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Experiments supporting a program of warm fog dispersal by electrical charge injection

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

EXPERIMENTS SUPPORTING A PROGRAM OF WARM FOG DISPERSAL BY ELECTRICAL CHARGE INJECTION

G. E. Schacher and W. Reese

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ABSTRACT

This report summarizes the results of a number of experiments conducted to support a program of fog clearing by the injection of electrical charges into the fog. Experiments were made to determine the charge transferred to water sprays which showed that contact charging mechanisms were as much as 10^6 times as effective as induction charging mechanisms. The charge on soap film bubbles was measured and it was found that for a 2 inch bubble formed at 30 kV the charge was on the order of 1 μ Coulomb. Tests of fog clearing in an environmental chamber indicated fair results with water spray techniques and much better results with techniques by which charge is injected directly into the atmosphere (corona injection). Preliminary tests of corona injection into the atmosphere were carried out and showed that considerable charge attached to windborne particles.

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ABSTRACT

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I. SUMMARY AND RECOMMENDATIONS

This report summarizes the results of a number of experiments conducted in support of the NWC (China Lake) fog clearing program. The goal of the program is to investigate methods of clearing warm fog on a practical scale suitable for clearing fog around airfields. The approach which this work supports is to inject electrical charge into the fog. The charge, if it attaches to water droplets, greatly increases the efficiency of collisions which lend to the formation of drops sufficiently large to fall out of the fog.

The experiments reported here were conducted with a view toward determining the best means of injecting charge into fog. Three classes of experiments were conducted:

1. Experiments to determine the optimum techniques for charging a spray of water droplets and to determine the charge carried by the droplets. (Water Spray Experiments).

2. Experiments to determine the charge carried by soap film bubbles when the bubbles were formed at a high electrical potential. (Bubble Experiments).

3. Moderate scale tests of fog clearing in an environmental chamber using the techniques developed in the previous experiments. (Fog Clearing Experiments).

The first two classes of experiments were performed at the Naval Postgraduate School while the third was conducted at NWC.

The basic conclusions reached in each class of experiments are as follows:

A. Water Spray Experiments:

a. Contact charging mechanisms were compared with induction charging mechanisms. It was found that contact charging results in charge per unit volume of water dispensed as much as 10^6 times that obtained by Induction charging. Although contact charging presents greater design difficulties than does induction charging, especially when conducted on a large scale, the advantage in charging efficiency greatly recommends increased consideration of contact charging mechanisms.

b. The charge per drop was determined by measuring the charge transported to an electrode and counting the number of drops on the electrode. For contact charging the <u>apparent</u> charge per drop was as much as 10^4 times the Rayleigh limit for the drops collected. The deduced charge per unit volume was approximately 4 Coulombs/liter. One explanation of the observed results was that the contact charging process produces large numbers of very fine droplets which carry charge to the electrode but which cannot be observed by gross examination. The radius corresponding to the Rayleigh limit if the volume charge density is 4 Coulombs/liter is approximately 0.5 microns. An alternative explanation is that corona is involved.

c. A lengthy series of experiments was conducted to test the corona hypothesis. It was determined that this hypothesis could neither be confirmed nor rejected by simple experiments.

d. A phenomenon termed "electrostatic spraying" was observed and investigated. When voltages on the order of 40 kV and above were imposed on a cone through which water was fed, a very fine water spray developed. This spray is a result of the interaction of the electric field at the cone and the charge on the water since the mechanism is effective even when no hydrostatic head was applied to the water. Increasing the hydrostatic head, and hence the flow rate of the water, causes a decrease in the effectiveness of electrostatic spraying and charge transfer.

e. The effects of water conductivity were investigated. No significant difference could be observed between the behavior of distilled water and water whose conductivity had been enhanced by dissolved KCl.

B. Bubble Experiments:

a. Measurements were made of the charge carried by bubbles formed at high potentials. For bubbles of approximately 2 inch diameter formed at 30 kV a charge of approximately 1μ Coulomb was carried by an average bubble.

b. It was observed that the presence of a electric potential affected the detachment rate of the bubbles. Using a 3/8 inch diameter bubble pipe it was observed that as the applied voltage was increased from 10 kV to 40 kV the detachment process was enhanced. The bubbles decrease in size and the rate of detachment increases as the potential is increased. The enhancement in the rate of detachment was by as much as a factor of 10. When the bubble pipe was operated above 40 kV the bubbles tended to rip apart because of the disruptive action of the electrostatic force. This indicates that the Rayleigh limit was being approached or that the detachment rate was too rapid for the rate at which the bubble solution could be supplied.

c. Observations were made which indicated the persistence of the charges on the bubbles. Occasionally a nitrogen filled bubble would become trapped in a suitable electrical field and remain bouyant until it was carried from the favorable position by a draft. Bouyant behavior was observed for as long as 1 minute for some bubbles. The behavior indicated no appreciable loss of charge.

C. Fog Clearing Experiments:

a. Using an electrostatic water spraying device operating at 100 kV fog was cleared in a small region around the spray head.

b. No noticeable clearing was observed when charged bubbles were tested.

c. Fog could be cleared from a reasonably large volume by using corona heads. The fog remained cleared from the region for several minutes after the potential was reduced to zero.

d. During the observations a "semi-catastrophic event" occured which was accompanied by substantial fog clearing. At one time during the experiments as large arc developed along a damp rope when the charging head was at 100 kV. A volume of fog approximately 8 feet on a side was cleared almost immediately and the volume remained clear for as long as suitable conditions for fog remained in the chamber (about 5 minutes).

Based on the results of the experiments, chiefly the Fog Clearing Experiments, we believe that methods employing corona appear to offer the greatest potential for clearing fog by electrostatic means. The reasons are two-fold:

(1) Clearing when using corona appeared to be more easily accomplished and to affect a larger volume than clearing using other techniques.

(2) The corona method is much less cumbersome and complex to realize on a large scale than any other method of injecting electrical charge into fog.

Further investigations of the mechanisms involved in the dispersal of warm fog by corona should be conducted. The purpose of these investigations would be to provide information capable of obtaining optimum parameters for this technique with a view toward engineering a full scale test.

II. EXPERIMENTAL APPARATUS AND PROCEDURES

A. Charge Measurements:

Measurements for the Water Spray Experiments and the Bubble Experiments were conducted in a specially constructed room, 10 feet on a side. Two walls and the ceiling of the room are grounded electrical conductors. The other two walls and the floor are reinforced concrete, which also forms an approximate ground equipotential. Charging was produced using a 6 inch diameter "charging sphere". The various apparatus for the various experiments were attached to the sphere. The sphere was located at the approximate center of the room, mounted on a plexiglass tube. Since other equipment, most importantly the high voltage power supply, high voltage lead to the sphere, and various ground and meter leads were also located inside the room, the sphere was not exactly in an electrically symmetric position.

Charge was measured by capturing the charge-bearing objects on a 2 inch diameter copper disk which was coated with enamel and connected to an electrometer. The disk could be located at a variety of positions around the charging sphere. The connection from the disk to the electrometer, which was located outside the room, was a coaxial cable. The shield of the cable was grounded and extended to within 1 inch of the disk to preclude charges falling on the cable from producing a spurious reading. It had previously been verified that this arrangement could provide reliable measurements of the charge of objects collected by the disk. (The charge coupling was via induction through the enamel coating. The purpose of the coating was to produce a dipole layer which would cause objects which strike the disk to stick so that their number could be determined.) For the bubble experiments difficulties were experienced with the enameled disk and a bare copper disk was substituted.

The electrometer was Keithley Model 610. With this system it was possible to measure charge transfer as low as 10^{-10} Coulomb and currents smaller than 10^{-13} amps. Smaller charges could not be measured due to the capacitive coupling between the charging sphere and the disk.

The charging sphere was connected to a Hipotronics Model 26-334 power supply which was capable of supplying voltages to 100 kV from ground with either polarity. The sphere voltage could be varied continuously through the range 0 to 100 kV by controls located outside the room containing the sphere. Instrumentation was provided to determine the sphere voltage and the input current and voltage to the power supply. For tests at NWC a portable high voltage power supply, Hipotronics Model 8GP160 was used which could provide voltages from 0 to -160 kV. This power supply was provided with instrumentation which allowed the high voltage and the current drawn by the high voltage lead to be measured.

B. Water Spray Experiments:

1. Experiments in which single drops of water were placed either directly on the sphere or in a truncated cone placed on the sphere. The cone was 1 inch high and had a base diameter of 3/8 inch and a tip diameter of 1/8 inch.

2. Experiments in which water was pumped through an induction charging device supplied by NWC. Devices of this design had previously been used extensively by NWC and the device will not be described here.

3. Experiments in which water was sprayed electrostaticly from a cone placed on the charging sphere. Most of the measurements were conducted with experiments of the third class.

A diagram of the electrostatic spray apparatus is shown in Fig. 2-1. Water is fed to the spray head by a plastic tube which passes through a metal shield. The purpose of this shield is to eliminate any sharp points, which would act as corona sources, in the water connection. The water reservoir was a plastic bottle which could be raised and lowered by an insulating cord which passed outside the room. Since the initial experiments (Class 1) indicated that for single drops much better spraying was achieved near sharp points, a cone was used for the sprayhead. A #20 hypodermic needle passed through the cone for the final water feed. Measurements were taken with the cone in place and with the hypodermic needle alone. The results of these experiments will be described in Chapter 3.

C. Bubble Experiments:

Helium and Nitrogen filled soap film bubbles were blown using a metal "bubble pipe" depicted in Fig. 2-2. The bubble pipe was located at the top of the charging sphere. The pipe diameter at the opening is 3/8 inch. The gas flow tube is 1/8 inch diameter. The soap solution inlet was 1/4 inch diameter. The flow of soap solution was controlled in a manner similar to the control of the water flow in the electrostatic spraying experiments. Typically, the soap flow was maintained so that the solution level in the pipe was approximately 1/4 inch below the pipe opening. For the experiments described here the soap solution consisted of equal parts "Ivory Liquid Detergent" and glycerine. Solution with disolved NaCl was tried, but was only slightly more conducting than the original solution and proved more difficult to use to produce satisfactory bubbles.

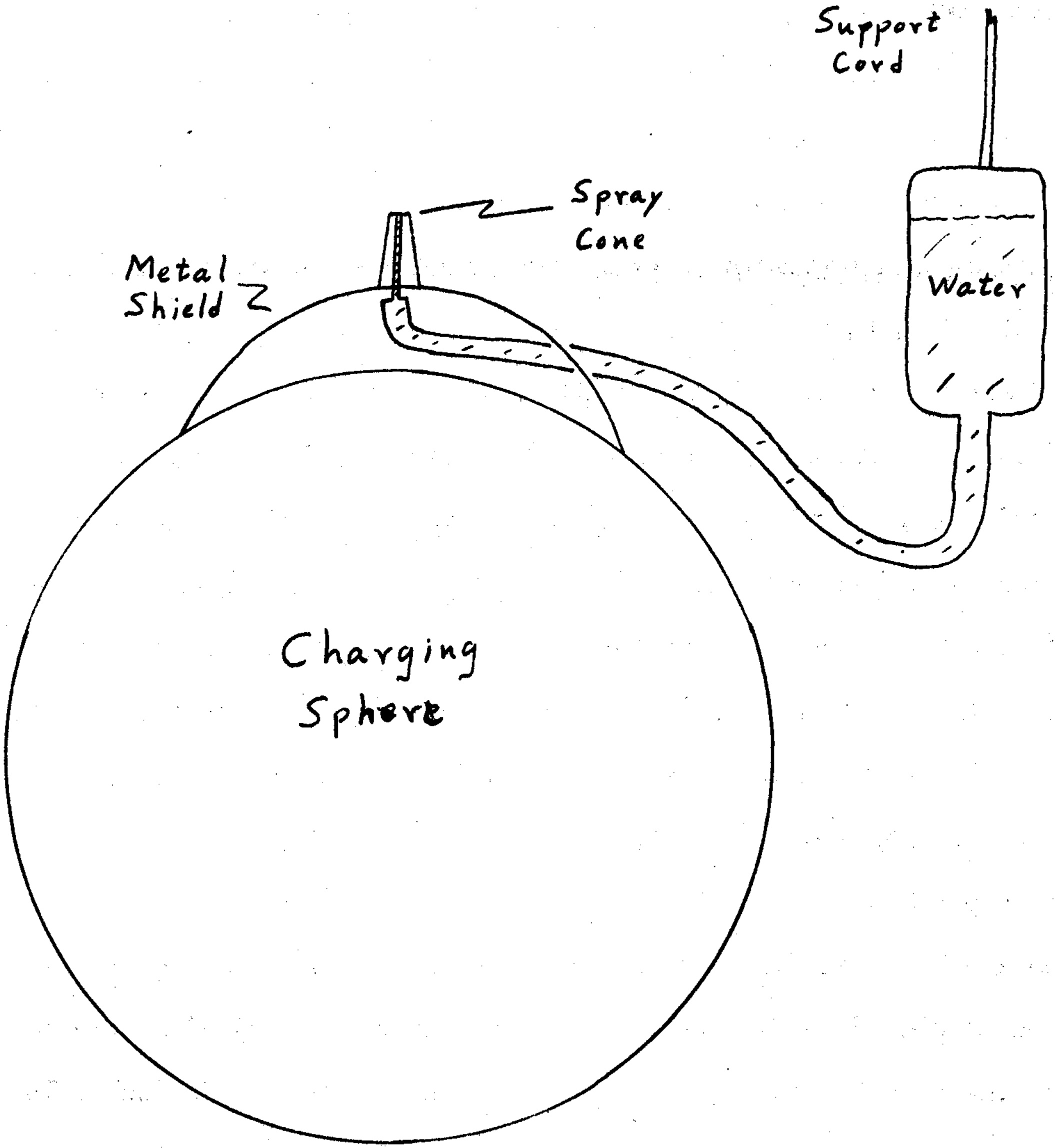

Fig. 2-1. Water Spray Apparatus (Not to Scale)

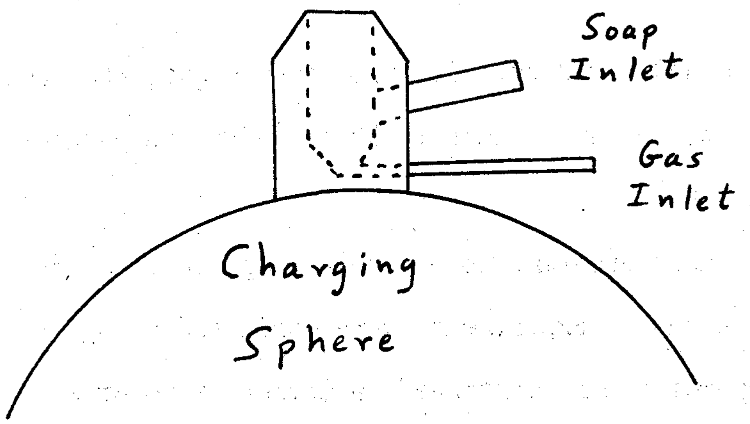

Fig. 2-2. Bubble Pipe (Not to Scale)

Gas flow was controlled using a pressure and flow regulator on an appropriate gas bottle. Very low pressures (a few psi gauge) and flow rates were required. The soap and gas flow rates were adjusted so that bubbles with the desired size and separation rate could be blown. The lower the gas flow rate the larger was the bubble which was produced. Adjustment of the flow rates was an imprecise art and many combinations of soap and gas flow led to unsatisfactory bubble pipe operation. Typical poor operation was "spitting" of the soap solution (soap solution too high and gas flow too high) or the formation of multiple, undetached bubbles (gas flow too low). Although the bubble pipe was somewhat difficult to operate and somewhat unreliable, it was the best of a series of designs which were tested, some of which were much more sophisticated in design and included an additional gas flow for detachment.

D. Fog Clearing Experiments:

The fog clearing experiments were carried out in Building X at NWC over a two day period. The building is a hemisphere approximately 40 feet in diameter. The environment in this room can be controlled over a wide range of temperature and humidity. For the measurements the humidity was adjusted as high as possible (approximately 99%) and the temperature varied between about 83 and 85°F.

Since the purpose of these experiments was to attempt to clear fog no charge measurements were made. Experiments were conducted using the water spray and bubble apparatus. As mentioned, a different power supply than that used in the experiments at NPS was employed.

The effects of clearing attempts were monitored optically using two separate systems. The first was a transmission measurement system using a helium-neon laser. The second was a scattered light system employing a Gamma Scientific Model 710 photometer.

For the transmission measurements the laser beam was directed to a mirror located behind the charging sphere. The laser path passed about 2 feet above and slightly to one side of the sphere. The laser detector was mounted in close proximity to the laser, about 20 feet from the sphere. The detector was a photodiode with a narrow bandpass filter. Performance of this system was not satisfactory because of water condensation on various glass components of the system, but primarly the mirror. Even though the measurements showed poor intermediate and long term stability, short term effects provided a reasonably reliable indication of the transmission over the optical path. These measurements served to confirm the results obtained with the photometer.

The photometer was mounted in close proximity to the laser system and measured light scattered from a 150 watt tungsten bulb located on the opposite side of the room. The detector of the photometer had a narrow field of view, about 6°, and was aimed so that its acceptance cone passed about two feet to the side of the charging sphere. Since the geometry was such that a 120° angle was made by the line from the photometer detector and the charging sphere and the line from the illuminating bulb and the charging sphere, light registered by the photometer represented scattered light, weighting most heavily the region in space near the charging sphere. However, because of multiple scattering and reflections some of the light entering the photometer detector reflected conditions elsewhere in the room. Light scattered from fixed objects represented a relatively constant background which could be taken into account. The photometer system appeared to work very well. Fog conditions which appeared similar gave similar readings and the readings were reasonably stable in time. Since fog tended to build from the floor upwards considerable experience was obtained with conditions which showed that the majority of the light which reached the photometer came from the fog in the vicinity of the charging sphere and not elsewhere in the room. All optical characterizations of the fog (except subjective visual estimates) in this report were obtained with the photometer system.

An unfortunate characteristic of the room was that constant fog conditions could not be maintained. This tended to limit the amount of time available for testing and to make some of the results more ambiguous than might be desired. The instability in the fog was directly linked to the environmental control systems of the room and the fog cycle reflected the cycling of the control systems. The humidity control was very simple. Water was dripped on a stack of hot bricks to produce steam. For the fog experiments, in which maximum humidity was desired, a constant stream of water was played on the bricks. The bricks were heated by the same heater which provided the temperature control. Thus temperature and humidity had a tendency to follow the heater cycle. When the heater would ignite fog would disappear, the fog level descending toward the floor. When the heater would shut off, fog would build up, rising from stratified fog several feet from the floor until almost the entire room would be filled with a uniform, thick fog.

A typical room cycle is illustrated in Fig. 2-3, in which the photometer readings are shown as a function of time. Since it was necessary to have conditions in which the fog was relatively calm and non-stratified to a height of at least 6 feet from the floor before significant experiments could be conducted experimental time was limited to about 20 minutes per hour. It must be emphasized that not all the room cycles were exactly the same, however the minimum and maximum intensity readings were reasonably consistent from cycle to cycle.

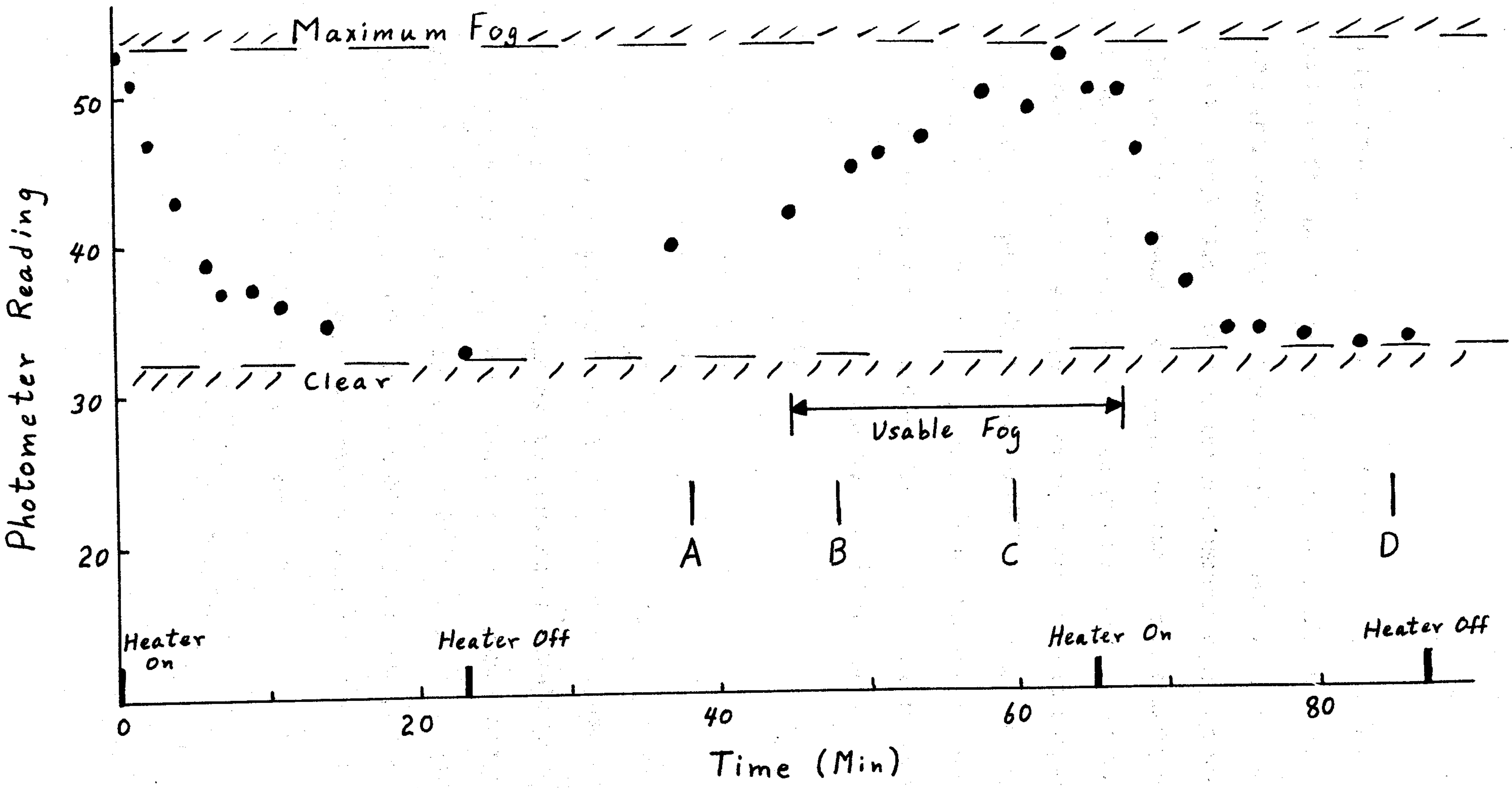

Fig. 2-3. Typical room fog cycle, Temperature 83.5°F, Relative Humidity 98.7%. Photometer readings are plotted as a function of time. Increasing readings imply a more dense fog in the measurement region. A. Fog to 5 feet, B. Fog to 7 feet, C. Visually stable fog filling most of the room, D. Stratified fog to 3 feet.

III. EXPERIMENTAL RESULTS

A. Bubble Experiments:

The charge carried by bubbles blown with the apparatus discussed in Chapter 2 was determined by allowing bubbles to strike a bare collector electrode located above the bubble pipe and near the ceiling of the room. Average values for the charge per bubble as a function of voltage are given in Table 3-1. There was no observed difference in the charges per bubble as a function of polarity or filling gas (Helium and Nitrogen).

Voltage (kV)	Charge (μ Coulombs)
20	0.3
30	0.6
40	1.0

Table 3-1. Average charge per bubble.

The numerical results are subject to considerable uncertainity, perhaps as much as 50%. This is due to both experimental problems and the fact that the charge per bubble was <u>not</u> constant but showed considerable actual variation. A histogram of a typical run with helium filled bubbles at 40 kV is shown in Fig. 3-1. As an example of the variation caused by the formation process, the one bubble observed to carry 3 μ Coulombs was exceptionally large. Some of the experimental difficulties included the fact that sometimes a bubble would burst when it struck the collector and no assurance was possible that the entire charge had been collected, sometimes bubbles striking the ceiling would drip on the back of the collector,

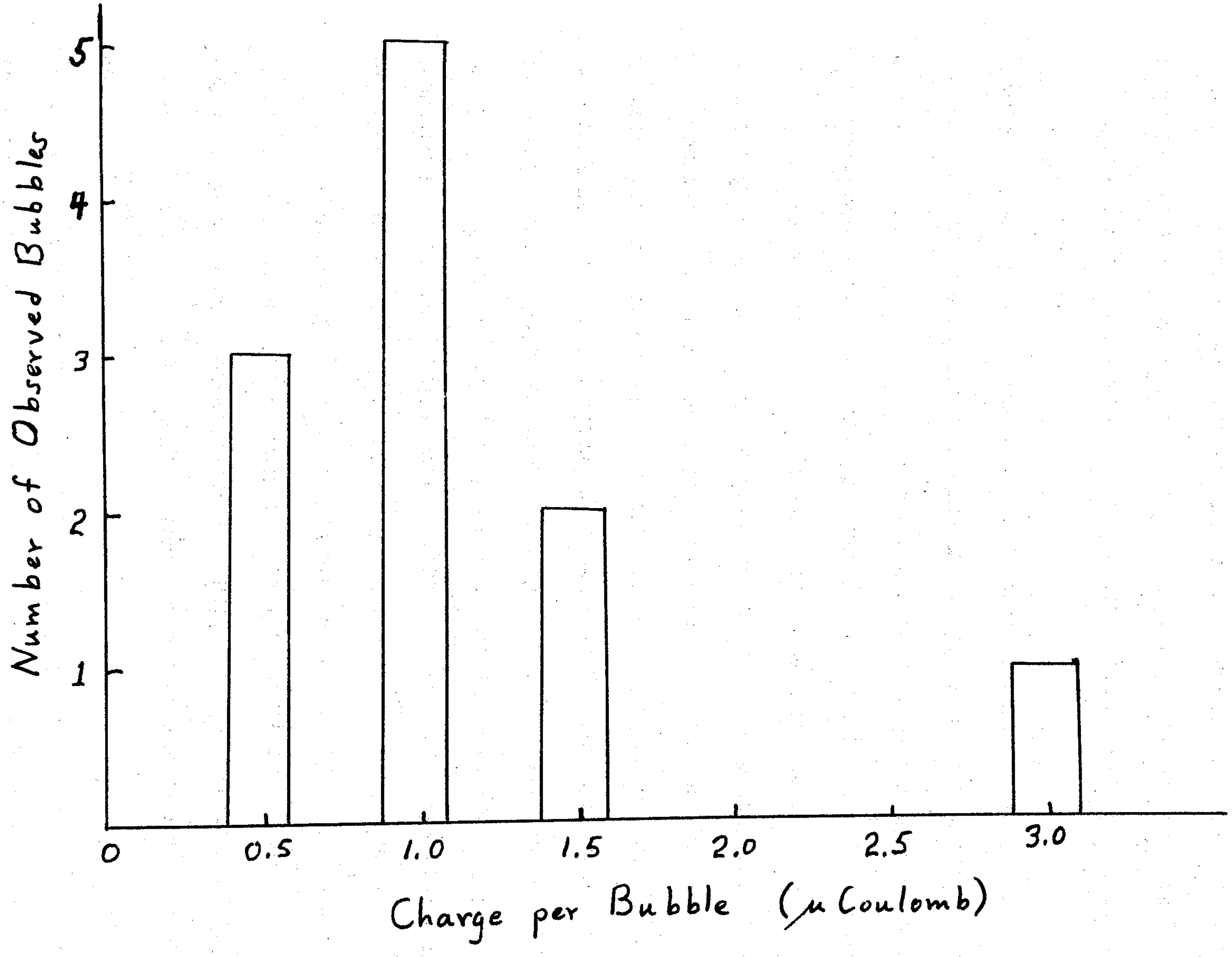

Fig. 3-1. Histogram of a Series of Charge Measurements.

possibly transfering some charge, sometimes a bubble would "brush" the collector, etc. It was attempted to limit recorded data to cases in which only one bubble struck the collector and no obviously complicating factors were involved.

The trend of average charge versus voltage indicates that higher voltages produce higher average charges. While this is intuitively satisfying it also indicates something about the chief charging mechanism.

The observations rule out a "bouyancy model" in which the bubbles accumulate charge until the electrostatic repulsion force equals the force required to overcome gravitational forces. If this were the case then one would expect different results with helium filled an nitrogen filled bubbles. In addition, the bubbles produced at higher voltages were smaller and hence less bouyant than those produced at lower voltages and yet carried more charge. Further, it was observed that nitrogen filled bubbles could be held bouyant at a considerable distance from the charging sphere where the electric field was much reduced from the value at the detachment point.

In a similar manner an "equipotential model" can be ruled out. In this model one assumes that a bubble has a certain capacitance and that the charge is given by $Q = C_B V$. Since the bubble capacitance should be an increasing function of bubble radius one would expect the ratio Q/V to decrease as the bubbles became smaller (higher potentials) while the opposite is actually the case.

Similarly a "resistance limited" model appears ruled out since the detachment rates were much higher at high voltages than at low voltages indicating that if the charging were limited by the dielectric relaxation of the soap film one should observe less, rather than more, charge at higher voltages than at low voltages.

The most likely model is a corona charging model previously developed to explain, in detail, charging of metal coated fiberglass fibers. In this model the majority of the charge is transferred by a corona mechanism in the immediate vicinity of the detachment point. This model predicts a voltage beyond which further charge is not transferred, which is not observed in these experiments. Since this maximum effective voltage is related to the speed at which the charged objects (here bubbles) can be made to leave the charging sphere and since the viscous drag for the bubbles was so high, one expects this plateau voltage to be quite high, perhaps above the Rayleigh limit for the bubbles. (A stability limit was reached slightly above 40 kV in our experiments.)

If the corona charging mechanism is the correct mechanism it would indicate that a bubble pipe with relatively sharp edges, such as the one used here, might be more effective since corona could more easily occur in the presence of sharp edges at the detachment point. This prediction may be supported by some subsidiary observations made using a very different bubble machine which was tested at NWC. In this machine bubbles are blown from a heavy guage wire mesh, the wire forming a rounded edge at the blowing surface. In this machine the stability limit was nearly 80 kV. The stability limit either indicates that the Rayleigh limit has been reached or the bubble has too large a velocity on detachment (see below). It is more likely that the latter is the case. The velocity is proportional to the product of the bubble charge and the average electric field at the bubble, and hence a higher stability limit indicates either a lower bubble charge or electric field (or both). The corona model predicts the charge would be very sensitive to the electric field.

Some observations were made which indicate that the charge persisted on the bubbles for times of at least one minute (and perhaps much more). These were observations of nitrogen filled bubbles which were held neutrally bouyant by the electric field at some distance above the charging sphere. Motionless bubbles were observed for times on the order of a minute until the bubble moved from the stability point (usually due to a draft in the laboratory as indicated by the subsequent bubble motion).

It was consistently observed that increasing voltage increased the bubble detachment rate (which is consistent with the corona charging model) and decreased the bubble size (which is consistent with the shorter time available for film flow). If the gas and soap flow conditions were set to form bubbles approximately 3 to 4 inches in diameter at a rate of 1/3 bubble per sec (one bubble in 3 seconds), application of 40 kV increased the detachment rate 15 fold (to 5 per sec) and decreased bubble diameter to about 1 inch diameter. The diameter decrease is consistent with the time reduction under the assumption of constant film flow rate.

If the voltage was raised much above 40 kV most bubbles broke before detachment. This could either be a result of the fact that the Rayleigh limit, the point where the self-repulsion of the charge on the bubble overcomes the surface tension, was reached or that the drag forces associated with the velocity upon detachment were too great. It is likely that this latter explanation is the more nearly correct since the detachment rates at the stability limit approached maximum rates obtainable with no applied potential.

B. Water Spray Experiments:

The first water spray experiments performed were to place a drop of water on the charging sphere and increase the voltage. At sufficiently high voltage the center of the drop deforms by moving away from the sphere to form a peak on the liquid drop. As the voltage is increased further an instability develops (probably the Rayleigh limit is reached) and a fine spray emanates from the drop. The next improvement in technique was to place a truncated cone on the charging sphere and place the drop on the cone. This improved the spray and allowed it to develop at lower voltages indicating that the electric field at the spray site is a significant variable. The next improvement was to design and construct the contact charging spray head described in Chapter 2, which allows a continuous supply of water to be brought to the cone tip.

Thus, the first observations were to (re)discover the phenomenon of electrostatic spraying. The spray which causes water to leave the cone creates a suction or pumping action which is very effective in bringing water to the cone, even when no external pressure head is applied. If the production of a fine spray is adopted as the quality criterion then the electrostatic spray is most effective when zero pressure head is applied. A positive head increases the size of the drops while a negative head reduces the rate of spray. With the apparatus described in Chapter 2 electrostatic spraying could dispense between 0.2 and 0.5 ml/sec of water. The flow rate was essentially independent of the applied voltage above 40 kV since the flow was limited by the hypodermic tubing through which the water was delivered to the cone.

Further indication that low flow rates produce the "best" spray are indicated by the measurements presented in Table 3-2. This data was taken with a potential of 80 kV with the collector located below the charging sphere in a region where most of the water fell. The background represents a corona current. The spray conditions were adjusted by changing the pressure head. Optimum spray conditions occured at very low pressure head. This experiment may well indicate that for contact charging too high a flow rate causes less efficient charge transfer. Substituting water with dissolved KCl produced a spray with larger drops.

Condition	Collector current (μ amp)
Background (wet condition)	1 - 2
Optimum Spray	7 - 10
High pressure spray	3

Table 3-2. Some representative collector current data for electrostatic spraying. The collector was located in a fixed position below and about ½ meter from the spray head. The pressure head was varied. The voltage was 80 kV.

When spray conditions were met the water emanated from the cone in a straight, well defined stream and continued in this manner for about 1 inch. At this point the stream broke-up and formed a conical spray subtending about a 30° angle. The height reached by the spray was about 2 feet when a potential of 100 kV was applied to the spray head. Although many drops were obviously highly charged since one could easily observe their rapid repulsion away from the charging sphere, not all drops acted in the same manner. If the charging voltage is increased the spray becomes finer. This can easily be explained if the drops are being charged to or near the Rayleigh limit. This is because the charge transfer is observed to be an increasing function of voltage while the volume transferred remains constant. If all drops are charged to the Rayleigh limit then the charge per unit volume will be given by

$$\frac{Q}{V} = \frac{6(\varepsilon_0 \gamma)^{1/2}}{r^{3/2}}$$

where ε_0 is the permitivity of free space, γ is the surface tension, and r is the drop radius. Thus, as stated above, if the charge per unit volume is increased the drops become smaller.

If we continue to make the assumption that all drops are charged to the Rayleigh limit (and some drops were obviously less charged than others) and that a typical drop diameter was 500 microns (which may well be typical) the charge per drop is approximately 2.5×10^{-11} Coulomb and the charge per unit volume is 3.8×10^{-4} Coulombs/liter. In the experiments cited in Table 3-2 the flow rate was about 0.3 ml/sec for the optimum flow. If we were to assume that the entire flow struck the collector (which was certainly not the case) and that the current associated with the flow was about 6 μ amps, then we would deduce a charge per unit volume of 3×10^{-2} Coulombs/ liter. This is about 100 times the Rayleigh limit! If more realistic assumptions were made about the fraction of sprayed water collected the number would become about 10^4 times the Rayleigh limit. This is typical of results obtained from these measurements and is an indication of problems with a corona transfer mechanism which is facilitated by the water spray.

In essence two types of experiments were performed which gave the charge transferred per unit volume of water. One type of experiment was similar to that described above in which a change in current which accompanied the onset of a water spray was measured and the flow rate was determined and coupled with an estimate of the fraction of the spray striking the collector. A typical experiment of this type yielded charge per unit volume on the order of 0.4 Coulomb/liter. In the second type of experiment spray was maintained for a short period of time (from 3 to 30 sec) and the excess of charge collected over a comparable period with voltage and no water was determined. The collector was then examined and the number and radius of the drops collected was determined. The collector was then wiped with an absorbant tissue and the mass gain of the tissue was measured to compare with the previous drop radius determinations.

Typical results from this latter type of experiment were to find that the diameter of the collected drops was about 300 microns and the charge per unit volume transferred ranged between 7 and 10 Coulombs per liter. Comparison of the direct charge determinations with the Rayleigh limit, calculated with the measured drop radius, typically gave results which were about 10^4 times the Rayleigh limit.

These results, obtained by two independent methods, can be explained in two ways: By envoking an extra charge transfer mechanism which is effective during spraying or by envoking the hypothesis of small drops which could not be visually detected and which evaporated before they could be collected by the absorbant tissue technique. If we take 4 Coulomb/liter as a typical experimental result, this corresponds to drops with a diameter of about 1 micron, (Rayleigh limit) which certainly are not visible.

Observations were made of a substantially constant current during spraying. This would not be the case if the charge was being transported by a few large drops. However, this observation is consistent with either hypothesis.

The second of these explanations seems harder to accept than the first since it leads one into difficulties in trying to quantitatively understand the results. Let us illustrate this by considering the results of a typical experiment in which 6 drops, with an average diameter of 300 microns, and an average charge of 10^{-7} Coulomb/drop were collected. For such drops the Rayleigh limit is 1.2×10^{-11} Coulomb/drop. Thus the measured charge was slightly more than 10^4 times the Rayleigh limit. Assuming that there was a large number of small drops carrying an average of 7 Coulombs/liter (the value obtained in this experiment) the average drop radius would be 0.4 microns so that the average drop would carry (at the Rayleigh limit) approximately 1.6×10^{-15} Coulombs. Thus it would require about 3.75×10^8 drops to deposit the measured charge. The volume of these drops would be about 8.6×10^{-8} liter and the associated mass would be about 0.086 mg, about equal to the measured mass of the 6 drops (0.1 mg). Thus the assumption of many small drops seems just within reason.

On the other side of the coin, it is difficult to account for increases in current during spraying by as much as a factor of 10 (which was commonly observed) solely by a corona mechanism. A moist atmosphere certainly did enhance corona transfer. Characteristic of this are a set of measurements presented in Table 3-3 which represents corona current when the appartus was entirely dry and when the apparatus was wet from having sprayed water. Typical currents are a factor of from 3 to 5 larger after spraying than before. However, it must be remembered that many of the background currents which were subtracted from measured currents to find the excess associated with the spray were obtained under moist conditions following sprays in preceeding experiments.

To summarize, measurements of charges carried by water drops generated by the electrostatic spraying technique typically yielded results on the order of 10^4 times the Rayleigh limit of the apparent drops. This result can either be explained by assuming that the bulk of the charge was transferred by drops too small to observe (with diameters in the range of 1 micron and below) or that there was an excess corona current associated with the water spray. In fact, both mechanisms may be operative. A number of simple experiments were attempted to distinguish between the two mechanisms but none were successful in rejecting either hypothesis.

V (kV)	Dry I (μ amp)	Moist I (μ amp)
60	0.03	0.09
80	1.5	5
90	3	15
100	10	25

Table 3-3. Corona current measured with dry and wet equipment. The collector was located 43 cm below the charging sphere and to one side.

In addition to the extensive experiments conducted with electrostatic spraying, an induction spraying apparatus, which was supplied by NWC, was also tested. The device consists of an isolated charging ring concentric to and in front of a nozzle. The nozzle was connected to the room water supply and hence was at ground potential. The charging ring was connected to the power supply. It was not possible to operate the device above 8 kV due to arcing between the nozzle and the charging ring and operation above 4 kV was not reliable. (When the device was dry the maximum potential of the ring was 12 kV.) As far as could be determined the device was very inefficient compared with the electrostatic spray. Measured currents were almost negligible (about 1% of those typically encountered with the electrostatic spray when flow rate was at least 1000 times higher than with the electrostatic spray.)

C. Fog Clearing Experiments:

The purpose of these experiments was to test the various charge injection methods in a controlled environment which approximated field conditions more closely than did the laboratory conditions in which the charge transfer measurements were made. The behavior of the environmental chamber in which these experiments were conducted has been described in Chapter 2. The behavior of the chamber was not exactly the same from cycle to cycle, however, Fig. 2-3 gives a fairly good representation of the fog cycle in terms of photometer readings. Only that portion of the cycle labeled "usuable fog" was utilized for the experiments. During the time period of "usuable fog" various charge injection experiments were conducted.

The tests which were conducted during the Fog Clearing Experiments were as follows:

1. With the charging sphere and spray cone in place the potential was raised to 40 kV for 1 sec but no water was sprayed,
2. Same conditions as 1 except 80 kV was applied,
3. Water spray as follows: 80 kV for 15 sec, 100 kV for 15 sec, 110 kV for 15 sec,
4. Same as 1 except 100 kV was applied for 30 sec,
5. Water spray at 100 kV for 180 sec,
6. Same as 1 except 100 kV was applied for 60 sec,
7. Water spray at 100 kV for 270 sec,
8. Semi-catastrophic incident (described below),
9. Corona discharge test (described below),

Tests 1, 2, 4, and 6 were "background" tests for which no clearing was expected. For the spray tests distilled water was used. Figs. 3-2 and 3-3 show the results (photometer intensity vs time) obtained in these tests.

Figure 3-2 shows the results obtained in tests 1-5. Experiments 1, 2, and 4, which did not employ a water spray, showed little or no rapid clearing. During the 3 minute pause between test 3 and 4 there may have been some slow clearing. However, the results of these tests are not an indication of the effects of corona, since the corona obtained in this configuration was mostly localized inside the plexiglass support tube for the charging sphere. These tests do demonstrate that any clearing observed in the other tests can be ascribed to the water spray. The water spray experiments, tests 3 and 5, produced much more definite evidence of clearing. In both tests clearing in the vicinity of the apparatus was noted by visual observation. After a prolonged water spray it took about 5 minutes for the visual appearance of the fog to return to the "before test" condition. The reestablishment of the fog appeared to be via a normal diffusive process.

During the chamber cycles which separated test 5 and test 6, about 2 cycles, a small scale corona test was made. A makeshift corona head was assembled from a ball of lathe shavings. The ball was about 4 inches in diameter. A roll of copper screeen forming a cylinder 8 inches in diameter and 3 feet long was placed with one end on the floor. This screen served as a ground electrode (because of the wet condition of the floor). The corona head was placed 1 foot above and to the side of the top end of the screen. The photometer field of view was aligned with the region between the corona head and the screen. When the corona head was raised to a potential of 100 kV the photometer reading dropped from 27 to 19 and complete visual clearing of the region around the corona head and screen was noted. (Note: Since the field of view of the photometer had been changed, the numbers obtained can not be directly compared with other photometer readings in this report.) The total cleared region not only included the region

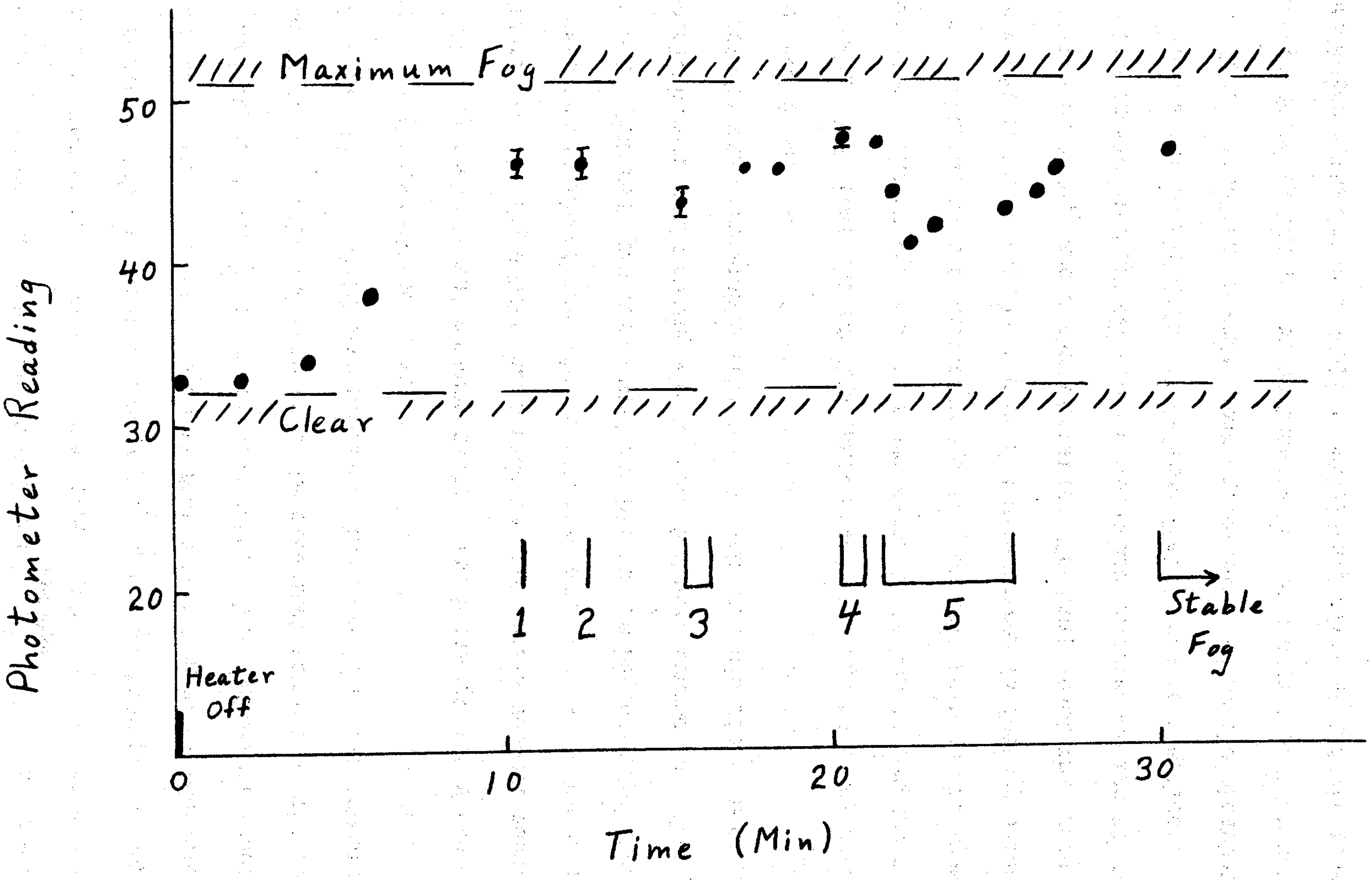

Fig. 3-2. The results of tests 1-5 Temperature 82°F, Relative Humidity 99%.

directly between the screen and the corona head but also included a volume having diameter approximately 5 feet centered on the apparatus. To achieve the maximum clearing it was necessary to apply the voltage for approximately 2 minutes. The time for reestablishment of the fog after the voltage was reduced to zero was approximately the same. This approximate equality of time scales may well indicate that the clearing, as well as the reestablishment, was controlled by a diffusive process. The experiment was repeated twice with similar results each time.

During the interval between tests 5 and 6 the apparatus was modified slightly by placing a heat gun inside the plexiglass support tube. This allowed the inside of the tube to be dried and eliminated corona inside the support. The heat gun was turned off before the beginning of the environmental chamber cycle during which tests 6-9 were conducted. Thus, test 6 is not directly comparable with test 4 since the distribution of corona had been modified.

Fig. 3-3 shows the results (photometer readings vs time) obtained in tests 6-9. The emphasis of this series of tests was to compare the water spray technique with corona techniques. For this purpose the apparatus was modified by installing a grounded wire screen (8 feet by 3 feet) a distance of 5 feet above the apparatus. The purpose of this screen was to provide an elevated ground which would cause injected charge to rise into the fog rather than follow ill-defined field lines to the floor.

Test 6 resulted in some clearing, as recorded by the photometer, which was not noted visually. Since the fog became denser (again as noted by the photometer rather than visually) immediately after test 6 the test was repeated about 3 minutes later. The second test showed no effects on either

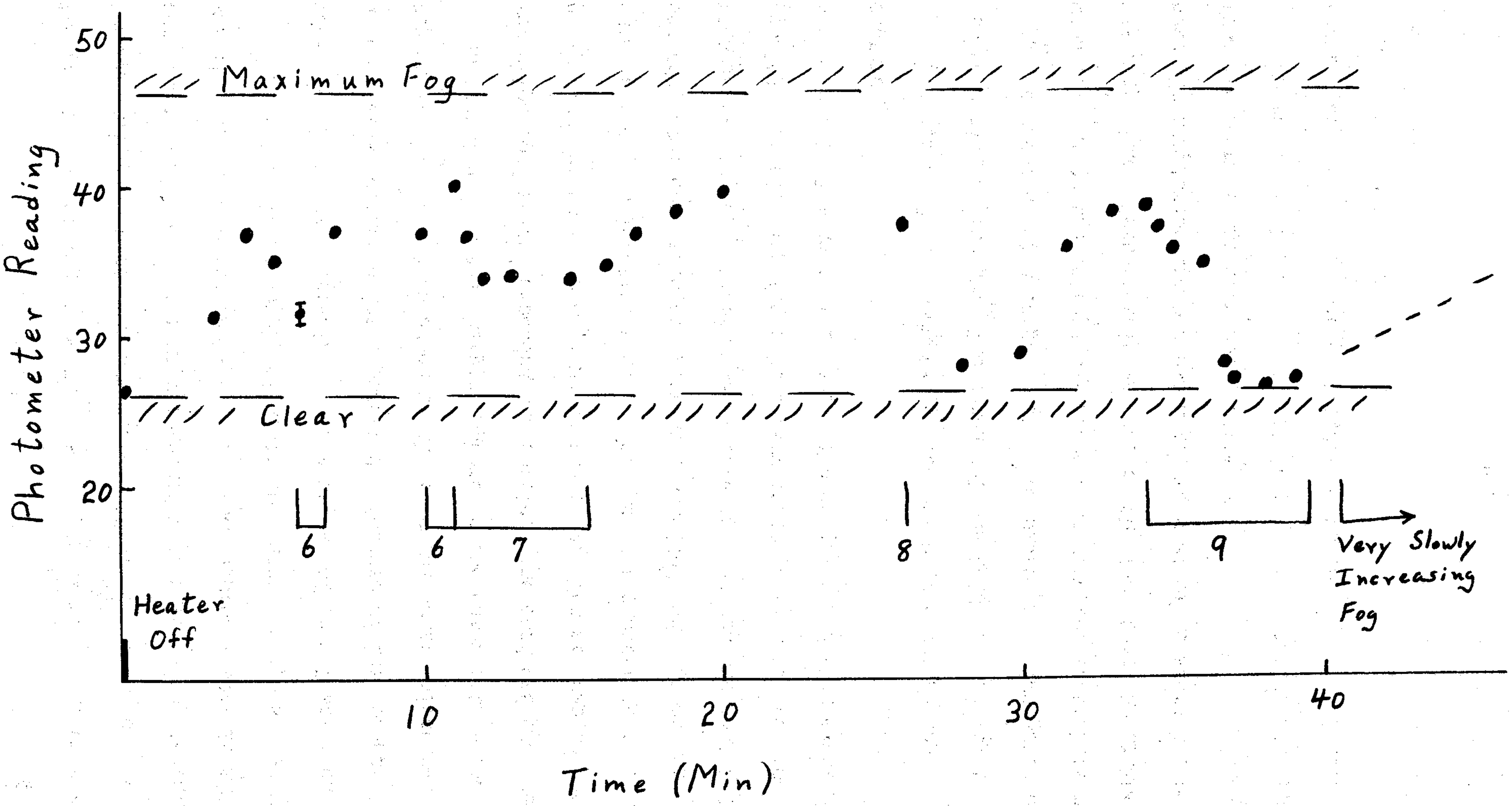

Fig. 3-3. The results of test 6-9. Temperature 82°F, Relative Humidity 99%.

the photometer reading or on the visual appearance. Following this "background" test water was sprayed at 100 kV for 4.5 minutes with clearing consistent with that previously obtained with water spray tests. The fog was then allowed to reestablish. This took approximately 10 minutes.

After test 7 the supply of distilled water ran low so tap water was added to the water reservoir. When a repeat of test 7 was then attempted a semi-catastrophic incident occurred. Because of the conductivity of the tap water which had been added to the reservoir an arc discharge developed which traveled from the charging sphere to the water bottle and up the wet nylon cord which suspended the bottle. The cord was grounded at a pully, located near the ceiling of the room. The arc caused the rope to burn in two at a location about 8 feet above the water bottle. About 30 seconds later our state of excitement subsided and we took note of our surroundings. To our amazement we discovered that the incident had been responsible for clearing fog from a very large portion of the room. It took approximately 7 minutes for enough fog to reform so that experiments could continue.

Experiment 9 was conducted by connecting the corona head and raising its potential to 100 kV. The potential was held at this level for 5 minutes. Complete clearing of a large volume took place in a time scale of about 3 minutes. After the voltage was reduced to zero the reestablishment of fog was very slow. Perhaps this was due to the fact that the chamber cycle was near its completion and because a great deal of moisture had been removed from the room by the previous experiments.

On the next chamber cycle tests were made of the bubble apparatus. The results were very poor since no clearing was noted either visually or in terms of the photometer readings.

From these tests we concluded that the corona method shows promise for warm fog dispersal. However, since these tests were conducted on a small scale compared to field tests, the results may not scale to field conditions.

APPENDIX A. PRELIMINARY EXPERIMENTS SUPPORTING FIELD TESTS OF THE CORONA CHARGING METHOD

In view of the results discussed in the main body of the report it was decided to devote the time remaining in FY 73 to preliminary experiments conceived to support the design of field tests. The purpose of the field tests will be the dispersal of fog by the injection of charge directly into the fog by a corona mechanism. At this point there seems to be so many possible variations and approaches that is likely that a suitable configuration will not be encountered by blind empirical trials. Hence the need for some preliminary information to provide guidance for future choices.

The first question which must be addressed is what is the best method for direct charge injection into the atmosphere. Of course, this question requires prior information before it can be answered since one must know what "best" means in this context. It seems obvious that "best" implies that the most fog is dissipated for the lowest system cost (initial investment and power and other opeating costs), but how is this to be translated into a screening program to select the most promising approach? There is the question of the amount of electrification introduced into the atmosphere. Does the "Chamber of Commerce" answer "More is better" apply here? Or are there differences in the subsequent behavior of the injected charge which reflect different injection mechanisms and which will affect grossly the efficiency of fog dispersal? As a preliminary criterion we shall assume that the amount of charge which can actually be injected into the atmosphere is an important parameter and attempt to maximize it subject to minimizing potential system costs. This means that a penalty should be attached to systems which imply significant construction and design problems and to systems which imply excessive power consumption.

At the outset there seems three distinct approaches which can be taken: a single-ended system, a double-ended system, and an arc discharge system. A single-ended system consists of a high potential electrode system located some distance above the earth (which acts as the other electrode). Single-ended systems seem to offer the lowest power cost approach to the problem since the currents are designed to pass through the atmosphere for most of their path. Some significant potential problems include space charge effects which may make the amount of charge which can be injected by this mechanism too small for effectiveness, and design questions concerning appropriate electrode configuration, elevation mechanisms which do not involve the introduction of nearby pseudo-grounds, etc. A double-ended system consists of an elevated electrode system containing both a high potential electrode and a ground. The chief problems here are associated with the efficiency of charge transfer to the atmosphere since if the charge is confined to the region between the two electrodes it will do little good for fog dispersal. An arc discharge system is a variation of the double-ended system in which an actual arc (sustaining or intermittent) is extablished between high potential and grounded electrodes. This system implies a fairly high power cost, but may produce particles in a higher charge state than the other mechanisms. Appropriate design to maximize charge transfer to the atmosphere is a key to this approach as well as to the approach using the double-ended (corona) system.

Associated with each of the approaches for injection of charges into the atmosphere there are additional significant questions not directly associated with the amount of charge injected. These questions concern the subsequent behavior of the injected charges. To what do the charges attach? What is the ultimate charge state of the electrified particles? Will these particles be effective in disipating fog? Of course this last question is the key question and its answer allows one to bypass the others.

Based on our state of ignorance our initial approach was to seek ways to maximize the amount of current injected into the atmosphere. Since it seemed that the least problem of separating atmospheric currents from internal system currents would be associated with the single-ended system attention was focused on this system. The experimental program consisted of two phases: Laboratory tests of electrode configuration effects in the same facility within which the charge transfer measurements were made, and preliminary outdoor tests to test the deductions made in the laboratory and to seek new effects associated with field conditions.

For the labroatory tests electrodes were substituted for the charging sphere. Currents were monitored by the collector electrode-electrometer system described earlier. The chief results of the laboratory tests were as follows:

1. A number of electode configurations were tested with only slight dependence of the current on electrode design and material. Typically the current-voltage (I-V) characteristics of the electrodes could be fit to the functional form

$$I = I_o [\exp\{a(V-V_o)\} - 1]$$

with I_o, a, and V_o parameters dependent on the electrode configuration. Typical parameters were those obtained for a copper braid electrode

$I_o = 8 \times 10^{-6}$ amp, $a = 36\ kV^{-1}$, and $V_o = 20$ kV. The exponential form and the lack of dramatic dependence of the I-V characteristics on electrode design can best be explained by the assumption that the bulk of the current is generated by secondary ionization processes in the neighborhood of the electrode rather than by direct injection from the electrode.

2. Tests of "multiple electrode" configurations were conducted in which identical electrodes were connected together and located a distance apart. The separation distance was varied and the I-V characteristics investigated as a function of separation. It was found that if the electrodes were sufficiently separated (more than 10 to 20 cm) the electrodes acted resonably independently. However, if the electrodes were too close together the current from the "multiple electrode" behaved more like that from a single electrode. This tends to confirm the deduction noted above that the most important charge injection process takes place external to the actual electrode.

3. For a fixed electrode configuration the current at fixed voltage was measured as a function of the separation between the electrode and the collector electrode. It was found that the current varied by as much as a factor of 10, depending roughly as the inverse cube of the separation. This may be a reflection of nothing more than decreased collection efficiency of the collector electrode since the high potential electrode is surrounded by a ground at a distance of about 0.85 m.

Following the laboratory tests a number of "outdoors" tests were constructed. For these tests the portable high voltage supply was used. This supply is capable of supplying voltage between 0 and -160 kV. It is so instrumented that the high voltage and the current delivered at the high voltage can be determined. For these tests a bamboo mast 25 feet in length was constructed, high voltage electrodes were mounted on the mast. This mast would be erected at various angles to the vertical so that the height of the electrode above the ground could be varied. A collector electrode was constructed of aluminum foil and copper screen mounted on a wooden frame. The collector electrode had an area of 0.67 m^2. Using this collector and the electrometer, current density could be monitored at various locations around the elevated high voltage electrode.

For the outdoor tests two sites were used. Preliminary investigations, which focused on the I-V characteristics of the electrodes as a function of mast elevation, were conducted on a flat grassy area near the academic area at NPS. Subsequently the tests were moved to a location overlooking Monterey Bay. This second site (beach site) was a large leveled area on an old sand dune. The elevation of the site above the beach was about 40 feet. Tests at this site concentrated on I-V characteristics of electrodes and current distributions with varying atmospheric conditions. It was hoped that this site might experience fog conditions, however during the time covered by these measurements only one foggy day occurred and this fog was at an elevation of 200 feet so that no direct experience in a fog environment was obtained.

At the initial site it was shown that identical currents (~50μ amps at 100 kV) were drawn by a simple sharp point electrode for heights between 7.5 and 2 meters. The current density pattern was reasonably symmetric about the electrode. The total integrated current density, determined from the measurements with the collector electrode, was within 20% of the total high voltage current. This finding tends to indicate the the bamboo mast does not act as a major perturbation.

The tests at the beach site were all conducted with the high voltage electrode at the maximum elevation (7.5 m). During these tests there was considerable evidence that breakdown to the bamboo mast played a considerable role in the observed I-V characteristics. As the system was "cleaned up" the total current drawn by the electrode decreased by as much a factor of three from that quoted earlier. Whether this is an indication of undiscovered problems with the measurements at the initial site or indications that the nature of the ground is important is not yet clear. The initial site was a well watered lawn and so should serve as a fair quality "ground electrode". The surface at the beach site was quite dry and so the quality of the electrical ground was much poorer there.

The most significant observation made at the beach site was a considerable wind dependence on the distribution of currents. In a steady breeze (5 to 7 knots) the maximum current density was observed about 6 m downwind from the electrode, rather than directly adjacent. Under these same conditions very little current was observed at distances more than 2 meters upwind or cross-wind to the electrode. In another test in which the winds were lighter, detectable current was measured to 12 meters downwind from the electrode (the maximum distance at which measurements were attempted). No surveys of the total density pattern were made so that the atmospheric currents could not reliably be determined. More extensive surveys will be conducted in the near future.

When measurements were conducted under conditions of variable winds (speed and direction) clear indications of the significance of wind borne charges were obtained. As the wind would shift toward the line between the collector and the high voltage electrode (collector downwind) the current would increase by orders of magnitude and more and then decrease as the wind died or shifted to another direction.

The observation of the wind dependence indicates that at least a portion of the injected charges attach to windborne particles. (It is possible that the particles are small salt crystals in view of the nature of the site.) The wind dependence of the currents indicates that the aerodynamic forces of the winds are sufficient to overcome the tendency of the charges to follow field lines. This may be inferential evidence that the particles are not highly charged. It is also very significant in that it indicates the possibility of distributing charge over a very wide area by direct injection from a fixed site. The observation also has favorable implications for the use of suitable (wide electrode spacing) double-ended systems for mobile use.

The observations which have been so far made constitute but a preliminary step in obtaining the needed information. It is necessary to make more extensive current surveys under a wider variety of atmospheric conditions (including fog). It is necessary to obtain a better indication of the height dependence of current from a single-ended system and to study the injection efficiency (atmospheric current to system current ratio) of double-ended systems. It is necessary to obtain clearer information concerning the possible influence of surface moisture. The measurements have been useful for perfecting measurement and test techniques and have already shown some highly interesting results.

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