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PRELIMINARY RESEARCH
ON A
LOW-PRESSURE IONIC WIND TUNNEL

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INTRODUCTION

Aeronautical research involving high Mach numbers at high altitudes has indicated a need for an improved type of hypersonic wind tunnel. The possibility of producing hypersonic wind by means of gaseous conduction electronic phenomena has recently been investigated at the University of Michigan.

This preliminary research has indicated that under low density conditions very high velocities can be obtained more easily by electronic means than by conventional methods. Many systems have been studied and tested, by which electrostatic or electromagnetic forces can be used to impart momentum to gas molecules. Several of these experiments have appeared promising enough to warrant further study. This report is mainly concerned with the two schemes which seem to be the most practical, although the other methods will also be briefly described.

The approach to this investigation has been, to a large extent, experimental. This approach was a consequence of the limited scope of the investigation, not a disregard for theoretical studies. A continuance of this research should stress accurate quantitative measurements and analyses of the characteristics of the gaseous discharges.

ELECTRONIC MEANS OF ACCELERATING AIR MOLECULES

There appear to be three distinct types of forces which can be employed to produce a "wind" from a gaseous discharge. These are: (1) magnetic forces; (2) forces associated with thermal expansion; and (3) electrostatic forces. These three principles will be described, first briefly, and then in somewhat more detail.

1. It is well-known that an electric discharge can be deflected by a magnetic field. If an electric arc is established between two concentric metal cylinders, an axial magnetic field will cause this arc to revolve between these cylinders like a spoke in a wheel. This "revolving arc" tends to drag the ions and air molecules around with it, setting up a high velocity "wind". Experimental tests with this type of apparatus have been encouraging and a small-size model has produced supersonic wind velocities at a static air pressure of 0.5 millimeters of mercury.

There are various other magnetic methods of causing air to rotate inside a cylindrical container. One method involves an apparatus which would resemble a polyphase induction motor with the rotor removed. The region ordinarily occupied by the rotor would be filled with ionized air at low pressure. When the windings are energized, the revolving magnetic field sets up eddy currents in the ionized gas and drags it around as it does a rotor. By using a high-frequency power supply, very large velocities of rotation might be obtained in this manner.

2. When a high-voltage bank of electrical capacitors is discharged through an electric arc, the instantaneous power input to this arc can easily be made as high as hundreds of millions of watts. If this explosion is confined

to a small container, a temperature can be attained which is much higher than can be produced by any known combustion process. If this exploding gas were allowed to expand through a suitable nozzle, extremely high velocities could be achieved. Since this device would operate on a pulse basis, the metallurgical problems would be far less serious than for a continuous jet.

3. An obvious means of utilizing electrical forces to impart momentum to gas molecules is to accelerate ions by means of an electric field. This would appear to be a straight-forward method of producing an electronic wind, since there is a rapid interchange of momentum between gas ions and molecules. However, the electric field strength is severely limited by the breakdown voltage of the gas, and the system appears to be restricted to air densities in the "molecular flow" region where the power input is only a few watts.

These three principles all involve ionized air in some form or other. But, the presence of ionized air is not an important limitation to the usefulness of such a wind generator for aerodynamic testing. In most electrical discharges, the actual percentage of ions present is a fraction of one per cent of the total number of molecules. When ions and electrons leave the plasma region of a discharge, they recombine very rapidly, and such devices as grounded screens have been shown to be very effective in speeding de-ionization processes. It is believed that the essential problem is to find the best method of producing high velocities, and then presumably a way can be found to provide an ion-free region for test purposes. For instance, it has been found that a revolving disk-shaped region of ionized plasma inside a cylinder causes an adjacent un-ionized region to rotate with it.

Another possible limitation to the methods proposed here is the high temperature of the air, which requires a higher velocity to attain a given

Mach number. However, it might be pointed out that: (1) higher temperature air can be expanded without producing condensation; (2) at very low densities the important objective is to obtain a very high air velocity, and the Mach number is less significant.

EXPERIMENTAL EQUIPMENT

In order to provide as much flexibility as possible for these low pressure experiments, a vacuum box was constructed which was large enough to contain all the various types of magnets, cylinders and other gadgets that were employed. This vacuum box (Figure 1) is made of one-fourth-inch steel plates with reinforcing ribs welded to the outside. The inside dimensions are 22 by 28 by 30 inches. A large sheet of "Tuflex" glass one inch thick covers the entire front side of the box and provides good visibility within the chamber.

The vacuum system consists of a Kinney CVD556 two-stage mechanical pump which will pump the cavity down to 0.5 millimeters in about seven minutes. A mercury manometer was used for measuring the higher gas pressures and a thermocouple vacuum gage was used for the lower ones. A considerable amount of vacuum trouble was caused by the effect of the electric discharge on the oil in the vacuum pump. When the pump and the discharge were operating simultaneously, the pump oil started to foam and bubble, and it turned to sludge at a rapid rate.

The current for the magnet was obtained from a war surplus "turret trainer" power supply which furnished 150 amperes at 30 volts. Current for the arc was obtained from a single-phase rectifier employing four 669B rectifier tubes. This rectifier delivered up to 20 amperes of current at voltages up to 1600 volts. For several experiments where higher voltages were required, the power supply shown in Figure 2 was available. This supply is variac-controlled and will deliver up to 2 amperes of current at voltages up to 30 kilovolts.

The magnet, which can be seen in Figure 1, provides 6000 gauss across a five-inch air gap. The pole pieces are eight inches in diameter. For experiments requiring a magnetic field extending over a larger area, this magnet was replaced by a large hollow solenoid.

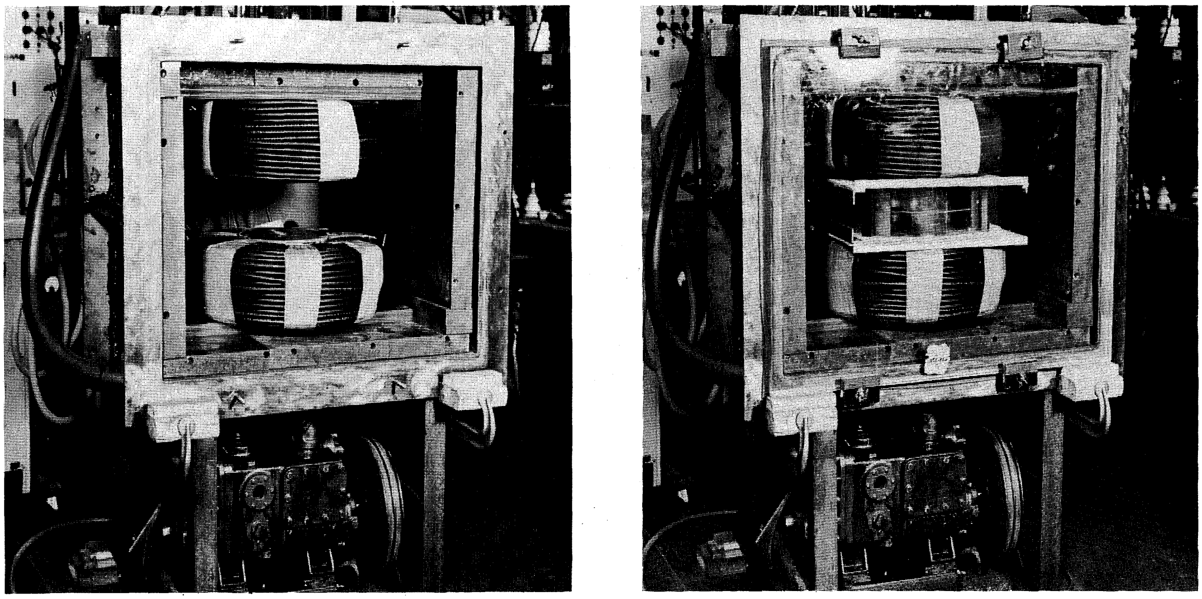


Figure 1

Vacuum Chamber With Magnet

Revolving arc wind generator is shown between the pole pieces of magnet. Thick glass window covers front of box.

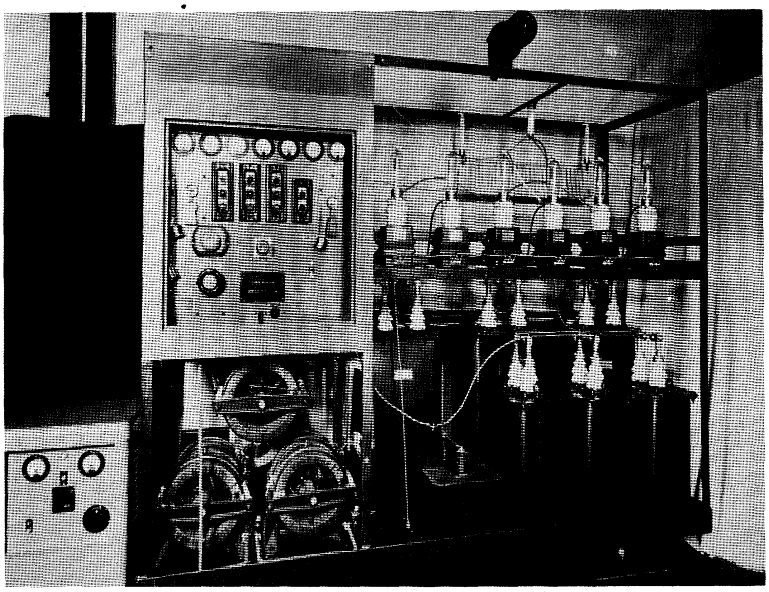


Figure 2

Variac controlled power supply

WIND PRODUCED BY AN ELECTRIC DISCHARGE IN A MAGNETIC FIELD

A considerable amount of technical literature is available, which discusses the behavior of an ionized gas in a magnetic field. Most of the experimental work reported has been done under conditions where the mechanical force produced by the magnetic field has not changed the general properties of the discharge. The importance of this force and the resultant wind has been recognized in the case of air circuit breakers, which operate at atmospheric pressure, but the important effects on low pressure discharges seem to have been ignored.

The present investigation has demonstrated that a supersonic wind can be produced by magnetic forces. This method appears to be very promising, and most of the experiments here reported have involved this principle.

Most of the experimental work was done at an air pressure of 0.5 millimeters of mercury, mainly because this was close to the lower limit of the vacuum pump. Also, nearly all of the tests were made with a magnetic field of 6000 gauss because this was the maximum that could be obtained from the available magnet. The power required to maintain the arc under these conditions was, in most cases, between 10 and 20 kilowatts. With the corresponding large quantity of heat produced in the vicinity of the arc, it was not feasible to establish the steady state conditions necessary for consistent quantitative measurements. The air pressure would increase quite rapidly after five or ten seconds of operation. By limiting the period of operation to about ten seconds, water cooling problems were avoided, and troubles involving the vacuum system were minimized. However, much of the numerical data were obtained under shifting conditions, and are not as accurate as might be desired.

Forces on the Positive Column of an Arc.

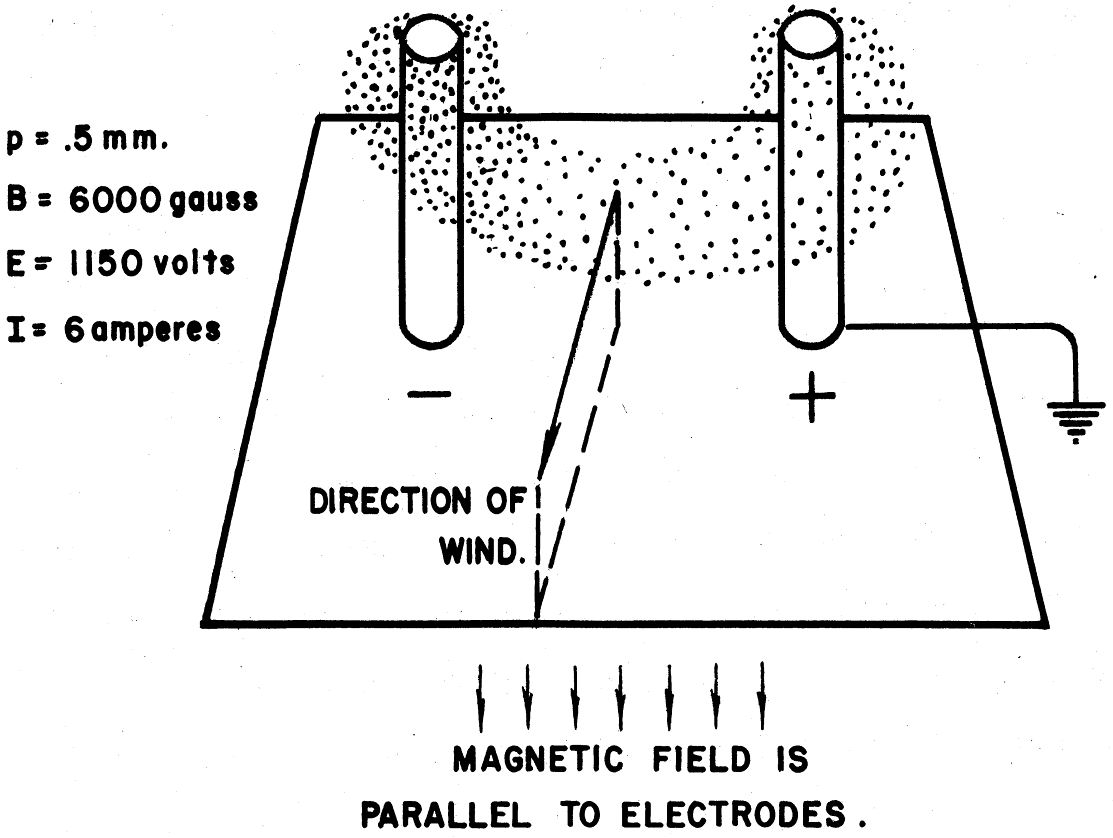
In the absence of a magnetic field the only significant movement of the gas in the plasma of a discharge is that due to thermal convection. The electric gradient in the plasma produces rapid acceleration of the electrons toward the anode, and the ions toward the cathode. But since the positive ion density is almost exactly equal to the electron density, the net electric force on any given volume of the plasma is essentially zero. If the positive and negative charge densities differ by as little as one-tenth of one per cent, the resultant space charge produces a large distortion of the electric field. This behavior is related to the production of wind by the acceleration of ions in an electric field, discussed in another section of this report.

An electrical discharge which is perpendicular to a magnetic field produces a directed momentum of the gas molecules. Although the mechanism by which the neutral gas molecules acquire this momentum is difficult to analyze, the magnitude of the force, per unit volume, is equal to the product of the net current density and the magnetic field strength. It is important to note that since the electrons and ions are moving in <u>opposite</u> directions, the transverse forces due to the magnetic field are in the <u>same</u> direction. The relative magnitudes of the ion current and electron current are difficult to measure. This is especially true under conditions of low pressures and strong magnetic fields, where the voltage gradient in the plasma is so large that ordinary probe techniques do not apply.

Arc Between Two Parallel Rod Electrodes.

Figure 3 illustrates the general appearance of a low-pressure arc in a strong transverse magnetic field. The arc is bent by the field in the expected manner. The positive column tends to maintain a cross-sectional area which is less than if the same current were flowing without the magnetic field. The voltage gradient along the positive column is about 100 volts per centimeter, and there is a potential drop of more than 500 volts within 3 millimeters of the cathode. The cross section of the arc column does not change appreciably as the current is varied in the range 1 to 10 amperes, but above about 10 amperes the plasma has a noticeably higher color temperature. Considering the very high power input to the arc (of the order of 1 kilowatt per centimeter of arc length) the low temperature of the positive column is quite surprising. The column is very transparent and has a bluish color, suggesting the same order of temperature as in a gas rectifier tube, perhaps 700 degrees Centigrade. Adjacent to the cathode, the color temperature is higher but the region is not nearly as bright as an atmospheric arc.

It is evident that heat is dissipated by the arc at a very rapid rate. This rapid heat removal is due to the high velocity wind which is caused by the magnetic field. Even when the arc was located in the center of a square vacuum chamber and no streamlined circulation was possible, this wind still approached supersonic velocity. The direction of the wind was consistent with the force predicted by Ampere's rule, and was always perpendicular to the direction of current flow. When the arc column was distorted into peculiar shapes by unsymmetrical electrodes, the wind emerging from the plasma always tended to be at right angles to the plasma boundary or surface.



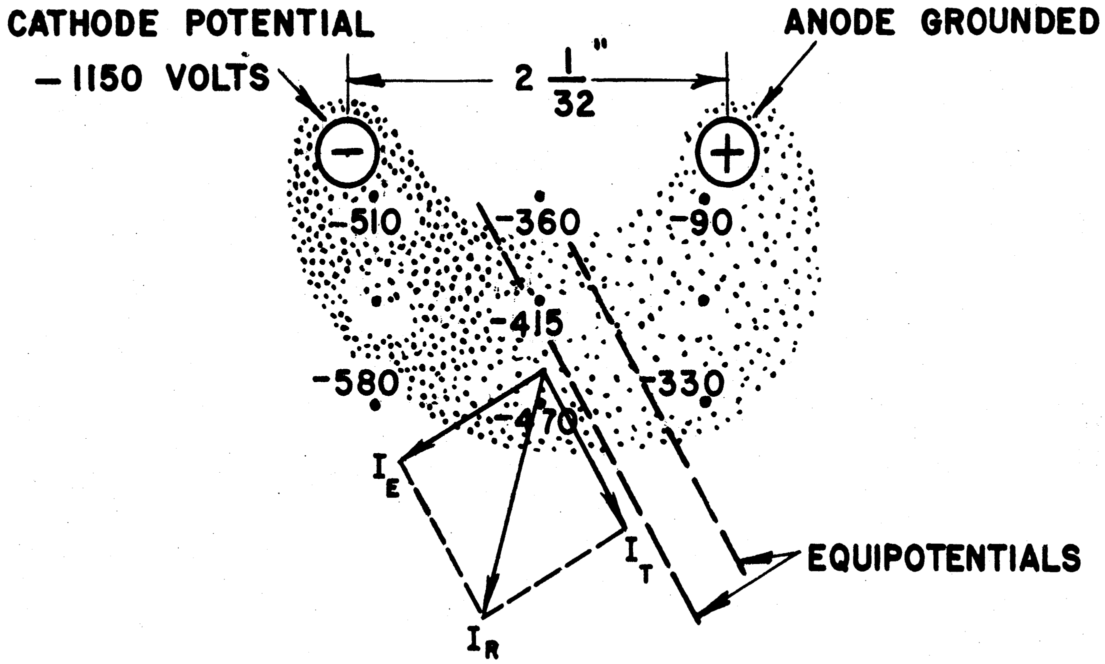


Fig. 3(a) Arc between two copper rods.

Fig. 3(b) Section of arc taken perpendicular to electrodes and probe measurements of potentials with respect to anode.
I_E = component of ion drift velocity in direction of electric field.
I_T = component of ion drift velocity transverse to electric field.
I_R = resultant velocity in direction of wind.

A sheet of mica was placed parallel to the arc column and on the "downwind" side so as to block the air flow. This caused the arc to flatten out and crawl along the surface of the mica giving the appearance of a white hot surface layer. When the mica sheet was placed on the "upwind" side of the arc so as to prevent the air from reaching it, the arc no longer tried to bend downstream, but spread out vertically as far as possible. A sensitive oil-filled manometer was used to measure the air pressure in the region between the mica sheet and the arc, and it was found that the arc was acting like a vacuum pump. The air pressure in the region between the arc and the mica sheet was lower than could be measured or detected with the manometer. A vacuum gauge of the pirini or thermocouple type was not suitable for this measurement because of the long time constant. However, the manometer indicated that the pressure was definitely less than 1 millimeter of oil, which was less than 10 per cent of the pressure on the "downwind" side of the arc.

Revolving Arc.

The preceding section has described the wind produced by a stationary arc. A somewhat more efficient wind generator is shown in Figure 4 where the arc is between two concentric cylinders. The magnetic field is in an axial direction and the force due to "motor action" causes the arc to revolve at a very high velocity. This force is also communicated to the neutral air molecules so that the air, as well as the arc, revolves at supersonic speeds.

Figure 5 is a slightly different arrangement which was more convenient for some of the experiments. The center copper cylinder (three inches in diameter) was the cathode, and the copper ring (made from 5/16 inches copper tubing) was the anode. The transparent mica cylinder was 16 inches in diameter and provided good visibility for observing the experiments. This mica served merely as a boundary for the revolving air stream. A leak-proof or gas-tight partition was not required, because the whole assembly was located inside the large vacuum box. The top and bottom end plates of the cylinder were made of transite, which also served as electrical insulation. In Figure 1 the apparatus of Figure 5 can be seen between the pole pieces of the magnet.

Experimental Observations: Since the behavior of the revolving arc depends on a large number of variables, seemingly inconsistent experimental data were sometimes obtained. Nevertheless, a few generalized observations apply over a very wide variety of conditions.

1. The arc revolves like a spoke in a wheel. This has been observed at all pressures from 0.2 millimeters to atmospheric pressure and over wide ranges of current and field strength. The speed of rotation increases with current and with magnetic field strength. At very slow speeds, the rotation is easily visible. At speeds of a few hundred rpm, the rotation can be observed by stroboscopic arrangements, and at still higher speeds by means of plasma probes and an oscilloscope.

Figure 6 is a sketch of the pattern on the screen of the oscilloscope when it was connected to two probes by means of an electronic switch. These probes were spaced 120 degrees apart around the cylinder, and the two superposed traces show that the arc passed Probe No. 1 about one-third of a revolution before passing Probe No. 2. The arc was revolving about 17,000 times per second. The direction of rotation observed in this manner was consistent with the wind direction indicated by a small flag or vane and with the direction of the force predicted by the "motor rule".

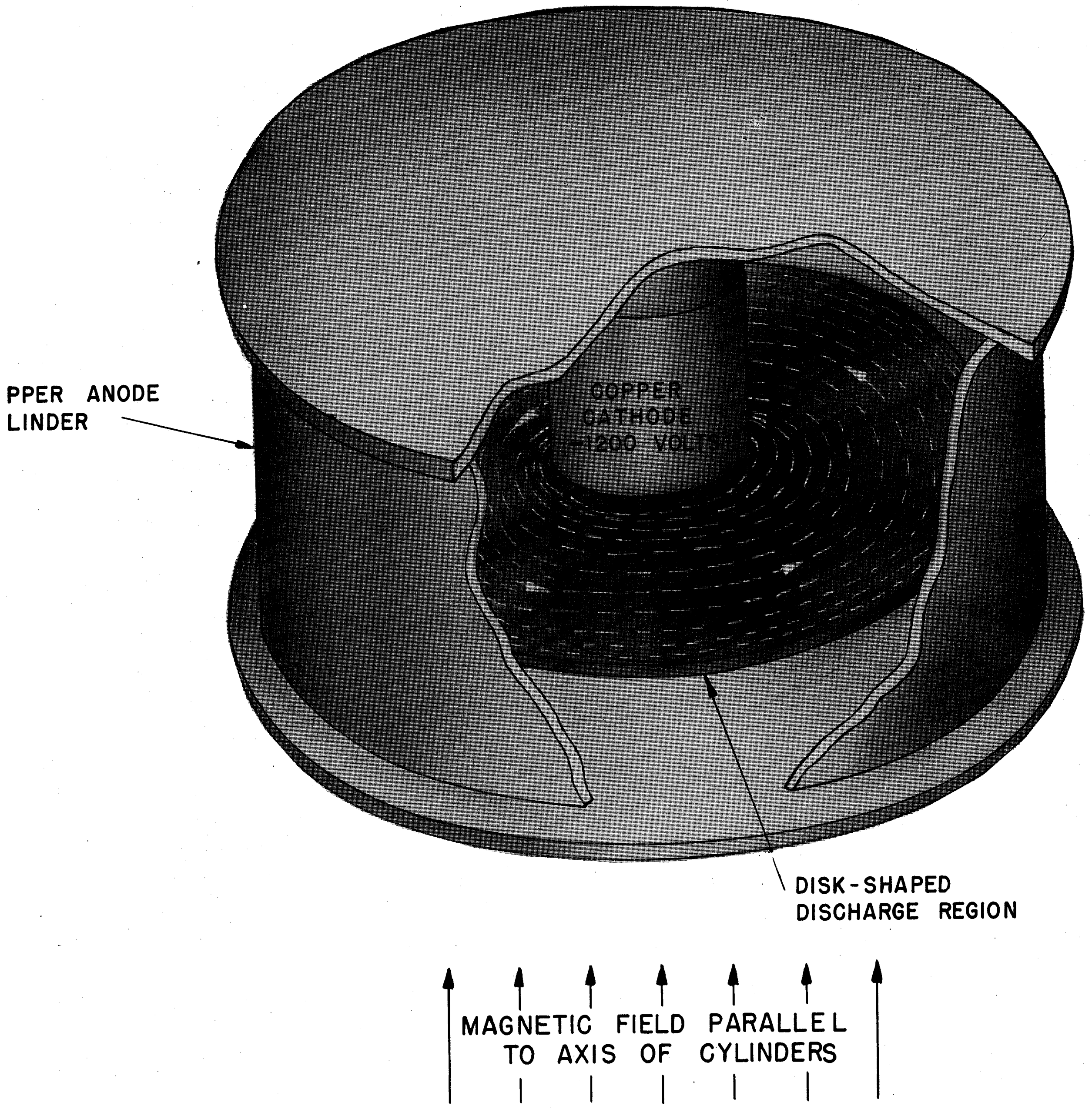


Fig. 4

Cutaway drawing showing "luminous disk" caused by revolving arc. Experimental observations were made through mica window in top plate.

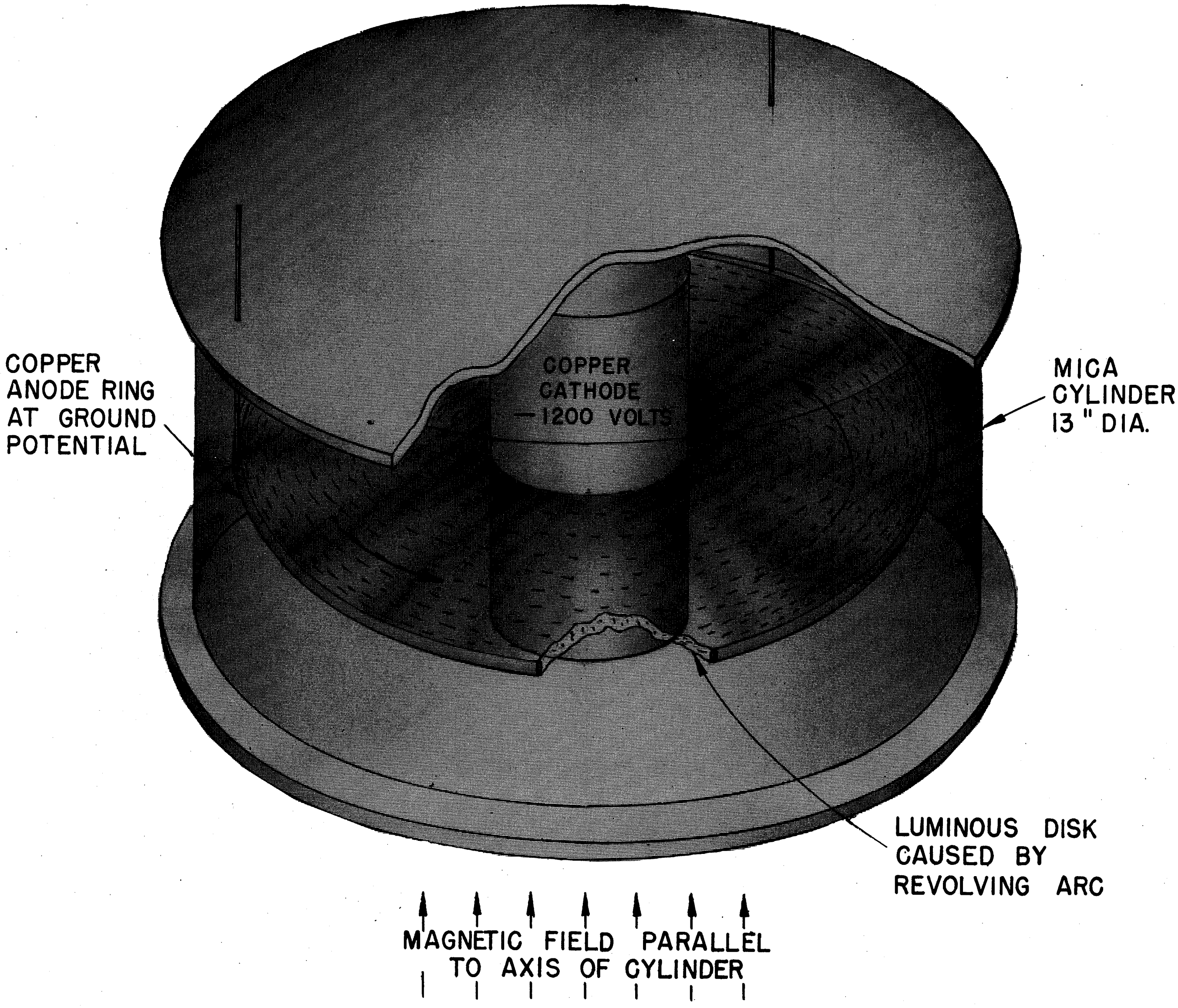


FIG. 5

REVOLVING ARC INSIDE A TRANSPARENT MICA CYLINDER.

2. The arc voltage is essentially constant as the current is varied. It is difficult to check this observation accurately because of variations in pressure, but it is certain that the voltage does not change more than a few per cent when the current is varied from a fraction of an ampere to over 20 amperes.

3. The arc will always concentrate where the magnetic field is the weakest. If the magnet pole pieces are at the ends of the cylinder, the fringing causes the flux density to be a minimum midway between the poles so that the arc concentrates in this region. If the field is unsymmetrical with respect to the axis of the cylinder, or if it is weaker near one end, the arc may cease to revolve and instead may localize along the path of lowest field strength.

4. In the pressure range 0.4 millimeters to 10 millimeters, an increase in gas pressure causes an increase in arc voltage. It is believed that this observation is true for increasing pressures, perhaps up to atmospheric and above.

5. The operating voltage of the arc is not greatly affected when the polarity of the two cylindrical electrodes is reversed. At low currents (less than one ampere), the cathode behavior appears to resemble a glow discharge, and the operation is steadier when the outer cylinder is the cathode. Under these low current conditions, when the polarity is reversed, intermittent flashes of light can be observed near the cathode, as if there is a tendency for establishment of a cathode spot.

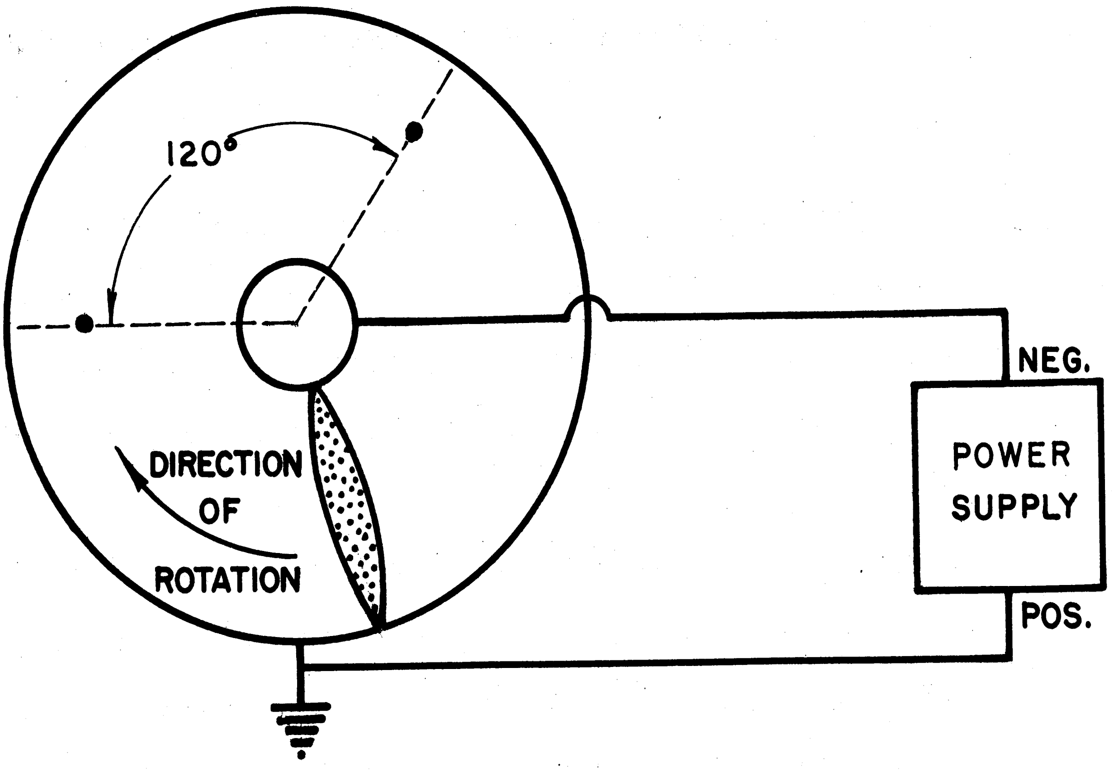


Fig.6(a) Probe arrangement for investigation of revolving arc.

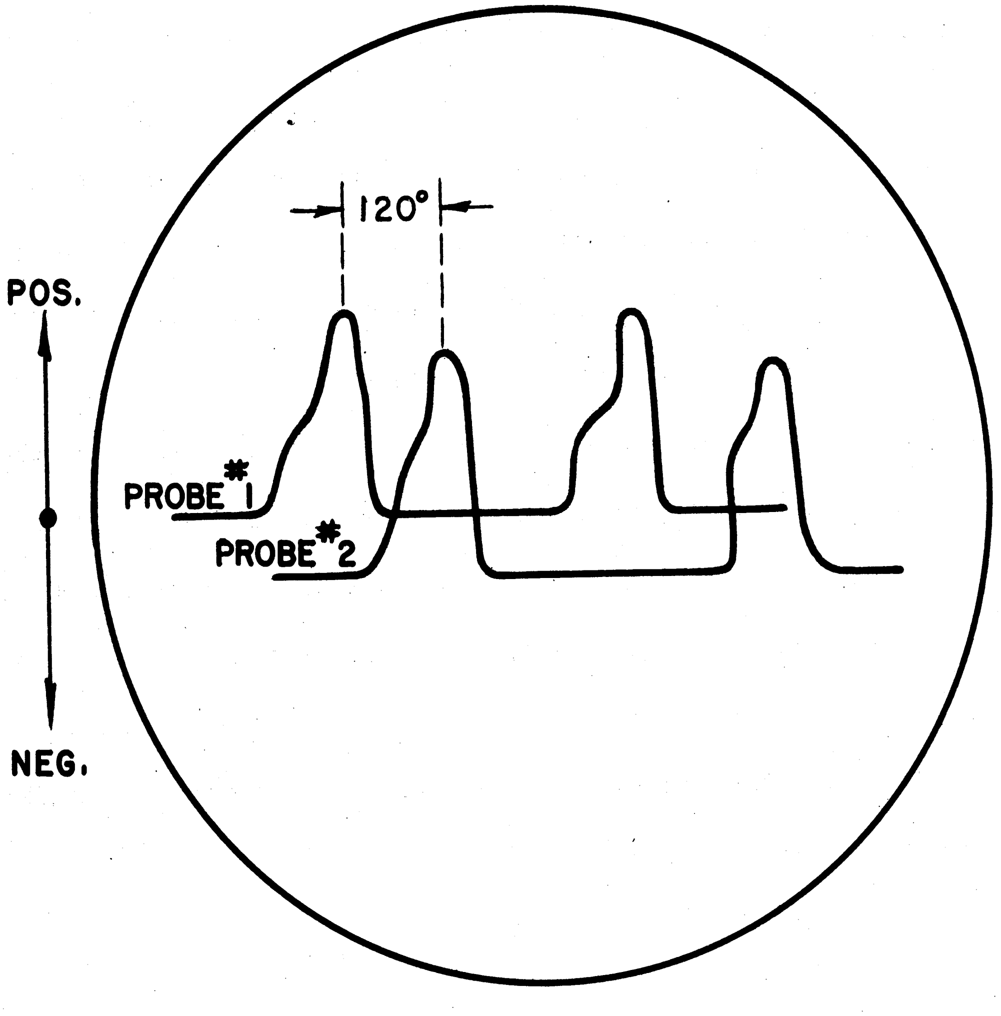


Fig. 6 (b) Oscilloscope pattern with the two probe voltages superimposed by means of an electronic switch.

When the inner cylinder is the cathode and when the arc current is about three amperes or more, arc tracks are always produced. These suggest a field emission type of cathode. A band of light around the cathode also indicates a higher gas temperature. However, with the arrangement of Figure 4, when the large outer cylinder is the cathode, arc tracks are not produced even for large currents, and the lighter arc-like glow next to the surface is seldom visible. Perhaps this can be explained on the basis of the larger diameter of the outer cylinder. Thus, it may be that the very high speed of the assumed cathode spot prevents it from leaving a track or from raising the temperature appreciably over the large area that it traverses. Under these conditions the cathode behavior resembles a glow discharge more than an arc, since it tends to spread out vertically along the wall of the outer cylinder.

6. When the spacing between the electrodes is several inches, and the operating voltage is of the order of 1200 volts, most of the voltage drop occurs in the plasma region between the electrodes; the cathode drop and anode drop probably do not account for more than 15 per cent of the total. To a rough approximation, the operating voltage is proportional to the spacing. On the other hand, when the electrodes are more closely spaced, so that the total voltage is perhaps only 300 volts, a sizeable part of this drop appears to be associated with the cathode. For example, an experiment was made in which the cathode cylinder was replaced with a copper-covered iron disk. The presence of the disk greatly decreased the tangential component of the magnetic field in the region close to the surface of the cathode, and the total arc voltage was decreased about 30 per cent.

Probe measurements of voltage drops are difficult to make because of the rapid motion of the arc, but the evidence indicates that the voltage drop in the positive column of a moving arc is about the same as in a stationary arc (in the same magnetic field).

The large cathode drop of 500 volts or more in the stationary arc is greatly reduced when the arc is moving.

Attempts To Reduce Arc Voltage: In order to obtain maximum efficiency as a wind generator, it is desirable to keep the arc current and the strength of the magnetic field as large as possible and the arc voltage as low as possible. The total arc voltage can be reduced somewhat, perhaps 10 per cent, by reducing the field strength close to the surface of the cathode. To reduce this field strength, a variety of devices were tried. For example, iron was placed inside the copper cathode so as to by-pass the magnetic flux which would otherwise have been tangent to the surface. These experiments and probe measurements indicated that the cathode drop was not more than 10 to 15 per cent of the total voltage, so that no major improvement could be made by reducing or eliminating this drop.

As previously mentioned, the arc voltage changed very little in the range 0.1 to 20 amperes. It was thought that perhaps if the current were increased to hundreds or thousands of amperes, lower voltage operation might be obtained. Of course a continuous current of this magnitude would involve excessive power and heat, but if the arc voltage were substantially reduced at very large currents, then perhaps a rapidly pulsed system would enable a given average current to be produced with much less power input.

When it was originally decided to experiment with a high current pulsed arc, it was intended to use the electrode arrangement of the revolving arc so that the arc could rotate during the pulse. However, it was experimentally convenient to make the first pulsed experiments with two rod electrodes, as illustrated in Figure 3. These tests involved only"single shot" pulses, but they gave interesting results and indicated that very high transient velocities might be produced in this manner. For the wind tunnel objective, a continuous flow wind generator is preferable, and in order to test the revolving arc on a rapidly pulsing basis, a rather heavy expenditure for suitable condensers would have been required. Hence, it was decided to discontinue the pulse experiments after a few preliminary tests.

Tests With High Current Pulsed Arc.

The pulsed arc tests were made with two parallel copper cylinders for electrodes. They were one and one-half inches in diameter and were spaced four inches apart on centers. The magnetic field was 6,000 gauss and the pressure 0.5 millimeters, as in most of the previous experiments. The pulse current was obtained from a bank of capacitors, having a total capacitance of 500 microfarad. These capacitors were connected directly across the electrodes of the arc. They were charged by connecting them to the power supply through a dropping resistor, and when a certain potential was reached, the discharge took place automatically. The current wave of the discharge was observed and measured by connecting a DuMont type 248A oscilloscope across a small non-inductive resistance in the discharge circuit. Voltage measurements were made by means of the oscilloscope and a voltage divider.

Considerable care was taken to make sure that the indicated voltage was the actual voltage across the electrodes and did not include any of the voltage drop in the leads.

Figure 7 shows the variation of arc voltage and current during a typical test. The resistance was high enough to critically damp the circuit, and there was no oscillation. Other experiments indicated that continuous operation of this arc at currents of only a few amperes would have required voltages of about 1,200 volts, so it is evident that the arc voltage was very much reduced by using a high current pulse.

The current pulse shown in Figure 7 was about the right magnitude to produce the minimum voltage drop. When the peak current was made larger by reducing the series resistance, the voltage was increased. The minimum voltage was obtained when the peak current was of the order of 500 to 800 amperes.

This reduction in voltage during a short pulse might not have continued if the pulse had been longer or had been rapidly repeating. There was evidence to indicate that the lower voltage was associated with the fact that the air at the beginning of the pulse was stationary and at room temperature, and if the pulses had been lengthened or repeated in rapid succession, the voltage would have increased. One bit of such evidence was the effect of placing a sheet of transite a few inches downstream from the electrodes. This had little effect when the arc was operating at a continuous current of a few amperes, because the wind continued to circulate in spite of the obstacle. However, when the current was increased to pulses of hundreds of amperes, the sheet of transite had a very pronounced effect, and reduced the

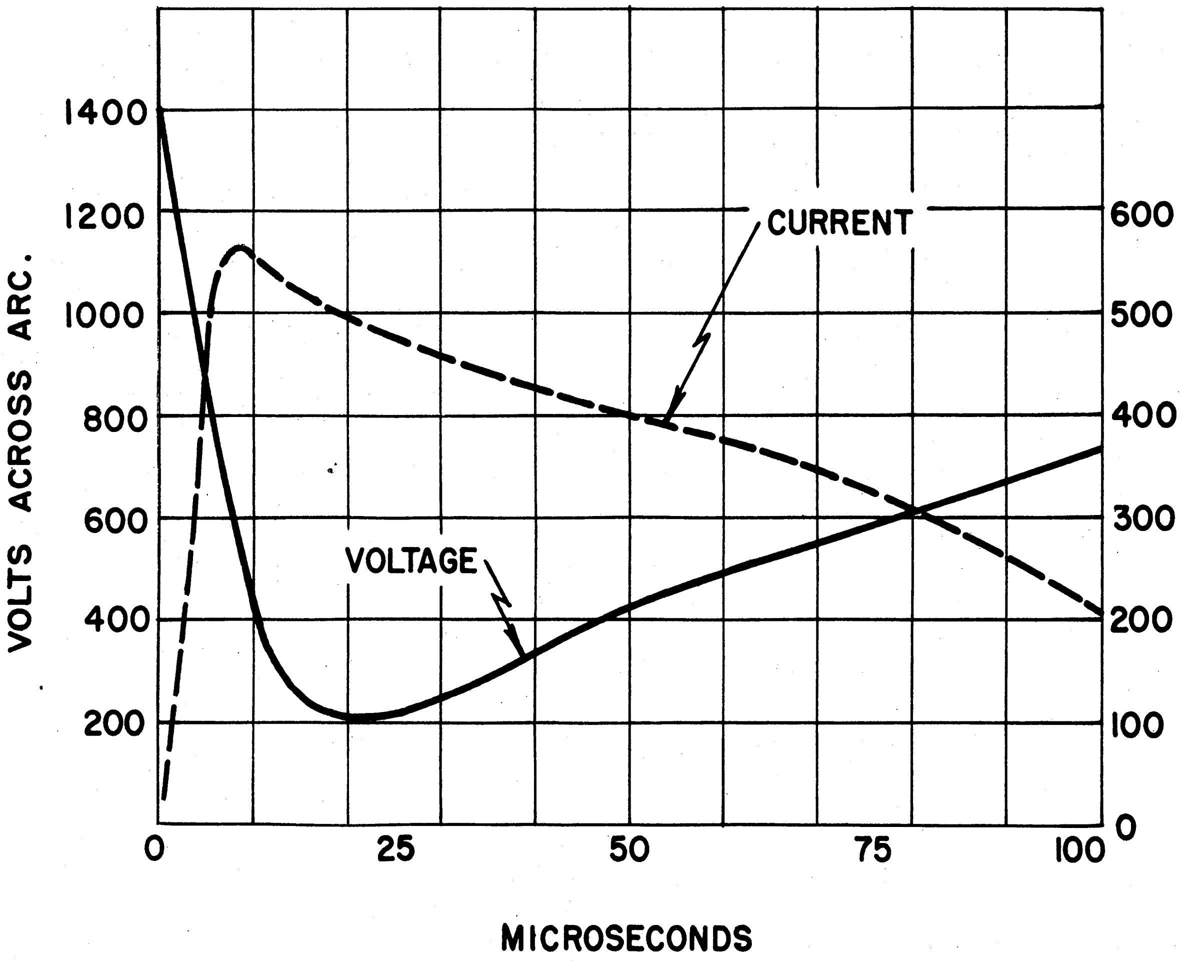


Fig. 7
Capacitor discharge between electrodes four inches apart. Maximum current limited by 2.5 ohm series resistor.

arc voltage as much as 50 per cent. The arc voltage depends to some extent on whether or not the air is free to move, and the sheet of transite was a much more serious obstacle to the "explosion" wind from the pulsed arc than it was to the steady wind from the continuous arc.

The probable explanation for some of these effects is as follows: When the charged particles in the arc start to cross the gap between the electrodes, they immediately acquire velocity in a transverse direction. They can not make any net progress in crossing the gap unless the transverse momentum is limited by collisions with neutral molecules. At the beginning of the pulse when the neutral air molecules are relatively stationary, the charged particles can lose transverse momentum much more effectively than after the air has started to move. Hence, the voltage across the arc tends to increase as the air acquires velocity. When the sheet of transite was located downstream from the arc, the pressure wave caused by a pulse of arc current was reflected back toward the arc again. This reflected wave had a substantial effect on the arc voltage during the latter part of the pulse interval.

It is interesting to speculate just how or where this transient force appears, when the air is free to circulate. Consider a 10,000-ampere pulse. The magnetic force exerted on an arc column 10 centimeters long is 6.0×10^7 dynes or about 130 pounds. This force of 130 pounds presumably acts on the gas particles and increases their momentum. The calculated resultant velocities are surprisingly large. For instance, assume that this force, having an average value of 6×10^7 dynes, lasts for 50 microseconds. Assume that all the air in the vicinity of the arc or all that could flow into the vicinity of the arc in 50 microseconds has a mass of 10^{-3} grams.

A rough calculation will show the magnitude of the velocity given to the gas.

$$\text{acceleration} = \frac{f}{m} = \frac{6 \times 10^{7}}{10^{-3}} = 6 \times 10^{10} \text{cm sec}^{-2}$$

$$\begin{aligned} \text{velocity} = \text{acceleration} \times \text{time} &= 6 \times 10^{10} \times 50 \times 10^{-6} \\ &= 3 \times 10^{6} \text{ cm per sec} \\ &= 30{,}000 \text{ meters per sec, which is comparable to Mach } 85. \end{aligned}$$

Plasma Characteristics.

The discharges described in this report are considerably different from the more familiar types of electric arcs, and a number of very interesting properties have been observed. Attempts to analyze the behavior of an ionized gas in a magnetic field have been made by Chapman,[1] Tonks[7,8] and others. The various assumptions involved in their analyses appear to make the results of limited value. This is especially true of studies dealing with a strong magnetic field, but neglecting effects due to the wind. The work here reported has furnished certain qualitative information about the nature of the discharge, but quantitative facts were difficult to obtain. An attempt to measure plasma characteristics by means of a fine wire probe led to the curve shown in Figure 8. As there are no observable sheath characteristics, this curve suggests that the plasma was behaving like a high resistance fluid.

If the current is carried by electrons, then the force due to the magnetic field must somehow be transferred from the electrons to the neutral gas molecules. Because of the tremendous difference in the mass of molecules and electrons, the momentum interchanged by elastic collisions is small. It is doubtful if the force is transferred in this manner.

It appears more likely that the current is carried principally by positive ions, the momentum transfer taking place between ions and neutral molecules. There are various reasons for believing that the mobility of the ions in the direction of the electric field is much greater than that of the electrons. Some of the reasons for this belief can best be explained by studying the behavior of individual particles under a definite set of conditions. This method lacks generality but helps to educate one's intuition as to the magnitudes of the various effects.

Before considering the behavior of an ion or electron in the environment of a gaseous discharge, it is appropriate to review the equations for the motion of a charged particle in orthogonal electric and magnetic fields. The derivation of this equation is given in the Appendix.

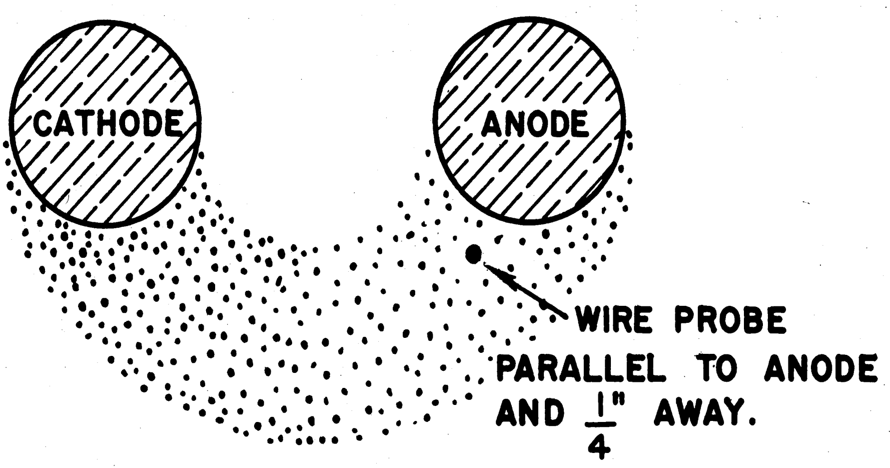
$$(x + jz) = (a + jb) + (\alpha + j\beta)e^{j\frac{q\,B_y}{m}t} + j\frac{E_x}{B_y}t$$

where

$$a = (x_o - \alpha)$$

$$b = (z_o - \beta)$$

$$\alpha = \frac{m}{q\,B_y}\left[\frac{E_x}{B_y} - \dot{z}_o\right]$$



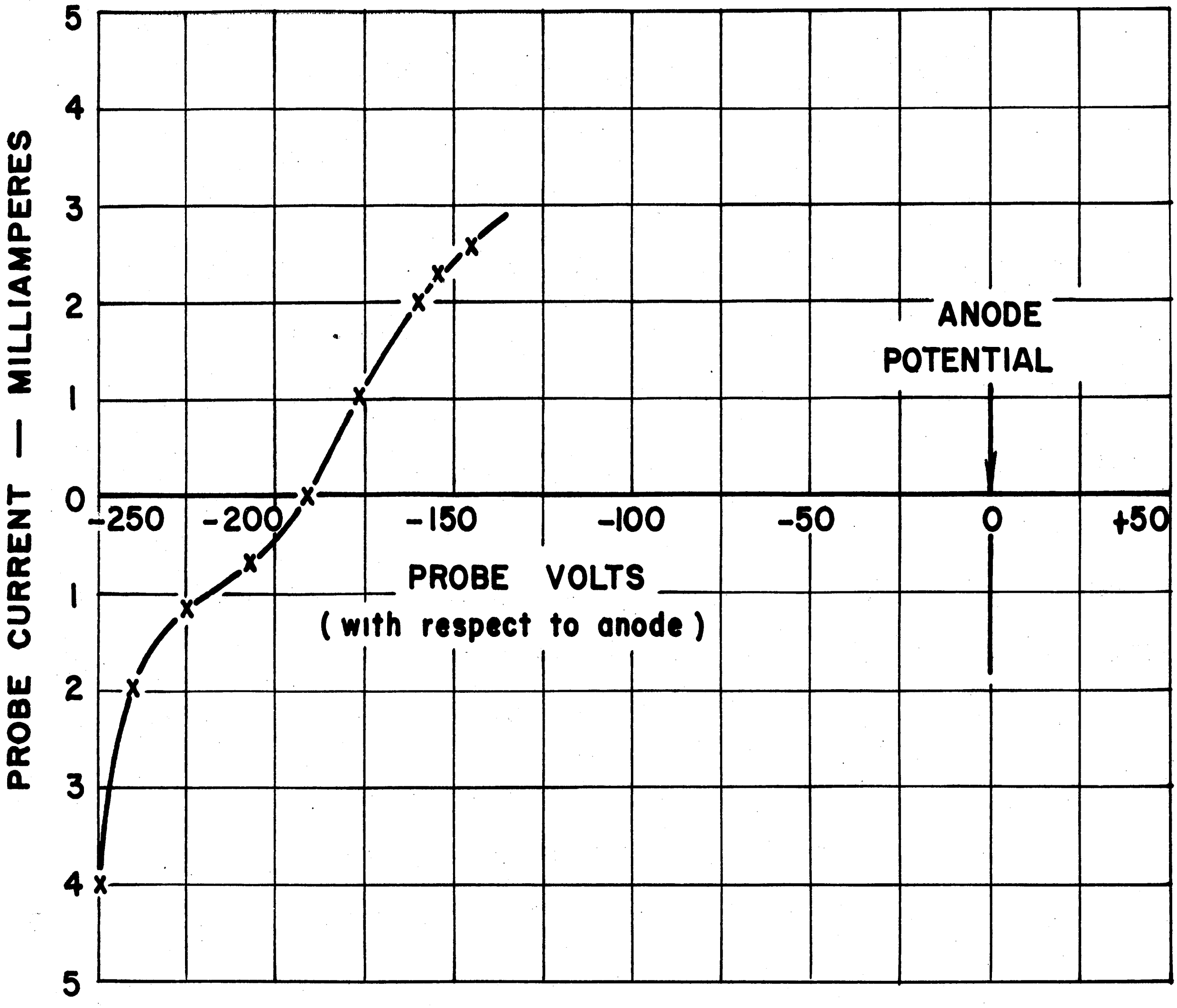


Fig. 8

Current versus voltage for a probe of .020-inch tungsten wire, 3/4 inches in length.

$$\beta = \frac{m}{q\,B_y}\,\dot{x}_o$$

q = charge of particle

m = mass of particle

B_y = magnetic flux density

E_x = electric field strength

x_o, z_o is position of particle when $t = 0$.

An interpretation of this equation is given in Figure 9. The "E" field is in the positive "x" direction and the "H" field is into the plane of the paper. The particle is progressing in the "z" direction along a cycloidal curve. Such a curve may be generated by a spot on the radius (or extended radius) of a rolling wheel. When $t = 0$, the center of this wheel is at $a + jb$. The vector $(\alpha + j\beta)$ represents the radial distance from the center of the wheel to the spot that is generating the curve, and E_x/B_y represents the constant velocity of the center of the wheel. In the first curve of Figure 9, the magnitude of the vector $(\alpha + j\beta)$ is equal to the radius of the wheel. In the second curve this length is less than the wheel radius and in the third curve it is greater. Motion perpendicular to the plane of the paper is not affected by the magnetic field.

An interesting observation from this equation is that the velocity of the center of the "wheel" is determined only by the ratio E_x/B_y. No matter what the initial conditions or instantaneous velocity may be, the average rate of progression across the electric field in the "z" direction is constant. Also, the angular rotational velocity of the wheel equals $\frac{q\,B_y}{m}$ and is independent of initial conditions.

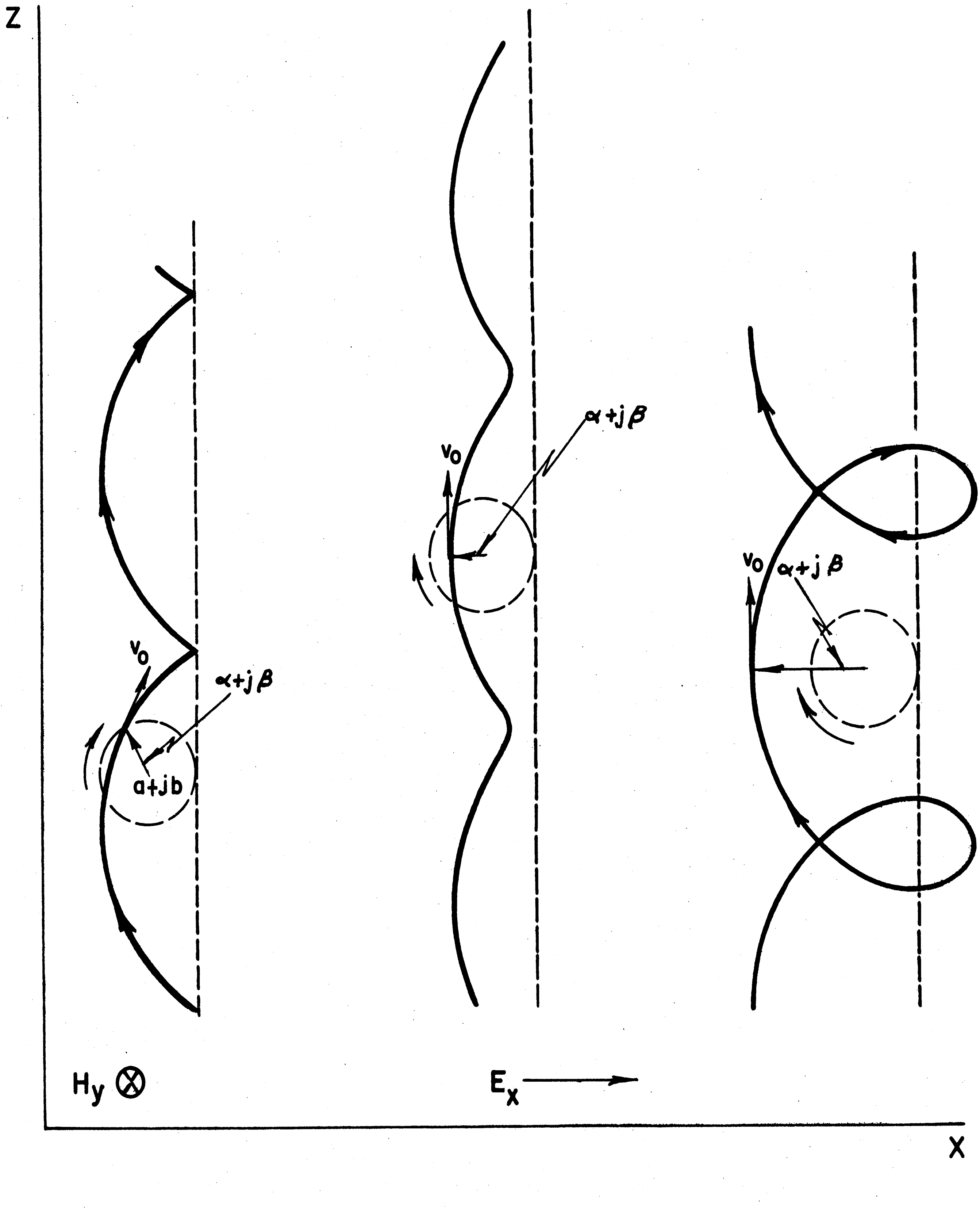


Fig. 9

Trajectories of positive ions in orthogonal electric and magnetic fields.

Numerical Illustration: In order to apply this theory to the wind generator experiments, the following numerical information has been compiled:

static pressure = 0.5 m.m.

gas temperature = 700°C (estimated)

molecular mean free path = 0.04 cm.

E_{T_g} = voltage equivalent of gas temperature = 0.086 volts.

α_g = 7.7×10^4 cm/sec = molecular velocity corresponding to characteristic temperature energy ------also the most probable velocity.

Characteristics of "typical" electron behavior are:

Electrons:

$\frac{E_x}{B_y} = 1.7 \times 10^4$ meters/sec

= the average velocity with which an electron will move, transverse to electric field (this velocity is not greatly affected by elastic collisions.)

$\omega_e = \frac{B_y q}{m_e} = 1.06 \times 10^{12}$ radians per sec = angular velocity associated with the rotating component of cycloidal motion.

kinetic energy per electron = 5 electron volts; (This value is probably too high as is explained in Appendix II.)

$\alpha_e = 1.3 \times 10^8$ cm/sec = velocity associated with energy of 5 electron volts.

T_e = 58,000 degrees = electron temperature which would exist if the velocity distribution were Maxwellian and if α_e were the characteristic or most probable velocity.

radius of rotational motion $\cong \frac{\alpha_e}{\omega} = 1.2 \times 10^{-4}$ cm

mean free path = 0.3 cm (or larger)

time to complete one mean free path = 2.3×10^{-9} sec.

time to complete one rotation = 5.9×10^{-12} sec.

number of completed rotations in one mean free path = 390

distance moved transverse to electric field in one mean free path = .004 cm.

Characteristics of "typical" ion behavior are:

Ions

mean free path = 0.04 cm (or larger)

$\omega_i = 2.0\dot{7} \times 10^6$ radians per second = angular velocity associated with rotational motion, in the absence of collisions.

average drift velocity = 1.1×10^6 cm/sec.

time between collisions = 3.6×10^{-8} sec.

time required to complete one rotation (if there were no collisions) = 300×10^{-8} sec.

This data helps to explain a number of experimental observations. The numerical values are, to some extent, an over simplification of kinetic theory, but even allowing for such inaccuracy, certain qualitative facts seem to be well established. The important conclusion is that the magnetic field has a far greater effect on the mobility of an electron than it does on an ion.

An ion does not have a chance to follow a rotational motion because of the frequent collisions. The average time interval between collisions is approximately one per cent of the time which would be necessary to complete one rotation. Consequently, the ionic mobility is not greatly affected by the magnetic field.

On the other hand, the motion of the electron is greatly affected by the magnetic field. The electron makes many hundreds of rotations during each mean free path. Its average motion is almost entirely transverse to the electric field. As long as the collisions are elastic, the electron does not dissipate kinetic energy and it can progress only in the transverse direction. At these velocities, nearly all of the collisions between electrons and molecules are elastic. (There is considerable evidence in the literature to support this statement.) However, even in the case of an inelastic ionizing collision, the electron recovers all of the lost energy by falling with the electric field a distance of less than one half of one mean free path. These considerations indicate that the electron mobility is very greatly reduced by the presence of the magnetic field. Hence, it appears that most of the current in the arc is carried by positive ions.

Calculations involving ion mobility indicate that the assumption of nearly 100 per cent ion current is entirely reasonable. Experimental data regarding the mobility of potassium ions in nitrogen is given by Loeb[4]. These data were obtained from measurements which were made at a pressure and electric field strength similar to the conditions in the wind generator experiments. A mobility of 2.4 centimeters per second per volt per centimeter was reported for potassium ions under these conditions (after correction to normal temperature and pressure). The mass of the O_2^+ ion (32) and the N_2^+ ion (28) is less than the potassium ion (39). Assuming that the mobility varies inversely as the square root of the mass, a mobility of $\sqrt{\frac{39}{28}} \times 2.5 = 2.8 \frac{\text{cm}^2}{\text{volt sec}}$ is indicated for N_2^+ ions in N_2. At a pressure of 0.5 millimeters and a temperature of 1000°K, the mobility would be

$$2.8 \times \frac{1000}{273} \times \frac{760}{0.5} = 15{,}500 \frac{\text{cm}^2}{\text{volt sec}} .$$

Using this value of mobility and assuming a current density of one ampere per square centimeter, a plasma ion density of 4×10^{12} ions per cubic centimeter would be predicted. This value of ion density appears to be of the right magnitude for a discharge of this type.

It is significant that the cathode drop of the stationary arc is as large as 500 volts. This high gradient suggests a positive ion sheath with space charge limiting the current flow. This sheath is additional evidence that the ions are the important current carriers.

Only part of the convection ion current flows towards the cathode. There is also a component at right angles to this direction. The magnitudes of these two components can be estimated from the following derivation: Consider the forces on a positive ion between the two electrodes in Figure 10. Let +q equal the charge, g the mobility, f the force and v the velocity. Then:

$$f_x = -qE + Bqv_y \qquad (1)$$

$$f_y = -Bqv_x \qquad (2)$$

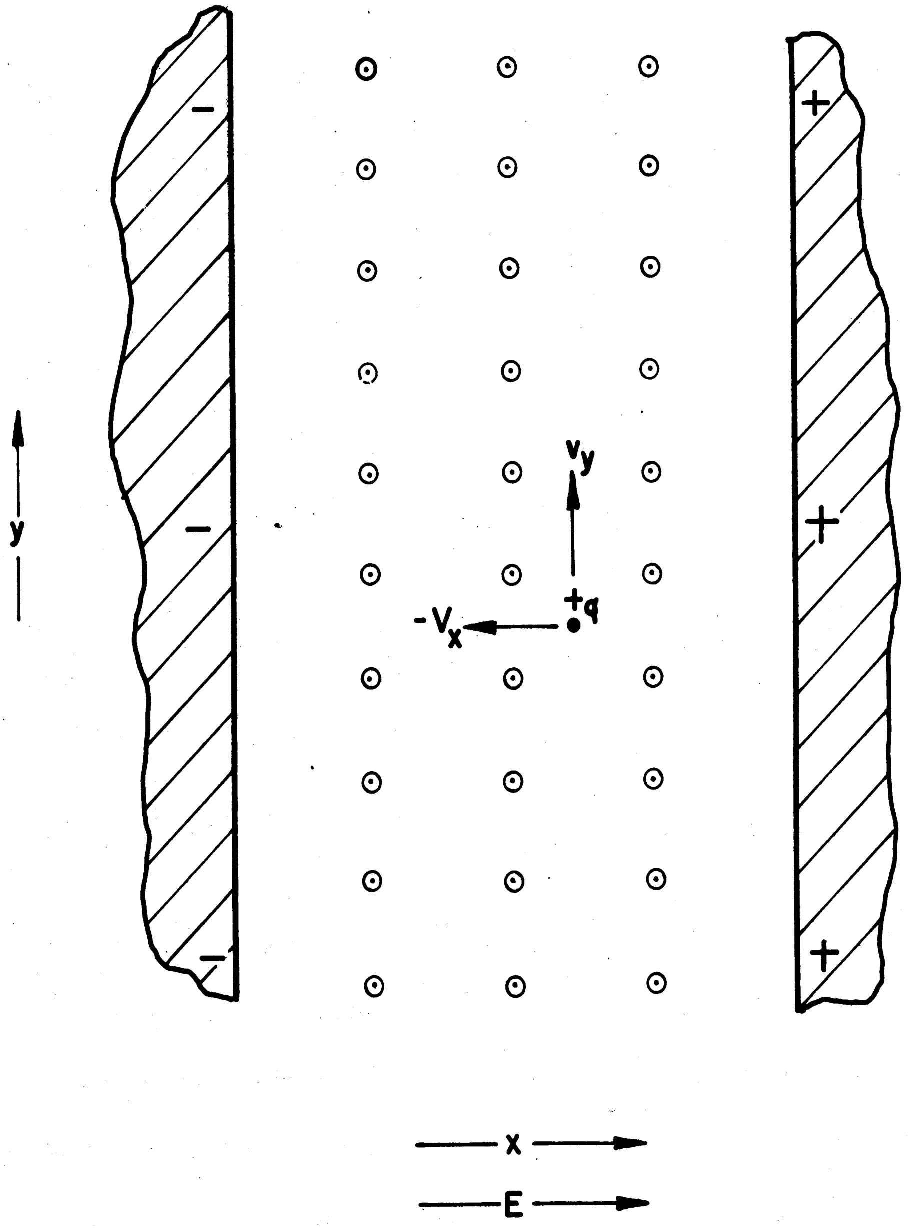


Fig. 10

Components of Ion Drift Velocity

The relations between the force, velocity and mobility for a positive ion are as follows:

$$v = -gE \qquad E = -\frac{f}{q} \qquad v = \frac{gf}{q} \,. \qquad (3)$$

Substituting (1) and (2) in (3)

$$v_x = -gE + gBv_y$$

$$v_y = -gBv_x \,.$$

Solving these equations

$$v_x = \frac{-gE}{1 + g^2B^2} \qquad v_y = \frac{g^2BE}{1 + g^2B^2}$$

Substituting numerical M.K.S. values

$$v_x = -\frac{1.55 \times 10^4}{1 + (1.55 \times 0.6)^2} = -\,0.83 \times 10^4 \text{ meters/sec}$$

$$v_y = \frac{(1.55)^2 \times (0.6) \times 10^4}{1 + (1.55 \times 0.6)^2} = 0.77 \times 10^4 \text{ meters/sec}$$

Apparently the transverse ion current density is approximately the same magnitude as the current density toward the cathode.

The question arises, as to what happens to this transverse ion current and where it is flowing. The obvious explanation is that the transverse ion and electron currents (sometimes called the "Hall" currents) are equal, and the two kinds of particles recombine outside the plasma to form neutral molecules. In this particular numerical illustration, the transverse electron velocity is assumed to be approximately the same as if there were no collisions with gas molecules, or 1.7 x 10^6 centimeters per second. This is somewhat larger than the transverse ion current but is of the same order of magnitude. When the conditions are such that the transverse ion current and electron current tend to be unequal, space charge accumulates and the voltage gradients in the plasma shift until a stable condition is reached. In Figure 3, the equipotential line through the plasma is not perpendicular to the plasma column; probably this is because of the inequality of the transverse ion and electron velocities. The slant of this line suggests that there is a negative space charge on the "downwind" side of the column. Probably this is due to a tendency towards an excess of transverse electron current.

The qualitative explanation of the behavior of the stationary arc is then as follows: Ions and free electrons are formed by ionizing collisions in the plasma. The ions acquire a drift velocity having a component in the direction of the cathode, and another component at right angles to this direction. Only part of the ions reach the cathode. A substantial fraction of the ions pass out of the plasma on the"downwind"side. The free electrons which are formed as a result of the ionization processes throughout the plasma region also move in a "downwind" direction out of the plasma where they recombine with the ions. The wind is produced by the transverse movement of the ions which results in many collisions with neutral gas molecules.

The behavior of the revolving arc is consistent with this explanation of the stationary discharge. At first thought, it might be expected that the arc would revolve at the same speed as the wind, in the cylinder. But there is no real reason for this assumption. Since a plasma consists of ions and electrons, the plasma tends to move at the same speed as these ions and electrons, and not at the speed of the neutral gas molecules.

The calculated value of the transverse ion velocity (0.77×10^6 cm/sec) agrees very well with the oscilloscopic measurements of the velocity of the revolving arc described in connection with Figure 6. In this experiment, the probes were located midway between the cathode and the anode. At this "average" radius, the arc which was revolving at 17,000 rps was moving past the probe at a velocity of 0.88×10^6 centimeters per second. Considering the various uncertainties in this experiment, this agreement is better than would be expected. The calculated ion velocity of 0.77×10^6 centimeters per second was based on the assumption that the air was stationary. But since the ions and the neutral air molecules are moving in the same direction, the transverse ion velocity and the velocity of the arc would be expected to be higher than the simple mobility calculation indicates.

The oscillograph picture of the voltages picked up by the probes is of interest in this connection. Figure 6 indicates that the potential at the front edge of the moving arc is more negative than at other points in the arc cross section. This accumulation of negative space charge on the leading edge of the arc could result from the electron velocity in this direction being greater than the ion velocity.

Possible Efficiency.

Certain considerations indicate that the efficiency of this type of wind generator could be fairly high. For instance, the fact that the transverse ion current is of the same magnitude as the ion current to the cathode is significant. This could be interpreted to mean that half of the energy which an ion acquires from the field is expended in moving transverse to the field and, therefore, in producing directed momentum of air molecules.

These experiments were made at pressures where the air velocity was severely limited by viscosity. The viscosity of air at 0.5 millimeters is nearly as great as at atmospheric pressure, but decreases greatly at the lower densities in the molecular flow region. If these experiments were to be continued at much lower pressures, extreme hypersonic velocities could probably be produced.

VELOCITY MEASUREMENT

The problem of measuring the wind velocity produced by the revolving arc has proved to be rather difficult, as none of the usual techniques of velocity measurement are suitable. Many possible schemes were considered and at least a half dozen of these were tried experimentally, but no quantitatively satisfactory measurement was obtained. No doubt, several of these principles can be made to work if sufficient time and equipment become available.

Stroboscopic Experiments.

The most successful of these measurements involved a stroboscopic technique. A method was devised for suddenly injecting salt vapor into the air stream so that a burst of yellow color was produced in the discharge. This yellow color was carried downstream by the air flow, and the rate of motion was used as an indication of velocity.

The salt vapor was injected into the air flow by means of a salt impregnated carbon electrode which was placed inside the cylinder. A pulse of current to this carbon electrode released salt vapor into the discharge. This electrode was "flashed" at a rapid rate by means of a revolving commutator. The flashes were viewed through slits in a revolving stroboscopic disk which was synchronized with the commutator. By suitable phase adjustments, it was possible to observe a slow motion picture of the flashing electrode, and to estimate the velocity with which the sodium yellow was carried away by the air stream.

The salt vapor was rapidly thrown out of the discharge by centrifugal force so the yellow color did not extend downstream more than a few inches from the carbon electrode. This was fortunate since otherwise the color produced by successive flashes would have colored the entire discharge and transient colors could not have been observed.

When viewing the spark through the spinning stroboscopic disk it was important that all parts of the field of view be observed at the same instant. Thus it was necessary to use a stationary mask containing a small slit, which was placed adjacent to the spinning disk. The only time the arc was visible was when the moving slit was in juxtaposition with the stationary one. The slit in the spinning disk was 1/8 inch wide and moved past the line of sight at a velocity of 1400 inches per second so that the viewing time along any one line of sight was 1/8 of 1/1400 seconds or approximately 90 microseconds. The actual viewing time was somewhat longer than this due to the width of the slot in the stationary disk.

The tests indicated that the time required for the carbon to spark and the sodium color to spread downstream was considerably less than 90 microseconds. When the apparatus was so adjusted that the instant of observation was just prior to the "electrode firing" there was no trace of sodium yellow in the field of view; but as the phase of the instant of observation was delayed, the field of view became more and more yellow as the sodium vapor was released by the carbon. A delay of 50 microseconds in the viewing period caused a large increase in the intensity of the yellow color. The significant fact was that the yellow always appeared downstream just as soon as it appeared in the vicinity of the carbon.

The field of view extended downstream about 4 inches from the carbon, and it appeared that the sodium yellow traveled this 4 inches in less than 50 microseconds which would tend to indicate a velocity of at least 4500 miles per hour.

These results were not considered too reliable, however, because the color from the sodium also appeared upstream as far as an inch from the carbon. This raised doubts as to whether or not the sodium color traveled downstream at the same speed as the air stream.

Force on Vane.

A very crude velocity indication was obtained by placing a small vane inside the cylinder in such manner that it was deflected by the impact pressure of the air stream. The amount of this deflection was measured and later calibrated in terms of impact pressure. The air pressure on the back surface of the vane was not known, but it was assumed to be something less than static pressure. Since this static pressure was about 8 per cent of the impact pressure, the error in neglecting the force on the back of the vane did not appear significant.

It was thought that the air pressure measured on the front surface of a small vane would represent the stagnation pressure of the air stream. However, the impact pressure apparently differed rather widely from the stagnation pressure, because the measured force per unit area on a very small vane was much greater than on a larger one. For instance, the pressure on a square mica vane having an area of 2 square centimeters, was 600 dynes per square centimeter, while a vane of flat tungsten ribbon only 0.07 centimeters wide and 1.6 centimeters long registered a pressure of 8000 dynes per square centimeter. Presumably a still smaller vane would have indicated a still higher pressure.

If the value of 8000 dynes per square centimeter were assumed to be the stagnation pressure, then the ratio of stagnation to static pressures would be approximately 12:1 which would indicate a Mach number of 2.3. At 700°C this would correspond to an air velocity of the order of 3400 miles per hour.

These vane experiments were not carried further because of the uncertainty in the interpretation of the results.

Pitot Tube Measurements.

Attempts to measure velocity by means of pitot tubes were completely unsatisfactory for several reasons. The principle difficulty was due to the fact that the air flow at this density was so sluggish that many minutes were required to obtain a pressure reading. This was so even when the manometer was located only a few inches from the pitot tube. Since the equipment was not designed to dissipate the heat resulting from such long periods of operation, no worthwhile measurements were obtained in this manner.

Another difficulty with pitot tubes is due to the lack of information as to how to interpret the readings. At these densities, the mean free path is comparable to the dimensions of the tube, and the boundary layer is several inches in thickness. Hence, the ordinary pitot tube formulae are believed to be unreliable under these conditions.

Mach Angle From Wedge.

A small wedge of transite was placed inside the luminous part of the discharge. It was hoped that the flow lines of the air stream in the vicinity of this obstacle could be observed and that perhaps the shock wave would be visible. However, nothing that resembled a stream line or a shock wave could be detected. It was thought that if the discharge were colored by a suitable chemical, better results might be obtained. An arrangement was devised for introducing small amounts of lithium chloride and sodium chloride into the cylinder a few inches upstream from the wedge. The discharge was colored, but no flow lines or shock waves were visible.

An interesting observation might be mentioned in connection with this wedge experiment. The wedge was mounted with the sharp edge upstream. The wind caused this upstream edge to become white hot, but there was no visible heating of any of the other edges or corners of the wedge. When the direction of the wind was reversed (by reversing the magnetic field), the blunt corners at the other end of the wedge became white hot, but the sharp edge did not. There was some doubt as to whether this heat was caused by air friction or electron-ion recombination, so the wedge was moved away from the luminous part of the discharge to a region that was cooler and less ionized. Since the same effects were obtained, it is believed that the major part of the heating of the wedge was caused by air friction.

Back Electromotive Force Due to Motor Action.

The behavior of this revolving arc is in some respects analagous to a Faraday disk or a d-c motor. When such a motor is suddenly disconnected from the power source, a generated voltage can be measured across the armature windings. Calculations indicated that if the power supply to the revolving arc were turned off suddenly, the kinetic energy of the moving ionized gas could be expected to generate a voltage across the electrodes which might persist long enough to be measured with an oscilloscope. If this voltage were known, the velocity could easily be calculated.

In order to try out this idea experimentally, it was necessary to find a means of interrupting the current to the arc in a few microseconds time. Because mechanical contactors were much too slow for breaking an 8-ampere, 1200-volt circuit, a vacuum tube switch was necessary. This consisted of two Eimac 304 T.L. triodes in parallel. These tubes could be biased beyond cut-off by closing a hand-operated switch.

The decay of the arc voltage was observed by means of the triggered sweep on a DuMont 248A oscilloscope. The oscilloscope indicated that the voltage was nearly zero in 1 microsecond and completely zero in two microseconds. However, it was uncertain whether this 1 microsecond indicated a generated voltage, or represented the time required for the stray capacitance to discharge. In order to check this uncertainty, the measurement was repeated with the air in the cylinder at atmospheric pressure so that there was no discharge present. Over 100 microseconds were required for the stray capacitance to discharge (through the resistance of the oscilloscope voltage divider). Next, a 12,000-ohm resistance was shunted between this stray capacitance and ground, making the discharge time less than 1 microsecond (with the arc still not operating). Finally the vacuum system was started and the chamber was pumped down so that the arc would operate. It was then found that the presence of the arc did not have the slightest effect on the shape of the discharge curve, and it was concluded that any generated e.m.f. was very difficult to measure.

Nitrogen Afterglow Experiments.

Recent research by Williams and Benson at NACA[10] and Kane and Folsom at the University of California[3] have shown that nitrogen afterglow can be used as a means of visualizing the flow in low-density wind tunnels. This system is based on the fact that after certain gases have passed through an electric arc, they will exhibit a luminescence that persists for periods ranging from a few microseconds to as long as several hours. The intensity of this luminescence is very sensitive to changes in density which are present in compressible flow and shock waves. Ordinary commercial nitrogen has been found to exhibit this property more than any other gas.

In the experiments performed at NACA the nitrogen was "excited" by passing it through a high-voltage spark gap before it expanded through a nozzle into the test section of the wind tunnel. The static gas pressure in the vicinity of the spark gap was over 60 millimeters of mercury and the static pressure in the test section ranged from 3 to 8 millimeters of mercury. Good photographs of shock waves were obtained at NACA by this method.

It is reported that the properties of the afterglow from a given sample of nitrogen are greatly affected by minute quantities of impurities which are always present. Before attempting to apply afterglow phenomena to the revolving arc, a test was made to determine the suitability of the available commercial nitrogen obtained from the Linde Air Products Company. A jet of this gas was directed at an arc between two tungsten electrodes which were inside the vacuum chamber. A good afterglow was visible as long as the pressure in the vicinity of the arc was at least two or three millimeters of mercury. At lower pressures less afterglow was obtained.

In order to experiment with the afterglow produced by the revolving arc, it was necessary to interrupt the arc current briefly at regular intervals and to observe the air flow during these intervals by a stroboscopic arrangement. The interruption of the arc current was easily accomplished by removing the filter from the d-c power supply, so that the arc was extinguished every time that the output voltage from the single-phase rectifier dropped below a critical value. Tests with a cathode ray oscilloscope indicated that the arc was extinguished for about three milliseconds every half cycle of the 60-cycle supply. The stroboscope consisted of a synchronous 60-cycle motor which was used to spin a slotted disk. The arrangement was so adjusted that the only time the slots in the disk were in viewing position was when the arc current was zero.

In order to make sure that the nitrogen in the system was as pure as possible, an arrangement was provided to bleed this gas into the wind tunnel continuously from the supply tank while the high-speed vacuum pump (Kinney CVD556) was simultaneously pumping out the system. The equilibrium gas pressure could be maintained at two to five millimeters depending on the adjustment.

The results of these tests were quite surprising. As long as the magnetic field was turned on, there was no trace of afterglow. When the arc was viewed through the stroboscopic disk the region was entirely dark, even when the eyes were sensitized by having the room completely dark.

One possible explanation was that the residual electric field was involved in some way or other. Even though the arc was completely extinguished when the supply voltage fell below 1000 volts and remained extinguished for about three milliseconds, the voltage across the electrodes did not go completely to zero at any time during this interval. It appeared that this residual electric field might be having an effect on the excited atoms which might otherwise have been producing an afterglow. To check this hypothesis, an electrical network was devised which made the current and voltage pulses from the rectifier nearly rectangular in shape instead of the familiar sine loop form. The voltage went completely to zero at the end of each rectangular pulse. However, this was not the answer to the problem as there still was no visible afterglow.

Another possible explanation involved the temperature. When the magnetic field was removed the temperature appeared higher, even though the power input for a given current was considerably reduced. Perhaps a critical number of electron volts per collision is necessary to "excite" the nitrogen, and this was not reached when the magnetic field was present. Another possibility was that the sputtering of cathode material, which was greater when the field was present, might have contaminated the nitrogen.

Doppler Shift.

The light given off by the moving arc consists of characteristic spectral lines. The possibility of determining the velocity by measuring the Doppler shift caused by the relative velocity of this light source was investigated. Calculations indicated that if the atoms, emitting light of 5500 Angstroms, were moving at a velocity equivalent to Mach 5, relative to the observer, a spectral shift of approximately 0.035 Angstrom would be produced, or if the direction of rotation were suddenly reversed the total shift would be twice this amount. This change in wavelength should produce a displacement of 2.5 fringes on a Michelson type interferometer operating with a path difference of 10 centimeters. Preliminary experiments with this type of interferometer indicated that in order to observe fringes clearly with a 10-centimeter path difference, the light had to be highly monochromatic. The sodium lines were much too broad. Mercury lines were considered, but the introduction of mercury into the apparatus and vacuum system involved a health hazard that was objectionable. Neon was tried briefly but since it had to be fed continuously into the cylinder during operation it was too expensive for use in large quantities. Various salts of cadmium and strontium were tried, but the temperature of the discharge was not high enough to give off much light. The least objectionable chemical that was found was lithium chloride. When this was tested in the flame of a Bunsen burner, good fringes were obtained with a 4-centimeter path difference in the interferometer. A Farand optical interference type filter having a pass band of 300 Angstroms was used to help isolate the 6708 Angstrom lithium line.

When the lithium chloride was tried with the arc, several difficulties at once appeared. In order to maintain the color in the arc it was necessary to continuously feed this salt into the region of the arc where it could be vaporized. It disappeared rapidly so that rather large quantities had to be introduced. The vapors from this chemical were very corrosive and rapidly caused trouble in the vacuum pump. Another difficulty was due to the Zeeman effect produced by the magnetic field, which caused the spectral lines to split into a fine structure. Much of this fine structure could have been eliminated with a polarized filter but the light intensity was already too weak as a result of the absorption of the band pass filter.

These difficulties with the Doppler method do not seem insurmountable, but it does seem likely that the surmounting of them is in itself a major project. Time and available resources have not been adequate to permit continuation of efforts to employ the Doppler shift principle.

The Doppler method appears for a number of reasons to be more attractive than other techniques. For example, it might be applied to conventional wind tunnels by means of a spark gap and photographic equipment. Further study appears warranted.

WIND PRODUCED BY THERMAL EXPANSION

The maximum gas velocity which can be produced by a rocket jet is limited by the temperature which can be obtained in the combustion chamber. This temperature is limited to several thousand degrees by the inherent nature of the combustion process, since molecular dissociation always increases with the temperature and the chemical reaction reverses at a sufficiently high temperature. The advantages to be gained by using higher temperatures are emphasized by the thermodynamic relation for the efficiency of a heat engine. The maximum efficiency of a nozzle in transforming thermal energy into directed gas velocity is limited by the well-known relation $\frac{T_1 - T_2}{T_2}$ where T_1 and T_2 are the initial and final temperatures. It is evident that a very large increase in efficiency and velocity would be obtained if T_1 could be increased by a factor of perhaps three or four.

An electric arc will produce much higher gas temperatures than any known combustion process. When an electric arc is operated on a pulsed basis, the instantaneous gas temperature can be many times higher than the melting point of the electrodes and other solid materials which are present. An experiment by J. A. Anderson in 1920 produced a temperature of 20,000 degrees centigrade by discharging condensers through an electric arc. His apparatus was very crude compared with equipment which could be built today by using a pulse-forming network and capacitors designed for rapid discharges.

It appears likely that the unusually high molecular velocities which can be produced in this manner could have useful application in

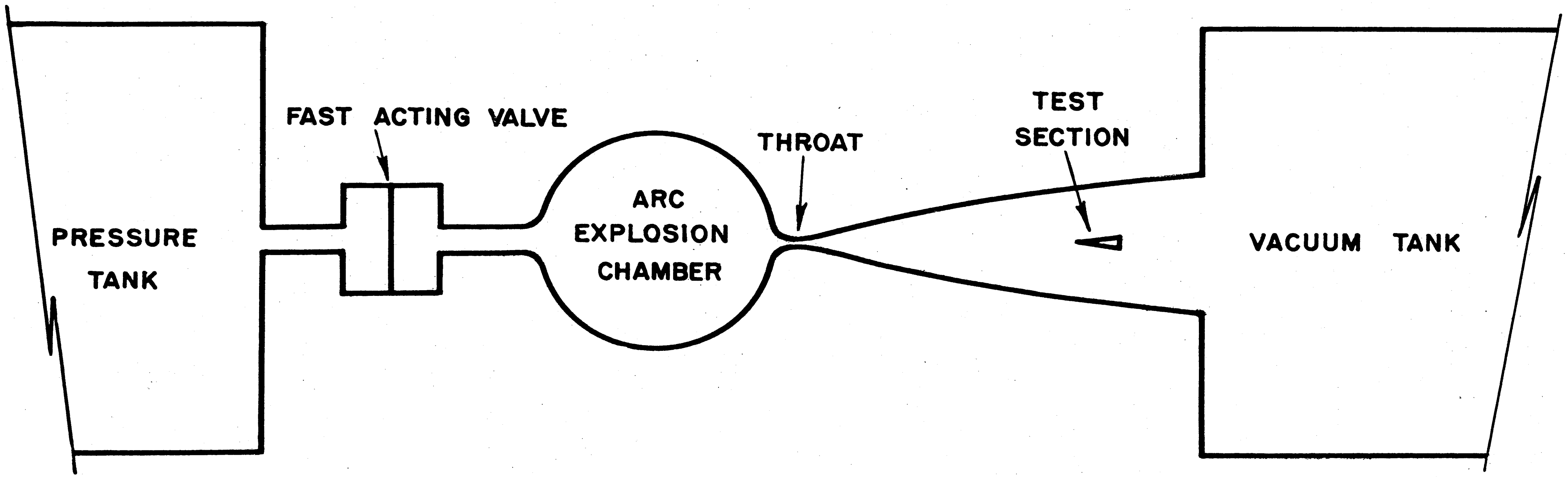


Fig. 11

Proposed apparatus for producing hypersonic wind by utilizing the extreme high temperature produced by an "exploding" electric arc.

connection with supersonic research. Calculations indicate that the air inside a closed chamber could be heated to perhaps 20,000 degrees centigrade in less than 5 microseconds time. This exploding gas would be under a pressure of perhaps 100 atmospheres, and if it were allowed to expand through a suitable nozzle, very high Mach numbers could be obtained.

Figure 11 is a suggested diagram for such a device. The explosion chamber and test section are connected to the vacuum tank so that they are normally at a very low gas pressure. The fast-acting valve would be arranged to open for an instant, allowing a burst of air to enter the explosion chamber. Before much of this air had time to pass out of the chamber through the throat, the bank of capacitors would be discharged. The tremendous increase in temperature and pressure would force the air through the throat into the test section at a very high velocity.

Since these extreme temperatures would be far above the melting point of all known materials, the system could be operated only on a pulse basis. The interval during which the apparatus would be exposed to high temperature would be only a few microseconds. Hence the chamber could be reloaded and fired many hundreds of times per second and the duty cycle would still be only a fraction of one per cent. The metallurgical problem should not be severe under these conditions.

In order to obtain a more nearly continuous flow of air through the wind tunnel it might be feasible to employ a number of arc explosion chambers all feeding into the same test section. These chambers would be fired in rotation like the cylinders of a gasoline engine. Such a scheme would provide the thermodynamic advantages of a jet, operating at extremely high temperatures, and at the same time avoid the metallurgical limitations.

Experiments With High Temperature Arcs.

A number of experimental tests were made with exploding arcs. The objective was to gain some familiarity with the problems and techniques that would be useful in designing a larger installation.

The first tests were made with a bank of capacitors totaling 8 microfarads, which could be charged to 20,000 volts. This represented 1600 watt seconds of stored energy. Since these capacitors were designed for filter applications the internal inductance and resistance were higher than desired. They were discharged across a spark gap which operated at atmospheric pressure. As this gap was 3 inches in length, the discharge had to be initiated by means of a small auxiliary tickler electrode which produced a small spark in the vicinity of the cathode and caused the main gap to break down. The wave form of the discharge was observed by means of the trigger sweep on a DuMont 248A oscilloscope.

The explosion from this arc was very violent and the compression wave of sound was painful to the ear. When the electrodes were placed inside a ceramic chamber, the ceramic was shattered into fine pieces which were scattered about the room.

Measurements indicated that only a small fraction of the energy stored in the capacitors was expended in the arc. The discharge was a damped oscillation at a frequency of 50 kilocycles but the total effective resistance of the circuit was much less than the value required for critical damping. Although the current was as high as 50,000 amperes, the voltage drop across the arc was so low that at least 99 per cent of the power was wasted.

Another experiment was devised to demonstrate that the forces in an exploding arc can be very large. A hole, three-eighth inches in diameter, was drilled in a block of Mycalex, and a plug or piston was made which would slide smoothly inside this hole. Both the end of the piston and the bottom of the hole were flat so that when the piston was pressed against the bottom of the hole there was very little residual air space. This residual air film was used as the "explosion chamber" for an electric arc. Two small holes were drilled into opposite sides of the Mycalex block in such manner that fine wire electrode tips could be exposed to opposite sides of the bottom of the hole. The spark could be made to jump from one electrode tip to the other by passing through the air film. The current for the spark was supplied by a 0.5-microfarad capacitor. When the capacitor was charged to 8,000 volts (16 joules of stored energy), the piston was ejected at a high velocity. The voltage was raised to 12,000 volts and the Mycalex piston was shattered by the impact. Pistons were made from other dielectric materials such as fused quartz and bakelite, but they would not stand the force of the explosion.

Measurements indicated that the force was present only for a few microseconds and the pressure was of the order of 10 tons per square inch. However, when there was any appreciable air space at the bottom of the hole, very little pressure was obtained. This emphasizes the fact that extremely high transient arc temperatures seem to require a very restricted cross-section or some other means of producing a high arc resistance.

The essential problem in utilizing "exploding arcs" is to find a means of increasing the resistance. Since a very high temperature gas is always highly ionized it tends to be a good electrical conductor. The most obvious way of increasing the power input to a given volume of gas is to increase the current density. This can be done by lowering the impedance of the discharge circuit, i.e., using more microfarads of lower voltage capacitors. However, only limited advantage can be gained in this manner because the problem of lead inductance becomes important and it becomes more difficult to discharge the condensers in a few microseconds of time.

A number of devices for increasing the arc resistance were investigated. One method was to start a low current "pilot" arc between a series of small point electrodes arranged to form a helix so that when the main discharge occurred it followed the long helical path. This method helped the situation somewhat, but did not appear to be an effective solution to the problem. Another scheme was to constrict the cross section of the arc by forcing it through small apertures in sheets of a refractory dielectric material. This method looked promising, but was somewhat objectionable because of the heat loss to the dielectric surfaces.

Experience at low pressures indicated that a magnetic field might have an important effect on the resistance of the arc. It also appeared likely that if the arc were free to move or rotate it would have a higher resistance. But this did not prove to be the case. A magnetic field of 3000 gauss had no noticeable effect other than to produce a slight deflection of the spot where the arc struck the anode. This was surprising since previous experiments at low gas pressures had shown that a magnetic field had a pronounced effect on a pulsed discharge. Also a much weaker field would completely "blow out" a steady state atmospheric arc between the same electrodes. Apparently at atmospheric pressure, the arc just did not have time to "get moving" during a half cycle of the discharge, and as long as the magnetic field did not actually produce lengthening of the arc column, there was little effect on the resistance.

The explanation for this lack of effect of the magnetic field is quite consistent with the discussion in the preceding section of this report regarding the low pressure discharge. At atmospheric pressure the mean free path of the electron was so short compared to the radius of the rotational motion that the magnetic field had little effect. The resistance of the positive column is not appreciably increased until a certain threshold magnetic field strength has been reached. This occurs when the period of the electron's orbital gyration in the magnetic field begins to compare with the interval between its collisions with molecules. This is discussed in Chapman[1] where it is calculated that, in air at atmospheric pressure, an important increase in resistance should occur at field strengths of the order of 10,000 gauss. A field of this magnitude or even more is not prohibitive and might be a solution to the problem.

ACCELERATION OF IONS BY AN ELECTRIC FIELD

An obvious means of building an ionic wind tunnel is to accelerate ions by means of an electric field. This idea is very simple and straightforward. When first suggested it appeared quite attractive, but further study and experiment have indicated some very severe limitations.

One major limitation results from the low breakdown voltage of the air at low pressures. The maximum electric field strength that can be used to accelerate the ions is a small fraction of the breakdown strength at atmospheric pressure. This difficulty is not serious at extremely low pressures where only positive ions are present, but wind tunnels at these pressures are of limited usefulness.

The second limitation is due to space charge. In order to obtain high velocities it is necessary to put substantial amounts of power into the air stream. To do this electrically requires that the convection ion current must be large enough tc be measured in amperes, <u>not</u> microamperes. Space charge effects are far more pronounced in the case of ions than electrons, because of the difference in mobility. The low mobility of the ions is associated with the fact that the mass of the ion is thousands of times larger than the mass of the electron. Also, only a small fraction of the gas molecules are ionized, so that most of the collisions are with neutral molecules. Since the mass of ions and molecules are similar, a large part of the kinetic energy of the ion is lost in each collision. As a result of the low velocity, a much greater charge density is required to produce a given current, and consequently there is much more space charge.

A simple numerical calculation will illustrate the severity of the space charge problem. Let us make the very optimistic assumption that the air is 100 per cent ionized so that the motion of the ions is not obstructed by collisions with neutral air molecules. The equation for space charge flow between parallel planes is

$$J = \frac{2.31 \times 10^{-6}\ V^{\frac{3}{2}}}{{}^{m}g/m_e\ S^2} \qquad \text{amps per sq cm,} \quad \text{(Cgs units)}$$

where "V" is the voltage between the plates, "S" is the spacing in centimeters, and ${}^{m}g/m_e$ is the ratio of the mass of an ion to that of an electron. Assume that the ionized low pressure air will withstand a voltage of 400 volts between plates 1 centimeter apart. When these values are substituted in the equation a space charge limited current density of 80 microamperes per square centimeter and a power input of only 0.03 watts per square centimeter are indicated.

Another type of illustration will be given to further emphasize the difficulty of obtaining any substantial amount of "push" on an air stream by means of electrostatic forces. Since every action has an equal and opposite reaction, the force on the ion stream due to the electric field cannot exceed the force on the electrode which is producing the field. If the voltage gradient at the surface of this electrode is limited to a few hundred volts per centimeter, the force which it could exert on the ion stream is also limited to a few dynes per square centimeter.

Thus it appears that the acceleration of ions by electric fields is limited to extremely low density applications where the power requirements are only a few watts.

APPENDIX I

TRAJECTORY OF A CHARGED PARTICLE

The initial conditions of the charged particle of Figure 9, discussed on page 25, are as follows:

$$\text{at } t = 0 \begin{cases} x = x_o \\ y = y_o \\ z = z_o \\ V_x = \dot{x}_o \\ V_y = \dot{y}_o \\ V_z = \dot{z}_o \,. \end{cases} \qquad \begin{aligned} \vec{E} &= E_x\vec{i} + 0\vec{j} + 0\vec{k} \\ \vec{B} &= 0\vec{i} + B_y\vec{j} + 0\vec{k} \end{aligned}$$

$$f = q\vec{E} + q(\vec{V} \times \vec{B}) \quad = \quad \text{force on moving plus charge.}$$

$$\overrightarrow{m\ddot{x}} = -q\vec{E} - q(\overrightarrow{V} \times \overrightarrow{B})$$

$$\left.\begin{aligned} m\ddot{x} &= -qE_x + qB_y\dot{z} \\ m\ddot{y} &= 0 \\ m\ddot{z} &= -qB_y\dot{x} \end{aligned}\right\} \qquad \begin{aligned} &(1) \\ &(2) \\ &(3) \end{aligned}$$

$$\text{If } m\ddot{y} = 0, \qquad \begin{aligned} m\dot{y} &= \text{const} = m\dot{y}_o \\ my &= m\dot{y}_o t + my_o \\ y &= \dot{y}_o t + y_o \end{aligned}$$

Multiply No. (3) by $\sqrt{-1} = j$ and add to No. (1):

$$m\ddot{x} + jm\ddot{z} = -qE_x + qB_y\dot{z} - jqB_y\dot{x}$$

$$= -qE_x + (-j)\left[qB_y\dot{x} + jqB_y\dot{z}\right]$$

$$m(\ddot{x} + jm\ddot{z}) = -qE_x - jqB_y(\dot{x} + j\dot{z})$$

let $x + jz = W$

$$m\ddot{W} = -qE_x - jqB_y\dot{W}$$

$$\frac{d^2W}{dt^2} + j\frac{qB_y}{m}\frac{dW}{dt} = -\frac{q}{m}E_x$$

$$D(D + j\frac{qB_y}{m})\,W = \frac{-q}{m}E_x \qquad \text{roots} = 0,\ -j\frac{qB_y}{m}$$

$$W = C_1 + C_2\,e^{-j\frac{qB_y}{m}t} + At$$

$$W_p = At \qquad dW_p = Adt \qquad \frac{d^2W_p}{dt^2} = 0$$

$$0 + j\frac{qB_y}{m}A = (-)\frac{q}{m}E_x \qquad A = +j\frac{E_x}{B_y}$$

$$W = C_1 + C_2\,e^{-j\frac{qB_y}{m}t} + j\frac{E_x}{B_y}t$$

Substitute initial conditions at $t = 0$:

$$W_o = C_1 + C_2 = x_o + jz_o$$

$$\dot{W} = -j\frac{qB_y}{m}C_2\,e^{-j\frac{qB_y}{m}t} + j\frac{E_x}{B_y}$$

$$\dot{W}_o = -jC_2 \frac{qB_y}{m} + j\frac{E_x}{B_y} = \dot{x}_o + j\dot{z}_o$$

$$C_2 = j\left[\dot{x}_o + j\left(\dot{z}_o - \frac{E_x}{B_y}\right)\right]\frac{m}{qB_y} = \frac{m}{qB_y}\left[\left(\frac{E_x}{B_y} - \dot{z}_o\right) + j\dot{x}_o\right] = \alpha + j\beta$$

$$\alpha = \frac{m}{qB_y}\left[\frac{E_x}{B_y} - \dot{z}_o\right] \qquad \beta = \frac{m}{qB_y}\,\dot{x}_o$$

$$C_1 = x_o + jz_o - C_2 = (x_o - \alpha) + j\,(z_o - \beta) = a + jb$$

$$a = x_o - \alpha \qquad b = z_o - \beta$$

$$\therefore W = x + jz = (a + jb) + (\alpha + j\beta)\,e^{-j\frac{qB_y}{m}t} + j\frac{E_x}{B_y}t$$

APPENDIX II

KINETIC ENERGY OF PLASMA ELECTRONS

The estimate of electron energy is based on rather indirect evidence. It is believed that the average energy per electron is well below the ionizing potential of the gas, which is about 15 volts. The value of 5 volts is merely a basis for calculation and discussion.

The main purpose in presenting the numerical data about the plasma is to justify the conclusion that the electron mobility is very low. Even if the average electron energy were as large as 15 volts, the qualitative argument in the text still appears valid. For any energy value less than 15 volts, the conclusion is even more justified.

It is not known to what extent the electron velocity distribution is Maxwellian, so that such expressions as "average energy", "electron temperature", and "characteristic velocity" have an uncertain meaning. However, the low mobility premise appears valid for any reasonable assumption as to the velocity distribution.

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