Reports

Electric Discharges Inside Tornadoes

Abstract. *Laboratory data on a vortex-stabilized arc suggest that its contribution to energy of a tornado would be small.*

Reports of luminous electrical phenomena associated with tornadoes have prompted laboratory studies of the interrelationships between high-voltage discharges and vortices (*1*, *2*). These experiments have shown that a vortex exercises a strong stabilizing influence on the discharge, presumably because the rotationally produced pressure gradient confines the hot ionized gases in the center of the vortex and thus reduces the voltage required to maintain the discharge. This glowing plasma in the axis of the vortex is referred to as a vortex-stabilized discharge or arc. The phenomenon, which incidentally has been employed for the arc fixation of nitrogen (*3*), has prompted the speculation that a similar electrical discharge might occur in nature through the interaction of a tornado with thunderstorm electricity. It has been suggested that the luminous activity sometimes reported in the axis of a tornado may be a vortex-stabilized discharge maintained by a continuous current from the storm and that the resulting electrical heating may contribute significantly to the energy of the tornado (*4*, *5*). This, however, has been questioned on the ground that there is insufficient electrical activity present to be instrumental in the formation or maintenance of the tornado (*6*).

It is possible to determine the characteristics of the laboratory discharges in vortices by measuring their current-voltage relationships and the way they are affected by various ion species. From this information it can then be estimated by extrapolation whether it is likely that similar discharges could occur in the thunderstorm and whether the resultant electrical heating could make a significant contribution to the energy of a tornado.

Experimental apparatus. The laboratory apparatus comprises a high-voltage d-c power supply for producing a vertical discharge between a pair of electrodes, a louvered chamber in which the discharge takes place, and an arrangement for introducing electrical probes into the plasma. The chamber, shown schematically in Fig. 1, is similar to that described by Ryan and Vonnegut (*2*). It is constructed of 12 louvers, 60 by 240 cm, in the form of an open truncated cone approximately 240 cm high. Air heated by the discharge rises out of the top of the chamber to be replaced by more air that enters through angular momentum–imparting louvers. This rotating air drawn into the center of the chamber forms a vortex, which stabilizes the discharge. A glass window is provided for observation and photography.

Some material from the lower electrode becomes vaporized and ionized in the plasma. These ions, which are then drawn into the vortex, exercise an influence on the characteristics of the discharge. To determine the nature of this effect the apparatus is arranged so that the lower electrodes can be made of various substances during the experiments.

The d-c power supply, operating from a three-phase, 240-volt power line, produces a maximum 5-amp current at 5 kv. A variable resistor of Nichrome wire capable of dissipating 25 kw continuously is used to limit the current. This resistor is immersed in an oil bath surrounded by a tank of cooling water. Currents beyond the capability of the power supply are produced by utilization of slowly decaying capacitor surges from a large bank of capacitors.

The capacitor bank of 840 μf at 5 kv, which provides a maximum stored energy of 10^4 joules, is charged with a d-c power supply through a protective resistance and inductance. The bank is discharged into an already established vortex-stabilized discharge with a "probe switch" by the use of the circuit shown in Fig. 2. This switch consists of a length

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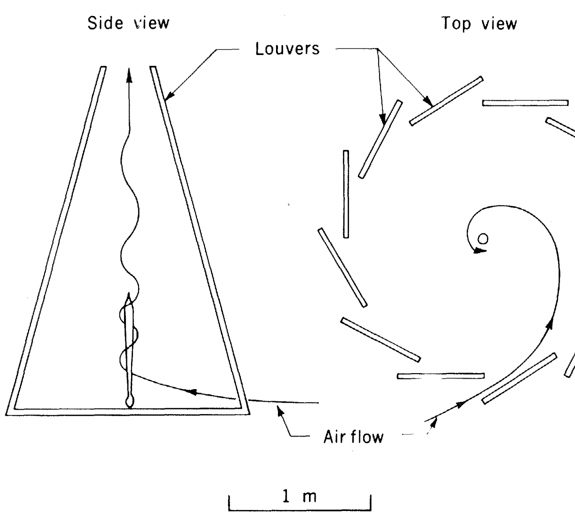
of number 2 copper cable that can be swung through the discharge at the desired position. Surge currents are measured with a noninductive shunt (model K-3200-8, TM Research Projects, Inc.). A Tektronix dual-trace cathode-ray oscilloscope was used throughout the studies to obtain simultaneous measurements of discharge voltage and current.

The voltage distribution along the column of the vortex-stabilized discharge is determined by means of a probe that can be passed through the discharge in a plane perpendicular to its axis. The insertion of such a cold probe causes a slight increase in the voltage across the discharge and results in a relatively small constant error in voltage measurements.

Experimental results. Typical experimental data are presented in Fig. 3, showing the voltage distribution along a 70-cm-long arc at 4.8 amp. The voltage distribution is linear within the limits of the experimental error except near the electrodes. The relatively small constant error introduced by the probe does not obscure or distort this basic linearity.

The voltage gradient as a function of current for various lower electrodes—iron, carbon, aluminum, lead, and a water slurry of NaCl—are shown in Fig. 4. (These electrode materials exhibit a fairly wide range of ionization potentials, such as might be characteristic of the materials in the path of a tornado. Variations in the ionization potential will affect the voltage gradient of the vortex-stabilized discharge, and would presumably cause a corresponding variation in the power input to an electrical discharge inside a tornado.) The data show the expected decrease in gradient for substances such as sodium and aluminum, which have low ionization potentials. This effect is comparable to that observed in short arcs by Suits (*7*), whose data are indicated by the dashed curves. In all cases of the data for the vortex-stabilized arc shown in Fig. 4, the lower electrode was positive. In a separate experiment in which the lower iron electrode was made negative instead of positive, it was found that the gradient was slightly larger. This can probably be attributed to the action of the downward electrical force that opposes the upward movement of positive metal ions from the electrode into the plasma.

Figure 5 shows the power dissipated per unit length of the discharge as a function of the current. Here again the effect of metallic ions from the lower electrode is readily apparent, even though they are



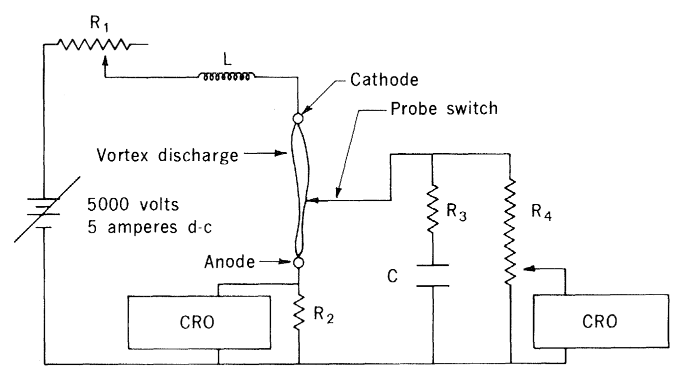
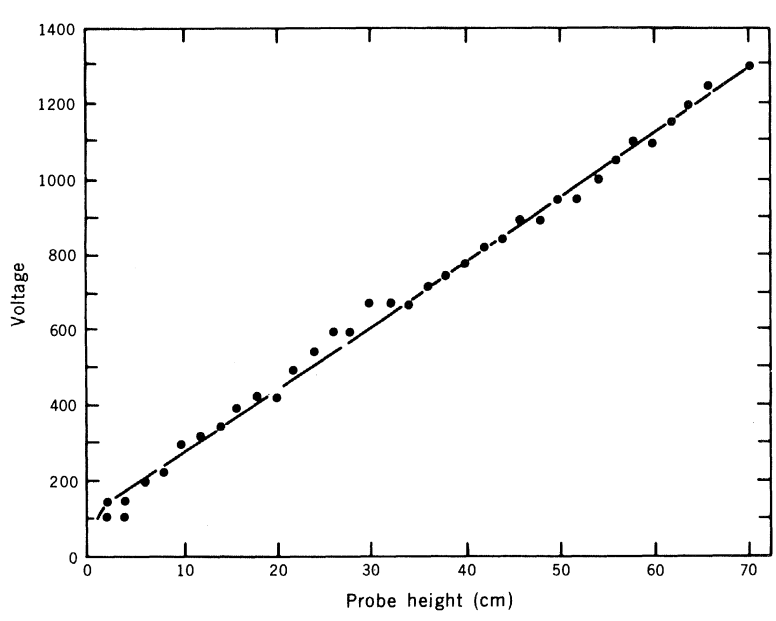


Fig. 1 (left). Louvered chamber and flow of air. Fig. 2 (right). High-current electrical circuit and instrumentation. Symbols: R_1, 1000-ohm current limiter; R_2, noninductive shunt; R_3, 5- to 10-ohm wave shaper; R_4, 22-megohm voltage divider; L, protective inductance; C, 10.5- to 840-μf capacitor bank; and *CRO*, cathode-ray oscilloscope.



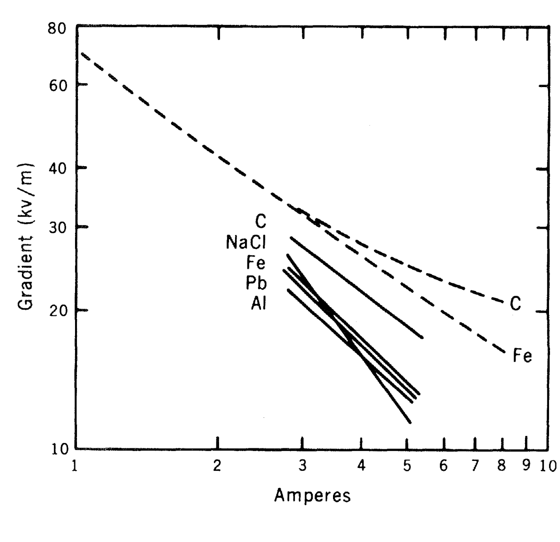


Fig. 3 (left). Probe voltage versus probe height for a 70-cm-long vortex discharge with current of 4.8 amp. Fig. 4 (right). Potential gradient versus discharge current for various lower electrode (anode) materials. Dashed curves from Suits (*7*) are included for comparison.

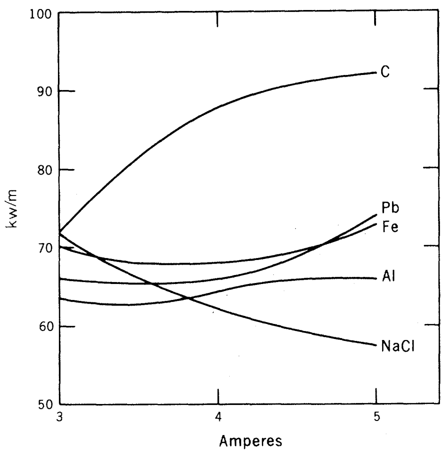


Fig. 5. Power per unit length versus discharge current for various lower electrode (anode) materials.

present in very low concentrations. At 5 amp the power dissipation is reduced by approximately one-third because of the presence of readily ionized NaCl slurry.

Thermal equilibrium is established in an atmospheric pressure arc in approximately 1 msec (*8*). It is therefore possible, by making measurements for times greater than 2.5 msec, to utilize a slowly decaying current surge from the capacitor bank to obtain data for currents as high as 300 amp. The discharge is initiated with the d-c power supply at a steady current of approximately 5 amp. A surge is then provided through the capacitor to have a maximum rate of current increase of 20 ka/msec. During the decaying part of the surge the maximum rate or current decrease was 30 amp/msec.

The voltage across the discharge was measured with a dual-trace cathode-ray oscilloscope. Since the discharge was of a known length, the measurements of the voltage across the discharge were converted to column gradients by dividing by the discharge length. This method assumes the gradient is approximately constant along the length of long arcs, which reference to Fig. 3 shows to be a reasonable assumption. Since the voltage across the discharge and the current through the noninductive shunt were synchronized with respect to each other, voltage gradients and their corresponding currents could be obtained and plotted. The resulting column gradients obtained in this manner are shown in Fig. 6 for lower electrodes of iron and carbon. In each case the lower electrode was of positive polarity. These gradients are considerably smaller than those reported by Maecker (*9*), probably because of the cooling effect produced by the stacked ring chamber he used for producing his cascade arcs. The shapes of the curves in Fig. 6 are essentially the same as those reported by Maecker.

Before these measurements, casual observation had suggested that the plasma stabilized in the vortex might be a variety of glow discharge that was taking place at atmospheric pressure. However, comparison with the data of Suits (*7*) (Fig. 4) and Maecker (*9*) (Fig. 6) shows that the voltage-current relationships presented in Figs. 4 and 6 exhibit the characteristics of an arc throughout the current range 1 to 300 amp. It is therefore concluded that this vortex discharge is not a glow but an arc-type discharge.

It is conceivable that the surge discharge could affect the aerodynamics of the vortex by changing the energy budget of the system; however, the energy input into the surge is negligible compared with that being supplied to the steady state discharge. The maximum energy from the capacitor bank was 10^4 joules, in contrast to the 2.5×10^4 joules delivered every second to the continuous discharge. Since the energy input from the surge is insignificant in the long run, no appreciable change in the aerodynamics would be expected. This is supported by observations of smoke traces in the vortex, which showed that the airflow was not visibly affected by the surge current.

Extrapolation of laboratory findings to thunderstorm phenomena. In estimating from laboratory results whether a similar arc could exist on a vastly larger scale in the axis of a tornado, it is necessary to make an extrapolation of three orders of magnitude. This is fraught with problems. Several factors will certainly have large effects on the physical conditions in the vortex and, therefore, on the electrical properties of the discharge. For example, the air velocity and pressure distributions that prevail in the tornado vortex are poorly understood and will be quite different from those in the small laboratory experiment. Undoubtedly the air velocities will be far larger in the tornado, resulting in higher rotation rates and lower pressures in the vortex axis. Furthermore, the pressure in the tornado will be significantly affected by the several-kilometer change in altitude from the top to the bottom of the vortex. Also, the tornado vortex diameter will be much larger—tens of meters instead of tens of millimeters. Another difficulty arises from the effects produced by the various ions that will be introduced into the plasma from dust and debris ingested into the funnel or vaporized from the earth's surface. Ingestion of ions of low ionization potential into the tornado will reduce the voltage gradient and power output of the discharge, causing a corresponding decrease in the power input into the tornado.

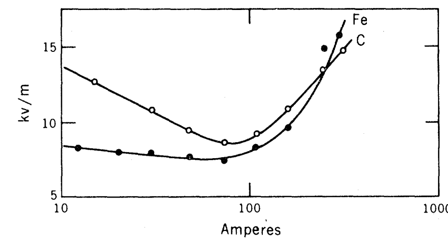


Fig. 6. Potential gradient versus discharge current for iron and carbon lower electrodes (anode).

If the electrical power input to the tornado by the vortex-stabilized discharge is maximized and is still found to be a negligible contribution to the power consumption of the tornado, then this type of electrical discharge cannot be a significant power source for tornadoes. The following discussion is based on data taken with the carbon electrode, thus minimizing the effects of ions of low ionization potential and maximizing the arc gradient and the power input of the discharge into the tornado vortex. It is assumed that a vortex-stabilized arc occurring in a thunderstorm would be about 5 km long, comparable in length to a lightning discharge or a tornado vortex.

The electrical characteristics of an ordinary thunderstorm are as follows. The average charging current of such a storm, estimated on the basis of the rate at which it produces lightning, is of the order of 1 amp, while the typical potential developed is estimated to be of the order of 10^8 volts (*10*). The electrical power developed by a thunderstorm is estimated by multiplying the average charge transferred per second by the potential difference across which the charge transfer occurs. Thus an ordinary thunderstorm, which dissipates approximately 1 amp across 10^8 volts, would develop around 10^5 kw.

Next, consider whether an ordinary thunderstorm can possibly satisfy the electrical requirements of the vortex-stabilized discharge. Should a vortex-stabilized arc of the kind we have studied become established, it can be estimated from the data shown in Fig. 4 that with a current of the order of 1 amp in the absence of ion contaminants, the maximum gradient that could exist would be no more than 10^4 volt/m. The voltage required for such an arc 5 km long would therefore be only of the order of 5×10^7

volts. Since this is less than the 10^8-volt potential that is estimated to be developed by an average storm, the maintenance of a vortex-stabilized discharge appears to be within the storm's voltage-current capability, granting the prior existence of a vortex.

Now consider the power output of a continuous current discharge situated inside a tornado. From the preceding discussion it is seen that if a thunderstorm were to supply a continuous current of the order of 1 amp through an arc stabilized in a tornado vortex, in which the voltage is only 5×10^7 volts, the power thus released by heating in the vortex would be at most of the order of 5×10^4 kw. This, approximately half of the estimated 10^5 kw being developed by the storm, would probably be unimportant compared with the 4×10^6 kw that would be required to produce a tornado with a radius of 50 m and a speed of 10^2 m/sec (*4*). Thus, although an ordinary electrical storm would be capable of supplying the continuous current and cloud-to-ground voltage required to maintain a vortex-stabilized arc inside a tornado, the power output of the discharge would be negligible compared to the aerodynamic power dissipated by the tornado.

Although an ordinary thunderstorm could not maintain a vortex-stabilized discharge with a power output comparable to that of a tornado, it is possible that a giant electrical storm could. These extraordinary storms rise to an altitude of 20 km, twice that of ordinary storms, and have comparably greater horizontal dimensions (*11*). The lightning stroke rates reach values as high as 20 per second in contrast to rates of under 20 per minute characteristic of ordinary storms. Assuming a charge transfer of 5 coulombs per stroke, it can be estimated that currents as high as 10^2 amp might be available in the giant storm. Even assuming the extraordinary continuous current of 10^2 amp, we find from Fig. 6 that the heating in a 5-km-long arc would still be only 10^6 kw, somewhat less than the 4×10^6 kw estimated to be required for a modest tornado.

Conclusions. Even though extrapolations of the results of our laboratory experiments indicate that either an ordinary or a giant electrical storm might be capable of maintaining a vortex-stabilized arc, the arc would not be of tornadic power. This is so because the impedance of the plasma associated with a steady discharge is so low that even the highest conceivable steady-state currents would produce insufficient heating to maintain even an average tornado. Therefore, although continuous current discharges may occur in tornado vortices, the energy supplied by this type of discharge would be at most 25 percent and probably a much smaller percentage of the energy budget of the tornado. Thus it would not constitute a major power source. Even if our extrapolations are correct, however, the possibility is not precluded that significant electrical heating could occur as the result of other kinds of electrical processes, such as a high-impedance glow discharge or an arc maintained by intermittent heavy current surges.

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12. We are indebted to the Research Laboratory of the General Electric Company for the gift of the capacitors for our capacitor bank. This research was supported by the Atmospheric Research Section, National Science Foundation.

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Methyl Chloroform: Impact on Stratospheric Ozone

Abstract. *Regulations to limit the use of trichloroethylene as a degreasing solvent have led to an increased use of the more photochemically inert solvent methyl chloroform as a substitute. Model calculations show that about 15 percent of the methyl chloroform released into the atmosphere will reach the stratosphere. Time scenarios based on past production figures and reasonable projections for future release rates lead to a steady-state ozone depletion due to this solvent about 20 percent as large as those resulting from the continuous release of chlorofluoromethanes at 1973 rates.*

Urban air pollution has been a matter of considerable concern for some time, and regulations have been enforced to limit the emissions of harmful substances (*1*). More recently, concern has also been expressed over possible depletion of stratospheric O_3 resulting from the release of certain halocarbons (*2, 3*), and steps are now under way to limit their release rates. The criteria for classifying substances as potentially harmful to the stratosphere and troposphere are not the same and are, in fact, more likely to be opposed.

The Environmental Protection Agency (EPA) has classified as "restricted" solvents those that they define to be photochemically reactive, that is, those that are readily attacked, for example, by O_3 and HO; the EPA has designated as "safe" solvents those that are not readily oxidized (*1*). One such restricted solvent is $CHClCCl_2$ (trichloroethylene), used largely for metal degreasing (*4*). In 1970, 16 states adopted legislation to restrict the use of this solvent; on 8 July 1976, the EPA announced that 28 states had been advised that they will be required to adopt more stringent controls over photochemical oxidants, including trichloroethylene (*5*). In 1970 the U.S. production of this solvent was 2.8×10^5 metric tons, but by 1976 it had decreased to less than half this amount (*4, 6*). The world production capacity of this solvent in 1976 was 9.8×10^5 tons, but only 54 percent of this total was utilized (*7*). Part of this diminished use resulted from the regulations which forced a changeover from this solvent mainly to CH_3CCl_3 (1,1,1-trichloroethane or methyl chloroform), which EPA has classified as a safe substance.

In 1970 the U.S. production of methyl chloroform was 1.7×10^5 tons, and by 1976 it had increased to 3.0×10^5 tons (*8, 9*). Worldwide capacity in 1976 was 5.3×10^5 tons with 90 percent utilization (*7*). Additional capacity figures have been announced: Europe, 9×10^4 tons for the last quarter of 1976; United States, 2.2×10^5 tons for 1978; and Japan, 7.3×10^4 tons for 1979 (*10*). Thus, by 1979 the world production capacity of this compound will be 9.1×10^5 tons.

The EPA classified methyl chloroform as safe because it is relatively inert in the troposphere as compared with trichloroethylene. The rate constant for the attack of methyl chloroform by HO radi-