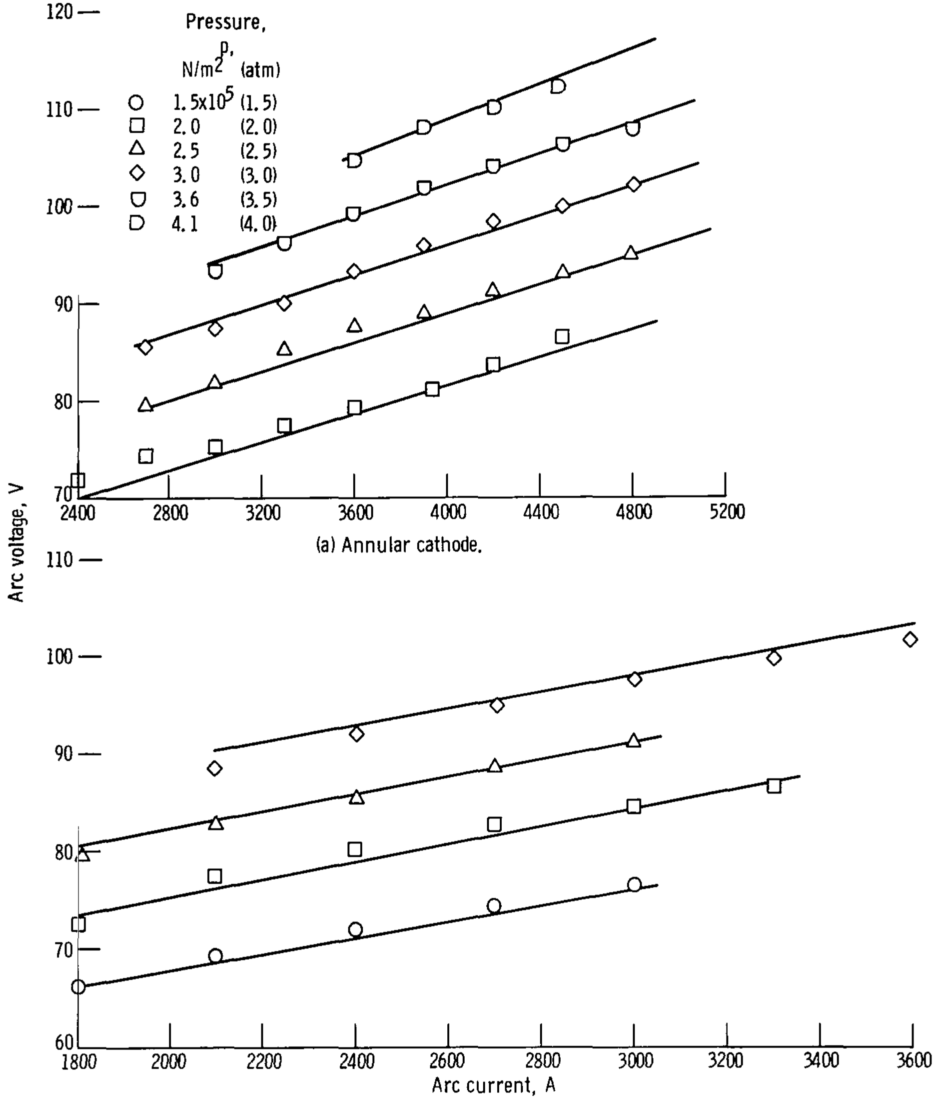
Figure 6. - Arc voltage as function of arc current. Separation, 5.1 centimeters (2.0 in.).



(a) Annular cathode.

(b) Point cathode.

Figure 7. - Arc voltage as function of arc current. Separation, 6.4 centimeters (2.5 in.).



(b) Point cathode.

Figure 8. - Arc voltage as function of arc current. Separation, 7.6 centimeters (3.0 in.).

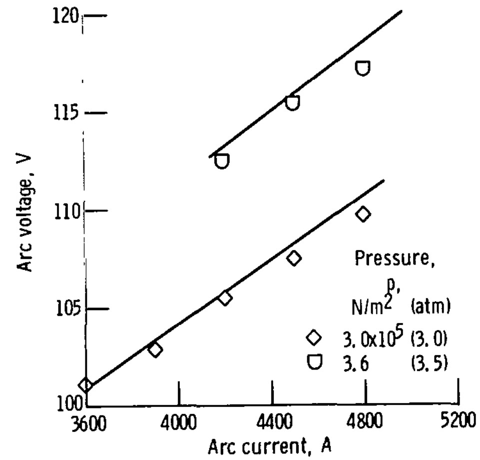


Figure 9. - Arc voltage as function of arc current for annular cathode. Separation, 8.9 centimeters.

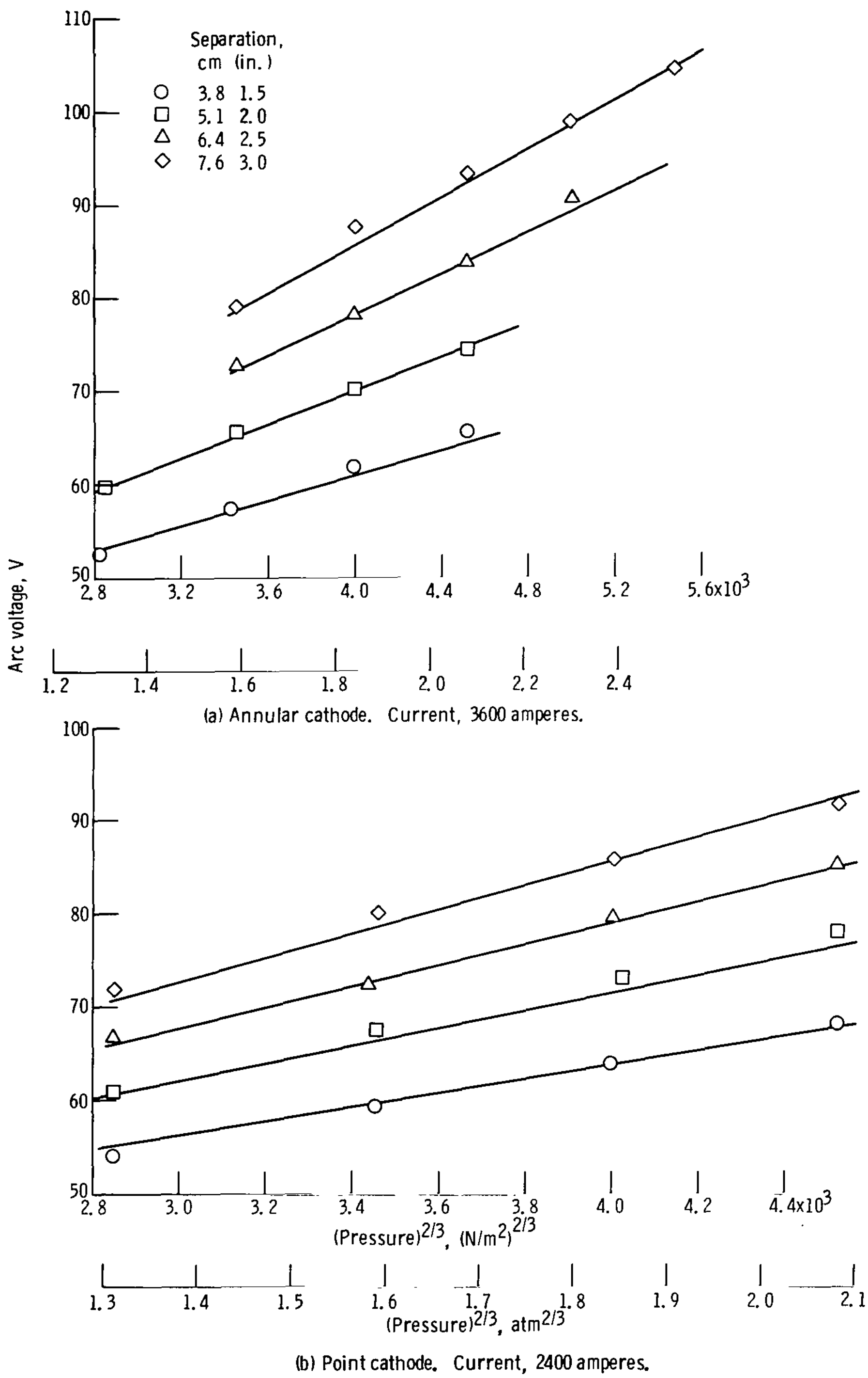
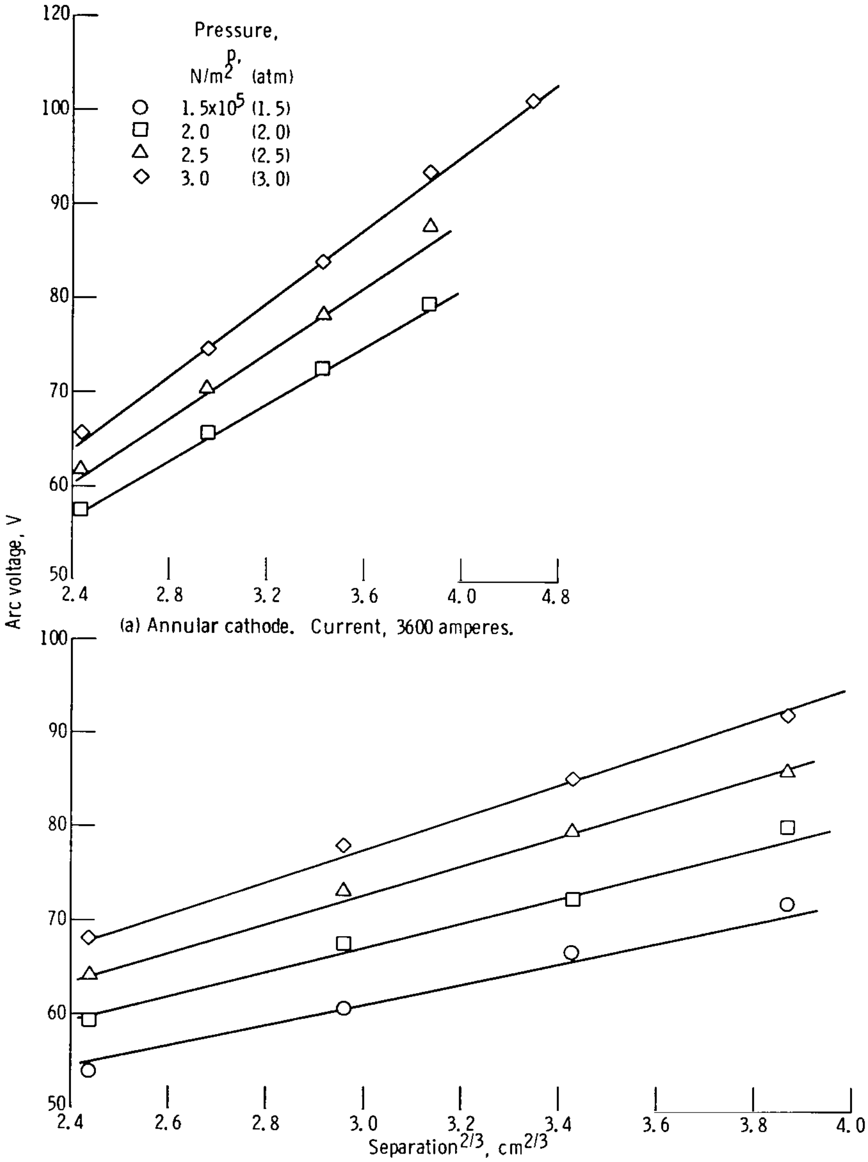


Figure 10. - Arc voltage as function of (pressure)$^{2/3}$.



(a) Annular cathode. Current, 3600 amperes.

(b) Point cathode. Current, 2400 amperes.

Figure 11. - Arc voltage as function of electrode separation.

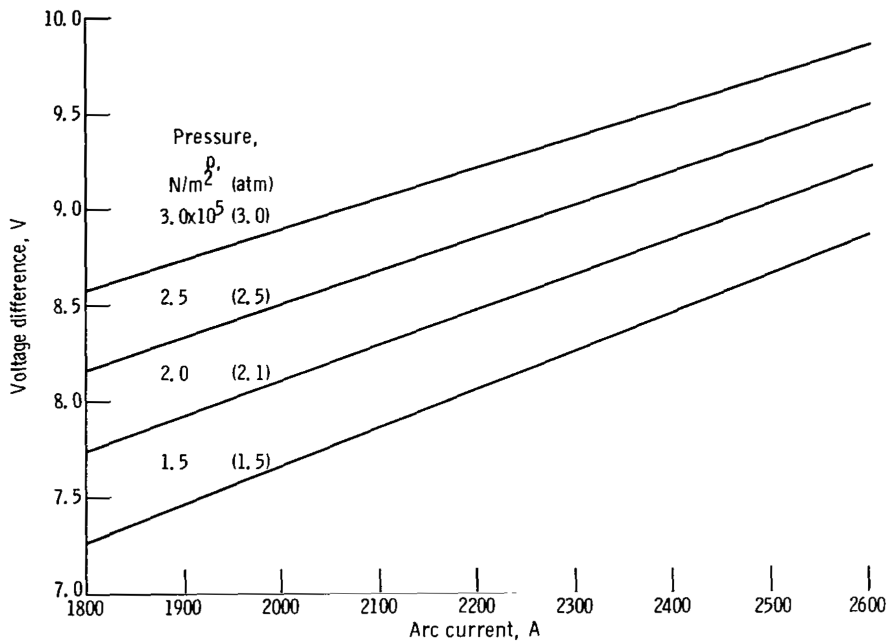


Figure 12. - Voltage difference as function of current for point and annular cathodes. Separation, 6.4 centimeters (2.5 in.); voltages calculated using empirical formulaes.

NASA-Langley, 1975 E-8316

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