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Controlled Thermonuclear Processes

IONIZATION AND DISSOCIATION OF ENERGETIC IONS BY A CARBON DISCHARGE – STATUS REPORT

John S. Luce

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OPERATED BY
UNION CARBIDE NUCLEAR COMPANY
A Division of Union Carbide and Carbon Corporation
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BY A CARBON DISCHARGE - STATUS REPORT

John S. Luce

January 1957

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ABSTRACT

Carbon discharges have been operated continuously in a magnetic field at pressures of approximately 10^{-5} mm. Spectrographic analyses show the ions to be predominately C^{++}. No trace of excited carbon neutrals can be observed; it is assumed that the carbon is essentially completely ionized. Ionization is measured ($N^{+} \rightarrow N^{++} + e$) when a 24-kv N^{+} beam is passed through the discharge. Forty per cent of a 27-kv D_2^{+} beam is dissociated ($D_2^{+} \rightarrow D^{+} + D^{o}$) without any measurable losses when passed through the discharge. Electrical and calorimetric measurements of the resultant beams (D^{+} and D^{o}) were made. Characteristics of the trapped half-radius atomic beam were studied briefly. Application of this discharge to accelerators is mentioned.

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THE CARBON DISCHARGE

For several months an investigation to determine the characteristics of d-c arcs in a magnetic field and under high vacuum has been conducted at the Oak Ridge National Laboratory. During the course of these experiments, it was found that a controlled energetic carbon discharge could be operated over long gaps if the proper conditions were achieved. The discharge has many interesting characteristics. It is not a true arc, in that no stable homogeneous structure exists; the discharge constantly undergoes segmentation, each section appearing as a filament of discharge. The filaments are in constant motion and readily cross the magnetic field. The life of each section appears to be limited, and new ones are constantly forming. These dynamic conditions induce appreciable impacts and/or thermal gradients at the cathode which cause charged carbon pieces of small size to be torn from the cathode and ejected at high speed away from the cathode in a wide arc toward the anode. These particles appear to carry charge of both signs, since some of the smaller pieces are observed to curve in opposite directions when crossing the magnetic field. Many of these charged masses have tails which point toward the discharge as they move away from it (Figure 1). Some of these particles adhere to the walls they strike and should have high pumping speed for neutrals.[1] In addition to these large particles, carbon ions also reach the walls and assist in occluding neutrals. The pumping characteristics of the discharge are being studied in a long solenoid where outgassing at the cathode and the anode ends can be reduced (Figure 2).

When first struck, the discharge is surrounded by an atmosphere of carbon and other neutrals. In this phase, its basic characteristics are essentially the same as a large d-c arc in a magnetic field. Under these conditions, a secondary plasma is observed around the arc. As the pressure drops, the discharge separates into segments, which move continuously across the magnetic field. As this motion increases, the secondary plasma disappears, and the amount of light emitted by the anode increases appreciably. The change in light intensity at the anode may be due to an increased number of energetic electrons reaching the anode. It is assumed that the average energy of the electrons increases as the pressure decreases and that this explains, in part, the unusual characteristics of the discharge.

Phenomena related to those described above have been observed in mercury arc rectifiers and in carbon arcs. It appears, however, that the techniques which have been developed[2] permit the use of carbon cathodes and anodes with wide gaps* in strong magnetic fields under high vacuum (Figures 3 and 4). The resultant discharge has characteristics radically different from those normally encountered in d-c arcs.

This discharge was observed during the first months of 1956. In August of the same year, operation had become stable enough to permit preliminary measurements. Energetic ion beams of He^+, N^+, H_2^+, and D_2^+ were passed through the discharge, and ionization and dissociation measured. Arc currents of approximately 250 amperes were used for these experiments. Higher arc currents cause severe heating at both the cathode and the anode ends; this results in high pressure from outgassing of

*These discharges have been run with a gap of 11 inches between cathode and anode. Apparatus is being constructed that will permit gaps of six feet. A method of striking the discharge has been developed that eliminates the use of gas. Solid cathodes of various shapes are now in use.

surfaces. New equipment under construction will permit higher currents, since the neutrals caused by outgassing will be reduced.

ELECTRIC FIELD MEASUREMENTS

Oscillographic measurements show the presence of oscillations in the radio-frequency range. Due to the internal impedance of the power supply, it has been difficult to measure accurately oscillations originating in the discharge. The work is continuing, however, and it is hoped that by the use of a more suitable power supply or by proper filtering circuits more exact results may be achieved.

SPECTROGRAPHIC MEASUREMENTS

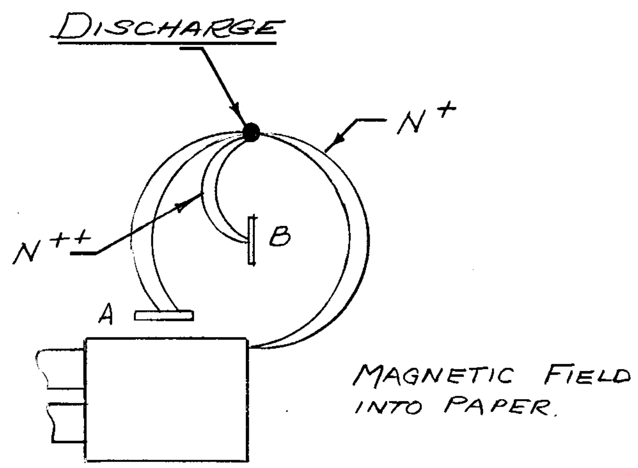
The spectrographic group observed the carbon discharge at short wave lengths[3] using a quartz window to permit study of the carbon resonance line at 2478A. With discharges of 170, 270, and 425 amperes, reasonably strong spectra of C^+ and C^{++} were observed. The ratio of C^{++} spectra to C^+ increased with increased current. No trace of the resonance line of neutral carbon was observed for these exposures; it was concluded that the high-current carbon discharges are more than 99% ionized.

Neutral argon gas was introduced into the discharge at both the cathode and the anode ends. Complete ionization of the argon into A^+, A^{++}, and A^{+++} ions was observed in the pressure range of 2×10^{-5} mm to 5×10^{-4} mm. The introduction of neutral gas causes a large decrease in the number of C^{++} ions. It appears that the introduction of neutrals into the discharge causes collision processes that reduce the average energy of the particles in the discharge.

During the course of these experiments, excitation levels requiring 43-volt electrons were observed.

IONIZATION OF ENERGETIC IONS

A single test was made using a beam of N^+ ions to see if additional electrons could be stripped from the N^+ ion when it was passed through the discharge. A schematic outline of the experimental setup showing the beam paths is shown below. Removal of electrons from the ions causes a change in the charge to mass ratio resulting in smaller radii for the stripped ions.



If it is assumed that the reaction involved here is $N^+ \rightarrow N^{++} + e$, then the current reading on plate B, due to the double charge, must be divided by two. The removal of a single electron is probably a good assumption, since the energy required for double ionization is 29.47 volts whereas the removal of the third electron requires 47.40 volts. When He^+ is passed through the discharge, very little ionization occurs; this seems to indicate that stripping under the conditions of this experiment is probably confined to ions whose ionization potential is below 47 volts. This assumption is strengthened by the spectrographic analysis where strong excitation levels up to 43 volts were observed.

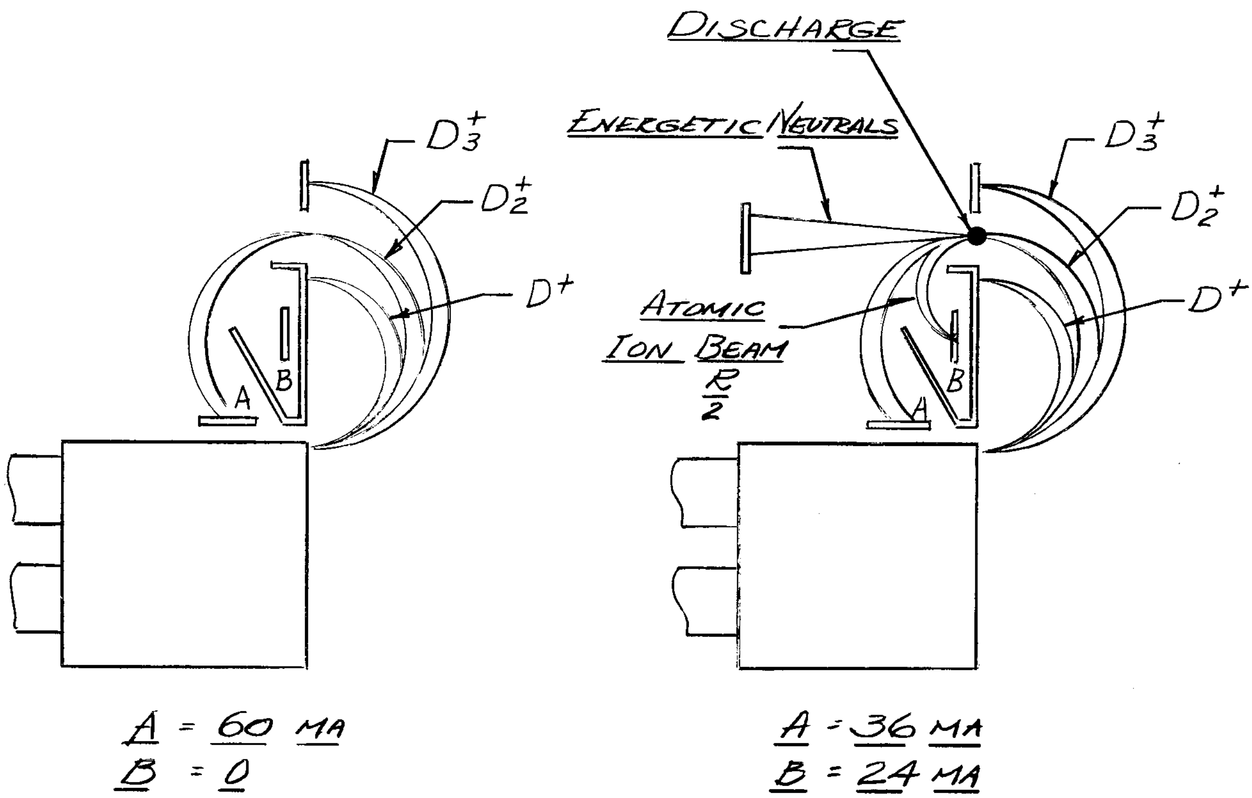
If the current to plate B is divided by two, the ionization efficiency appears to be about 12 per cent. When longer discharges at higher voltage and current are available, the energy of the discharge will be increased, and more efficient stripping of energetic ions may be possible.

The need for studying trapped D^+ beams has necessitated postponement of electron stripping experiments, but in the future it is planned to identify the stripped ion beams by the use of a scanning mechanism.

DISSOCIATION EXPERIMENTS ($D_2^+ \rightarrow D^+ + D^0$)

The phenomenon of dissociation (and ionization)[4,5,6] of energetic ions may be pertinent to Project Sherwood, since it provides a means of trapping energetic ions in a magnetic field and produces an energetic neutral beam. Twenty-five per cent of a 60-ma D_2^+ beam has been continuously dissociated for 50 minutes when the beam was passed through the discharge; 40 per cent dissociation has been maintained for 10 minutes. Complete dissociation could probably be achieved by using higher current or two or more discharges.

In these experiments, a narrow source slit was used to provide 180° focusing. The carbon discharge was placed so that it intersected the beam at 180°. The dissociated atomic ion beam was measured on a water-cooled target which was well shielded by a water-cooled copper box. The neutral beam was measured 10 inches from the carbon discharge on a water-cooled copper plate.



Both calorimetric and electrical measurements of the atomic (R/2) beam were made, and good correlation was achieved. The following data are typical of calorimetric measurements: With an R/2 beam of 0.010 amperes at 13 kv, or a power rate of 130 watts, the temperature increase of the cooling water was 3.9° C. With a flow of 0.473 kg/min, an increase of 3.9° C is equal to a power rate of 129 watts. No metered loss of ions can be detected in the electrical measurements. Adding the R/2 and the residual D_2^+ beam (plates A and B) always gives the same current reading as the total D_2^+ beam before dissociation (see sketch above).

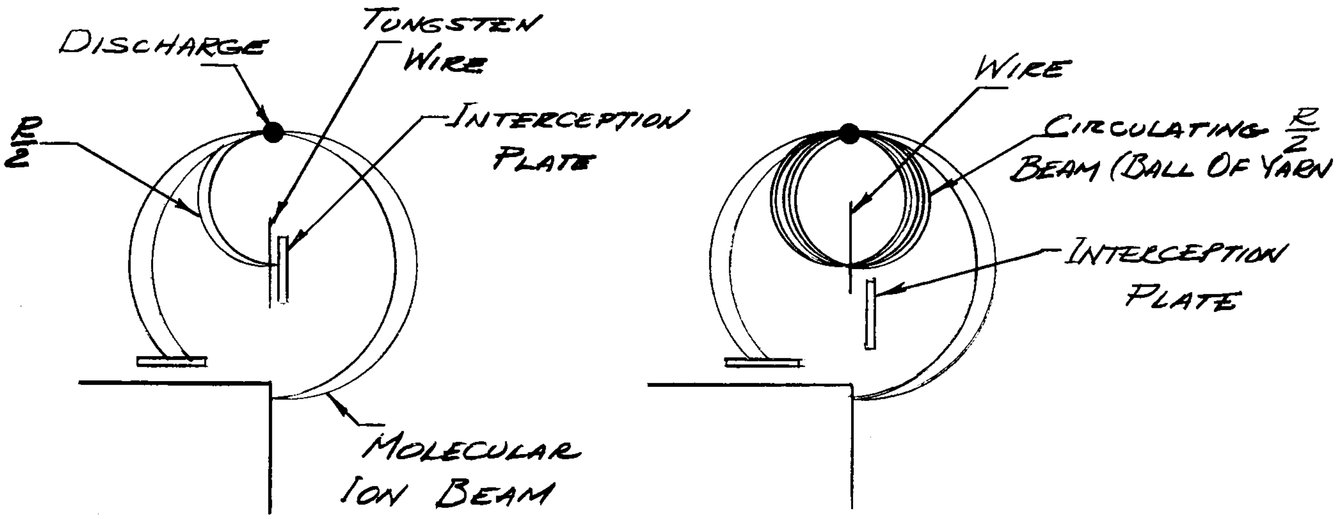
Measurements of the energetic neutral beam were less successful, because it was impossible to shield the neutral target as well as the R/2 target. The target is exposed to the carbon discharge which causes thermal fluctuations. It was possible, however, to identify the energetic neutral beam despite a large variation in the readings.

Neutral argon gas fed into the carbon discharge during the course of these experiments caused attenuation and loss of all the ion beams. The argon lines were studied spectroscopically during the tests. The neutral argon line was not observed, and it is assumed that the argon gas is essentially completely ionized. These experiments seem to shed some light on the dissociation mechanism in the discharge. At least it appears that collisions between high-energy ions in the D_2^+ beam and low-energy ions in the discharge is not the predominant process causing dissociation of energetic D_2^+.

MEASUREMENTS OF TRAPPED ENERGETIC IONS

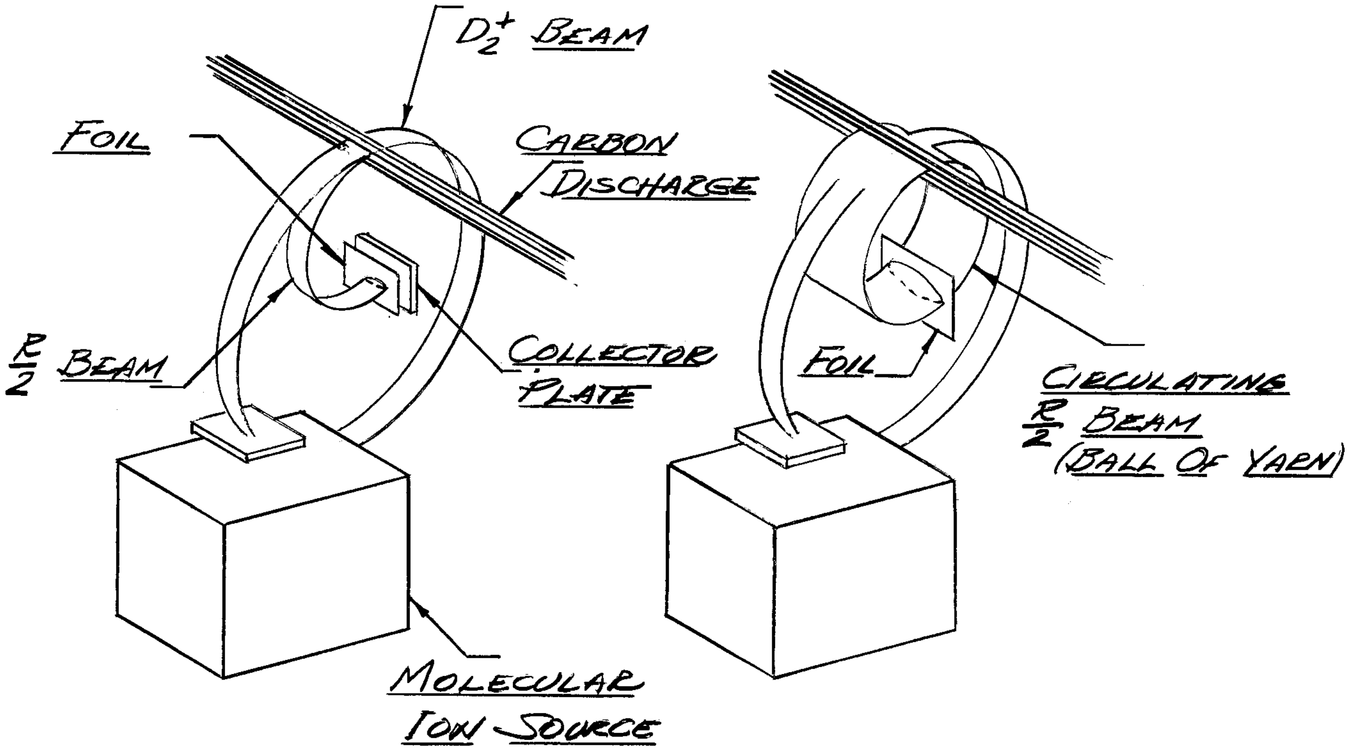
At the writing of this report, only brief studies of the behavior of trapped ions have been made. Probe measurements show plainly that a circulating current of energetic ions does exist. It is extremely difficult, however, to make accurate probe measurements in the presence of the carbon discharge, since the probes read some current from the discharge.

Despite these difficulties, qualitative measurements were made with small tungsten probes when the R/2 beam was intercepted at 180° and compared with R/2 readings made with the circulating beam.



The R/2 current readings per unit area of beam increased by at least a factor of five with the circulating beam. By using multiple probes, it was also shown that the circulating beam occupied a larger area than the intercepted beam. While it is impossible to show accurately from these experiments the magnitude of the beam multiplication, it is certain that conversion of energetic molecular ions into a circulating atomic beam has been achieved.

"Burnouts" showing the shape of the trapped beams were made by passing them through foils. In one test, the R/2 beam was intercepted at 180° after passing through a foil. A second test was made under the same operating conditions except that the R/2 beam was allowed to circulate.



Reference to Figure 5 will show the difference in burn-through in the two cases.

NEW EXPERIMENTS

Several new experiments are planned for the near future. In one experiment, the average life of the trapped ions will be measured by pulsing the molecular beam and making oscillographic measurements of the decay of the circulating atomic ions.

An attempt is being made to understand the mechanism that provides dissociation and ionization of energetic ions that are passed through the discharge. It is not clear how to proceed experimentally, but the problem is being studied. Collision processes, gradients in the magnetic field (caused by the discharge filaments), photons, electrons, electric fields, etc., are considered in an attempt to understand the breakup phenomena.

Two experiments are under way to measure the pumping speed of the carbon discharge. One experiment will be made in a solenoid facility (Figure 2). These experiments will be made without energetic ions. Another experiment to investigate the vacuum conditions with approximately one ampere of D_2^+ ions being dissociated is planned in a new facility.

This facility (Figure 6) will provide for studying the trapped ions by spectrographic, photographic, and oscillographic methods. A neutron collimator is being designed by the Physical Electronic Group to study the origin of any neutrons that may be produced.

OTHER APPLICATIONS

The availability of trapped, circulating ion beams and large high-energy neutral beams opens several new possibilities in accelerators. The University of California[7] has considered the breakup of H_2^+ as a method of injection in proton synchrotrons. A gas target was considered in this study. Several advantages accrue from using the carbon discharge described in this report.

Under proper conditions all the H_2^+ could very probably be dissociated. Dissociation occurs in a small area (approximately 1/8-inch thick) as shown by the extremely sharp focus of the dissociated beam. Scans made of the 180° focal line of the H_2^+ beam and the 180° line of the trapped H^+ show no difference in width of focus. Stainless steel strips placed at the focal line of the trapped H^+ beam can be melted through with ease even when small beams (10 to 15 ma) are used, indicating sharp focus (see Figure 7).

Another advantage is the low pressure associated with these discharges, due to the pumping effect of the small particles as well as the pumping action of the discharge itself. Thus losses from scattering and degradation of energy are reduced because of low background pressure; this enhances the possibility of "storing" ions in a ring for longer periods of time. Also the discharge can be stopped in the microsecond range, if desired.

Application of this discharge to heavy ion accelerators may make a higher degree of ionization possible. In addition, the obvious advantages of stripping at low pressure in a small area could be exploited.

The dissociation experiments described in this report show the feasibility of producing large, well-defined neutral beams ($H_2^+ \longrightarrow H^+ + H^o$). High-energy neutral beams should be easy to obtain since the cross section for dissociation decreases slowly as the energy increases. These neutral particles could be injected into accelerators where the neutrals would be converted into ions.

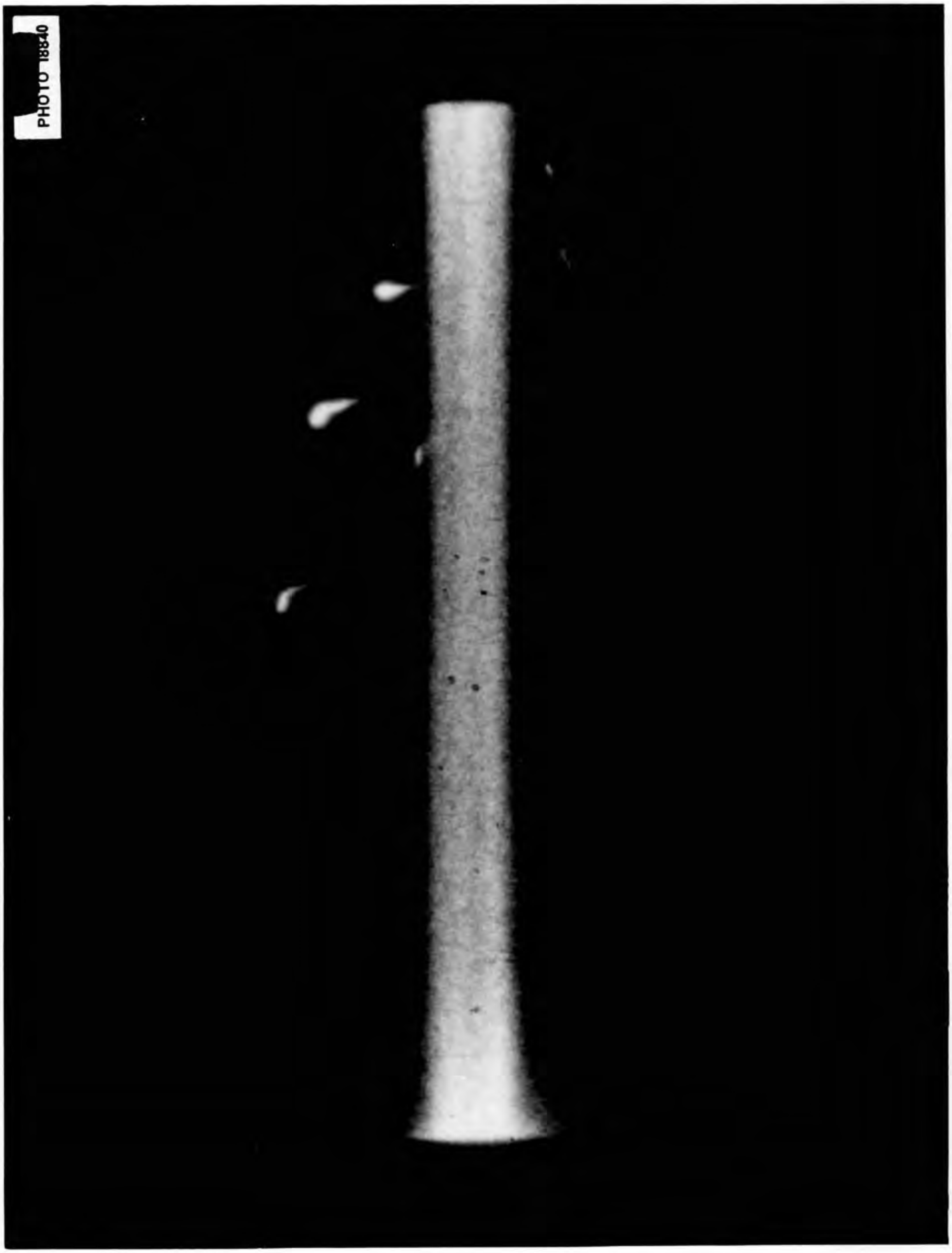


Fig. 1 Motion of Large Charged Carbon Particles

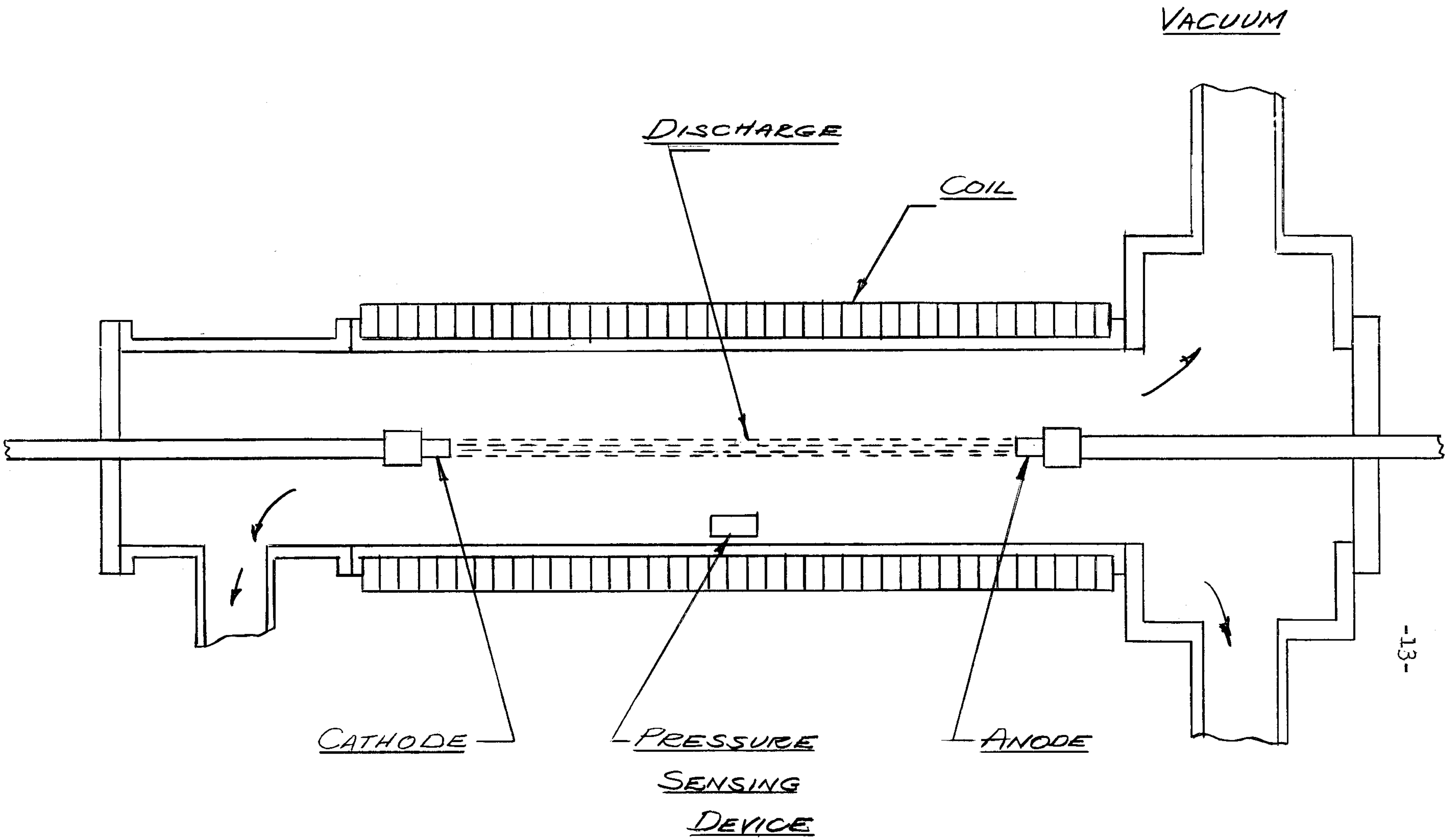


FIGURE 2. PUMPING EXPERIMENT

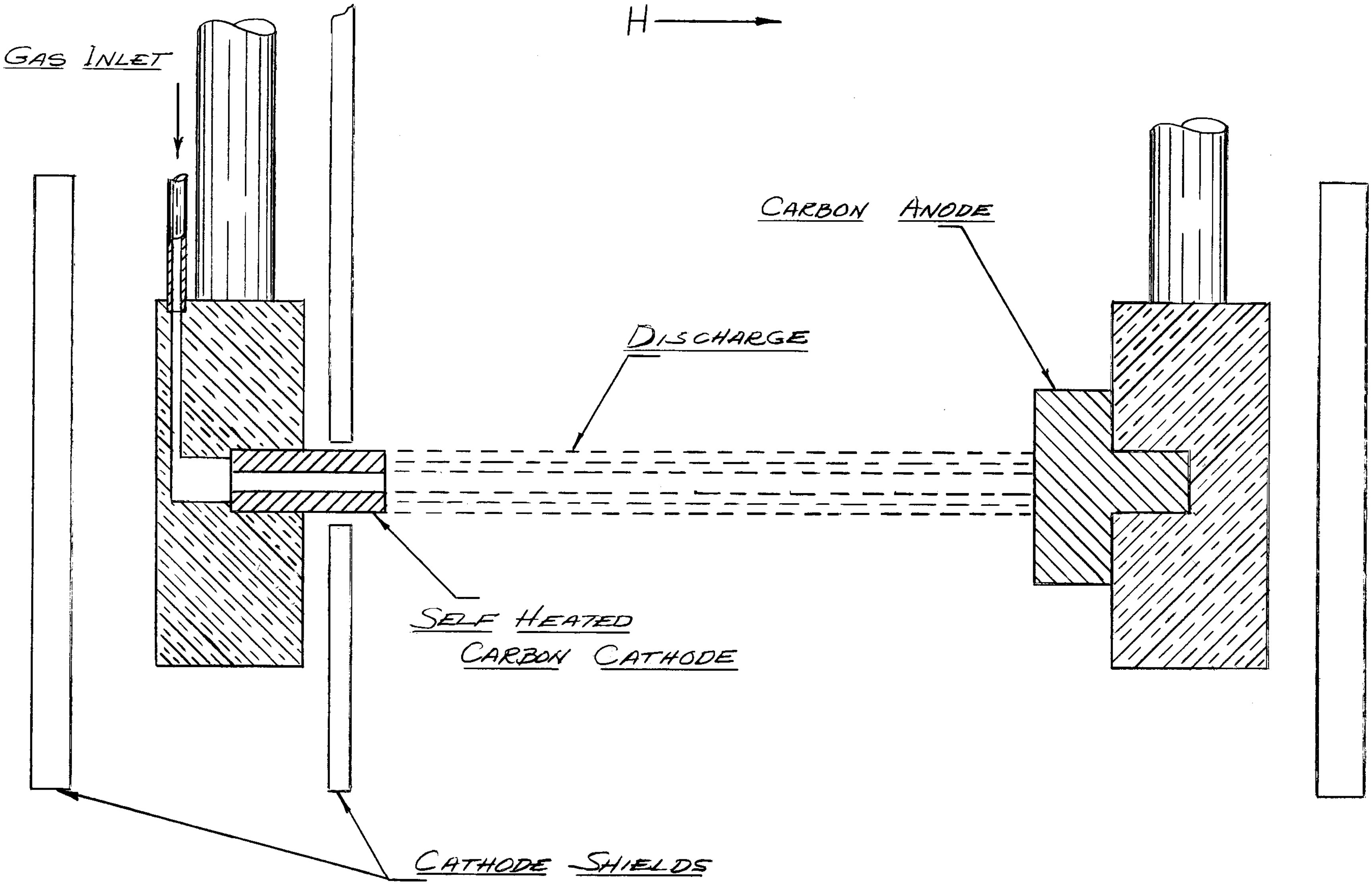


FIGURE 3. - DC ARC

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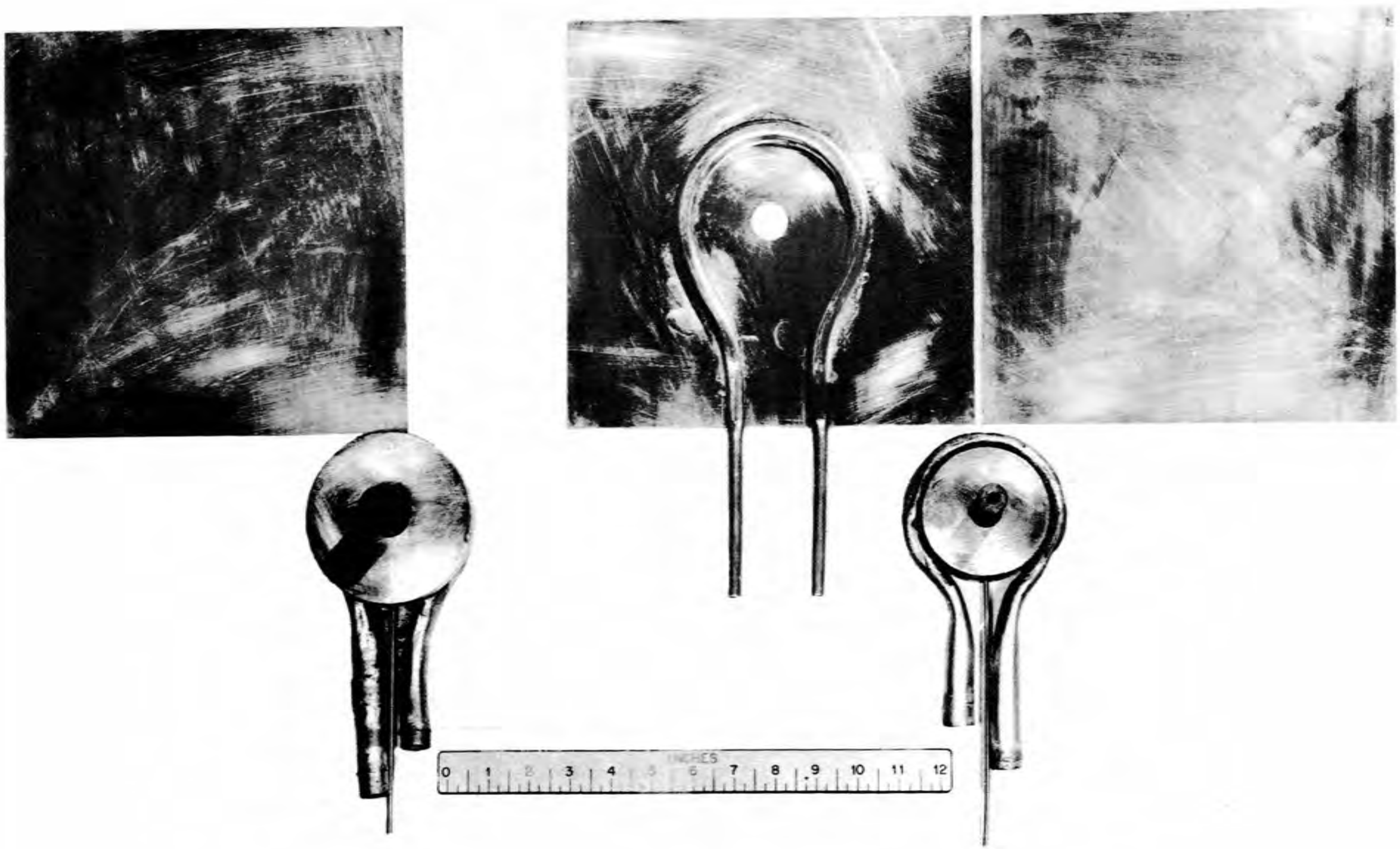

Fig. 4. Carbon [redacted]ge Components.

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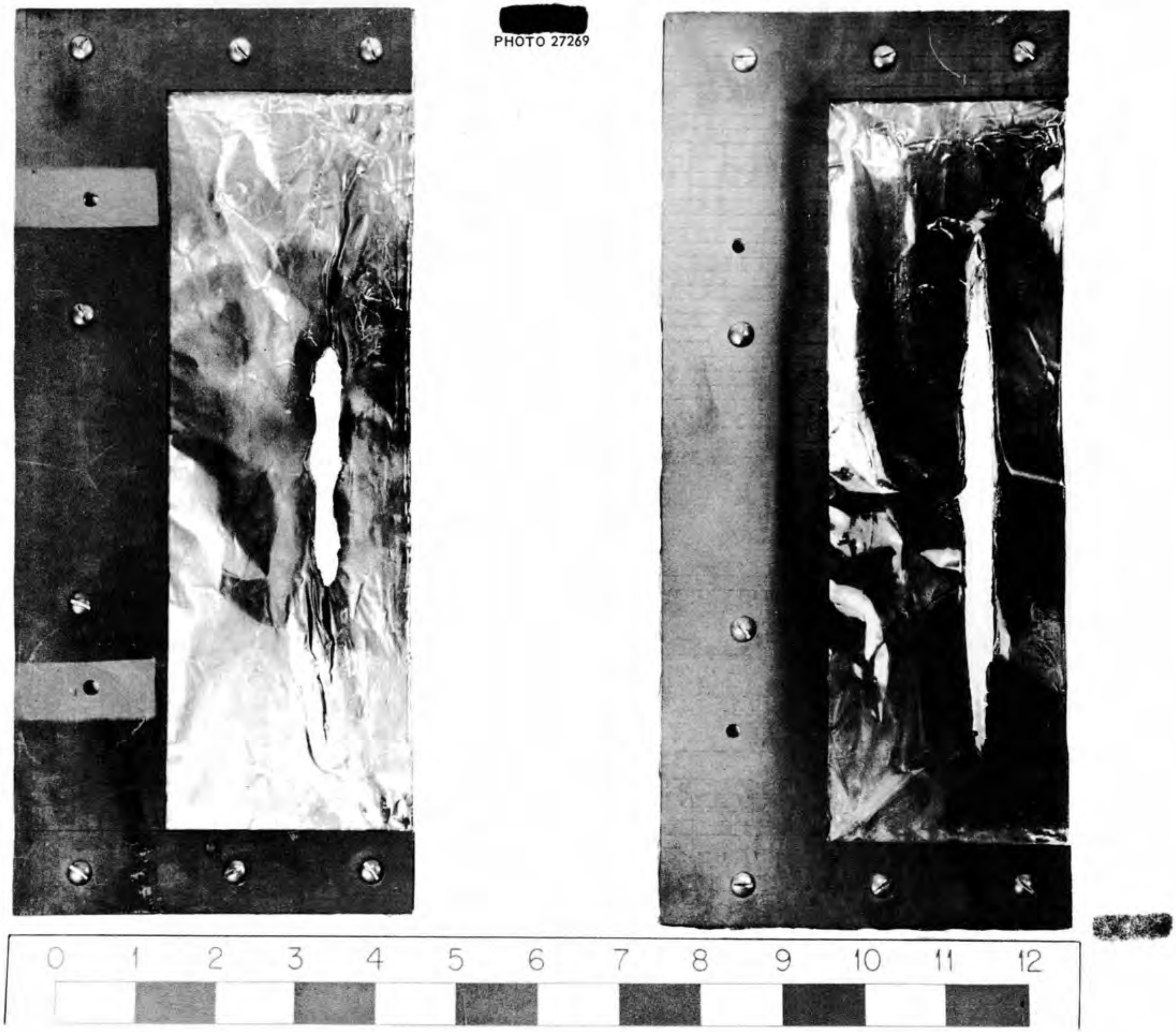
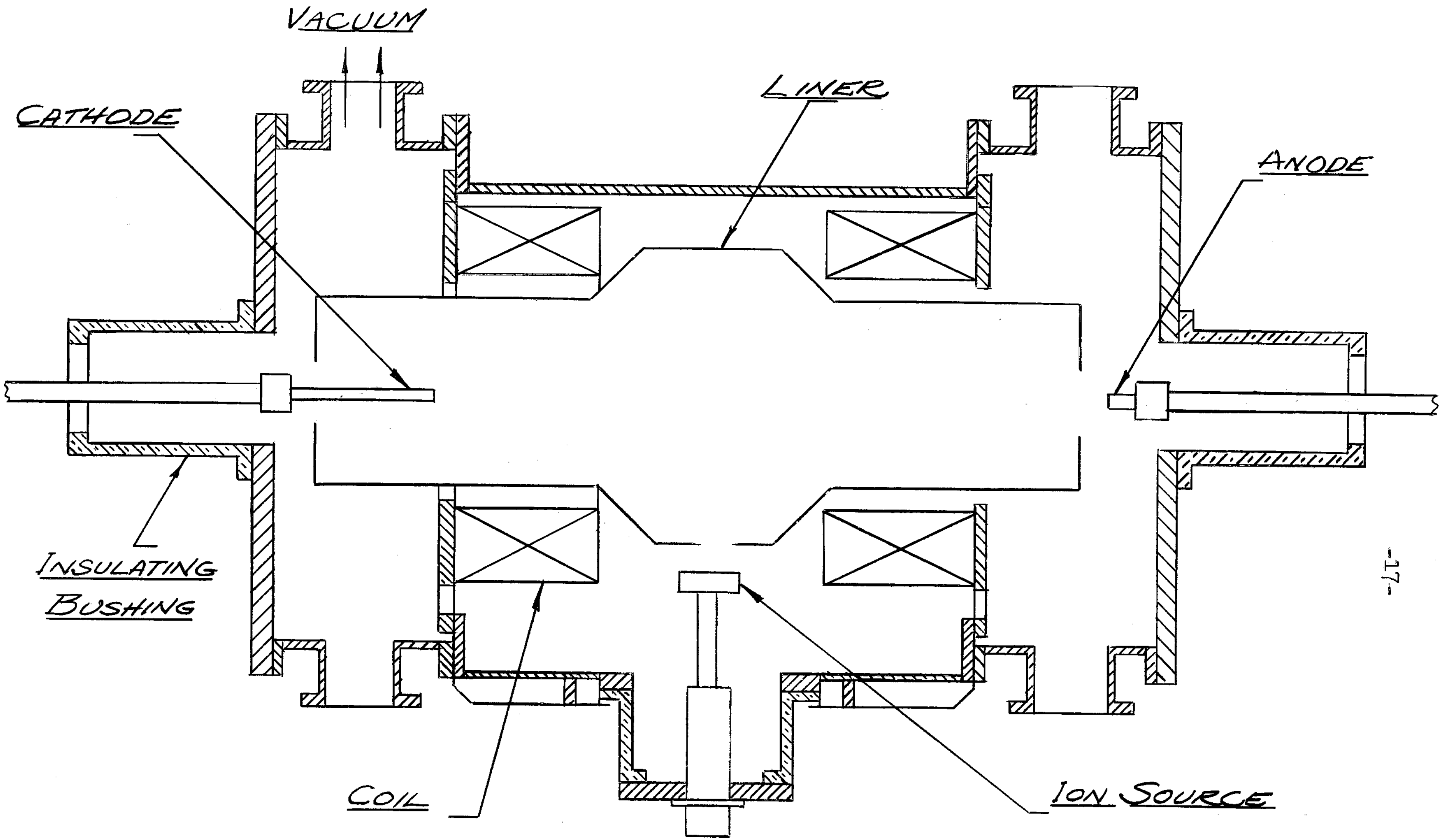


Fig. 5. Foil Burnouts.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CATHODE
ANODE
INSULATING BUSHING
COIL
ION SOURCE

FIGURE 6. DC X

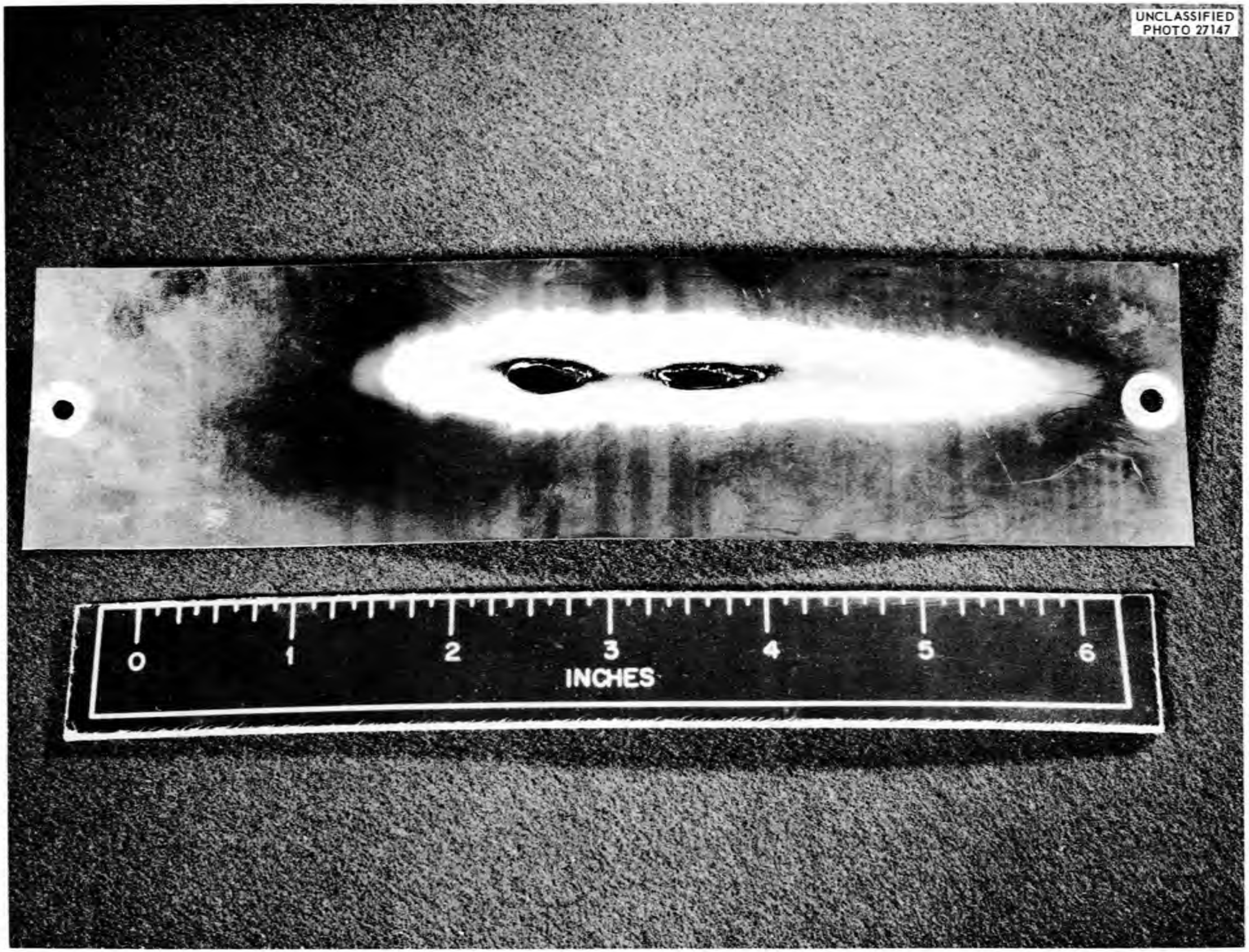

Fig. 7. Stainless Steel Burnout.

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