

ELECTROSTATIC PRECIPITATION
OF DUSTS FOR AGRICULTURAL
APPLICATIONS

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**ELECTROSTATIC PRECIPITATION OF DUSTS
FOR AGRICULTURAL APPLICATIONS**

By

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AN ABSTRACT

**Submitted to the School of Graduate Studies of Michigan
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THESIS

ELECTROSTATIC PRECIPITATION OF DUSTS FOR AGRICULTURAL APPLICATIONS

A study of certain aspects of the electrostatic precipitation of agricultural dusts has been made. The principal reason for the study has been the need for more effective precipitation of dusts on vegetation for the effective control of the diseases and pests of agricultural crops. The electrostatic precipitation of agricultural dusts is accomplished by placing an electric charge on the individual dust particles.

Laboratory experiments in which the individual dust particles were given an electric charge resulted in an increase in the amount of the smaller particles that were deposited on plant foliage. These favorable results give promise for possible field application.

Specific tests were performed to show the relation of dust deposit as a function of the distance from the charging nozzle and the effect of relative humidity on the precipitation of charged particles.

The particles are charged by passing the air-dust stream of a conventional field dusting machine through an electric charging head. An ionized inhomogeneous electric field is produced within the charging head by the corona discharge formed around a thin wire connected to a high potential source. The ionized electric field charges the particles to one electrical sign.

The theory of particle charging is given in some detail and a general discussion of the forces active in precipitating charged particles is presented.

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INTRODUCTION

For many years disease and pest control of field crops has been accomplished either by spraying or dusting of the various insecticides, fungicides and herbicides. Dusting has been secondary to spraying on many crops because of inherent inefficiencies of the dusting method and because some of the control materials are normally liquid.

Sprays are known to have greater sticking qualities than dusts, and spray residues do not wash off as readily as dusts during rains. Dusting on the other hand, is a much simpler process than spraying and requires less expensive machinery. Sprays have the added disadvantage of requiring relatively large quantities of water that are usually not readily available in the field.

In the conventional dusting machine and with sprayers it has been observed that only those plant surfaces directly facing the discharge nozzles get thorough coverage. Coverage in spray or dusting work means the amount and distribution of control materials on a plant surface. The resulting poor coverage on the under sides of outside leaves and on all surfaces in the interior regions of the plants has been of concern to workers in the spraying and dusting fields for many years. The insects often feed on the under surfaces of plants as these surfaces are shaded from the sun and from the sight of birds. Thus it is important that the control materials are placed on the under sides of the plant surfaces for insect control. Disease control is effective

only when all surfaces have good coverage, since the disease organisms do not in general do any moving and the control material must be brought to them.

A great deal of work has already been done to improve the spraying method, but a relatively small amount of work has been done with the dusting method. Dusting could be a much more advantageous method than spraying if its effectiveness could be improved. For the above reasons and because it appeared that it would be easier to work with dusts than with sprays in the laboratory, the improvement of coverage in the dusting method through the use of electricity has been attempted.

The electrostatic precipitation of agricultural dusts is the technical name given to the process of increasing the deposition of an agricultural dust by means of charging the individual dust particles.

Review of Literature

A review of literature has revealed some very interesting information related to the problem. Dr. Fred Potts (1946) of the Connecticut Storrs station has the following to say about the relation between particle size and deposition of control materials under field conditions.

Recent developments in the application of insecticides in the form of smokes, liquified-gas, aerosols and finely atomized sprays, with equipment operated from the ground and from aircraft, have attracted attention to the significance of particle or droplet size as a factor in determining deposit, distribution and effectiveness of dusts and concentrated sprays. Under field conditions extremely minute individual particles of finely ground dusts, insecticidal smokes, finely atomized aerosols and concentrated sprays are not deposited on the surfaces of plants, insects and other objects. Apparently such objects are surrounded by a film, or field of resistance, the nature of which is not known and through which minute particles cannot penetrate. An electric field around such objects may possibly cause a repulsion of minute particles.

Potts expressed the opinion that for the application of concentrate sprays with ground equipment the optimum range for diameter of droplets should be between 30 and 80 microns because tests have shown that there is very little deposition of droplets of less than 20 microns diameter and only a very few are deposited unless the droplet diameter exceeds 30 microns.

The author is inclined to believe that the barrier next to the plant and insect surfaces mentioned by Potts is of thermal origin rather than an electrostatic field. The reason for this belief is that neutral particles would be attracted to an electric field because of electrostatic forces set up by an electrical process known as induction.

Other interesting information on particle size and disease control was given by Wilcoxon and McCallan (1931).

The adherence, following an artificial rain treatment to glass slides and leaves, depends on the degree of fineness of dusts, the smaller particles being the most adherent. For a given dust an increase in the amount applied results in a decrease in the percentage adhering. The adherence to leaves is in general greater than that to glass slides and increases with the roughness and hairiness of the leaf surface.

The most important single factor determining the toxicity of sulfur dust is the number of particles furnished by a unit weight of the material. The greatest number of particles is furnished by the dust of the smallest mean particle diameter as measured above, and the dust of the smallest mean diameter is most adherent, and will give a denser distribution for a given weight. This relation between particle size and toxicity seems to hold within wide limits from relatively coarse particles down to those of colloidal dimensions. The dust having the highest toxicity as determined by these tests is not necessarily the one showing the best dusting qualities.

In the interest of economy of material for disease control at least it would be advantageous to use dusts with a relatively small particle size. There is approximately one thousand times as many

particles in a given weight of material of two microns diameter as compared to the same weight of material with particles of twenty microns diameter.

Wilson, James, and Campen (1944) performed some interesting experiments concerning the role of the electrostatic charge in dusting as is produced in the ordinary dusting machine due to frictional electricity.

The principal cause for some differences in aphid control seemed to result from poor dispersion of dust particles to aphids feeding on the underleaf surface. If little or no charge was produced the dust particles tended to aggregate and did not give a fine dispersion on the underleaf surface. If a relatively high charge was produced the dispersion of finely divided dust particles on stems and the underleaf surface was greatly increased. Theoretically these conditions may prevail due to differences of electric potential in the dust cloud which in turn causes the charged particles to repel one another and to be drawn to the plant by the opposite induced charge.

To what extent electrostatic charges may effect dust dispersion and insect control under field conditions is yet to be determined. The sign and charge was found to depend on several factors. Particle size was an important factor, large particles, 40 μ generally gave high charges. Very fine particles, 2 μ or less in size as are found in sedimentary clays, generally produced very low charges. Rapidity of dispersion, atmospheric conditions and quantity of materials are other important factors. In the laboratory the records were taken with temperatures between 80 and 85° F. and a relative humidity between 30 and 40 per cent. The voltage produced by any material was found to decrease with lower temperatures and increased with higher temperatures. Not much change in the voltage was observed with a relative humidity of 40 per cent or less. When the relative humidity was increased to 50 per cent the voltmeter either did not record a voltage or lost it too quickly for making satisfactory records.

Regardless of the sign of the charge, materials of the same nature reproduced charges of the same sign. Materials high in silica always gave a (+) charge on the blower and a (-) charge in the dust stream. Dusts of plant or animal origin always produced (-) charges on the blower and (+) charges in the dust stream.

When dusts capable of developing electrostatic charges were blown against plants an induced charge opposite to that of the dust was imparted to the plant and carried for the full length of the plant.

The above work was done in the laboratory and consisted of measuring the electrostatic charge accumulated by 0.5 cc of various insecticidal, fungicidal and diluent dusts as they were blown through a roughened nozzle. An electrostatic voltmeter was used to measure the charge.

Other Facts Related to The Problem

The conventional dusting machine employs air-dust mixture velocities of the order of sixty miles per hour at the discharge nozzle for several reasons. First, there must be sufficient velocity to prevent deposition of dust in the flexible metal distribution tubes. Secondly, wind velocities amounting to between five and ten miles per hour are encountered in field dusting conditions. The discharge nozzle velocities must be sufficient to prevent too great deflection of the dust stream in passing from the nozzle to the plant. Lastly, there must be sufficient velocity of the dust stream to penetrate the interior regions of the plants.

The dew is an aid to the sticking of the dust to the plants and so a good deal of the dusting is done under conditions where the plants are wet and the relative humidity at the plant near one hundred percent.

From the material gathered from the review of literature several important ideas regarding the nature of the problem have been revealed.

1. A resisting film of some kind is present near the surface of plants and other objects under field conditions.
2. Particles under twenty microns diameter seldom penetrate this resisting film under gravity forces.
3. The toxicities of some fungicides are proportional to the number of particles and not the size of the particles on a leaf surface.

4. Electrostatic forces play a part in the dispersion of dusts under laboratory conditions and dusts exhibiting a relatively high charge seem to provide a better kill on aphids than dusts exhibiting a low charge.
5. All of the dusts used for control materials exhibit some characteristic charging effects when blown out of the nozzle of a dusting machine.
6. Duster discharge nozzle velocities of between four thousand and five thousand feet per minute will be necessary with any type of duster to keep the distribution tubes clear, to prevent a great deflection of the dust cloud due to the wind, and to cause the air-dust mixture to thoroughly penetrate the interior regions of the plant.
7. A considerable saving of control materials would probably result if the particles between five and ten microns could be more successfully precipitated.
8. Any dusting machine must be capable of operating at relative humidities of near one hundred percent to be accepted for general use.

The conventional dusting machine has been obtaining good coverage on the surfaces facing the discharge nozzles for the reason that the high velocity of the dust-air stream is sufficient to allow the larger dust particles of the mixture to penetrate the resistive film that surrounds the leaf. On the other hand, the low velocities associated with the interior regions of the plant are not sufficient to allow the particles to penetrate the resistive film.

The large particles are dropped by the air stream as the velocity of the air stream is reduced and so it is to be expected that the larger share of the particles that are circulated to the undersides of the leaves are the smaller particles. Experimental observation has shown this to be true.

Statement of The Problem

Now that the factors involved are known, attention can be given to defining the problem in general terms and specifically.

In general terms the problem is to provide an improved coverage of the under surfaces of the outer leaves and of all surfaces in the interior regions of the plants, and to do so with less of the control material than is necessary with the conventional duster.

In specific terms the problem is to charge all of the particles to one sign, and to place those particles, with their charge intact, close to the plant surfaces to be coated.

APPARATUS AND METHODS

General

The theory of electrostatic precipitation is rather long and has been included in Appendix I. Suffice to say the theory requires that the individual dust particles be charged by some means and transported to the plants with the charge intact. The dust particles must be physically placed within a small fraction of a centimeter from a plant surface before their paths are greatly influenced by the electrostatic forces involved. Many people when first informed of the method, picture the particles being attracted to the plant from quite an appreciable distance, but unfortunately this is not the case. We still have the need for good dusting machines that will place the dust near the surfaces to be coated.

Other Methods Using

Charged Dust

In the past, some considerable work has been done in France on charging the dust particles by means of the friction between dust and air provided by high velocity air jets. The method, as does any friction method yet tried, breaks down rapidly at relative humidities above sixty percent. For the ground operated model the air supply required is quite large.

P. Hame and others of France have developed a method of charging the particles by means of the electric field set up between a charged

thin wire or metal points and the plants when the wires or points are suspended above the plants at a distance of fifteen to fifty centimeters. The particles are charged and precipitated by the same electric field. The dust is blown into the electric field by the usual methods. Some considerable decrease in the amount of dust required for the job has been reported when using Mr. Hampe's method. A complete test of the equipment is to be made (1951) by an Agricultural testing agency of the French government. The method differs from the work described in this thesis in that a separate particle charging chamber is not used by the French, but is used in the experiments of this paper. The voltages required by the French machine are considerably greater than those required by the method here described.

Equipment Used For Charging Particles

A high potential of either positive or negative sign was needed for charging the particles and producing the electric fields of the experiments. The negative potential is the most efficient for charging dust particles as regards power consumption. Also the negative corona is more stable than the positive corona. This is explained in Appendix I.

The power supply that was purchased for this work produced a high potential of the positive sign and a good deal of work was done with the positive high potential. Later the power supply circuit was altered so that it produced a negative potential. The only difference in results noted, due to the change, was that less current was required to produce the same results with the negative. There may be other differences as regards charging at high humidities that have not shown up as yet.

The power supply (high voltage) was purchased from a manufacturer of electronic equipment, and has a maximum output of 30 KV D.C. potential at 1 milliamp, and requires 300 volts D.C. at 150 milliamps input. In the laboratory this was supplied by a plate power supply unit with a variac to vary the voltage. This was operated off a 110 volt A.C. line.

For test purposes in determining the value of inducing plates, on the charge induced on the plants, two different high voltages were needed at one time. For this reason a voltage divider was built up. The voltage divider was constructed by soldering, in series, 22 ten-megohm resistors. The resistors were insulated from the backing board and the wires between them were left bare so that one could tap the voltage off between any pair of resistors.

The charging head through which the dust passed consisted of a small wire of critical diameter and a geometrical arrangement of parts so that relatively low field intensities were produced in the greater cross-sectional area of the charging head. Even in the low intensity regions the electric field is of the order of from 1000 to 3000 volts/cm. Corona voltages were produced in the immediate vicinity of the wire, and it was there that the ions for charging the dust particles were formed. In all, four dust charging heads were devised and the later two have been described in detail in the following pages. The first attempts served to show that the basic concepts were sound but their inherent limitations led to the adoption of the more satisfactory heads described in detail.

The designing of a suitable dusting machine was hampered by problems of accurately metering small amounts of dust. A great deal of

effort was wasted in the design of a metering mechanism that would meter accurately enough for test purposes. The continuous metering principle was abandoned in favor of using a measured volume of dust for each plant or test plate.

A Ford automobile centrifugal defroster fan was used as a blower and was placed with its air inlet up. A pair of branching ducts were attached to the outlet of the fan. A four foot length of flexible steel tubing was attached to each of the ducts to carry the air-dust mixture to the charging heads. The charging heads were arranged to face each other. This arrangement was selected to produce a gently turbulent, but low velocity dust cloud around the plant surfaces or metal plate. The fan intake was throttled to produce a low velocity air-dust stream at the discharge nozzle and yet have the fan speed high enough to shatter the dust as it was introduced into the fan intake.

The evaluation of dust deposited on a leaf is a complex problem and allows no simple method to be used. Evaluation of deposits of lead arsenate on a leaf may be made in a qualitative sort of way by a printing technique that has been in use by the horticultural department for some years. The method results in a deposit of lead sulfide being formed where ever a particle of arsenate of lead had been on the leaf. The method is very useful in determining relative amounts and distributions of the dust on leaves. The method has the further advantage of allowing both the fronts and backs of the leaves being evaluated at one time. A comparison of the dust deposited on plants with two methods of charging and just ordinary dusting has been included in a later section.

A more direct method of measuring dust deposits was needed for numerical evaluation of the results of the various tests. The most satisfactory method yet turned up was conceived by a co-worker, Mr. Peter Hobblesmith. The method utilizes a blackened metal disk onto which the light colored dusts are precipitated. The deposits are evaluated by directing reflected light off the disks into a sensitive lightmeter. However, there is no direct correlation between the amount of light reflected and dust deposited.

In this manner it was possible to quickly evaluate the amount of dust precipitated per cm^2 of surface area. The lightmeter registered very low values for plain blackened disks, but increased for larger amounts of dust. In this manner dust deposits that could barely be distinguished by the naked eye could be assigned definite values with the lightmeter. The range for no dust to a thin white coating with very little black showing through was from two to a hundred or more foot-candles.

The high voltage power supply was operated off a 300 volt D.C. plate power supply which was operated off 110 volts A.C., and the dust fan was operated off a six volt lead acid storage battery. In the field the power supply will be operated off a dynamometer that is designed to run off of the tractor battery system.

The first dust charging equipment as shown Figure 1 was powered by the power pack of a Westinghouse precipitron. It had taps for 13,000 and 6,000 volts negative potential. There were two serious drawbacks to this arrangement. The dust was reluctant to pass through the grid and a good deal of it passed around instead of through the

grid. The arrangement of the charging wires and the fact that they were of the same diameter for both the anode and the cathode resulted in a rather inefficient field for charging the particles.

The results of the first test were not significant except that they served to show the weaknesses of the charging grid and that dust was more active in collecting on the charged plant and with charged dust than when uncharged. As can be seen by referring to the sketches, the ground side of the power supply was connected to the plant. This charged the plant to the positive sign by drawing the electrons off the plant and placing them on the charging wires of the grid. This resulted in a decided fringing of the dust collected. The dust collected on the points and edges of the leaves as was predicted by the theory of charge distribution. Since it would be impossible to isolate a plant from the ground and give it a charge by attaching the ground of the machine to it in the field, all further efforts were directed toward charging the plant by means of induction.

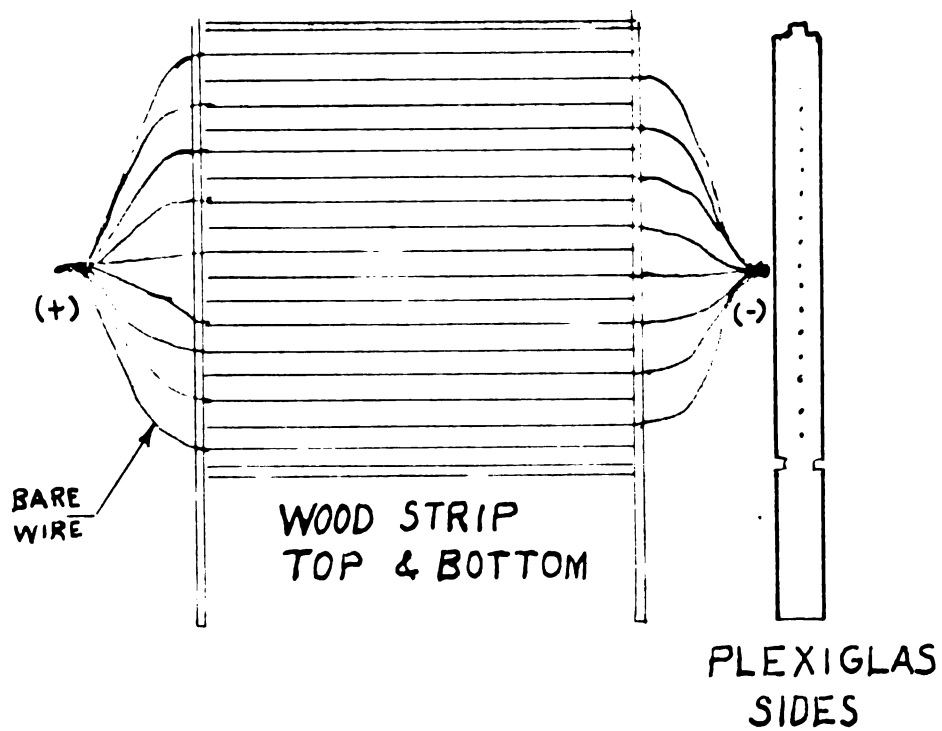
In the induction process there is no direct connection between the electrical parts of the machine and the plants being charged.

With the weaknesses of the first grid in mind, a closed charging head was designed to fit on the outlet of a Ford auto defroster fan. This was to insure that all of the dust would go through the charging grid. This charging head is shown in Figure 3. The induction effect was worked into the design of this head by arranging the grid so that there were two planes of closely spaced wires. The planes of wires were insulated from each other and from the rest of the head by a strip of

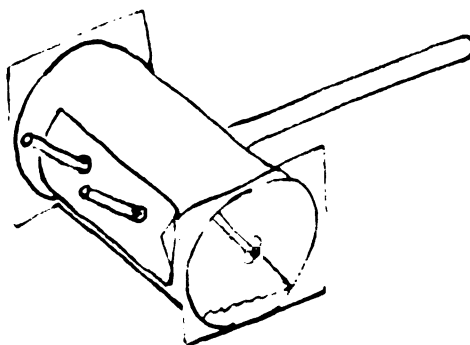
Fluorides. The rearmost plane of wires was given a voltage of near 30,000 volts and the front plane that would be closest to the plant was placed at 17,000 volts positive potential.

The third charging head is pictured and described in detail and was patterned after the Westinghouse precipitron particle charging chamber. A wire of .008 inch diameter was centered between two aluminum half-pipes, Figure 4. This charging head was attached to the dust discharge nozzle as shown in the photograph, Figure 5. The theory of this charging head is included in Appendix I. This head was used for all of the tests described in this paper. It is a low velocity head and will probably find small use except perhaps in greenhouses and places where little wind would be encountered.

The fourth head shown in Figure 6 is a high speed head designed for air-dust velocities between thirty and forty miles per hour. This charging head is an adaptation of the Cottrell fine gas precipitator and is to be operated at velocities sufficiently great to practically prevent precipitation of the dust particles within the unit. This charging head has only been subjected to preliminary tests.



FIRST CHARGING GRID



FIRST DUSTER

Figure 1 Charging grid and duster used in first electrostatic precipitation test

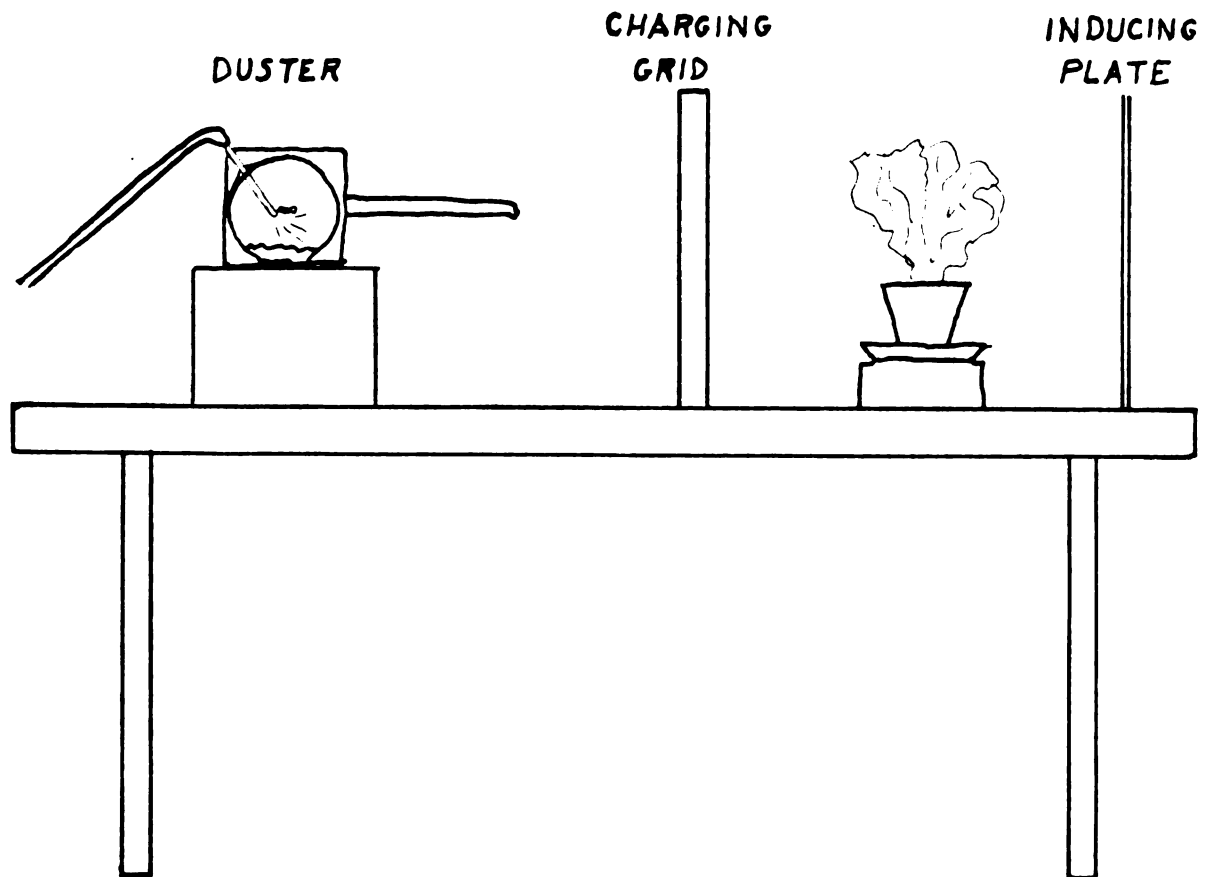


Figure 2 Arrangement of duster, charging grid and plant for first electrostatic precipitation test of this investigation

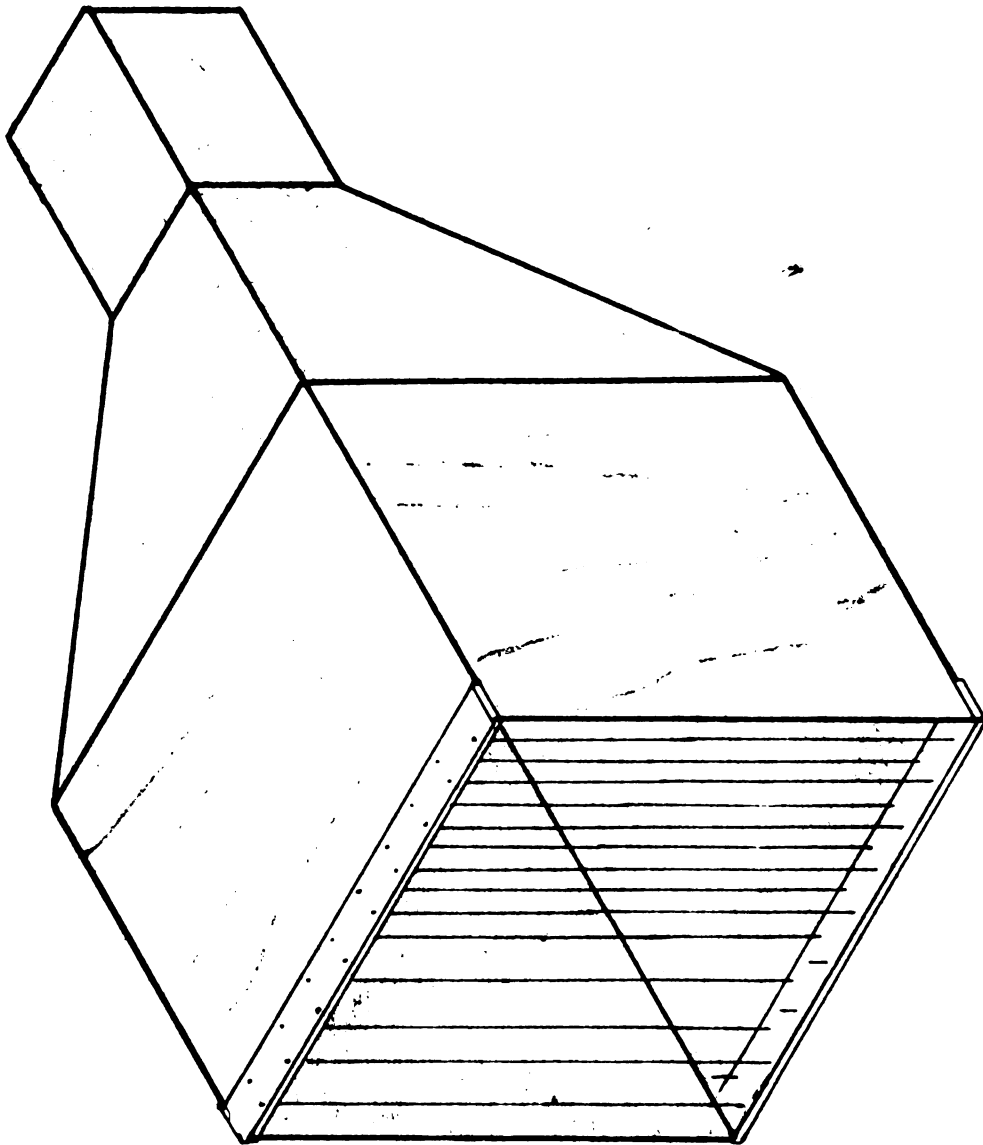


Figure 3 Second charging head built utilizes two planes of wires for the charging field

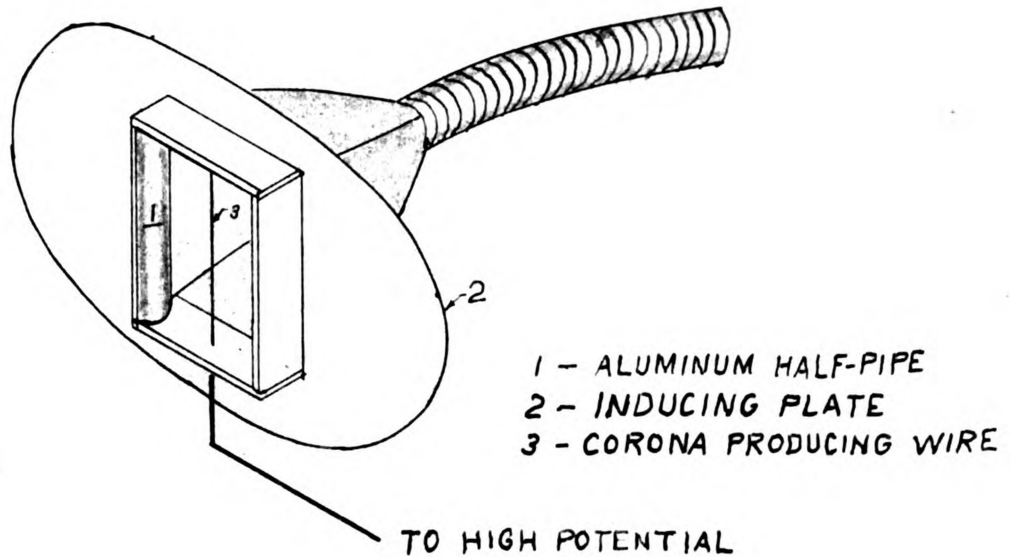


Figure 4 Sketch of low velocity charging head used for relative humidity test, distance test and bean plant test



Figure 5 Manner of attachment of electric charging head to dust distributor tubes

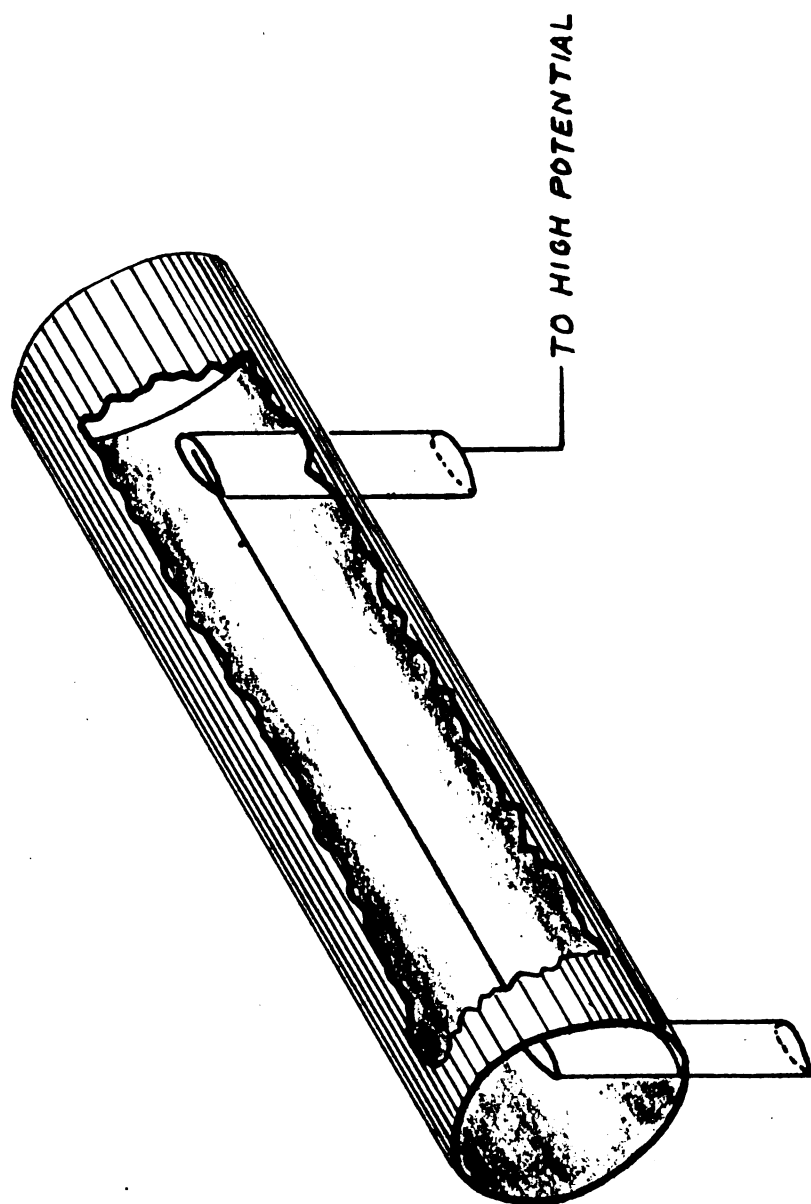


Figure 6 High velocity electric charging head

**DUST DEPOSIT AS A FUNCTION OF
THE DISTANCE FROM THE
CHARGING DEVICE**

General

The practical importance of electrostatic dusting as a field method will depend to a large extent on the distance from the charging device that the charged dust is effective in increasing the deposit. Any increase in the dust deposit due to the charge will have disappeared when the particle has become discharged.

It is not known how quickly, in seconds of time, a charge on a dust particle is lost, and undoubtedly this time varies with conditions. The practical application is not concerned with how the charge is lost, but rather how long and for what distances from the charging device the charged dust can be expected to exhibit attraction characteristics.

The manner in which particles are electrically discharged is of importance in the design of equipment and the methods of application. This is discussed in Appendix I.

The following experiment was conducted to obtain some conception of the distance from the charging device that originally charged dust is effectively precipitated. To demonstrate this, a comparison was made using an uncharged cloud as the standard.

Test

Apparatus and Methods

The test to determine the effect of distance on precipitation was carried out as follows at the USDA Pest Laboratory at Toledo, Ohio: The dust cloud was blown into the open end of a tunnel with the air in the tunnel moving at one-half mile per hour in the direction of the entering dust stream. This air drift in the tunnel was accomplished by drawing the air from one end of the tunnel with a large fan, Figures 7 and 8.

The purpose of the tunnel and moving dust stream was to show the relation of the amount of dust deposited by a slow-moving cloud of dust to the distance from the dust nozzle.

Three-and-one-half inch metal disks coated with carbon black were put in the tunnel at distances varying from two, four, six, eight, twelve, sixteen, twenty-four and thirty-two feet from the nozzle. The collecting surfaces were arranged as shown in Figure 11. The blackened disks were hung on standards that positioned the surfaces at the central axis of the tunnel. The collecting surfaces were facing the dust stream and were grounded to the water system of the building.

The tests were made by passing dust through a charging device. When the current was on, the particles were charged to the positive sign, and when the current was off, there was no intentional charge put on the particles.

The dust was passed into the air stream at the rate of one-fourth pound per minute for a period of fifteen seconds. The dust machine was

a small Peerless model having a nozzle velocity of about five thousand feet per minute. The dust used was a white tale having an average particle diameter of 0.6 microns.

Observed Results

An idea of the results of this test may be obtained by studying the photograph of the dust coated disks in Figure 10.

The top full row of disks show the deposits of the uncharged dust cloud at the various distances from the charging nozzle. Reading from left to right, the disks are, A to H, at two to thirty-two feet distances from the nozzle of the charging device. These disks all were placed at three feet above the floor of the tunnel and along the tunnel axis.

The second row containing two disks, C' and F', was for the uncharged cloud, and these two disks were at stations C and F. They were placed at six inches above the floor and were used as indicators to determine how well the dust cloud was diffusing from the central stream.

The third row of disks represents the deposits of dust accumulated when the dust was charged for each of the stations A to H. The fourth row of two disks at stations C and F were to indicate the extent of diffusion of the dust cloud.

The single disk in the center and at the bottom of the group was a check disk. The check disks were blackened disks and were not subjected to dust. They were used for getting more readings of the light-meter.

The lightmeter readings verify the visual observation that the deposit of the charged dust was significantly higher than the uncharged dust for all distances from the duster nozzle.

Discussion of Data

The resulting lightmeter readings for the various stations are recorded in Table I. There were two repetitions of the complete experiment. Unfortunately the experiment took considerable time and more repetitions could not be obtained in the one afternoon; however, the results for both repetitions agree closely enough to show the general relations desired.

There is approximately one unit increase in the value for each station except A on the second repetition of the uncharged dust test. This can be partially explained by the fact that the tunnel fan was not turned on before the dust stream was started. The fan was turned on as soon as possible after it was discovered that it was not on, but it appears that the delay caused an increase in the deposit.

There is a considerable variation in the lightmeter readings of station A, which it is felt is largely due to the presence of large agglomerates of dust thrown onto the plate by the duster. The readings are high for both the charged and uncharged dusts at station A due to the same type of agglomeration. There were a few small agglomerates of dust on the disks at station B, but none for the rest of the stations. The relative values of dust collected would remain about the same at station A since both the charged and the uncharged disks reflected about the same amount of light due to the agglomerates.

The readings for the check disks have been subtracted from the lightmeter readings of dust coated disks. This is the correction for the zero reading of the meter. The averages of the test readings, the correction for the zero reading of the meter, and the ratio of the net lightmeter readings, charged over uncharged, are given in Table II.

Analysis and Conclusions

The factors largely influencing the amount of dust deposited, when the dust is uncharged, are the velocity of the air-dust stream and the density of the air-dust stream (number of particles per unit volume).

The factors largely influencing the amount of dust deposited, when the dust is charged, are the velocity of the air-dust stream, density of the air-dust stream, the value of the field intensity surrounding the collecting surfaces induced by the space charge, and the amount of charge on the particle as related to the mass of the particle.

The lightmeter readings show more than a six hundred percent increase in reading due to the charge for station A. At station B there was a large decrease in the amount of dust collected for both charged and uncharged dust as compared to the deposits at station A. For the uncharged dust this decrease is due to the decreased density of the dust cloud and the decreased velocity of the air-dust stream. For the decrease of the charged dust deposit from station A to station B there is the decrease in velocity, the decrease in density of the air-dust stream, the decrease in the space charge induced field, and the decrease in the charge on the individual particles.

There are too many variables to accurately determine the percentages of decrease in deposit that are due to the separate factors, but the net

effect is to yield a much greater deposit at each station in the case when the dust is charged as compared to the case when the dust is uncharged.

The indicator disks and visual observation showed that the dust stream had not diffused to the extent of a homogeneous density throughout the tunnel cross section even at station F.

The lightmeter readings showed that the amount of dust collected at thirty-two feet from the nozzle when the dust was charged was slightly greater than the amount of dust collected at four feet from the nozzle when the dust was uncharged. The increase in deposit due to the charge is five hundred percent or higher for each station.

The conclusion that may be drawn from this experiment is that ~~under the specific circumstances,~~ the charged particles considerably increase the precipitation of dust from a slowly drifting cloud for any distance up to thirty-two feet. It may be speculated that the charged dust would exhibit the increased precipitation for a much greater distance.

This test was run under conditions that could hardly be expected in the field as the relative humidity was only 44 percent, the wind velocity very low, and the diffusion of the dust stream confined. There is a distinct possibility that a great deal more of the charge on the particles would be lost and a consequent decrease in deposit result if the dust were free to diffuse into the open air. After the tunnel was completely filled, the diffusion was restricted and the source of neutralizing ions was also restricted to those already in the tunnel.

It may be safely stated that the charging of dust will give a substantial increase in the deposit of dust deposited by a dust cloud drifting at very low velocities for distances up to and including sixteen feet from the charging source. This does not exclude the possibility of an increased deposit for much greater distances.



Figure 7 View of equipment and tunnel used for distance test



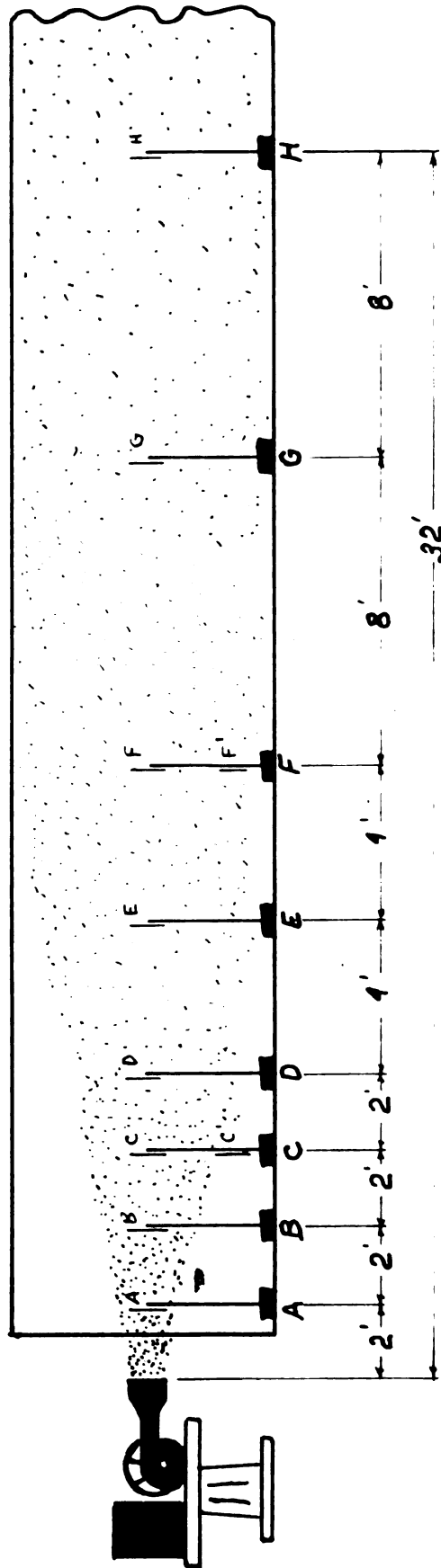
Figure 8 View of equipment and tunnel used for distance test



Figure 9 View of equipment used for distance test



Figure 10 Blackened collection disks showing results of charged and uncharged dust as a function of distance



LOCATION OF STATIONS IN TUNNEL

Figure 11

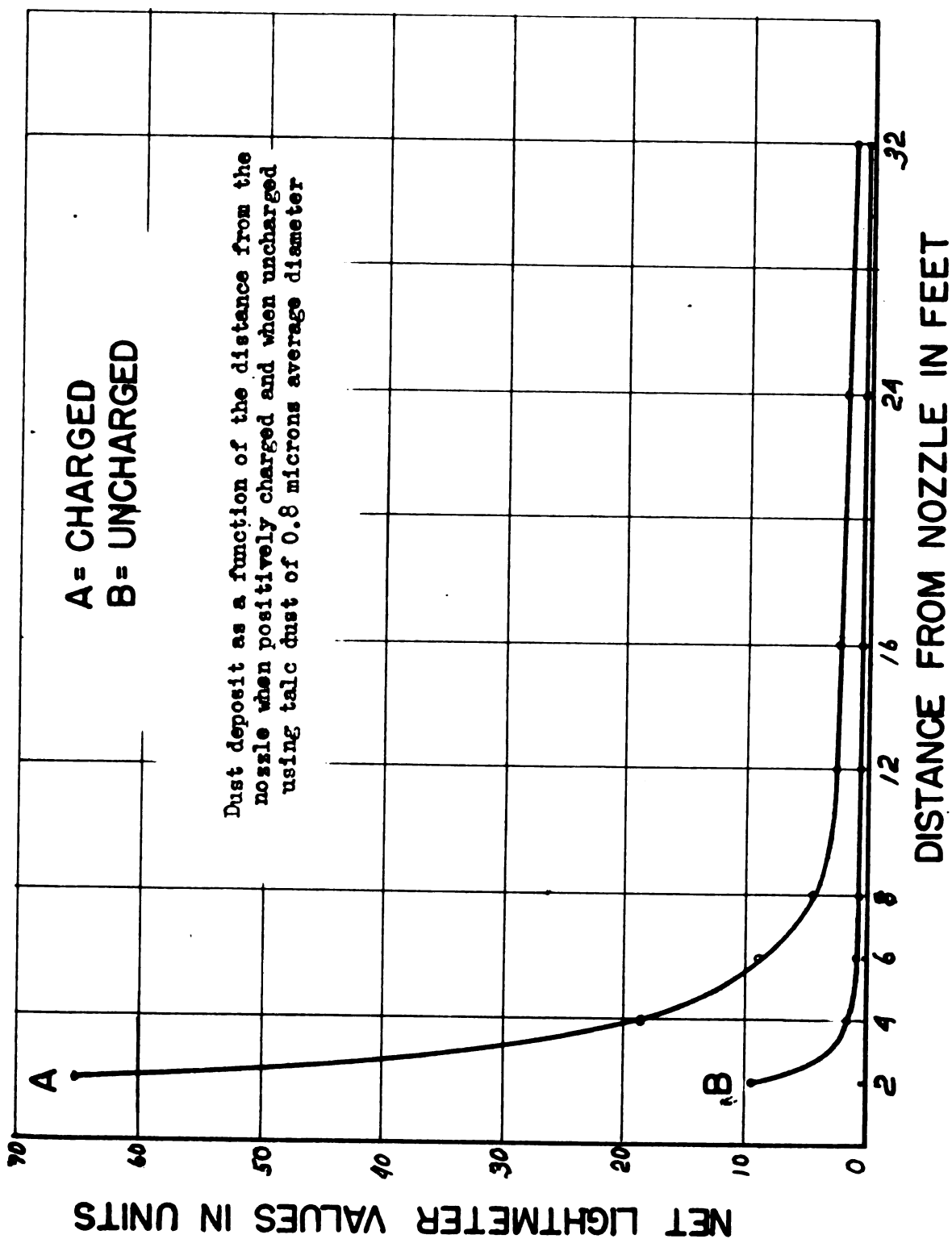


Figure 12 Net lightmeter values of light reflected from dust deposit as a function of distance from the nozzle

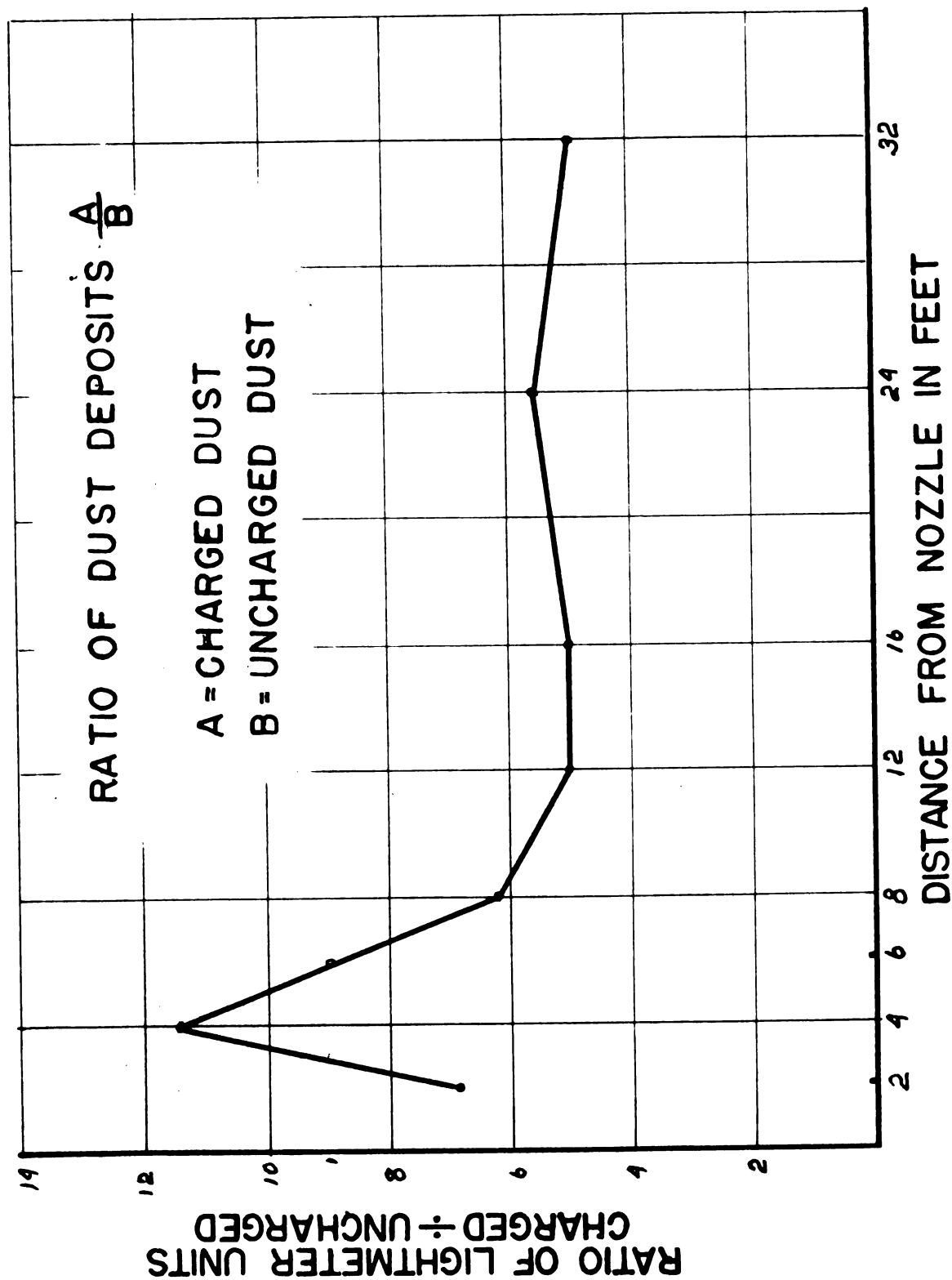


Figure 13 Ratio of net lightmeter units as a function of distance from the nozzle

**RELATIVE HUMIDITY AND ITS EFFECT ON
ELECTROSTATIC DUST
PRECIPITATION**

General

The effectiveness of any control material on disease or pests depends to a large degree on the timeliness of the application. Often this means that the farmer must make a particular application within a period of one or two days or the control measures are ineffective.

The relative humidity may vary as much as fifty percent in a single day in Michigan. The farmer cannot wait for a particular relative humidity to do his dusting work. This means that he may be forced to dust under widely different relative humidity conditions in a single day. Friction charging breaks down at relative humidities of around 90 percent and higher, Wilson (1944); therefore, the increased deposit due to the electric charge is not realized at relative humidities above 90 percent. With the above considerations in mind, it was thought necessary to determine the effect of relative humidity on the precipitation of dust when charged by the method used in this investigation.

Apparatus and Methods of Test

The increase in dust deposit due to charging the dust particles has been thoroughly demonstrated for relative humidities below 90 percent but has not been demonstrated for relative humidities from 90 percent to 100 percent. The effectiveness of the method at various

relative humidities will be compared to the effectiveness at 45 percent relative humidity since the other tests of this paper were run at close to 45 percent,

A single dusting nozzle was used for this test and had the inducing plate (2) of Figure 16 removed. The collection disk was placed at 24 inches from the wire (3) of Figure 14 and the disk was positioned with the faces parallel to the direction of the air-dust stream.

The arrangement of the apparatus is shown in Figure 14. This arrangement in a large part eliminates the effect of velocity on the amount of dust precipitated. There was little chance for agglomerates of dust being thrown onto the disks and giving rise to possible error in the evaluation.

The test was primarily to show the effect of relative humidity on the precipitation of charged dust. There were three disks dusted at each relative humidity value tested for the charged dust and only one disk dusted with uncharged dust at each relative humidity value.

It was felt that for a survey test, increments of ten percent over the range of 40 percent to 100 percent would show the general trend for the effect of relative humidity on electrostatic dust precipitation. The results of this test would then show any particular relative humidities that should be studied in further detail.

The test was performed in a large walk-in refrigerator. The relative humidity of the atmosphere outside of the refrigerator was 36 percent. The relative humidity of the refrigerator was raised by allowing steam at atmospheric pressure to pass into the refrigerator. The

electrical equipment was removed from the refrigerator to prevent condensation and the resulting short circuiting of the equipment.

It was a very difficult matter to control both the relative humidity and the temperature with the equipment available and as a result the 100 percent relative humidity test was run at a higher temperature than the test at the rest of the relative humidity values.

The air-dust stream velocity at the disk position was 640 feet per minute and the charging current was 75 microamps. A level half teaspoon of talc dust of average diameter of 1.5 microns was used for each disk. The results of the test was given in Table III and Table IV and are shown in graphical form, Figure 15. The points do not fall on a smooth line and, therefore, an approximate curve was drawn through the means of the values of the adjacent points.

Discussion and Conclusion

The mean curve of Figure 15 is used as a basis of discussion. At 70 percent relative humidity the net lightmeter value is approximately eighty percent of that of the net lightmeter value at 45 percent relative humidity. At 85 percent relative humidity the net lightmeter value is approximately sixty percent of the net lightmeter value at 45 percent relative humidity. At 100 percent relative humidity the net lightmeter value is approximately thirty percent of the net lightmeter value at 45 percent relative humidity.

The indication from this test is that the amount of dust deposited decreases as the relative humidity is increased over the range of 45 percent to 100 percent. The approximate value of the dust collected at

100 percent relative humidity is one-third of the amount collected at 45 percent relative humidity.

It is not known at this time whether the decrease in deposit with the increase in relative humidity is due to a decrease in the effectiveness of the charging mechanism or whether the dust particles gain mass by absorbing water. This could conceivably reduce the charge over mass ratio enough to account for a large portion of the decrease in deposit.

Further studies on this problem may reveal the nature of the decrease in deposit.

The single disk for the no-charge test generally read very low values. No net lightmeter value of the no-charge group compares favorably with the net value of the charged dust for any value of relative humidity.

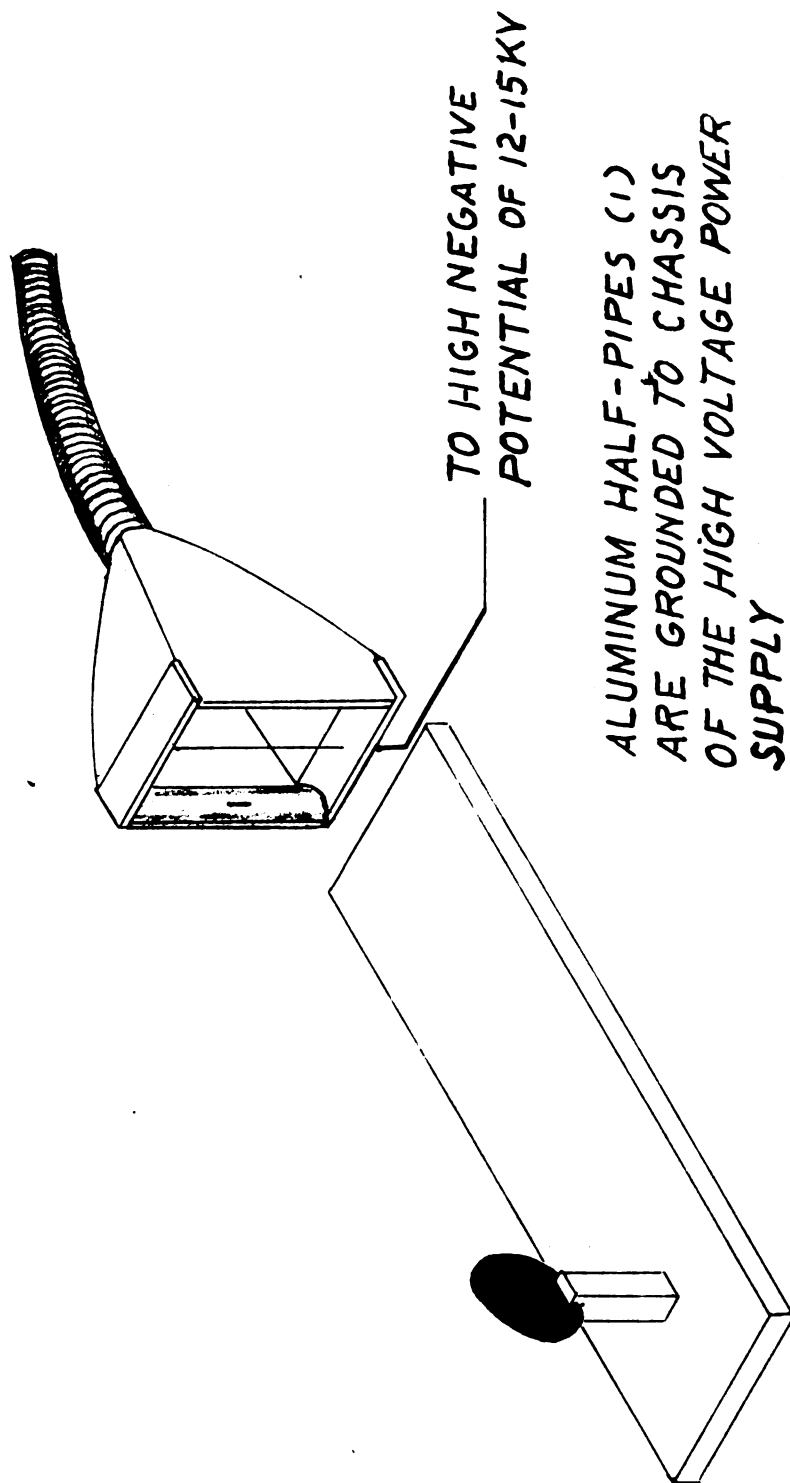


Figure 14 Arrangement of collection disk and charging nozzle
for relative humidity test

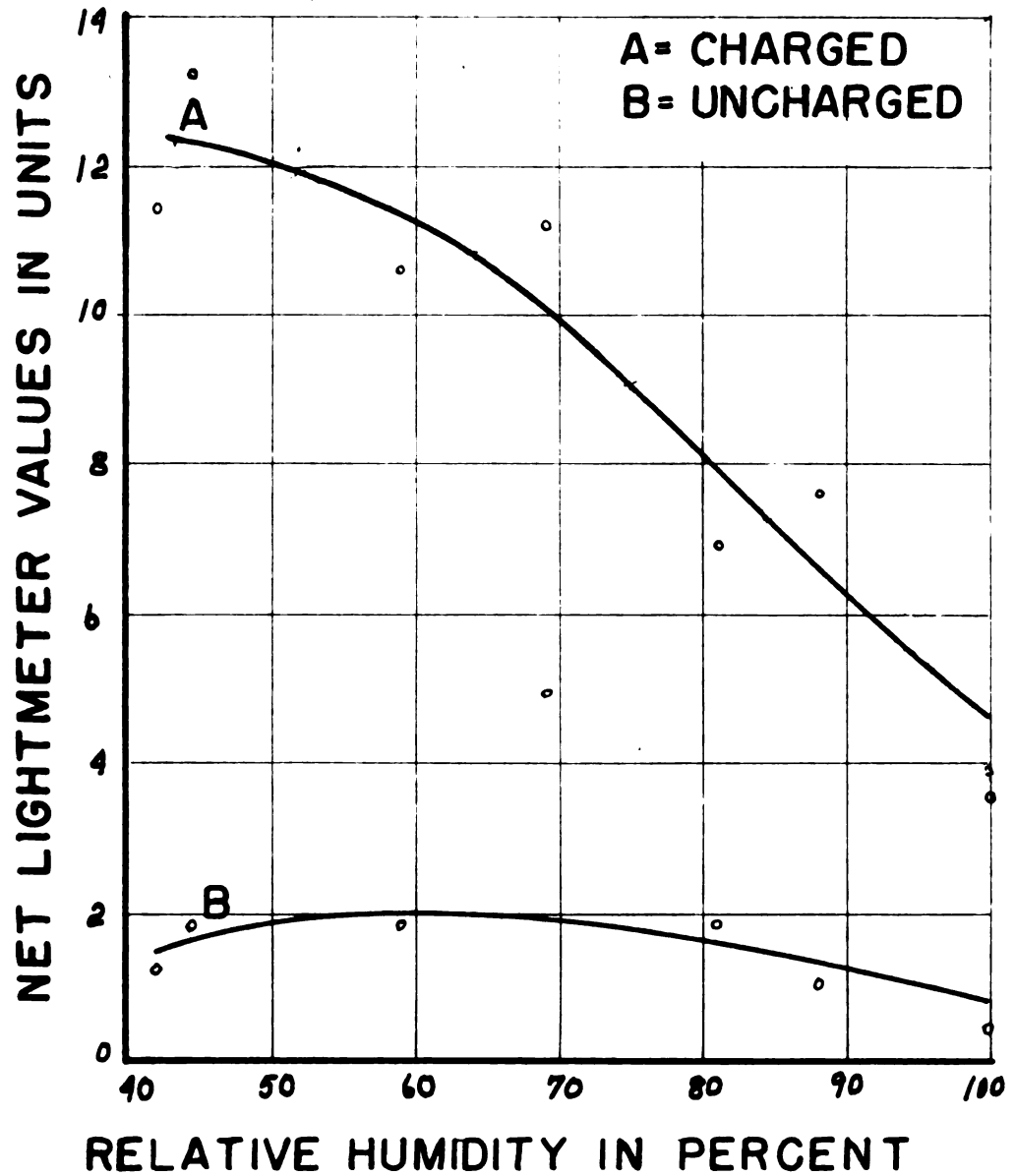


Figure 15 The net lightmeter values of the deposit of negatively charged talc dusts of 1.5 micron average diameter as a function of relative humidity

THE AMOUNT AND DISTRIBUTION OF DUST
ON BEAN PLANTS RESULTING FROM
THREE DIFFERENT TREATMENTS

Because a numerical evaluation of the amounts of dust deposited on a leaf is an almost impossible task, while a numerical evaluation of a blackened disk is a relatively simple matter the largest share of experimental work in the laboratory was done using blackened metal disks for collection surfaces. However, a very valuable comparison of the amount and distribution of dust deposited on growing bean plants has been made.

Apparatus and Methods

The results of three distinct methods of dust application are here compared. The first method of dust application used was the conventional method. An air-dust stream was blown into the region surrounding the plant. There was no current applied to the charging device and at the low air-dust stream velocities used, the friction charging was negligible. There was essentially no charge on the dust particles or the equipment for the first method.

The second method was accomplished by placing a charge on the particles of dust. The only charge occurring on the plant from this method was due to the inducing effect of the space charge of the charged particle system. The particles were charged by connecting wire (3) of Figure 16 to a positive voltage of 13,000 volts. The plate (2)

and the half-pipes (1) of Figure 16, which were connected together, were placed at ground potential.

The current to each of the two heads, Figure 17, was 35 microamps when the dust was not flowing. The field set up between the wire and the half-pipes of Figure 16 caused a stream of positive air ions to move swiftly from the wire to the half-pipe. The dust particles in the air-dust stream passed through the electric field of the wire and the pipes at right angles to the path of the positive air ions. The collisions that resulted between the positive air ions and the dust particles caused a positive charge to accumulate on the dust particle. The charged dust then passed into the region surrounding the plant. The theory of particle charging is given in Appendix I.

The third method was performed with the hope of increasing the dust precipitated by increasing the charge induced on the plant leaves. A higher charge on the plant would mean an increased electric field surrounding the plant surfaces. The increased field would then produce a greater force acting to attract the dust particles to the plant surfaces.

The increase in charge on the plant was accomplished by charging the aluminum plate (2) on each charging head, Figure 16. The charge on the plates corresponded to that produced by a voltage of 17,000 volts and the capacitance resulting from the geometric arrangement of the leaf surfaces and the plates. The wire (3) of Figure 16 was connected to 30,000 volts and the plates and half-pipes were connected to 17,000 volts. This maintained the differential of 13,000 volts between the wire and the half-pipe needed for charging the particles. The wiring circuit is shown in Appendix I.

The comparison of the three methods would show the relative increase in dust deposit due to charging the dust and would show whether any significant increase in deposit could be attributed to the inducing plates.

The experiment was specifically designed to test the precipitation of dust at extremely low velocities. This was to determine whether the dust particles would penetrate the surface barrier¹ when the air-dust mixture was moving at very low velocities relative to the plant leaves. The actual velocity was less than one mile per hour.

The dusting heads were facing each other, Figure 17, so that a large, slightly turbulent cloud of dust surrounded the plant for a period of from one to two seconds.

It is believed that if dust can be made to precipitate at the near zero velocity, it is assured that precipitation will be even greater at higher velocities. These near zero velocities are present in the interior regions of the plant when dusting with the conventional dusting machine. A reference to the photograph, Figure 18, will show a general comparison of the amount and distribution of arsenate of lead dust on the fronts and backs of leaves treated by each of the three methods explained above.

The dark spots on the leaf prints indicate an arsenate of lead dust particle. The leaf prints were taken on a white bond paper and where the print shows up as white there is an absence of dust.²

¹Explained in the Introduction.

²Klingbeil, George C. Pruning as a Means of Adapting Apple Trees for Concentrate Spray Applications. M. S. thesis. Michigan State College, 1930, 56 numbered leaves, 6 tables, 9 figures.

A one teaspoon charge of dust was introduced into the throttled inlet of a centrifugal fan. The throttling of the fan inlet was to allow the fan to run at a high rate of speed to assist in breaking up the dust agglomerates and yet have a low volume of air coming out of the discharge nozzle.

The relative humidity was 34 percent and the temperature was 70° F. These particular conditions would seldom be present under field conditions. Other tests have been performed showing the relationship between temperature, relative humidity, and dust precipitation.

Twenty-five plants were given each treatment for a total of seventy-five plants for all three treatments. All of the plants were field bean seedlings with the second set of true leaves partially developed. The middle leaf of the set printed was placed in a standard position relative to the discharge nozzle. In general the whole plant was covered in a uniform manner. The results for all the plants of a single treatment were substantially the same. A representative selection of leaf prints was made for the photograph.

Observations and Discussion

The group of six leaves marked FNC shows a light coat of dust in random coverage of a very uniform nature. This resulted when no charge was placed on the dust particles or the apparatus. The leaves printed faced the air-dust stream and were about five inches from the discharge nozzle.

The group marked BNC shows the underside of the same leaves as FNC. There is scarcely any dust indicated on the underside of the

uncharged leaves, and this would afford practically no protection for the underside of the leaves from the ravages of disease.

The group marked FCD are prints of the fronts of leaves after having treatment number two. Only the dust particles were charged. This treatment shows a very good coverage of the leaves as they faced the duster nozzle both as to uniformity and amount of dust. As can easily be seen, there is many times as much dust on the leaves of this group than is on the leaves of the no charge group.

The leaves marked BCD are the backs of the leaves of the FCD group. A much greater amount of dust was precipitated on the backs of these leaves than was precipitated on either the fronts or backs of the no charge group. The dust distribution leaves something to be desired, although it is quite uniform except for a small area in the central portion of the leaves near the stem ends. This was probably due to the combined effect of a low concentration of dust in that region and the electric field around the leaf being of low intensity in this particular area. It is expected that both the electric field and the amount of dust in the region will be increased by higher velocities of the dust stream that will penetrate the interior regions of the plant and displace the air already there.

The groups marked FCDP and BCDP are the results obtained when both the dust particles are charged and the infusing plates are charged. These two groups definitely have a heavier coat of dust upon them than either of the other methods. This treatment has the disadvantage that there is a very heavy fringe of dust on the edges and tips of the leaves. This cannot be seen on the photograph but may be visually observed on

the plant. This heavy deposit of dust on the edges could possibly have some detrimental effect on the physiological functions of the leaves. This extreme fringing is due to the fact that the induced charge of the plates seeks the edges and points of the leaf surface according to the surface distribution theory of a charge on a thin conducting surface of finite boundary. The charges will seek the edges and points of the leaves because of their mutual repulsion.

This method using the inducing plates or some other inducing method besides the space charge may well have merit for some types of crops. Those crops with narrow leaves such as cereals and onions and those crops with fine, lacy leaves such as carrots would not be as seriously affected by the fringing tendencies as the plants with broad leaves such as beans and melons.

The results indicated by the photograph for arsenate of lead are obtainable for all kinds of dusts. It is true, however, that the results will vary for different particle sizes of the dusts and for different dielectric constants of the dusts.

The results of this comparison caused the author to lay aside temporarily the method utilizing the inducing plates in favor of concentration on the method utilizing the charged particles only.

Conclusions

General conclusions obtained from the comparison between the three methods of dust application are given below.

At low air-dust stream velocities the amount of dust deposited is greatly increased on the top and bottom surfaces of living bean plants

when the dust is charged as compared to uncharged dust. The use of inducing plates will increase the deposit of dust over either of the other methods, but a serious fringing of the dust deposit is present on plants with broad leaves. Part of the dust recorded on the prints of the leaves treated with charged dust was precipitated on the hairs of the plant surfaces. Such dust will not be active in disease control until it has been pulled onto the leaf surface by the action of dew or by some other means.

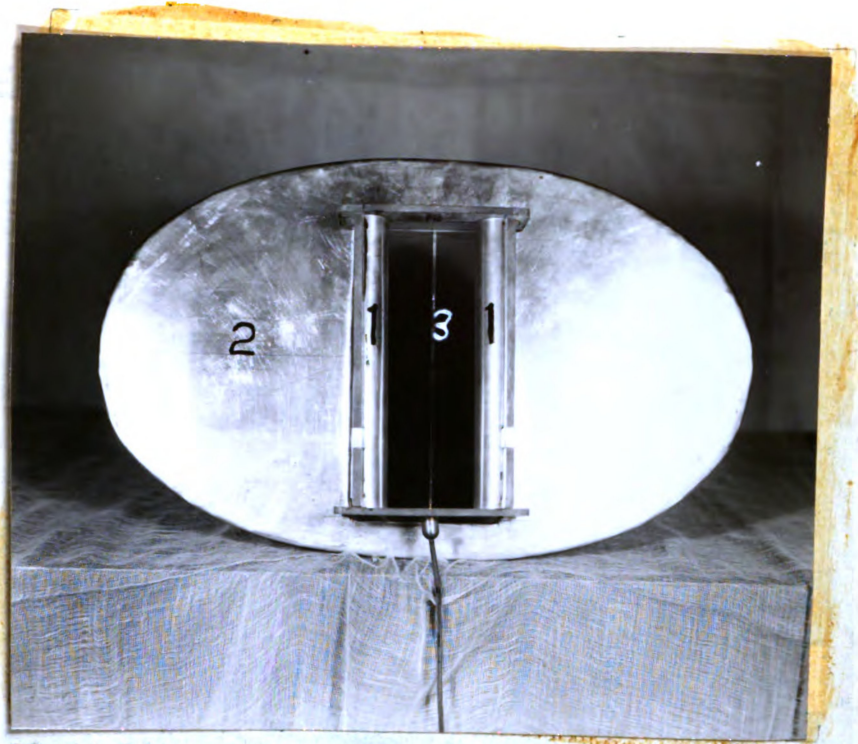


Figure 16 Three components of the charging head

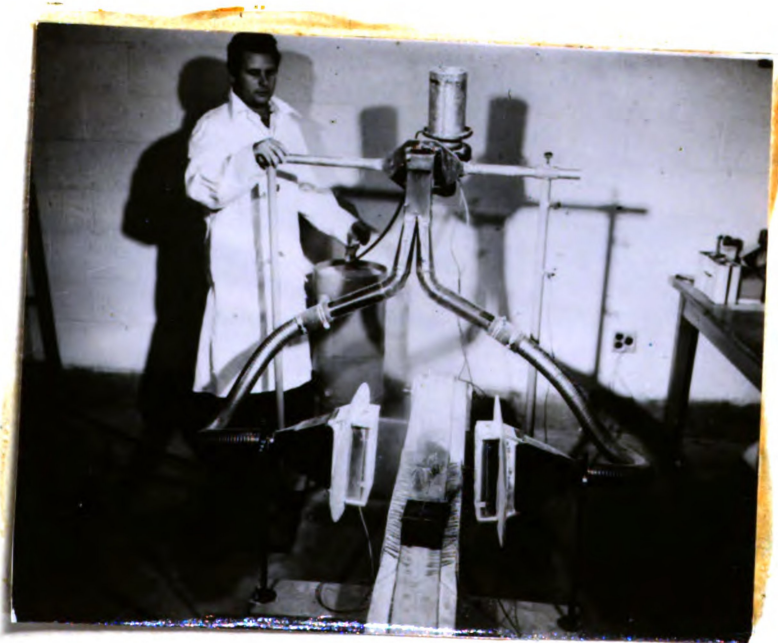


Figure 17 Arrangement of charging heads for bean plant test

ELECTROSTATIC DUST PRECIPITATION

Key:

FNC= Front No charge

BNC= Back No charge

FCD= Front charged dust

BCD= Back charged dust

FCDP= Front charged dust & charged plates

BCDP= Back charged dust & charged plates

FNC



FCD



FCDP



BNC



BCD



BCDP



Figure 18

SUMMARY AND CONCLUSIONS

The electrostatic precipitation of agricultural dusts is a method for increasing the deposit and improving the distribution of dusts on growing vegetation. This is accomplished by placing an electric charge on the individual dust particles.

The dust particles are charged either to the positive or the negative sign as desired by passing the air-dust stream of a conventional field duster through an electric charging head. The head produces an ionized electric field which is active in charging all of the dust particles to one electrical sign.

The electric field and the supply of charging ions are formed by the corona discharge that surrounds a thin wire connected to a potential of from twelve thousand volts to twenty thousand volts. The potential used may be either positive or negative depending on the sign of the particles desired. The positive corona will produce positively charged particles and the negative corona (negative voltage on wire) will produce negatively charged particles. The negative corona is the more stable of the two and is generally more efficient in charging the particles with respect to the power required.

The object of the investigations regarding the electrostatic precipitation of dusts was to increase the amount of dust deposited on the surfaces of the plant that are in the interior regions where the air-dust stream velocities are relatively low. The deposit on all surfaces

has been greatly increased by charging the dust which should allow the dusting job to be done with a considerably saving in material.

Tests of this investigation have been directed at determining the improved deposit that can be obtained by charging small dust particles (those under ten microns).

For the electrostatic method to be of any practical value, the charge must remain on the particles for at least a distance of four to six feet from the charging nozzle. A test was performed using tale dust of an average diameter of 0.8 microns that showed that the charge was effective on the particles for a distance of at least sixteen feet. The velocity of the air-dust cloud was only one-half mile per hour. On the average an increase of four hundred percent in the amount of dust deposited was obtained by charging the dust as compared to the deposit of the uncharged dust.

The effect of relative humidity is to decrease the amount of dust deposited as the relative humidity is increased. The charged dust is only about one-third as effective in depositing on the surfaces at a relative humidity of 100 percent as compared to a relative humidity of 45 percent.

A comparison of the deposit of arsenate of lead dust when applied to bean seedlings showed a very substantial increase in the quantity of dust deposited when the dust was charged as compared to the deposit of the uncharged dust. The distribution of the dust on the undersides of the leaves was greatly improved when the dust was charged.

The results of the laboratory investigations appear to be very gratifying and the principle has been subjected to rather rigid tests.

The principle will be tried in the field in the summer of 1951.

The power consumption of the machine is very low and will probably require somewhere in the neighborhood of 10 watts per discharge nozzle at between twelve and twenty thousand volts potential. A tractor battery system in conjunction with a dynamotor and a high voltage D.C. power supply would be sufficient to supply a four-row duster. For large scale operations special generators would be needed.

APPENDIX I

The Theory of Electrostatic Dust Precipitation

The theory of electrostatic dust precipitation may be separated into two distinct parts. The first is a process of charging the dust particle. The second is the precipitation of the charged dust particle onto the plate. Both processes may be accomplished at one time in the same electric field or the processes may take place at different times in different electric fields. The latter method was the one utilized in the experiments of this paper. The reason for using the separate fields for charging and for precipitation was that the field for charging the particles could be held relatively constant when it was not used for precipitating the charged particles also.

General laws involved in the phenomenon. Coulomb's law of attraction and repulsion for point charges is that unlike charges attract and like charges repel. The force is given by the following equation:

$$F = \frac{Q_1 Q_2}{k r^2} \quad (1)$$

where

F is the force on the particles in dynes,

Q_1 and Q_2 are values of the charge on the particles 1 and 2 respectively in electrostatic units (esu),

k is the dielectric constant of the medium (for air=1),

r is the distance between the particles in centimeters.

The force on a charged particle in an electric field of intensity E , where the particle is small as compared to the distances involved, may be given by the equation below.

$$F = EQ_2 \quad (2)$$

where

F is the force on the particle in dynes,

E is the field intensity in esu, which is $1/300$ of the field intensity in volts/cm,

Q_2 is the charge on the particle in esu.

The "image force of attraction" is that force of attraction which occurs between a charged particle and a plane conducting surface. This force is always attractive regardless of the sign of the charge. It may be calculated using Coulomb's law and considering that there is an equal and opposite charge located at twice the distance from the particle as the particle is from the conducting plane.

$$F = \frac{Q_1^2}{4Kx^2} \quad (3)$$

where

F is the force on the particle in dynes,

Q_1 is the charge on the particle in esu,

K is the dielectric constant,

x is the distance of the particle from the surface of the conductor in cm.

Stoke's law gives the terminal velocity of a particle acquired when moving through a viscous medium under the force of gravity.

$$V = \frac{2dg r^2}{9\eta} \quad (4)$$

where

v is the velocity in cm per second,

d is the density of the particle in grams per cubic centimeter,

g is the acceleration of the particle due to gravity equals 980 cm per second squared,

r is the radius of the particle in cm,

η is the coefficient of viscosity for the medium (for air is about 200×10 poises).

The law of electrostatic induction states that "a charge induces an equal and an opposite charge on a surrounding surface". A charge cannot exist on the inside of a conductor, unless this region also contains an equal and an opposite charge, but will reside on the outer surface. This fact may be accounted for by the fact that like charges repel one another causing them to be moved to a region as far from a neighboring like charge as possible.

General discussion of particle charging. There are at least three recognized principles by which particles suspended in a gas may become charged. The first is by means of friction. The friction may be between the particles and the gas, the particles and the sides of the conducting tube, or possibly between particles of unlike materials. The charge gained on individual particles by this method may be quite large, but unfortunately particles of different sizes are not necessarily

charged to the same electrical sign. Whitman (1926) has shown that particles of both positive and negative signs do exist along with neutral particles in the same dust cloud.

Yadoff (1946) has done considerable work employing the friction charge gained by the friction of a high speed air jet as the jet of air is blown through the dust. In all cases so far studied where friction is used as a charging principle, the high relative humidity of the field has seriously impaired the charging action and thus prevented the accompanying increased precipitation of the dust that was hoped for. In the laboratory where the relative humidity is usually around 40 percent in the winter time, the friction method shows up very well, but the charging action is drastically cut down at relative humidities greater than 50 percent as was shown by Wilson (1944) and indicated by Whitman (1926).

Both of the other two principles of particle charging are dependent upon a copious supply of gas ions. The charged ions of either positive or negative sign may be used, depending upon whether the sign of the particle being charged is to be positive or negative. In any event, there must be a great preponderance of one sign or the other present in the charging field.

The supply of ions may be obtained by any one of several methods. Ions of both signs are produced by radiation from an ultra violet light or x-rays. The corona discharge of a sharp point or a thin wire when subjected to a high potential (greater than 10,000 volts) will produce ions of both positive and negative signs.

Inasmuch as an electric field is needed to separate the positive ions from the negative ions, the corona discharge method is the one

exclusively used for dust precipitation at the present time, although the other methods for producing ions for charging particles could conceivably have merit for some applications. The corona discharge produces its own electric field that leaves all but a small part of the cross-sectional area of a charging field filled with ions of one electrical sign. The ions of the other sign are drawn to the wire or point producing the corona discharge and are neutralized.

A corona discharge is observed when a sharp point or a thin wire having a very high curvature is connected to a high electric potential. Atwood (1949) had the following to say regarding corona discharge.

With a sufficiently high voltage gradient (3×10^6 volts/meter for normal air), free electrons that may be present in this region acquire enough energy in falling against the field to ionize neutral atoms into new electrons and positive ions, which are propelled in opposite directions by the field. The new electrons as well as the original group continue to generate still more electrons and positive ions. The process is known as "cumulative ionization". Some of the neutral gas atoms in colliding with electrons may be raised to "excited" energy states below the value needed for ionization, and later returning to their normal states they emit this energy in the form of radiation. Some of the radiation lies in the visible portion of the spectrum. This visual display is known as corona.

A general discussion of the manner in which dust particles are charged by the force of the electric field is given below.

When a corona discharge is formed around a thin wire in air both positive and negative ions are formed. These ions are in equal numbers in the corona glow area, but the ions of one sign are attracted to the wire and the ions of the other sign are repelled away from the wire by the field gradient.

The negative corona is more stable than the positive corona, Ladenburg (1930), and is more effective in power usage with respect to the

amount of ions used. The negative corona is usually more effective in electrical precipitation according to Strong (1913).

If a negative voltage is used on the wire then the positive air ions within the corona glow area are attracted to the wire. The glow area is very thin around a clean negatively charged wire. It may be plainly seen in a dark room and has a series of small, button-like luminous tufts at about one centimeter intervals along the wire. Panthouier (1934) has shown that the current emitted in the form of negative ions from a thin wire is at a very uniform special density throughout the field.

Nearly all theoretical work on the charging of particles has been done with a cylinder condenser. A cylinder condenser is a grounded metal cylinder with a charged wire running along its longitudinal axis. The cylinder condenser is used for theoretical evaluations because it is a simple geometry for calculating its electric field. The results obtained from the theoretical charging of a particle in a cylinder condenser are valid for other geometries of fields according to Ledenburg (1930).

The theory for charging particles by the negative ions assumes that the particles are dust, smoke or liquid spheres. According to Ledenburg (1930) special tests have shown that the irregularly shaped particles will absorb similar charges and have similar electrical mobilities as the spherical particles.

Panthouier (1933) and Ledenburg (1930) have shown that the electric field of a cylinder condenser or a condenser of any geometry is greatly influenced by the space charge of the negative ions in transit from the

corona discharge area to the grounded cylinder. The value of the field intensity E does not follow the curve of the static cylinder condenser when no current is in transit. The value of E falls off very rapidly close to the wire and then is essentially a constant for the greater part of the space from a small distance from the corona glow area to the grounded cylinder wall. The value of the field intensity E across the greater portion of the field is given by Pauthenier as approximately

$$E_0 = \sqrt{\frac{2i}{\mu}} \quad (5)$$

where

i is the current per centimeter of wire length in esu,

μ is the mobility of the ions in esu equals approximately 500.

The distribution of the field with a current i due to the negative ions in transit is compared with the distribution of the field intensity from the wire to cylinder wall when no current flows and no ions are present in Figure 19.

Pauthenier (1933) and Ladenburg (1930) have independently derived the theoretical maximum charge that may be acquired by a particle of a given radius in a field intensity E .

Ladenburg gives this equation as

$$Q_2 = ne = E_0 \left[1 + 2 \left(\frac{g-1}{g+2} \right) \right] r^2 \quad (6)$$

where

n equals the number of elementary charges e ,

e is the charge of an electron equals 4.8×10^{-10} esu,

g equals the dielectric constant of the particle,

r equals the radius of the particle in centimeters,

E_0 is the intensity of the field in esu.

Derivation of Ladenburg's equation. The particle is assumed to be a sphere and to be suspended in the gas of the ionized field. The "image force" (3) is of no consequence in the case of particles ($r > 3 \times 10^{-5}$ cm) according to Ladenburg (1930). The particles of radius ($r < 3 \times 10^{-5}$ cm) in which the "image force" would have an effect are charged to their maximum by an entirely different principle, which will be described later.

The negative ions are forced towards the suspended particle with a force $F = EQ = E \cdot e$ (2). When a charge has built up on the particle of Q we then have a force of repulsion between the negative charge on the particle and any negative ion just off the edge of the particle is present whose value is $F = \frac{Qq}{kr^2} = \frac{EQ \cdot e}{kr^2}$. This force opposes the force of the field and when it is equal to the force of the field the maximum charge, Q_1 , under the particular value of the field, E , has been reached.

The value of the field E , is modified by the dielectric polarization of the particle which is the change in the field surrounding the particle due to the presence of the particle. Rohmann (1923) has shown this to be equal to $\left[1 + 2 \left(\frac{\epsilon - 1}{\epsilon + 2}\right)\right]$ where ϵ is the dielectric constant of the particle. This has the effect of multiplying the field intensity E by a factor of from 1 to 3 depending upon the dielectric constant of the particle. The value for the dielectric polarization term for most non-conducting dusts is between 1.5 and 2 and for conducting particles is equal to 3.

The force of the field and the force of the repulsion are equal when the maximum charge has been reached. By equating these two forces

the equation for the maximum charge $Q_s = ne$ may be found.

$$\frac{ne \cdot e}{(1) \lambda^2} = E \cdot \left[1 + 2 \left(\frac{\delta-1}{\delta+2} \right) \right] \cdot c$$

and
$$Q_s = ne = E \cdot \left[1 + 2 \left(\frac{\delta-1}{\delta+2} \right) \right] \lambda^2$$

which is the value as given by Ladenburg for non-conducting particles. The value of the charge for conductors is $ne = 3E \cdot r^2$.

Pauthenier (1934) has made certain experiments that indicate that non-conducting particles will receive the maximum charge according to the law pertaining to conductors if the particles are coated with a conducting material.

The above equation for maximum charge has been experimentally verified to within one or two percent by both Pauthenier (1933) and Ladenburg (1930). The equation above does not consider the time necessary to attain that maximum charge. Pauthenier (1934) has shown that the time to reach the maximum charge is independent of the radius of the particle and depends only on the density of the ions in the neighborhood of the particle. An exact formula is not given but the time required to reach one-half maximum charge in cylinder condensers with field intensities used is of the order of .01 seconds.

The third principle of charging is active in charging those particles of radius ($r < 10^{-4}$ cm.) to a greater charge than is indicated by the equation of Ladenburg and Pauthenier and is due to what is known as the heat motion of the air molecules. An electrical field is not necessary for this process except for keeping the air surrounding the particles filled with only one sign of ions. If both signs of ions are

present, the heat motion is just as active in putting both signs of charge on the particles and the result is a neutral particle.

Therefore, this type of charging is most active in an electric field containing ions of one sign only. The kinetic energy of the air molecules due to the absolute temperature of the gas in the air causes the molecules and ions to have a very large velocity and a random motion. This motion causes the molecules to strike a particle many times a second. The negative ions do not always "stick" when they strike a dust particle but a charge is quickly placed on the particle up to that critical charge that the repulsive forces of like charges prevents more negative ions from impinging upon the dust particles.

This is a very complicated theory to explain and may be studied in more detail by referring to the work of Schweitzer (1930).

The equation given for the number n of elementary charges e on a particle of radius ($r \leq 10^{-4}$ cm) in a field with an ion density given by a current of 10^{-6} amperes per cm of wire is given below. Here the ions that charge a particle are those that are produced by the corona voltage but the equation would be valid if the ions were produced by any other means as long as there were only ions of one sign present.

$$n = 20 \pi r \times 10^5 \quad (7)$$

where

r is equal to the radius of particle in cm,

n is equal to the number of elementary charges e .

It must be remembered that the maximum charge is determined by one or the other principle of charging, and that the sum of the charges produced by each principle cannot be taken.

According to Ladenburg (1930) any charge on the particle due to friction or any other means before the particle enters the field will not affect the maximum charge acquired but will increase or decrease the time to reach the maximum charge depending on which sign or charge was already on the particle.

Panthouier (1934) has shown that the electric field intensity is considerably changed by the introduction of a dense cloud of dust into an ionized field. The dust has the effect of stifling the corona discharge. In order to maintain the current i that was present before the dust was introduced an increased voltage must be applied to the wire. This occurs because the dust carries only a very small part of the current but does influence the space charge considerably. A comparison of the fields present when current is flowing in a cylinder condenser with and without dust present is shown in Figure 20.

General discussion of precipitation of charged particles. There is no simple way of treatment of the forces involved in precipitating dust upon a plant surface, but a general discussion of the factors involved will show the part played by the various forces. By way of comparison of the dust precipitation when the cloud is charged and when the cloud is uncharged we will show first the forces acting on the dust particle when there is no electric charge on either the dust particle or the collecting surface. The particle is simply falling to the surface by gravity forces.



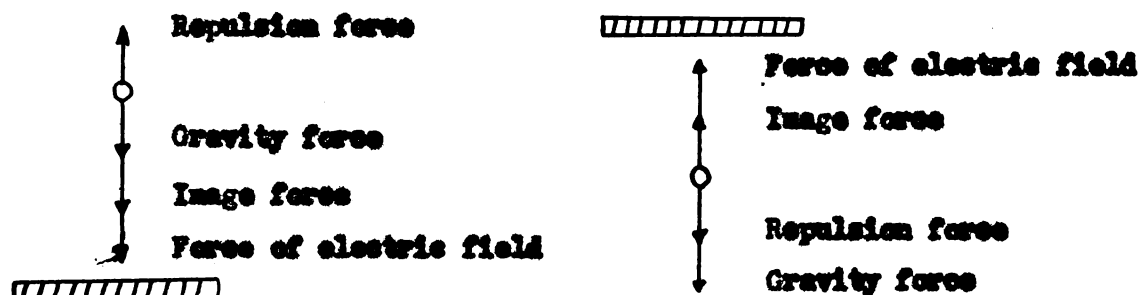
The force acting on the particle repelling it from the surface is due to the surface barrier near the leaf surface. The force pulling down on the particle is the force of gravity. It can be easily seen that in still air there would be no force acting to deposit a particle on the underside of a leaf.

When an electrical charge is placed on the particle, the forces acting on the particle will be as shown below.



The added force on the above figure is due to the "image force" of attraction which will be insignificant except at very small distances from the leaf surface.

When a charge is placed on the particle and an opposite charge is placed on the collecting surface, the following force system results.



The added force is due to the force of the field on a charged particle and is active for a considerably greater distance than the "image force".

Although the magnitudes of the forces are not known we can see that we have added to the ease of deposition of the particle by the sum of the magnitudes of the forces due to the electric field and the "image force" of attraction.

The foregoing has been a representation of the forces acting on a particle placed first above and then below the surface in still air. It may be said at this time that the field surrounding the surface will be due to the charge induced upon the surface by the charged dust cloud. This charge on a particle surface will be of greater magnitude when the cloud is very dense than when the cloud is very diffused considering a constant charge on the individual particles. This is accounted for partly because the field of the charged cloud will be extended to other surfaces besides the particular one being studied when in its diffused state. Also the charge induced is not as concentrated in the particular object to be charged when the cloud is at a distance from the object.

The "image force" of attraction will act on the particle even though there is no other electric field generally surrounding the particle. This may be clarified somewhat by saying that a single charged particle with no other fields present will be attracted to a neutral conducting surface. The "image force" of attraction is due to an induced charge on the surface caused by the single charge of the particle.

From the above discussion it would be speculated that for clouds that have been charged and are very dense we should expect a great deal more dust deposit on a surface than for a charged cloud that was diffused. The decrease in deposit is a result of there being fewer particles and also because there is a smaller electric field around the surface.

The depth of the repulsion field near the collecting surface is not known. It is known that with gravity forces plus the force of momentum of a falling particle acting on the particle, only those particles 20 microns or larger are able to penetrate the surface barrier. Particles under 20 microns seem to slide off the surface according to Potts (1946). Only a small percentage of particles of 30 microns are able to penetrate the barrier under the forces of gravity alone. The magnitude of the force then is equal to the weight of the particle of 20 microns and is of sufficient depth to absorb the momentum of the particle mv where m is the mass of the particle and v is the terminal velocity as given by Stoke's law.

If one knew the exact nature of the repulsive barrier and how it varied from the distance from the surface, one could calculate the exact charge necessary to precipitate a particle of a given size, from either above or below the surface.

It would appear from the material given that as the charge was increased on the particle the smaller the importance of the gravity forces and the nearer to being equal would be the deposit collected by the top and bottom surfaces.

From the first figure of the force system it is plain to see that no dust would be collected on the underside of the surface as long as no charge was on the particles, since there is no force of attraction to the underside and there would be a collection of those particles 20 microns and larger on the top of the surface. Experiment shows this to be essentially true.

The "image force" is very large at small distances, but cannot be considered of importance at distances greater than one millimeter from the collecting surface.

The magnitude of the charge that can be placed on a particle can be calculated by the equation of Ladenburg (1930) for any size particle. Although this does not give the exact charge on every particle it does give an indication of the order of magnitude of the charge that may be placed on the particle. With these values of charges on the particle the value of the "image force" may be calculated at any specified distance from the surface.

The value of the field intensity E surrounding a surface can only be estimated and will be a fluctuating value at all times but an average value may be assumed with some degree of reason.

All of the forces previously mentioned act on a particle close to a conducting surface when the particle is at rest or is moving. Another force is active in depositing the particle when it is in motion. That force is present when the air stream carrying the particle toward a surface is deflected by the surface. The particle tends to continue in the direction it was moving before the air stream was deflected.

From Newton's second law of motion, a body moving in a straight line will continue in a straight line with undiminished velocity until acted on by an external force F for a time t . This means that if the friction forces of the air and gravity forces could be neglected, a particle once directed at a plant surface would continue on its path until it fell against the resistive barrier of the surface. The particle would then be precipitated or repelled depending on whether the force developed by the momentum was greater or less than the force of the barrier next to the plant surface.

The force due to the change of momentum ($mv_2 - mv_1$) in a time t , is given below.

$$F = \frac{mv_2 - mv_1}{t} \quad (8)$$

where

F is the force in dynes,

m is the mass of the particle in grams,

v_1 and v_2 are the original and final velocities of the particle in cm per second,

t is the time in seconds.

The actual conditions are such that any movement of the particle with respect to the air is countered by a force due to the friction of the air on the particle. This force for spherical particles is given as

$$F = 6\pi\eta r v' \quad (9)$$

where

F is the force in dynes,

η is the viscosity coefficient of the air in poises,

v' is the velocity of the particle relative to the air in cm per second,

r is the radius of the particle in cm.

It is this force due to friction between the particle and the air that allows the particle to be carried by a moving air stream. This force is very large for small particles when moving at a relatively slow rate with respect to the air. For example, the force due to the friction on a spherical particle of 2 microns diameter and a density of 2, is equal to the force due to gravity when the particle is moving at a velocity 2.2×10^{-2} centimeters per second.

The force due to the momentum of the particle is aided by the electrical forces that are present as a result of the charge on the particles. The combination of the force due to the movement of the particle and the electrical forces results in an amount of deposition from a cloud of dust far greater than could be deposited from the same cloud by either of the force sources acting alone.

The theory of the discharge of particles. The rate of the discharge of the originally charged particles is of the greatest importance if the method is to be successful for such operations as dusting trees or airplane dusting.

The actual discharge rate is not known and is a variable quantity depending on the amount of charge on a particle, the number of free ions of each sign present in the air surrounding the particle and the mobility of these ions. There are other factors involved but they will probably be small as compared to the factors mentioned above.

There are between five hundred and a thousand ions of each sign present in one cubic centimeter of free country air according to Hess (1928). These ions are usually singly charged and are of various sizes and mobilities. The ions are formed by the secondary radiation of

the cosmic rays from outer space and by radiation from the naturally radioactive materials in the soil.

The mobilities will vary from 1 to 500 cm per second per statvolt per cm. The mobilities are related to the masses. The masses are widely varied. The small ions have the mass of an air ion, and the large ions have masses of perhaps a thousand times that of the air ion. These are formed when an electron or air ion becomes attached to an impurity in the air. The ions of large mass will have a low value of mobility.

The ions of sign opposite to the sign of the charge on the dust particles are active in neutralizing the charge on the particles. Thus if the dust particles are charged to the negative sign, the positive ions in the air are active in neutralizing the particles.

It would require somewhere in the neighborhood of 3×10^4 cubic meters of air to completely discharge the theoretical charge that could be put upon the spherical particles of dust contained in one gram of dust of a density of two and a particle diameter of two microns. This would correspond to the air contained in a room of dimensions 60 x 60 x 300 feet.

It can be concluded that the discharge of the particles will not be a great factor in the precipitation of dust until the dust has diffused through a considerable amount of air.

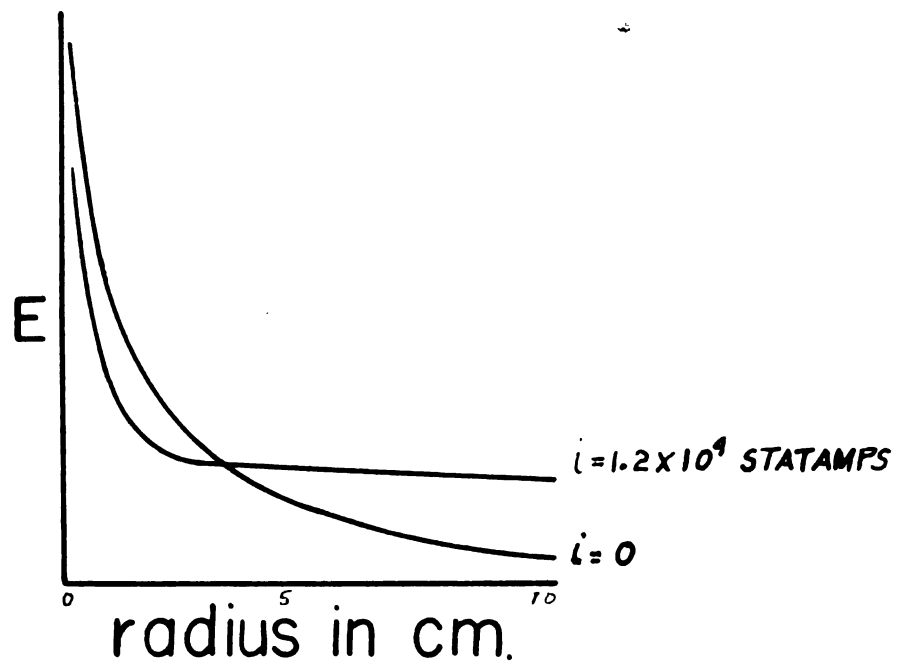


Figure 19 Field distribution in a cylinder condensor with and without current flowing

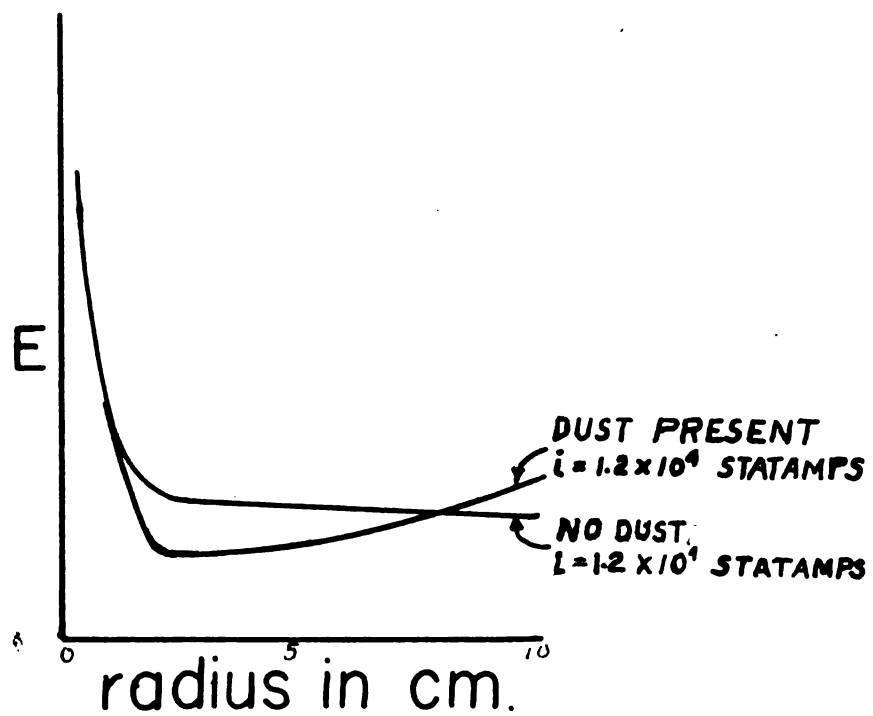


Figure 20 A comparison of the ionized electric field of a cylinder condensor, with and without dust present

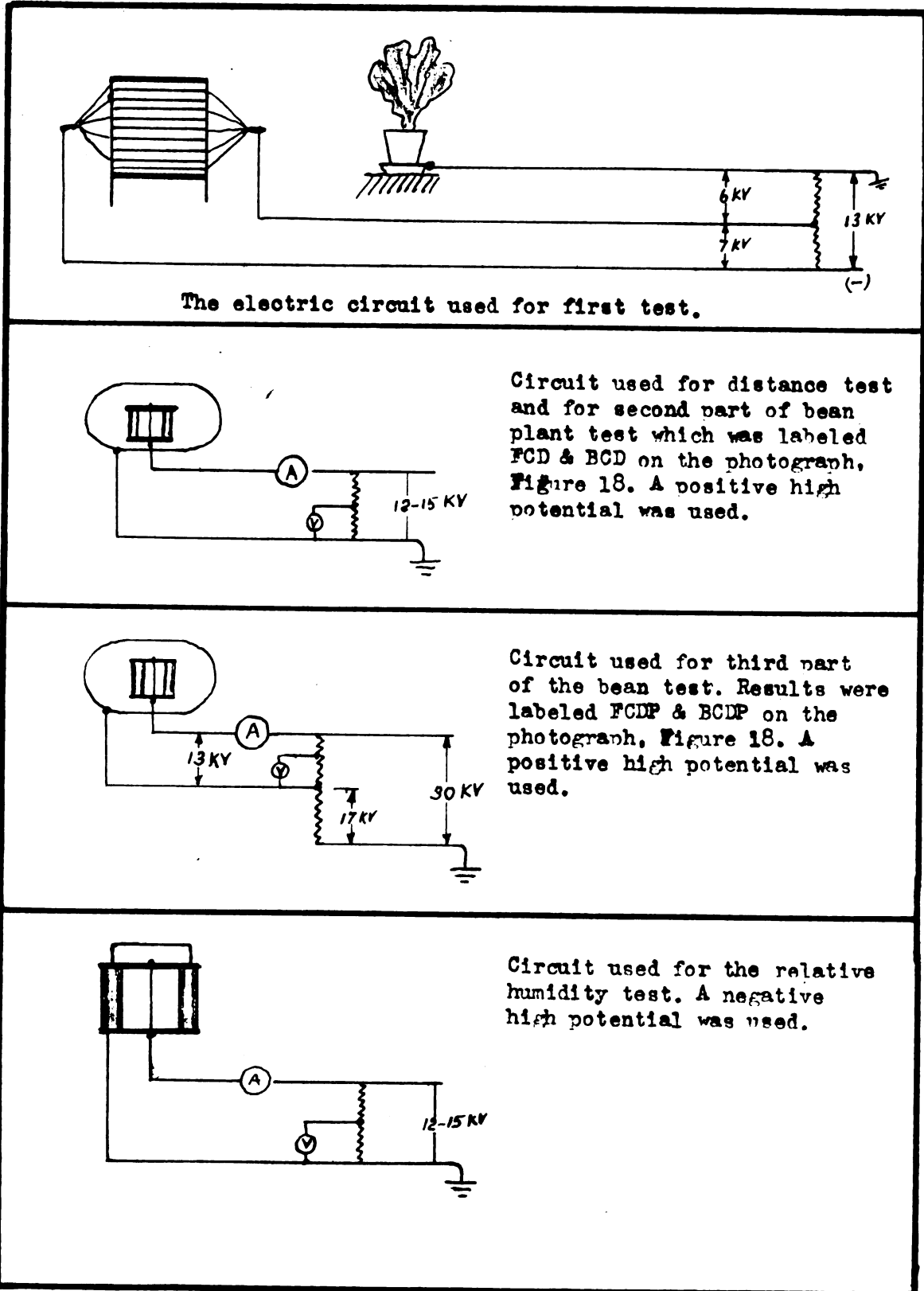


Figure 21 Electrical circuits used in the investigation.

TABLE I

EFFECT OF DISTANCE FROM CHARGING
SOURCE ON PRECIPITATION

(Dust deposit as a function of the distance from the nozzle
when positively charged and when uncharged using talc
dust of 0.8 microns average diameter)

Data Sheet

Station	Distance from Duster Nozzle in Feet	Lightmeter Reading for No Charge		Lightmeter Reading for Charged	
		Test		Test	
		1	2	1	2
A	2	10.50	14.50	82.00	55.00
B	4	4.00	7.00	19.25	24.00
C	6	3.25	4.50	12.00	12.00
D	8	3.00	4.25	6.25	9.00
E	12	2.75	4.00	5.00	6.00
F	16	2.75	4.00	5.00	6.00
G	24	2.75	3.75	5.00	5.00
H	32	2.75	3.25	4.75	4.75
C'	6	3.00	3.50	4.00	4.25
F'	16	3.00	3.00	4.50	4.00
Check		2.75	3.00	2.75	3.00

TABLE II
EFFECT OF DISTANCE FROM CHARGING
SOURCE ON PRECIPITATION

Calculated Data

Station	Not Charged		Charged		Ratio Charge/No Charge
	Average	Net	Average	Net	
A	12.50	9.63	68.80	65.63	6.83
B	4.50	1.63	21.62	18.75	11.50
C	3.88	1.01	12.00	9.13	9.04
D	3.62	0.76	7.62	4.76	6.27
E	3.38	0.51	5.50	2.63	5.15
F	3.38	0.51	5.50	2.63	5.15
G	3.25	0.38	5.00	2.13	5.60
H	3.25	0.38	4.75	1.88	4.95
Check:	2.87	0.00	2.87	0.00	----

TABLE III

RELATIVE HUMIDITY AND ITS EFFECT ON
ELECTROSTATIC DUST PRECIPITATION

(The deposit of negatively charged talc dust of 1.5 micron average diameter under varying relative humidities and a nearly constant temperature)

Data Sheet

Relative Humidity	Temperature	Lightmeter Reading for Charged	Lightmeter Reading for Uncharged	Lightmeter Reading for Check Disk
42.0%	83.5°F	16.0 14.3 13.2	4.3	3.0
44.5%	85.0°F	16.0 15.9 17.0	5.0	3.1
59.0%	84.0°F	17.2 14.0 13.0	5.0	3.0
69.0%	85.0°F	15.9 14.1 13.0	8.0	3.1
81.0%	85.0°F	11.0 10.0 9.0	5.0	3.1
88.0%	82.0°F	10.0 10.0 12.0	4.1	3.1
100.0%	93.0°F	6.0 7.0 5.3	3.0	2.5* 2.6 2.5

*Two groups of disks were used and the average of the zero readings for all stations but the 100 percent relative humidity group was 3.1, and the average zero reading for the 100 percent relative humidity group was 2.6.

TABLE IV
RELATIVE HUMIDITY AND ITS EFFECT ON
ELECTROSTATIC DUST PRECIPITATION

Calculated Data

Relative Humidity	Average Lightmeter Reading, Charged	Net Lightmeter Reading, Charged	Net Lightmeter Reading, Uncharged
42.0%	14.5	11.4	1.2
44.5%	16.3	13.2	1.9
59.0%	13.7	10.6	1.9
69.0%	14.3	11.2	4.9*
81.0%	10.0	6.9	1.9
83.0%	10.7	7.6	1.0
100.0%	6.1	3.5	0.4

*Other tests have shown that at 70 percent relative humidity the net lightmeter value should lie between the values for 60 percent and 80 percent.

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