

THE EFFECT OF PLANT SURFACES ON
PESTICIDAL DUST DEPOSITION

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This is to certify that the

thesis entitled

"Effect of Plant Surfaces on Dust Deposition"

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Engineering

Walter M. Johnston

Major professor

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by

Robert Willis Brittain

AN ABSTRACT

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Walter M. Carlisle

THADIS

The purpose of this study was to obtain basic information indicating the manner in which plant surfaces affect the deposition of pesticidal dusts. It was not intended to give complete information on the effect of plant surfaces on deposition under all conditions, but it was intended to show the types of effects which might be expected. Thus, it would point the way toward any further investigations which seem desirable.

In order to accomplish this, a series of surfaces were "dusted" under controlled conditions in the laboratory and the weights of the resulting dust deposits were evaluated and compared. The nature of the surfaces and the conditions under which they were exposed to an aerosol stream were chosen in such a manner as to represent as many practical conditions as possible.

The study was divided into two experiments. In one of these artificial leaf surfaces were used, while in the other actual plant leaves were used.

In the artificial leaf-surface experiment four surfaces were used -- smooth aluminum, sandblasted aluminum, wax coated aluminum, and petroleum-jelly coated aluminum. They were "dusted" with hydrated copper sulfate of two particle sizes. Three air velocities were used, but other conditions were held constant. There was no significant difference between the two aluminum surfaces, but

the two softer surfaces showed greatly increased deposits. Significant deposition effects were found for particle sizes, air velocities, and all three possible interactions as well as surfaces. These results suggested a somewhat complicated relationship between the variables involved and a hypothesis was advanced to explain this.

In the plant leaf-surface experiment both the top and bottom surfaces of bean, tomato, and lettuce leaves were tested. The conditions varied were the air velocity and the surface angle with respect to the air stream. Significant effects were recorded for surfaces, angles, air velocities, and, for part of the data, the surface-angle interaction. The pubescent bean and tomato leaves held a somewhat higher deposit than the smooth surfaced, but wrinkled, lettuce leaves. The bottoms of each of the leaf species received a distinctly higher deposit than the tops. This was particularly true at the 45-degree leaf angle. The results also showed that a leaf at an angle of 45 degrees held a larger part of the dust which was directed at it than a leaf perpendicular to the air stream.

A technique was developed in cooperation with other investigators and used in the plant leaf-surface experiment to adapt the polarograph to dust deposit evaluation. The use of volumetric copper titration as a deposit evaluation method was also investigated.

It is believed that the information obtained may prove valuable as a step toward a better understanding of dust deposition.

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INTRODUCTION

Background of the Study

The application of insecticidal and fungicidal dusts to crop plants has long been an important part of the insect and disease control program in the United States and elsewhere. However, the existing dust application machinery is very inefficient.

In an attempt to improve the efficiency of dusting machinery, the Department of Agricultural Engineering at Michigan State College initiated a research project in 1950 to investigate the possibility of utilizing electrostatic forces in dust deposition. As this project progressed, it became apparent that before any real progress could be made the mechanism of dust deposition on a plant surface would have to be thoroughly understood.

To this end Bowen (1)* in 1953 did a theoretical study of the electric and inertial forces involved in deposition. Splinter (2) in 1955 applied Bowen's work to an experimental study of the relative importance of electric, inertial, and gravitational forces.

* Numbers in parenthesis indicate appended references.

Another serious problem which presented itself to the Michigan State College investigators, was the lack of adequate evaluation techniques. To solve this problem, Brazee (3) in 1953 investigated several possible evaluation techniques and found one, volumetric copper titration, which showed promise. Another approach to the evaluation problem, the use of the polarograph, was investigated by Ban (4) in 1954.

Among the factors still to be studied after the previously mentioned investigations were deposition forces resulting from thermal gradients, the effect of the nature of the plant surface on deposition, the effect of the dusting material on the dusting process*, the development of adequate metering devices for accurate dusting at low rates, and others.

Statement of the Problem

The purpose of this study was to determine experimentally the manner and extent to which the nature of the plant surface affects the deposition of dusts.

The study was not intended to give complete information on the behavior of all dusts when being deposited on all surfaces under all conditions. Neither was it intended to explain all the theoretical implications of the findings.

* This was investigated to some extent by Splinter (2).

The study was intended to show the effect on dust deposition of a few typical surfaces under certain conditions in the laboratory. This information attempts to show the importance which should be attached to surfaces in dust deposition problems, and should point to where further work needs to be done. Further, the experience gained in instrumentation and technique should be useful in further work along similar lines.

Review of Literature

Although an intensive search of the literature was made, none was found.

Approach to the Problem

The approach used to the problem was that of dusting actual surfaces under controlled conditions in the laboratory and evaluating the deposits.

In one set of tests artificial leaf surfaces were used in an attempt to remove as many variables as possible. This set of tests should also facilitate the correlation of actual leaf surface tests with the work of Splinter (2) who used artificial leaf surfaces.

The other part of the experimental work involved the use of certain selected plant leaf surfaces. The latter data are more directly applicable to field dusting problems.

LABORATORY EXPERIMENTAL EQUIPMENT

As the dusting investigations proceeded at Michigan State College it became apparent that it would be necessary to have laboratory dusting equipment in which a high degree of control over conditions was possible if reliable information about dust deposition was to be obtained. Brazee (3) made recommendations for such equipment and its construction was started that year. Splinter (4) first used the equipment in the spring of 1954.

Conditions to be Controlled

In the construction of the laboratory dusting equipment, an attempt was made to control the following conditions:

1. Relative humidity. This was found to be very important in the dusting process by Bowen (5), Hebblethwaite (6), and Splinter (2). It is of particular importance in dealing with electric deposition forces.
2. Air velocity. The air stream which carries the dust imparts to the dust the kinetic energy which is responsible for the inertial deposition forces.
3. Dust feeding rate. In most present day field dusters it is impossible to maintain a very accurate feeding rate. However, the accuracy of the results in any dust

deposition experiment is dependent upon the accuracy of the dust feeding.

4. Electric charge. In studying the electric forces involved in dust deposition it is necessary to be able to place an electric charge upon the dust particle and to measure that charge. No direct use of the charging equipment was made in this study.
5. Temperature. It is thought that thermal forces may play a part in dust deposition. To the author's knowledge this has not been extensively investigated. Temperature control was limited to thermostatic control of the laboratory temperature.

Description of Laboratory Equipment

The laboratory dusting apparatus consisted essentially of (1) a dust-feed chamber, (2) a dusting chamber, (3) a system of ducts to bring air in and take dust laden air out, and (4) suitable means of measuring and controlling the conditions throughout the system. A schematic diagram of the apparatus is shown in Figure 1.

The Dust-feed Chamber

The dust-feed chamber contained the main feeding fan, G, and the dust-metering mechanism. The feeding fan mixed the dust and air and delivered the aerosol* to the dusting

* Aerosol is defined for this study as a suspension of dust particles in air.

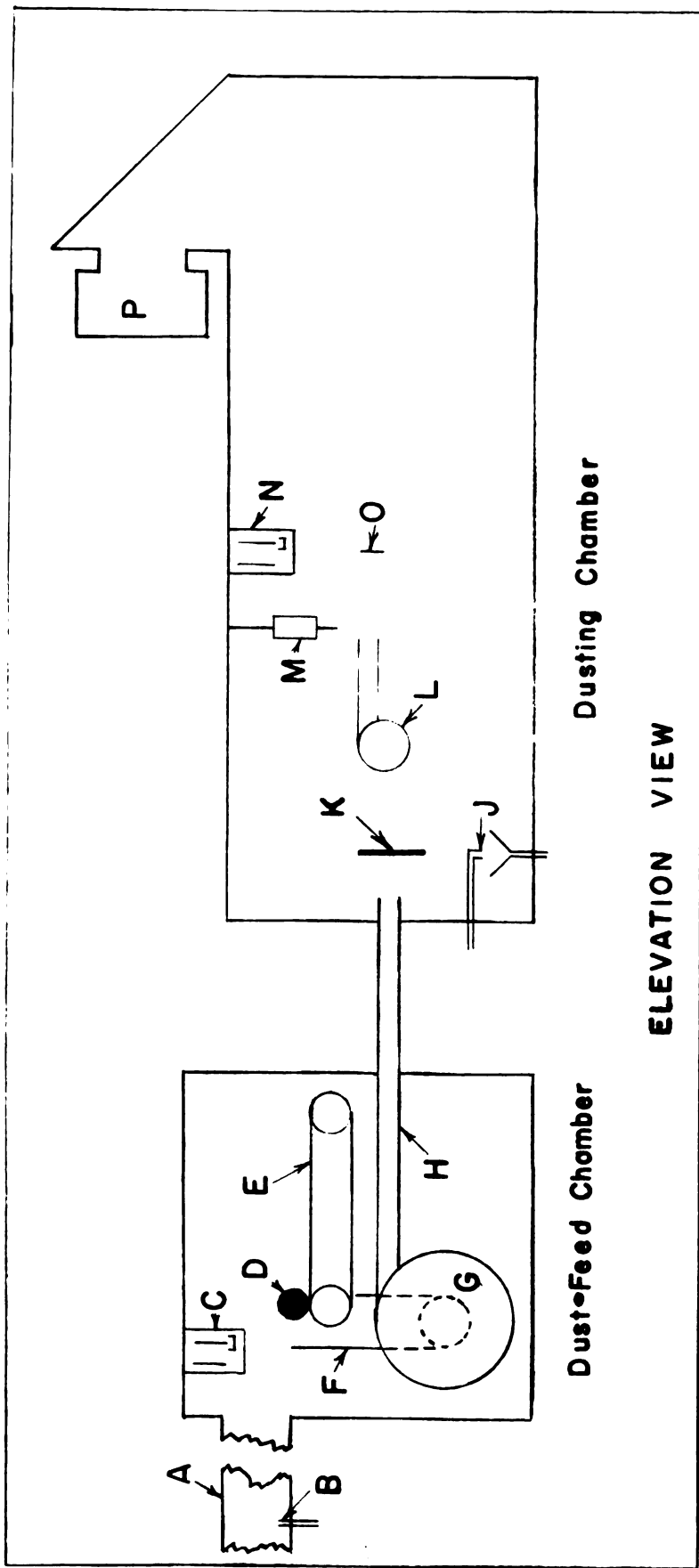


Fig. 1. Schematic diagram of experimental dusting equipment. The apparatus indicated by letters is the following:

- | | |
|----------------------------------|--------------------------------------|
| A. Air intake duct | J. Steam injection nozzle and drain |
| B. Steam injection nozzle | K. Aerosol baffle |
| C. Wet and dry-bulb thermometers | L. Inertial fan |
| D. Dust-feed brush | M. Membrane filter holder |
| E. Dust-feed belt | N. Wet and dry-bulb thermometers |
| F. Dust-feed chute | O. Experimental surface to be dusted |
| G. Feeding fan tube | P. Exhaust fan |

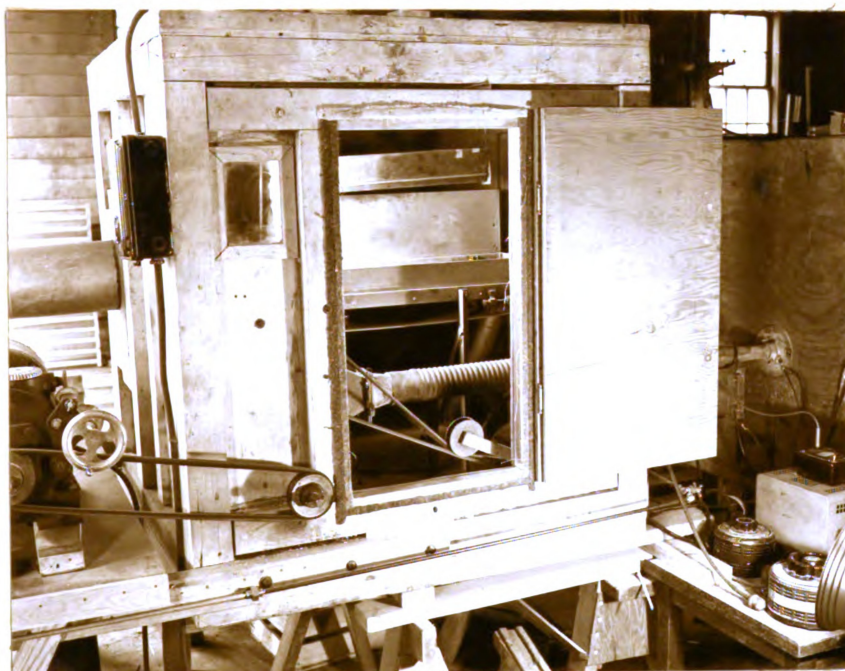


Fig. 2. Dust-feed chamber showing the variable-speed feeding-fan motor at the left and portions of the feeding-fan tube and dust-feed belt through the open door.

chamber through the feeding-fan tube, H. This fan was of the centrifugal type with radial blades. It was driven by a variable speed motor with a speed range of from 600 to 3600 revolutions per minute. In this study the fan was operated at 3600 revolutions per minute at all times.

The size of the dust-feed chamber was approximately four by four by four feet.

The Dusting Chamber

The dusting chamber was the area where the experimental surfaces were exposed to the dust aerosol. During a test it contained a relatively uniform dust cloud. An inertial fan, L, directed a part of this aerosol at the surface to be dusted.

As the aerosol entered the dusting chamber from the feeding-fan tube, H, it struck a baffle, K. This baffle dispersed the air stream, eliminating any strong air currents, but directing weaker turbulent air currents into all parts of the chamber. The back of the baffle can be seen near the center of Figure 3.

Also contained in the dust-feed chamber were instruments for measuring temperature, relative humidity, and aerosol density* which will be described below. The size of the chamber was 42 by 42 by 116 inches.

* Aerosol density is defined for this study as dust weight per unit volume of air.

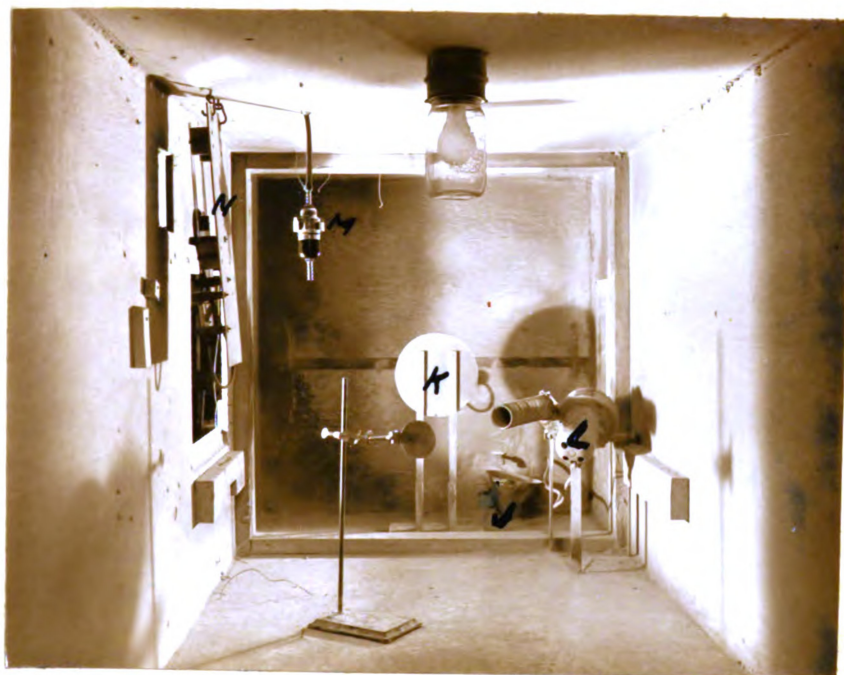


Fig. 3. Interior of dusting chamber. The dust enters the chamber just behind the baffle, K. The equipment designated by letters is the following:

- J. Steam injection point
- K. Aerosol baffle
- L. Inertial fan
- M. Membrane filter holder
- N. Wet and dry-bulb thermometers

Air Intake and Exhaust System

Air was drawn into the dust-feed chamber by the suction of the feeding fan, G, Figure 1. The eight-inch intake duct, A, was arranged so that air could be drawn from either the interior of the laboratory or from outside the building.

The exhaust fan, P, drew the aerosol from the dust chamber and exhausted it from the building through a chimney. This fan was of the centrifugal type with forward curved blades.

The flow of air through the system may be traced as follows: (1) it enters the dust-feed chamber through the intake duct, (2) moves through the feeding fan where it is mixed with dust, (3) enters the dusting chamber through the feeding-fan tube and is dispersed by the baffle, (4) it may or may not be blown at the surface to be dusted by the inertial fan, (5) is drawn from the dusting chamber by the exhaust fan and leaves the building through a chimney.

A simple U-tube manometer containing water was connected to the dusting chamber to measure the pressure differential between the chamber and the laboratory. An adjustable gate on the intake of the exhaust fan permitted the static pressure inside the dusting chamber to be controlled. The chamber was normally operated at a vacuum of approximately one-eighth inch of water to prevent aerosol from leaking into the laboratory.

Relative Humidity Control System

The relative humidity of the system was controlled by means of injecting steam at one or both of two points. The primary injection, B, Figure 1, was located in the intake duct approximately 15 feet from the dust-feed chamber. This nozzle was adequate for relative humidity control except at values near 90 percent or above. At such high humidities it became necessary to inject steam directly into the dust chamber at point J. A drain was provided at this point to take any liquid water which came through the steam line out of the chamber. A drain was also provided in the steam line at the main valve to take the water out of the line. This drain was left partially open whenever steam was being injected at either nozzle.

Relative humidity was measured by means of two wet and dry bulb thermometer sets such as the one shown in Figure 4. A constant water level was maintained in the cup under the wet bulb thermometer by means of a syphon arrangement similar to a system reported by Henderson (7). Humidity measuring instruments were placed in both the dusting chamber and the dust-feed chamber (N and C, Figure 1).

In the dusting chamber it was found that when both the feeding fan and the exhaust fan were running there was sufficient movement of air past the wet bulb thermometer to give a maximum depression. However in the dust-feed

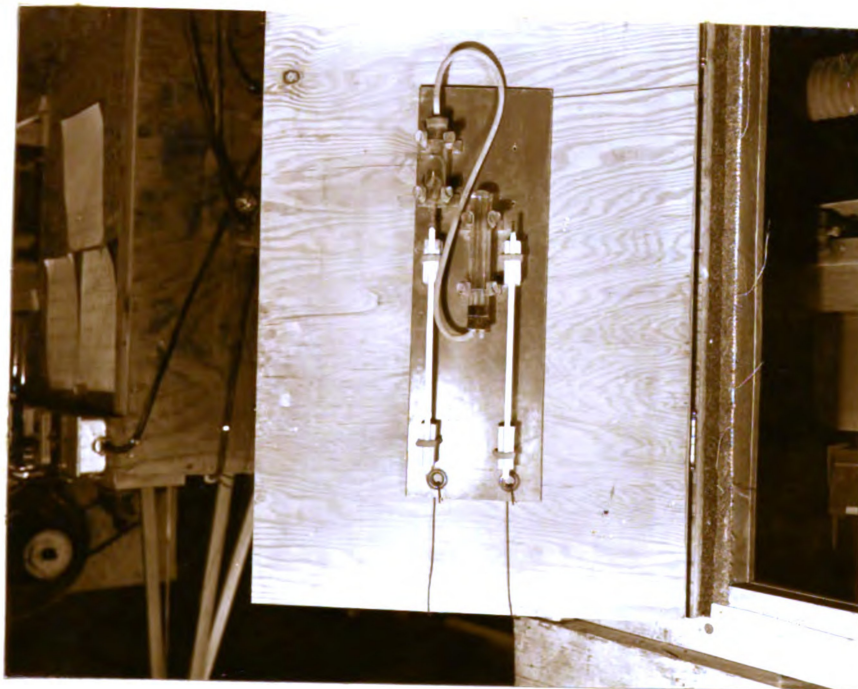


Fig. 4. Wet and dry-bulb thermometer set for the measurement of relative humidity. Two such instruments were used in the experimental dusting equipment.

chamber it was necessary to use a small fan to obtain sufficient air movement past the wet bulb. Some difficulty was experienced with the inexpensive commercial "hair drier" type fans when used for this purpose. Part of their air output is drawn through the motor for cooling purposes with the result that the air temperature is raised a few degrees after the motor has warmed up.

Dust Metering Mechanism

The dust metering mechanism consisted essentially of a horizontal conveyer belt on which dust was distributed uniformly by hand. As the belt moved forward the dust was removed evenly by means of a rotating cylindrical brush. It then fell into a sheet metal chute and from there into the intake of the feeding fan. The dust-feed brush, belt, and chute are shown schematically as D, E, and F in Figure 1.

The dust-feed belt was seven inches wide and 28 inches long. It was driven through a system of belts and gears by a variable speed electric motor. The belt speed could be varied from one-half to two feet per minute.

The dust-feed brush was two and one-half inches in diameter and six inches long. It was driven by a one-quarter inch electric drill. The speed of the brush was controlled by connecting a slide-wire type variable resistance into the motor circuit in series to reduce the input voltage.

A portion of the brush and part of the belt drive are shown in Figure 5.

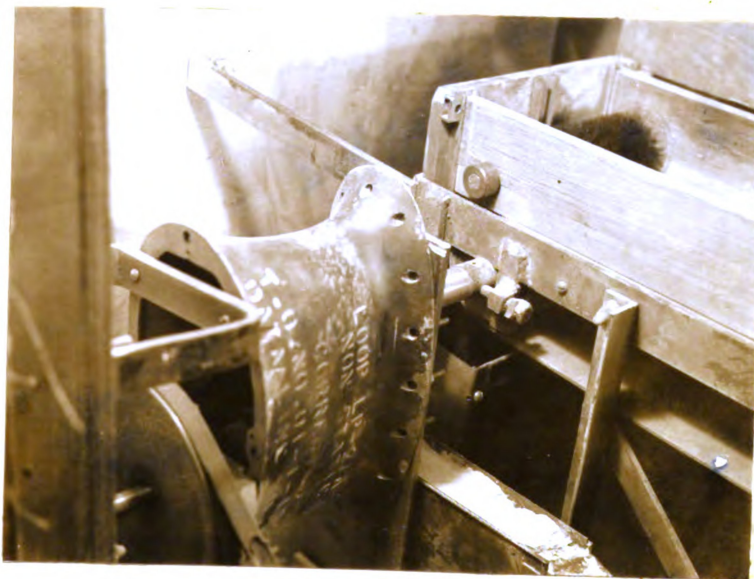


Fig. 5. Drive of the dust-feed belt. This 500 to one gear reduction was manufactured as part of a directional antenna rotator for aircraft. Part of the dust-feed brush is visible in the upper right.

Measurement of Aerosol Density

The term aerosol density was defined for this study as the weight of dust per unit volume of air. This quantity was measured by passing a known volume of air through a filter and weighing the deposit of dust on the filter. Commercial membrane filters known by the trade name of Millipore Filters which will filter particles well below a micron in size were used. Figure 6 shows two Millipore Filters together with the filter holder. The filters were weighed on an analytical balance both before and after the aerosol was passed through them.

A laboratory-type vacuum pump was used to draw the aerosol through the filter. The flow rate of this positive displacement pump was determined by measuring the time required to pump a known volume of air from a jar inverted in a pan of water. A correction was made for the change in volume of air due to the change in pressure as the water was drawn into the jar.

The Inertial Fan

The means have been described by which an aerosol of controllable density could be obtained in the dusting chamber under controllable conditions. However, a means of applying controllable inertial forces to the dust particles in the aerosol was necessary. This was accomplished by placing a fan, L, Figure 1, in the dusting chamber which

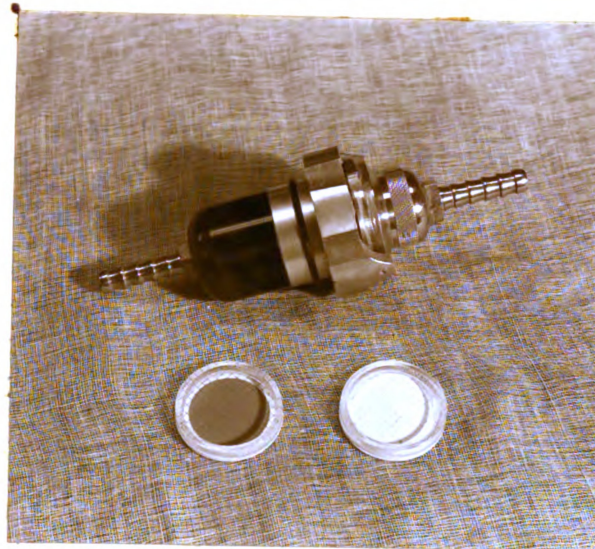


Fig. 6a. Membrane filter holder and two membrane filters. The filter at left contains a deposit of dust.



Fig. 6b. Disassembled membrane filter holder and two filters. The filter is placed flat against the portion of the holder at the left and the other portion of the holder clamps it in place.

would direct an air stream at the surface on which deposition was being measured. The fan used was a radial centrifugal fan taken from a vacuum cleaner. It can be seen in the lower right of Figure 3. The motor was the series wound type, and its speed was controlled by varying its input voltage with an autotransformer.

The air velocities delivered by the fan were measured by means of a hot-wire anemometer. The autotransformer was calibrated in terms of air velocity before each series of tests.

Due to the fact that the inertial fan was connected to a power line, one side of which was grounded, the housing must be considered to be near ground potential. For this reason charged dust particles might lose their charge in moving through the fan. It is apparent then that the inertial fan would not be satisfactory for use with charged dust.

Another factor that must be taken into consideration in connection with the inertial fan is the computation of the total amount of dust which is directed toward the experimental surface under test. In a field duster this quantity would be simply the quantity of dust that was fed into the machine. However, in the laboratory dusting equipment the amount of dust going through the inertial fan and being blown toward the surface under test is proportional to the aerosol density and the total quantity of aerosol run through the fan. It follows that for a constant aerosol density and

a constant time of exposure the amount of dust directed toward the surface is directly proportional to the air velocity at which it strikes the surface. The aerosol density is determined by the dust feeding rate.

Charging Apparatus

The laboratory dusting equipment also contained equipment for placing an electric charge on the dust. However, since the charging equipment was not used in this study it is not described here. The electric charging and measuring equipment is discussed by Splinter (2) in describing his study of the importance of electric forces on dust deposition.

Shortcomings of the Experimental Dusting Equipment

As the laboratory dusting equipment was used certain difficulties and shortcomings presented themselves. Some of these shortcomings place serious limitations on the usefulness of the equipment.

Irregularity of Dust Feed

The flow of dust into the dusting chamber as measured by the aerosol density readings taken from the membrane filter weights was far from uniform. At times the aerosol density

varied by almost a factor of three within an experiment (Figure 38).

The dust feed belt appeared to function properly, but excessive accumulation of dust in the dust-feed chute, feeding fan, and feeding-fan tube appeared to cause the inconsistency. The extent of this accumulation varied with different dusts, but appeared to be a factor with all dusts used.

With at least one type of dust, micronized copper sulfate, the most serious accumulation took place on the vertical wall of the dust-feed chute just in front of the rotating dust-feed brush. The brush threw the dust particles against the side of the chute as it removed them from the belt. In the case of micronized copper sulfate the dust particles adhered to this vertical surface and to each other, and a deposit as much as one and one-half inches thick was formed. At times a deposit three-fourths of an inch thick was formed while one twenty-gram sample of dust was run through the machine. When this difficulty was observed the feeding brush was removed and the dust allowed to fall freely from the end of the belt into the dust chute.

The problem of dust accumulation was made more serious by the fact that it was impractical to properly clean the feeding system. The cleaning problem is discussed further under "Cleaning Difficulty" below.

When wide variations occurred in the aerosol density in the conduct of an experiment the surface deposition data was corrected by a factor proportional to the deviation of the aerosol density from an accepted standard value.

Dust Clumping in the Inertial Fan

Dust was deposited on the interior surfaces of the inertial fan as well as in the dust feed system. At times the deposit in the inertial fan broke off in small clumps and these clumps were deposited on the experimental surface.

This clumping problem was largely solved by (1) cleaning the outlet tube of the fan with a cylindrical brush before running each test, (2) running the inertial fan at full speed for 30 seconds between tests to clear loose dust, and (3) cleaning the fan every ten to twenty tests by running a small amount of fine sand through it. Dust deposits obtained on microscope slides and examined under the microscope indicated that there was no excessive clumping when these precautions were taken.

Cleaning Difficulty

The excessive accumulation of dust in the feeding system was discussed above under "Irregularity of Dust Feed". However, it was very difficult to properly clean

out many parts of the system. There was no practical way of gaining access to the interior of the dust-feed fan and tube. The only way found to clean these parts of the machine was to pass a small amount of fine sand through them. The dust-feed chute was also very difficult to properly clean.

The inability to properly clean the equipment caused not only the inconsistency of dust feed discussed above, but also a mixing of dusts where more than one type of dust was used in a series of tests.

Clogging of the Exhaust Fan

The exhaust fan which was of the forward curved blade centrifugal type was completely clogged by micronized copper sulfate dust in one instance. This clogging occurred after the equipment had been used continuously for approximately a week using only micronized copper sulfate dust.

Recommendations for Changes

It was felt that before further experiments were run using the laboratory experimental equipment certain improvements ought to be made. In general it was felt that the feeding equipment ought to be redesigned to reduce the amount of dust deposited in the system and to facilitate

the cleaning of the system. Specific recommendations are the following:

1. Relocate the dust-feed belt with respect to the fan in such a way that the dust is thrown directly from the belt into the fan intake by the dust-feed brush. This would eliminate dust deposited in the dust-feed chute which was excessive under some circumstances.
2. Replace the feeding-fan tube, H, Figure 1, with a smooth tube of constant diameter. Provision should be made for cleaning this tube by means of a long-handled cylindrical brush.
3. The feeding fan should have a housing, one side of which could be removed easily for cleaning.
4. With the previously mentioned improvements made it should be possible to eliminate the inertial fan and use the air stream from the feeding fan to deposit dust by inertial forces. This would be more nearly analogous to field dusting. It would also eliminate the discharging of charged aerosols by a grounded inertial fan.
5. When the feeding fan is operated at less than 3600 revolutions per minute the air flow past the wet bulb thermometer in the dust chamber should be investigated. If necessary a small fan which would not heat the air should be directed at the wet bulb.

ARTIFICIAL LEAF-SURFACE EXPERIMENT

Equipment and Technique

Artificial Leaf Surfaces

Four artificial leaf surfaces were used. These surfaces were chosen in such a way as to isolate certain surface conditions.

All the surfaces used were placed on aluminum disks three inches in diameter. Each had an area of 7.07 square inches.

Polished aluminum surface. This was the surface used by Splinter (2) in his work on inertial and gravitational dust deposits. It was included to facilitate a comparison between the other leaf-surface data obtained in Splinter's work. It also served to show the magnitude of deposition on a smooth surface. It is pictured in Figure 7.

Sandblasted aluminum surface. This surface was made by sandblasting an aluminum disk such as the ones described above. It was included in order to evaluate the effect of surface roughness on dust deposition. Figure 8 is a photomicrograph of this surface. The depth of the "valleys" averaged about 0.02 millimeters and in some cases was as much as 0.04 millimeters. The width of the "valleys" was

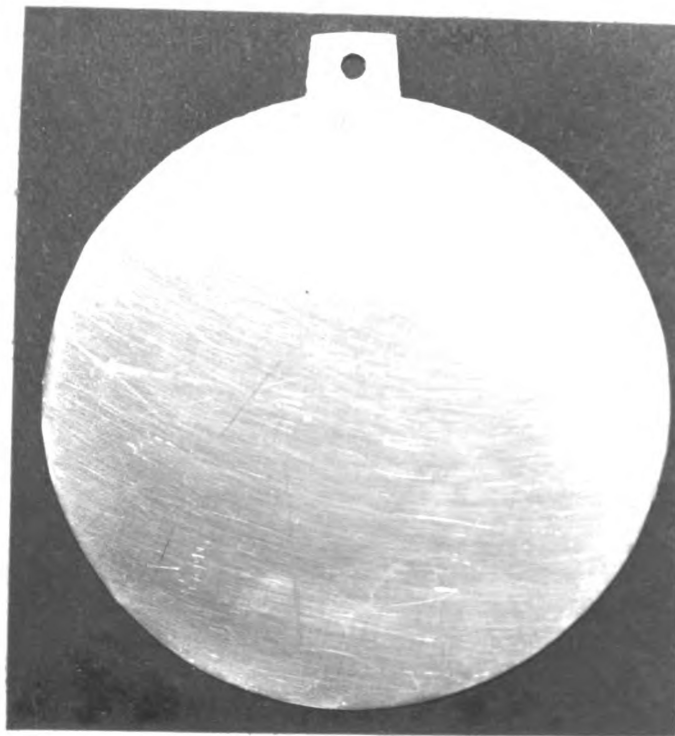


Fig. 7. Polished aluminum artificial leaf.

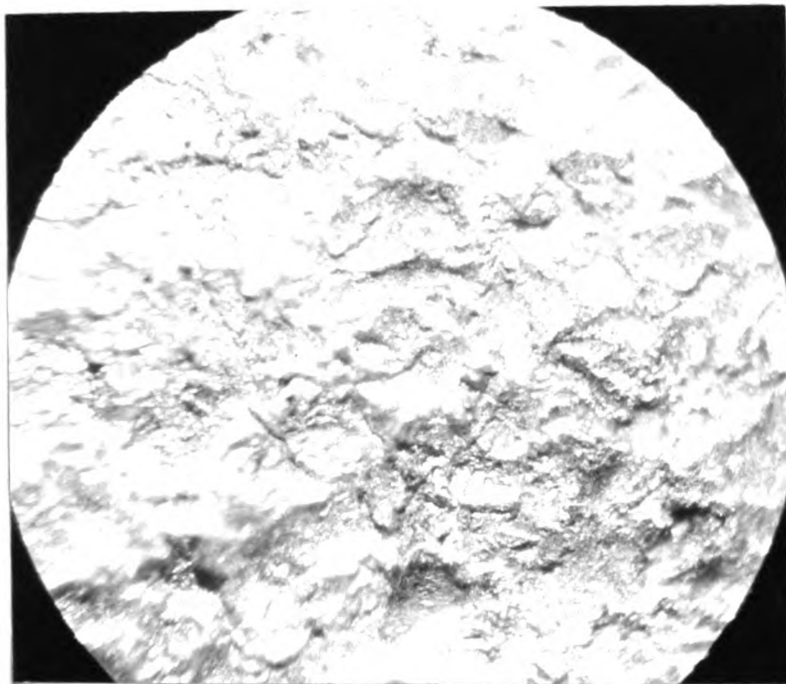


Fig. 8. Photomicrograph of sandblasted aluminum surface. The magnification is approximately 70.

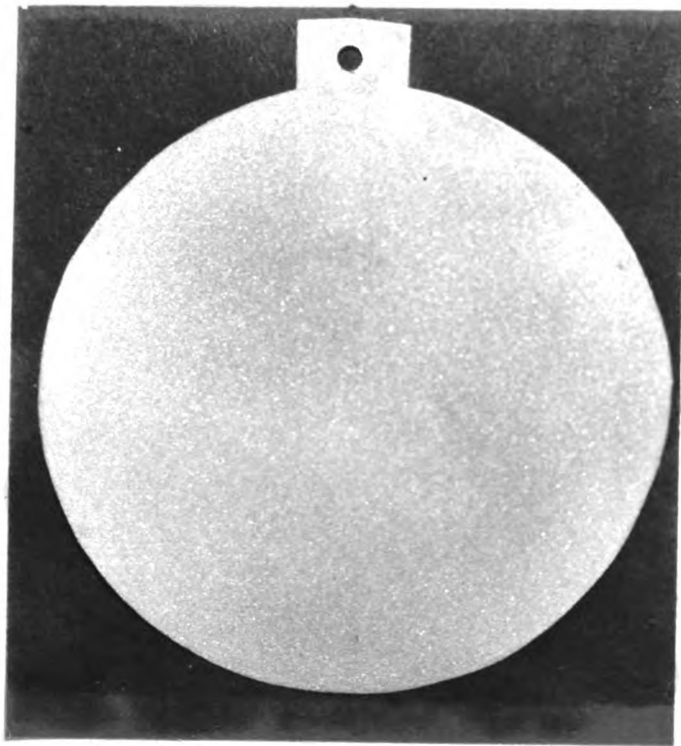


Fig. 9. Sandblasted aluminum artificial leaf.

of the order of 0.1 millimeters. Figure 9 is a picture of a sandblasted aluminum disk.

Wax surface. Many leaves have a wax covered surface and such a surface was included in this experiment. It was made by dipping an aluminum disk into a beaker of molten sealing wax as shown in Figure 10. A closeup of the surface is shown in Figure 11.

Petroleum jelly surface. This surface was included in order to obtain a sticky surface which would hold all particles which struck it. By comparing the deposition on such a surface with the deposition on other surfaces the degree of erosion from the latter surfaces could be determined. The petroleum jelly surface was made by applying petroleum jelly to an aluminum disk with a cotton swab as shown in Figure 12. The surface is pictured in Figure 13.

Selection of a Dusting Material

Hydrated copper sulfate was chosen as a dusting material because (1) it was adapted to chemical evaluation methods which would be necessary in the second experiment, and (2) it could be obtained with a "standard" particle size and could be ground to a "micronized" particle size.

Standard copper sulfate. This material was obtained under the commercial name "powdered bluestone". It had a range of particle sizes from one to thirty microns (4).



Fig. 10. Coating artificial leaf with wax.

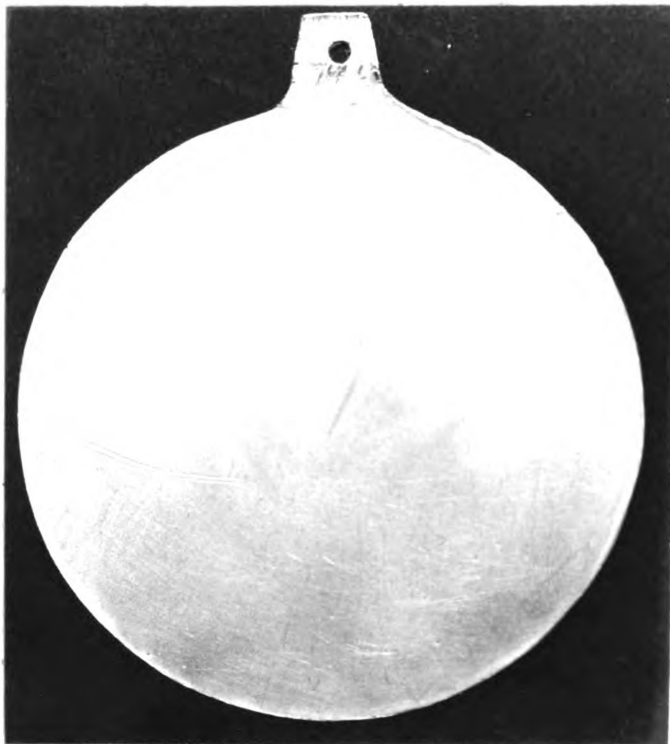


Fig. 11. Wax-coated aluminum artificial leaf.



Fig. 12. Coating artificial leaf with petroleum jelly.



Fig. 13. Petroleum-jelly coated aluminum artificial leaf.

A complete size analysis is given in Table I. The apparent density was approximately .86 grams per cubic centimeter. This dust had comparatively little tendency to adhere to the surfaces of the dust-feeding system of the laboratory dusting equipment.

Micronized copper sulfate. Standard copper sulfate was run through a "micronizer" to obtain micronized copper sulfate. The "micronizer" was a commercial machine operated by compressed air. It had no moving parts, but the grinding action was accomplished by two high velocity air streams perpendicular to each other. After going through this machine the particle size was reduced to a range of from less than one to eight microns (4). Table I gives a complete size analysis.

The properties of the dust changed rather sharply when it was "micronized". The micronized dust was distinctly lighter in color and the apparent density changed from 0.86 to 0.34 grams per cubic centimeter. However the finer dust was more easily compacted. It also had a very marked tendency to adhere to any type of surface it contacted when suspended in air.

Before going into the air stream the micronized dust was made up entirely of small clumps and the individual particles had a strong tendency to adhere to each other. To determine the condition of the dust while being deposited

TABLE I
DUST PARTICLE-SIZE DISTRIBUTION*

Particle Size Microns	Percent of Number of Particles	
	Standard $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	Micronized $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$
Less than 1	10.0	20.5
1 - 2	32.3	57.1
2 - 4	19.5	17.7
4 - 6	10.2	3.4
6 - 8	5.4	.9
8 - 10	5.4	.3
10 - 12	3.3	.1
12 - 20	10.2	--
20 - 30	2.8	--
More than 30	.9	--

* Particle-size analysis was made by microscopic means by N. T. Ban (4).

a microscope slide was exposed to the inertial air stream. Upon examination it was found that many small clumps of particles existed in the air stream but that few of these were over 15 microns in size.

Air Velocities

Three air-stream velocities were used to deposit dust on the artificial leaf surfaces. These were 300, 900, and 1400 feet per minute. They were selected as a range which would go all the way from a low velocity to one which might be expected at the plant surface in the direct air blast from a field duster.

Evaluation Method

Direct weighing was the deposit evaluation method used in this experiment. The artificial leaves were weighed on analytical balances before and after exposure to the aerosol stream. These balances were accurate to within plus or minus 0.1 milligram.

Experimental Design

A randomized block design of three classifications was used for the experiment. There were four surfaces, two dusts, and three air speeds. In addition the experiment was replicated four times giving a total of 96 tests.

Within each replication all the tests with one dust were run in a group to help avoid the mixing of dusts. Otherwise the tests were completely randomized.

Test Procedure

Layout. Figure 14 shows the arrangement of equipment for the artificial leaf-surface experiment. Two persons were used in the conduct of the experiment. One was on the left of the table in Figure 14 and operated the experimental dusting equipment, B. The other was on the right of the table and operated the analytical balance, C.

Experimental conditions. The conditions under which the experiment was run are listed below.

1. Temperature. The temperature was maintained between eighty and ninety degrees Fahrenheit.
2. Relative humidity. The relative humidity was maintained at sixty percent plus or minus three percent.
3. Feeding rate. The dust feeding rate was twenty grams of dust per test run.
4. Exposure time. The artificial surface was left in the dusting chamber while the inertial fan was run for two minutes.

Experimental procedure. The experimental procedure for the operator of the dusting equipment was as follows:

1. The outlet tube of the inertial fan was cleaned with a brush and the inertial fan allowed to run at full speed for thirty seconds.
2. A twenty-gram sample of dust was weighed out and placed in a uniform band four and one-half inches long on the dust-feed belt.

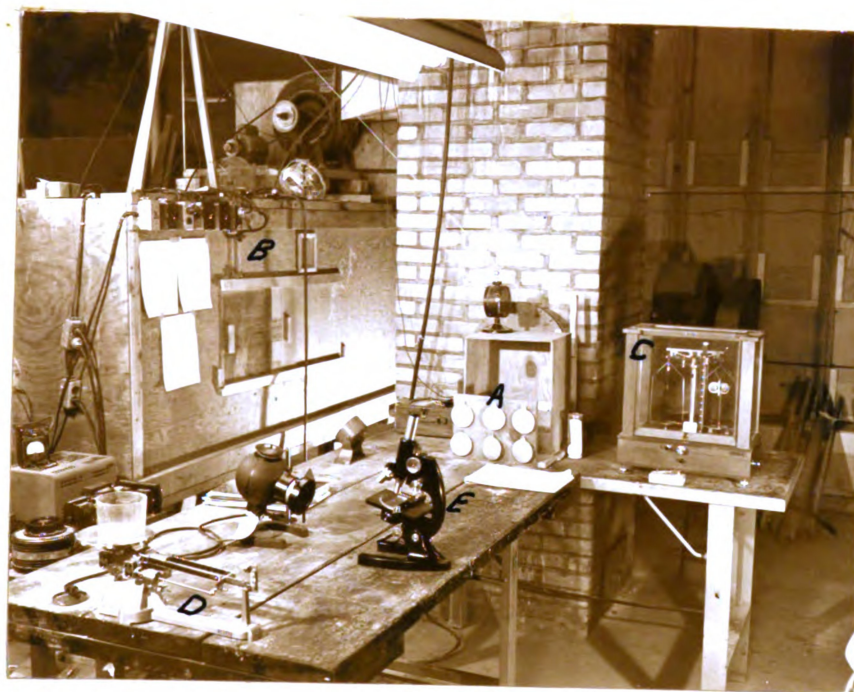


Fig. 14. Arrangement of equipment for artificial leaf-surface experiment. The equipment designated by letters is the following:

- A. Artificial leaves
- B. Dusting chamber
- C. Analytical balance
- D. Balance for measuring dust for feeding
- E. Microscope

3. The air velocity was set by means of the autotransformer and entered in the data book.
4. The proper artificial leaf was placed in the dust chamber and its surface type entered in the data book.
5. The relative humidity reading was taken and entered in the data book.
6. The inertial fan and the metering mechanism were run for two minutes.
7. The artificial leaf was taken from the dust chamber and any remarks pertaining to the test were entered in the data book.

If an aerosol sample was taken, the filter was placed in its holder before the test was begun and the vacuum pump turned on one-half minute after the metering mechanism and turned off one minute later. The operator of the balance weighed the artificial leaves and the membrane filters.

Cleaning procedure. The outlet tube of the inertial fan was cleaned before each test. The dust-feed chute, feeding fan and tube, and inertial fan were cleaned with sand every 16 tests when the dust particle size was switched.

Aerosol sampling. Membrane filter samples* of the aerosol density were taken every second test during the first half of the experiment and every fourth test during the last half of the experiment.

* See "Measurement of Aerosol Density," page 15. .

Re-run of First Replication

A number of refinements were made in the experimental procedure while the first replication was being run. For this reason the data obtained at this time was not used, and another replication was run to replace it.

Miscellaneous Re-runs of Tests

In certain tests there were errors in technique, such as poor timing, or failures in the equipment, such as the depositing of large clumps of dust on the experimental surface. In these instances the errors were noted and the tests were re-run at a later date.

Use of Electrically Charged Dust

In addition to the tests described above, tests were run using charged dust in the artificial leaf surface experiment. The investigators did not realize until after the experiment had been completed that these tests would be invalid because of the possibility of the dust being discharged as it passed through the inertial fan.* Because of this situation the results of these tests are considered to be of little value and are not included in this report.

Results of Artificial Leaf-Surface Experiment

Dust-Feeding Consistency

As was discussed under "Shortcomings of Experimental Dusting Equipment" (page 18) problems were encountered in

* See "Inertial Fan", page 15.

holding the amount of dust entering the dusting chamber constant. In this experiment aerosol samples taken on the membrane filters varied by as much as a factor of two in some cases as shown in Figure A-1. The results were consistently low immediately after cleaning the feeding system. These extremely low readings were re-run, but otherwise no correction was made for variation in dust feed. It was felt that the error in interpolation to obtain correction factors for tests where no aerosol sample was taken would be greater than the irregularities in dust feed.

Analysis of Variance

One analysis of variance was made of the data for the smooth and sandblasted aluminum surfaces and another of the data pertaining to the wax and petroleum jelly surfaces. This division of the data was made because the significance of the difference between the two groups of data was obvious upon inspection (Table A-I).

The two analyses of variance are given in Tables II and III. The analysis for the smooth and sandblasted aluminum surfaces shows significance at the one percent level for the difference between air speeds and the difference between dusts, but no significance at the five percent level for the difference between the deposit on the two surfaces. The interaction between air speeds and dusts was also statistically significant.

TABLE II
ANALYSIS OF VARIANCE OF DEPOSIT DATA FOR POLISHED
AND SANDBLASTED ALUMINUM SURFACES
(Data in Table A-I)

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F
Total	47	7513.886		
Surfaces	1	18.253	18.253	.88
Velocities	2	3213.826	1,606.912	77.05**
Dusts	1	1395.363	1,395.363	66.91**
Surfaces- Velocities	2	23.313	11.656	
Surfaces- Dusts	1	5.070	5.070	
Velocities- Dusts	2	2094.805	1,047.402	50.22**
Sur.-Vel.- Dusts	2	12.466	6.233	
Error	36	750.790	20.855	

** Significant at 1% level

TABLE III
ANALYSIS OF VARIANCE OF DEPOSIT DATA FOR WAX
AND PETROLEUM JELLY SURFACES
(Data in Table A-I)

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F
Total	47	47,287.227		
Surfaces	1	8,970.801	8,970.801	129.41**
Velocities	2	19,350.833	9,675.416	139.58**
Dusts	1	11,156.901	11,156.901	160.95**
Surfaces- Velocities	2	3,403.895	1,701.947	24.55**
Surfaces- Dusts	1	1,160.333	1,160.333	16.74**
Velocities- Dusts	2	606.878	303.438	4.38*
Sur.-Vel.- Dusts	2	142.096	71.047	
Error	36	24,954.490	69.319	

*Significant at 5% level
**Significant at 1% level

In the analysis of variance of the wax-petroleum jelly data all treatments and all interactions showed significance. The practical significance of these results will be discussed below.

Effect of Surfaces

There was no significant difference between the polished and the sandblasted aluminum surfaces. However, the wax surface had an average deposit twice as great as that on the two aluminum surfaces as can be seen in Figure 15. The petroleum jelly surface had an average dust deposit almost four times as great as that on the aluminum surfaces. The increased deposit on the latter two surfaces was attributed to reduced erosion of dust from these surfaces. This apparently was due to the tendency of the dust particles to be embedded in the softer materials and to any forces of adhesion between the particle and the surface material. Figures 16, 17, 18 and 19 show dust deposited on the four types of surfaces.

Effect of Particle Size

In order to understand the effect of particle size on deposition, the relationship between the effects of particle size and surfaces must be considered. This relationship

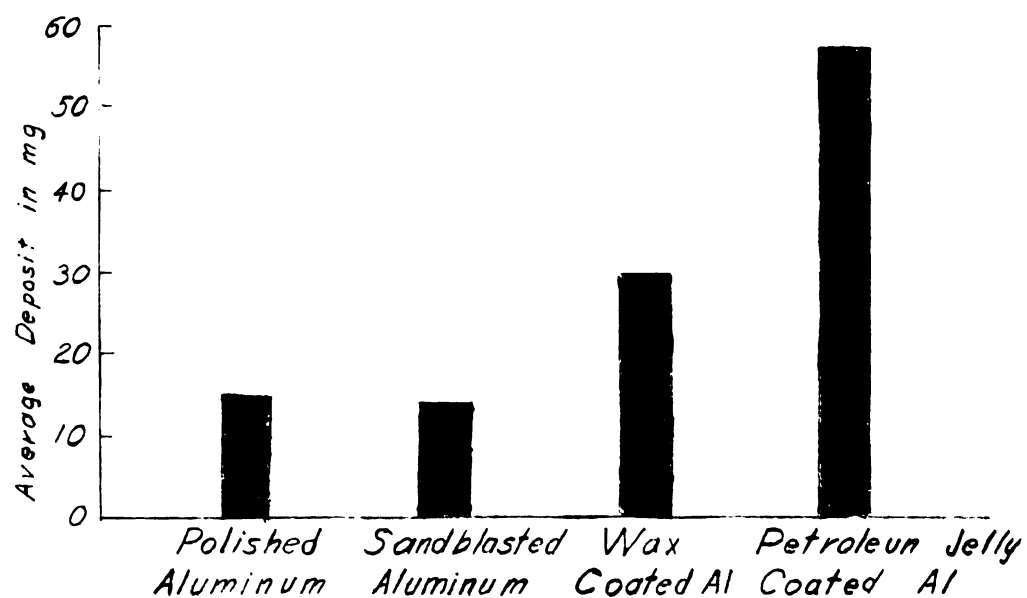


Fig. 15. The effect of artificial leaf surfaces on dust deposition. These values are the average of the deposits of copper sulfate dusts of two particle sizes at three air velocities.



Fig. 16. Dust deposit on polished aluminum artificial leaf. "Micronized" dust was deposited at a 300 fpm air velocity. It can be seen that at this velocity the deposit was nearly invisible.



Fig. 17. Dust deposit on sandblasted aluminum artificial leaf. "Standard" dust was deposited at a 1400 fpm air velocity.

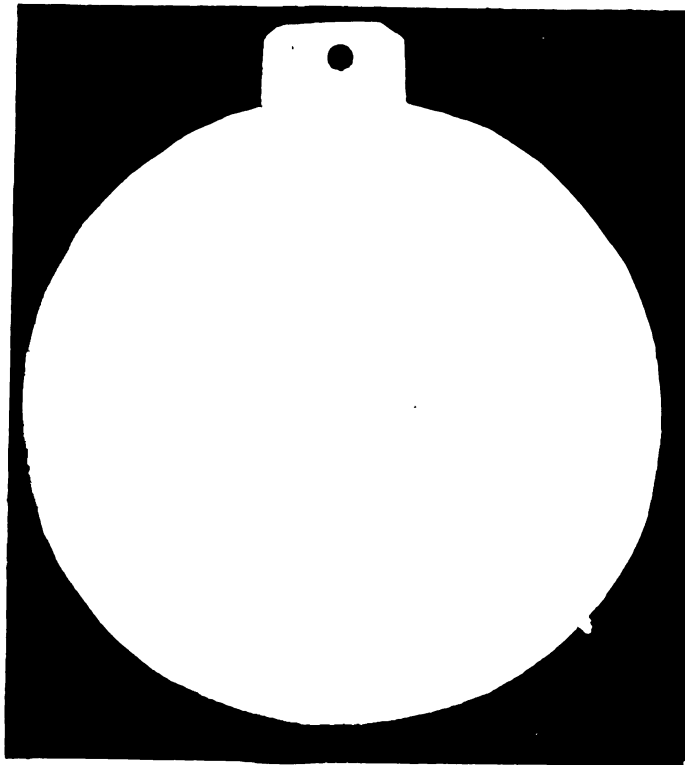


Fig. 18. Dust deposit on wax-coated aluminum artificial leaf. "Micronized" dust was deposited at a 1400 fpm air velocity.

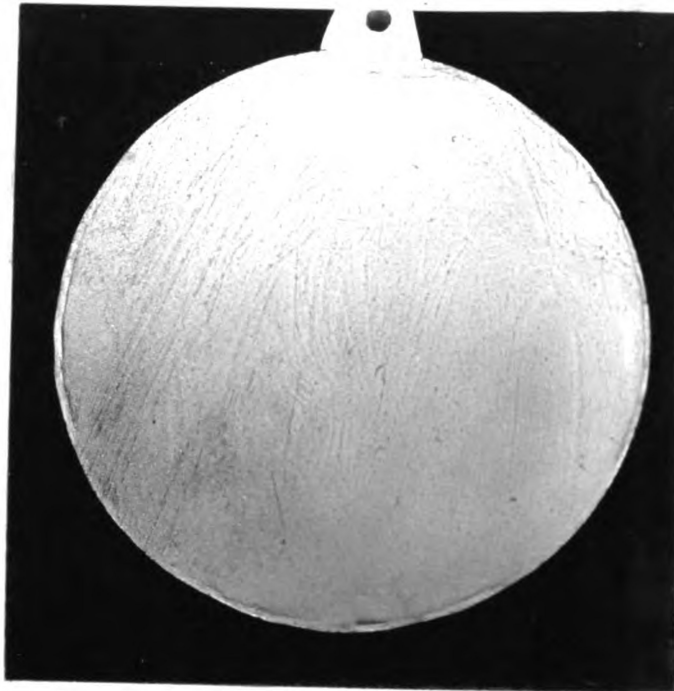


Fig. 19. Dust deposit on petroleum jelly coated artificial leaf. "Micronized" dust was deposited at a 1400 fpm air velocity.

is shown in Figure 20. It will be noted that in the case of the standard dust the deposit on the aluminum surfaces was very low, while the deposit on the "soft" surfaces was comparatively very high. On the other hand, in the case of the micronized dust the variations in deposition were much less extreme. The aluminum surfaces had a greater deposit of micronized dust than of standard, while the two "soft" surfaces had lower deposits of the micronized dust.

A possible explanation of the facts mentioned above is as follows:

1. The dust deposited on a surface will be equal to the quantity of dust striking the surface minus the quantity "eroded" away by the air stream or by bombardment by other particles.
2. The quantity of dust striking the surface will be dependent upon the momentum of the particles since the air stream will bend as it nears the surface and tend to carry the dust particles with it. Since momentum is proportional to velocity and mass, the momentum of the particles will be dependent on the particle size.
3. Erosion will be retarded by the adhesive forces between the particle and the surface and by the embedding of the particles in the material of the surface.
4. Forces of adhesion are assumed to be greater in relation to forces causing erosion for smaller particle

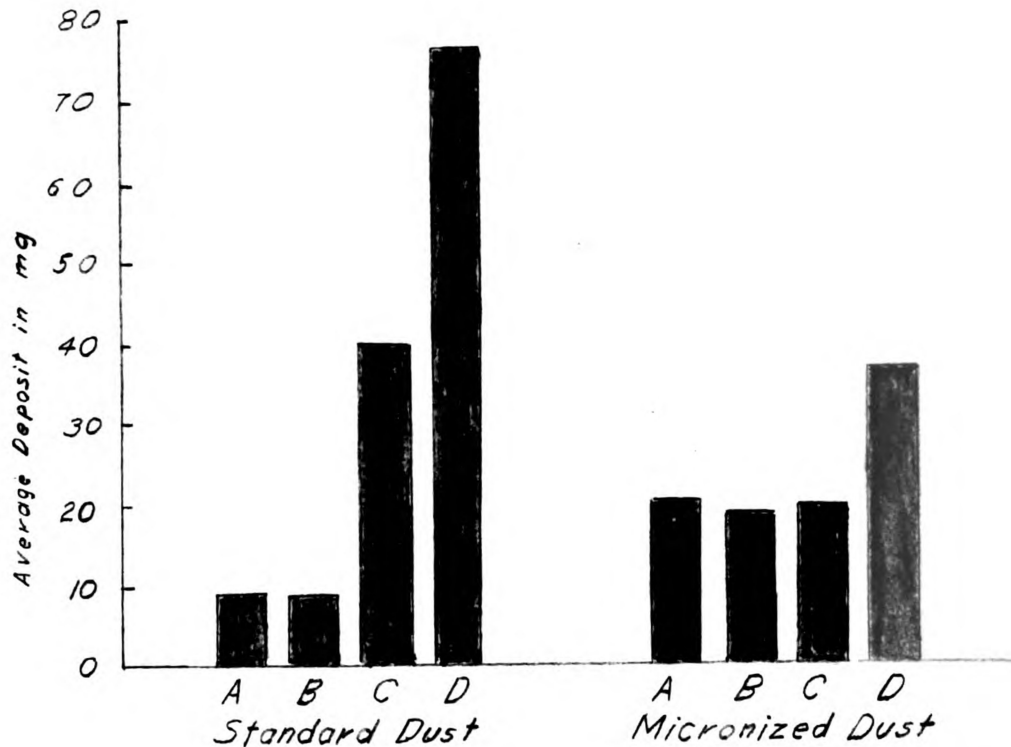


Fig. 20. The effect of dust particle size and artificial leaf surfaces on dust deposition. These values are averages of the deposit at the three air velocities reported on page 34. The particle size distributions for the standard and micronized copper sulfate dust are given in Table I. The artificial surfaces represented by letters are the following:

- A. Polished aluminum
- B. Sandblasted aluminum
- C. Wax coated aluminum
- D. Petroleum jelly coated aluminum

sizes. That is to say that under the same conditions there will be greater erosion of standard dust than of micronized dust.

5. On the aluminum surfaces the forces of adhesion were relatively small and there was no embedding of particles. Therefore in the case of the standard dust there was a very low deposit on these surfaces because of a very high degree of erosion. However, there was less erosion of the micronized dust; consequently a larger deposit was left on the surface as shown in Figure 20.
6. On the wax and petroleum jelly surfaces the forces of adhesion were much greater, and there was also a possibility of particles with high momentum embedding themselves in the surface material. Since the larger particles in the standard dust had greater momentum than the smaller ones in the micronized dust, a larger proportion of them struck the surfaces. Since erosion was retarded on the wax and petroleum jelly surfaces, these surfaces had very large deposits of standard dust as shown in Figure 20. However, the deposits of micronized dust on these surfaces was lower, because a smaller quantity of this dust strikes the surface. This was due to the lower momentum of the smaller dust particles.

Effect of Variation in Air Velocity

As was pointed out in the discussion of the inertial fan (page 15) the quantity of dust directed at a surface was proportional to the air velocity. However, the discussion which follows is based on deposit data which has been corrected to represent a constant quantity of incident dust. This correction assumes a linear relationship between deposit and quantity of incident dust and neglects any increased erosion that increased incident dust might cause. The details of the correction are given in Appendix A.

The variation of the air velocity of the incident air stream gave distinctly different results with the two dust sizes used. The corrected deposit of the standard dust decreased with increased air velocity while the reverse was true for micronized dust as can be seen in Figures 21 and 22. This might be explained in terms of the proposed explanation discussed under "Effect of Particle Size" as follows:

1. The erosional forces of standard dust increase so rapidly with increase in air velocity that the increased erosion more than offsets the increased amount of dust striking the surface.
2. The reverse situation is true of the smaller micronized particles, so their corrected deposit increased with increased air velocity.

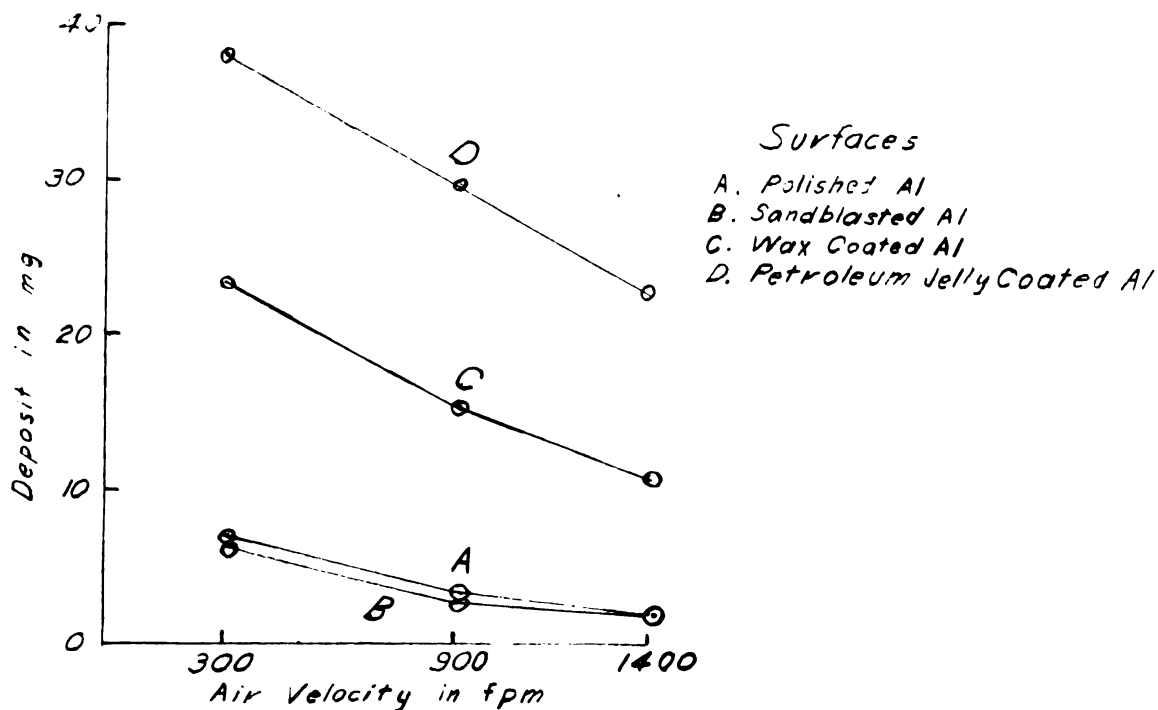


Fig. 21. The effect of artificial leaf surfaces and air velocity on deposition of "standard" copper sulfate dust. Table I gives a particle size distribution of this dust. The data has been corrected for variation in incident dust quantity with air velocity as explained in Appendix A.

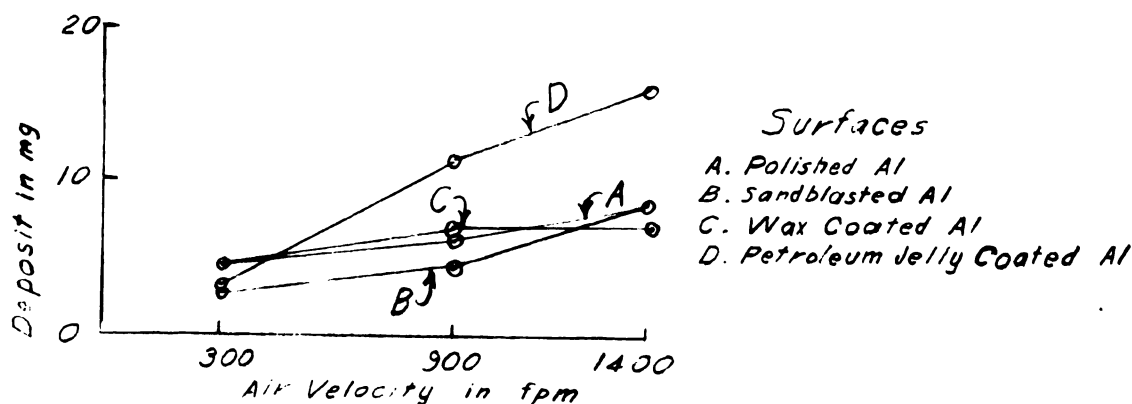


Fig. 22. The effect of artificial leaf surfaces and air velocity on the deposition of "micronized" copper sulfate dust. Table I gives a particle size distribution of this dust. The data has been corrected for variation in incident dust quantity with air velocity as explained in Appendix A.

It is interesting to note that the curves of corrected deposit against air velocity in Figure 21 and 22 are all very close to straight lines. This would tend to indicate that both the quantity of erosion and the quantity of dust striking the surface are related to the air velocity in a linear manner, although this indication is far from conclusive.

Interactions

The cause of the significant velocity-dust interaction is apparent from Figures 21 and 22 and the discussion above. The slope of the velocity-dust curve is positive for micronized dust, but negative for standard dust.

The dust-surface interaction was significant for the wax and petroleum jelly surfaces. It can be seen from Figure 23 that the magnitude of the difference of the deposit on these two surfaces varies from 3.72 milligrams for standard dust to 1.76 milligrams for micronized dust.

Figure 23 shows the reason for the significant velocity-surface interaction. There is a definite difference in the slope of the air-velocity versus deposit curves for the wax and petroleum jelly surfaces.

Further study would be required to evaluate the practical significance, if any, of the latter two interactions.

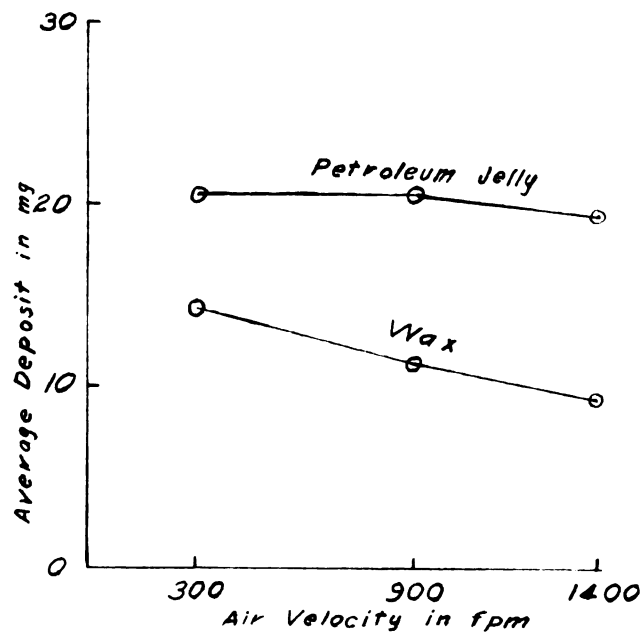


Fig. 23. The effect of wax and petroleum jelly coated aluminum surfaces and air velocity on copper sulfate dust deposition. The data has been corrected for variation in incident dust quantity with air velocity as explained in Appendix A. It represents the average deposit of both particle sizes described on page 27.

Quantity of Dust Directed At Surface

It was possible to compute the amount of dust which was directed at the test surface by knowing the aerosol density* and the air velocity. This involved making the assumption that the aerosol density at the outlet of the inertial fan was the same as that at the membrane filter where the aerosol sample was taken.

With an aerosol density of 14.3 milligrams dust per cubic foot of air, which was average, and an air speed of 300 feet per minute, 420 milligrams of dust were directed at the test surface. This was from nine to 400 times the quantity of dust which was actually deposited on the surfaces at that speed. The details of the foregoing calculations are in Appendix A.

* See "Measurement of Aerosol Density" page 15 .

CHEMICAL EVALUATION METHODS FOR PLANT LEAF-SURFACE EXPERIMENT

Before an experiment could be conducted using actual leaf surfaces, a method had to be devised to evaluate the dust deposits obtained. Preliminary tests indicated that leaves lost weight through evaporation far too rapidly to permit the use of direct weight evaluation.

Another approach to the evaluation problem is that of chemically analyzing a solution in which the dust deposit has been dissolved. This method has been quite generally used, but the analysis has been restricted to time-consuming procedures confined to the chemistry laboratory. In this investigation it was thought impractical to depend on a chemistry laboratory for deposit evaluation, and a method was sought which was more rapid and which could be carried out outside of the laboratory.

Two possibilities for rapid deposit evaluation were tried -- volumetric copper titration and polarographic analysis. They are discussed below.

Perfection of Volumetric Copper Titration

Preliminary Investigation by Brazee

After investigating three deposit evaluation possibilities, Brazee (3), working at Michigan State College,

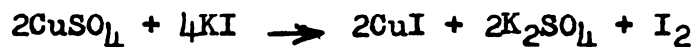
found one which showed promise. This method, which has the chemical name of volumetric copper titration, is actually a fast, simple, method of determining the copper content of a solution. Brazee tested the method for accuracy using known copper concentrations and adding impurities such as might be encountered in washing deposits from leaves in the field. These tests gave satisfactory results.

Brazee did not report testing a leaf washing procedure by evaluating actual dust deposits, although he did suggest such a procedure. Also his work dealt with larger quantities of copper than was anticipated in the leaf surface experiment for this study. These two problems, then, remained to be worked out before the method could be used.

Summary of Technique

The volumetric copper titration technique is summarized below. A detailed description of the mechanics of the technique are included in Appendix B, while the reader is referred to the thesis by Brazee (3) for a more detailed discussion of the theory involved.

1. Potassium iodide is added to the solution containing an unknown amount of copper. It reacts to release free iodine in a quantity proportional to the amount of copper present. The formula for the reaction is the following:



2. A starch indicator is added which turns a dark blue in the presence of free iodine.
3. A measured quantity of sodium thiosulfate is added just sufficient to clear the blue color from the solution. The sodium thiosulfate reacts with the free iodine and brings it into a combined state, thus removing the cause of the blue color. This occurs according to the formula



The quantity of sodium thiosulfate added, then, is proportional to the quantity of copper present in the solution.

Adaptation to Plant Leaf-Surface Experiment

Increasing sensitivity. Brazee, in his study of the volumetric copper titration procedure, used quantities of copper in his test solutions ranging from approximately ten to 100 milligrams. It was found in preliminary tests that in the plant leaf-surface experiment of this study it would be necessary to measure quantities of copper well below one milligram. Consequently a way was sought to increase the sensitivity of the procedure.

The method used to accomplish this was to reduce the concentration of the sodium thiosulfate solution. Brazee had used a solution one milliliter of which would titrate

approximately ten milligrams of copper. The concentration of this solution was cut by a factor of ten so that one milliliter would titrate only about one milligram of copper.

Preliminary tests with this more dilute sodium thio-sulfate solution indicated an accuracy of plus or minus 0.05 milligrams of copper could be obtained. It seemed impractical to further dilute the titrating solution, however, because the end point in the procedure was not sufficiently sharp to give any further increase in accuracy.

The use of a five milliliter capacity burette which was calibrated in hundredths of a milliliter was also useful in increasing the accuracy obtainable. This burette is on the right in Figure 24.

Leaf washing technique. If the results of a chemical analysis type of deposit evaluation are to be accurate an efficient method of dissolving the deposit in the wash solution must be devised. Tests indicated that washing the leaf samples by agitating them for 30 seconds with 50 milliliters of distilled water in a one-half pint fruit jar was adequate.

Preliminary tests of this washing technique included both washing the leaf samples a second time and dry ashing the leaves after the first washing. In neither case was any copper detected which had been left on the leaf after the first washing. Both tests were replicated four times.

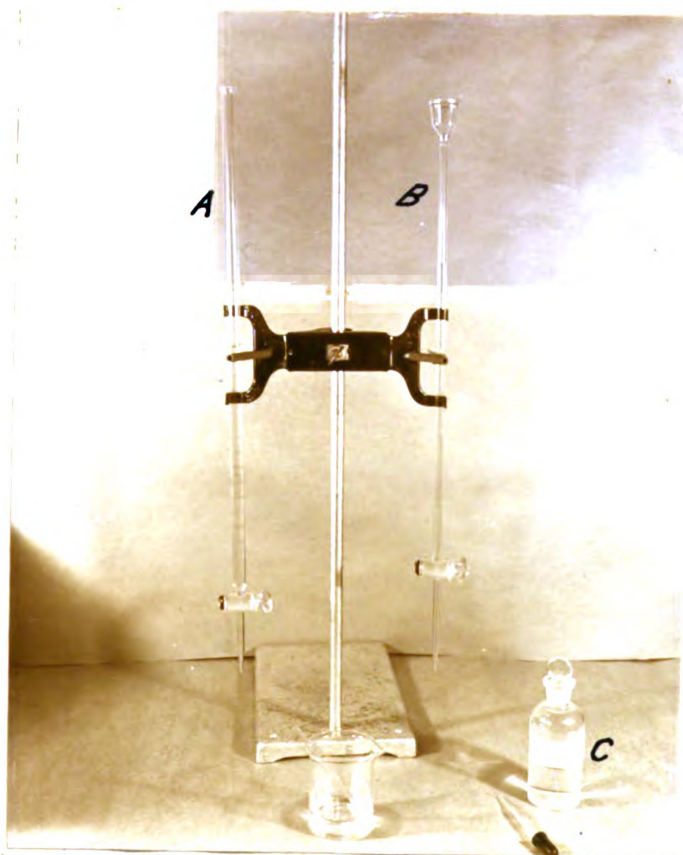


Fig. 24. Apparatus used for volumetric copper titration. The apparatus indicated by letters is the following:

- A. Twenty-five ml burette containing potassium iodide.
- B. Five ml burette containing sodium thiosulfate.
- C. Starch solution.

Advantages and Limitations

The advantages and limitations of volumetric copper titration may be listed as follows:

1. Rapidity. The entire evaluation including sampling could be accomplished in less than five minutes.
2. Portability. All necessary equipment could easily be set up in the field.
3. Simplicity. Comparatively little chemical knowledge is required of the operator.
4. Cost. All necessary equipment and supplies could be procured for less than 25 dollars.
5. Versatility limited. Since the technique is one for copper analysis, it is limited to materials containing copper. It has only been tested using hydrated copper sulfate.
6. Sensitivity limited. The maximum sensitivity which has appeared practical is plus or minus 0.1 milligram of copper.

Polarographic Evaluation

The polarograph is a very versatile instrument for both qualitative and quantitative chemical analysis. It was adapted by Ban (4) to use in the analysis of solutions containing small quantities of copper sulfate such as those encountered in copper sulfate dust deposit evaluation. The

development of a leaf washing technique is reported below together with a simplified theory of the instrument. A detailed description of the polarographic evaluation technique is included in Appendix B.

For a more thorough treatment of the polarograph the reader is referred to Chapter XVII in Instrumental Methods of Analysis by Willard, Merritt, and Dean (8) and to the two volume work, Polarography by Kolthoff and Lingane (9).

Simplified Polarographic Theory

The polarograph is essentially an apparatus for plotting the voltage-current curve of an electrolytic cell containing the unknown solution. As shown in Figure 25 it contains a battery and a rheostat for applying any desired voltage within its range (usually zero to three volts). The electrolytic cell is a container for the test solution which is equipped with two electrodes to place a potential across the solution. One of these electrodes is comparatively very large while the other is very small. A very sensitive galvanometer measures the current flowing through this cell.

In order for current to flow through such a cell, the chemical ions in the solution must migrate to the electrodes and gain or lose electrons. In other words, the dissolved compound of unknown concentration must be electrolytically decomposed. However, below a certain potential no decomposition will occur, and, in theory, no current will flow.

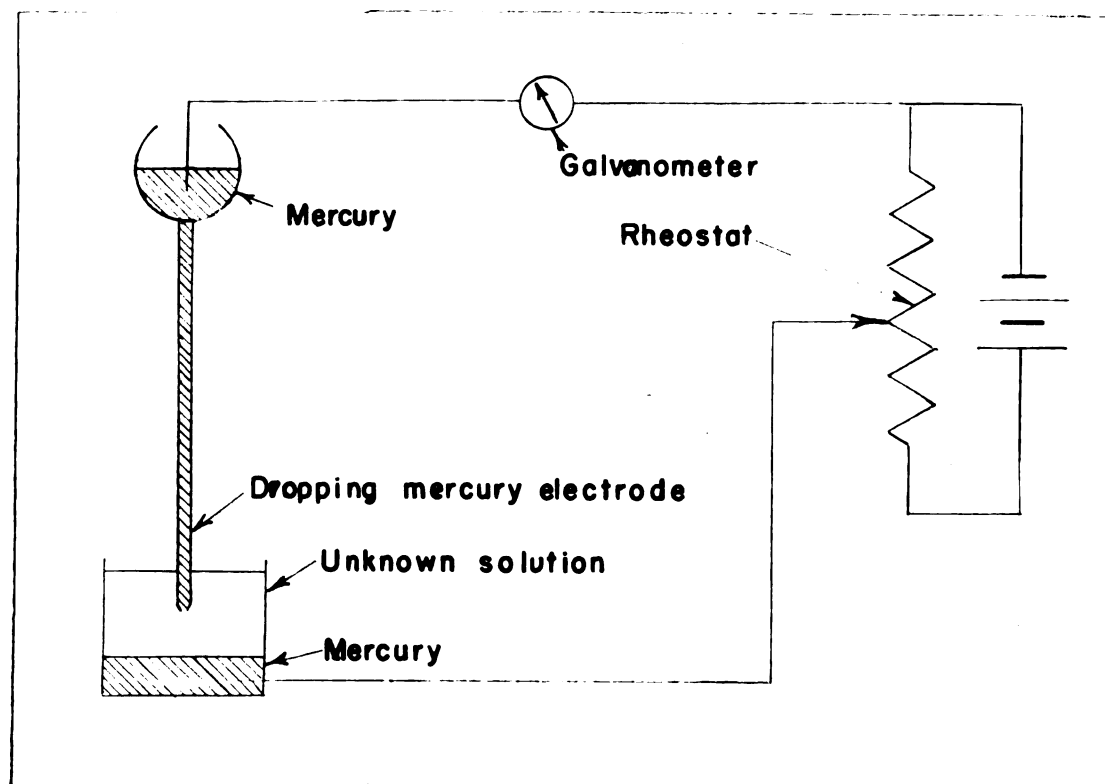


Fig. 25. Schematic diagram of polarographic circuit.

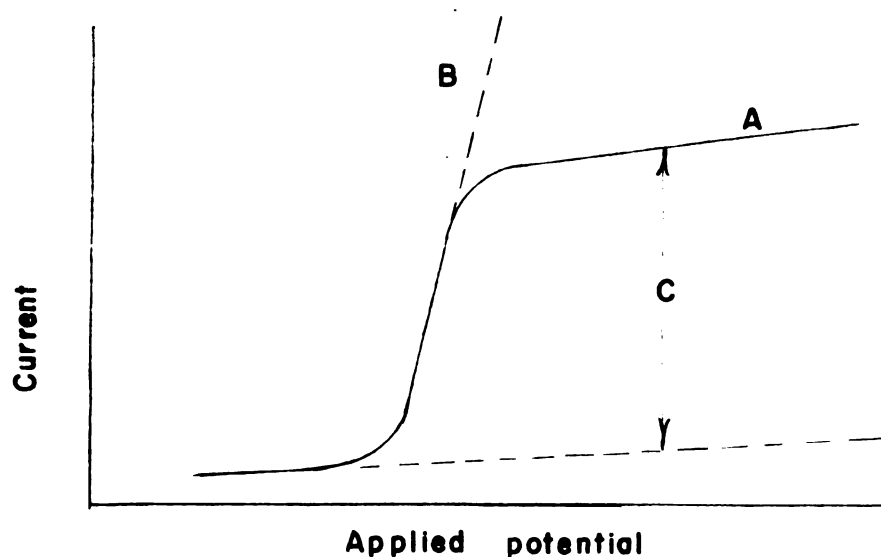


Fig. 26. A typical polarographic curve. The voltage at which the step occurs determines the nature of the material while the height of the step, C, determines the concentration of the material in solution.

This critical potential is known as the decomposition potential. Each element has a characteristic decomposition potential of its own.

In plotting the voltage current curve, then, very little current flows until the decomposition potential is reached. At this point there is a sudden jump in current as shown in Figure 26. The voltage at which this jump occurs indicates the type of ion which is being oxidized or reduced at the small electrode.

If there were an abundance of ions to be oxidized or reduced at the small electrode the curve in Figure 26 would follow a straight line after the decomposition potential was reached as shown by line B. However, very soon after decomposition begins the supply of ions around the electrode is depleted. This sets up an ion concentration gradient between the area around the small electrode and the rest of the solution. Diffusion through this concentration gradient will bring ions into contact with the electrode at a definite rate which is proportional to the concentration. This will permit a definite current to flow through the cell which is proportional to the concentration of the unknown solution. This current is known as the diffusion current and is indicated by the height of line A.

It is necessary to add to the unknown solution another compound known as a supporting electrolyte to prevent

electric forces from disturbing the normal migration of ions through a concentration gradient.

In order to prevent the surface of the small electrode from becoming covered with the material which it is oxidizing or reducing, a constantly changing drop of mercury coming through a capillary tube is used for this electrode.

There are other factors which must be considered, but the foregoing discussion attempts to give a general picture of polarographic theory.

Adaptation to Deposit Evaluation

Washing technique. Since the polarograph measures concentration and not the quantity of the unknown in a solution, it was important that the volume of the wash solution be as small as practicable, and that its volume be accurately measured. Consequently a quantity of 24.5 milliliters of wash solution was used, and it was measured by means of a specially calibrated volumetric pipette.

In order to polarographically analyze the wash solution it had to contain a 0.4 normal potassium-sulfate electrolyte concentration and a 0.02 percent concentration of gelatin. A stock solution containing 0.071 grams potassium sulfate per milliliter was made up. When 0.5 milliliters of one percent gelatin solution were added to 24.5 milliliters of stock wash solution immediately before the analysis, 25 milliliters of a solution containing the

proper concentrations of both materials was obtained. The gelatin had to be added immediately before analysis because it fermented within a period of a few days.

A standard procedure of agitating the leaf sample and wash solution for one minute and then allowing the leaf sample to remain in the solution for at least five minutes was adopted. Washing tests similar to those described under "Washing Technique" for the titrimetric evaluation indicated that this washing method was adequate. In some cases in these tests as much as 0.01 milligram of dust was detected on the second washing, but this was below the accuracy of the evaluation method and would have no effect on the results.

Calibration of polarograph. When the nature of the material which is being polarographically analyzed is known and all that is desired is quantitative results a complete polarographic curve need not be drawn for every test. All that is necessary in this case is to know the diffusion current. This can be determined by taking only one reading at a definite voltage above the "step" on the curve, once the characteristics of the curve are known.

For this reason a calibration was made of the polarographic current readings at 0.400 volts. Figure A-2 shows this calibration plotted on a curve of centimeters on polarograph galvanometer against milligrams copper sulfate

dissolved in 25 milliliters of solution. Copper solutions of known concentration were used in the calibration. The weight of copper sulfate dissolved in 25 milliliters solution was obtained by calculation.

Use of multiple polarographic cells. In the polarographic analysis it is necessary to remove the oxygen from the solution under test by bubbling nitrogen through it for approximately ten minutes. In order to speed up the procedure a special stand capable of holding five polarographic cells was constructed. This permitted the operator to analyze the solution in one cell while nitrogen was being bubbled through other solutions in other cells. Figure 27 shows the multiple cell arrangement with the polarograph.

In practice it was found that three cells is the optimum number to be used at one time in such a procedure. The use of three cells permitted the time per analysis to be reduced from approximately 15 minutes to seven minutes.

Advantages and Limitations

The advantages and limitations of the polarographic evaluation method may be listed as follows:

1. Sensitivity. The instrument can detect as little as a fraction of a part per million of copper. This is equivalent to less than 0.01 milligrams of hydrated copper sulfate dissolved in 25 milliliters of solution.

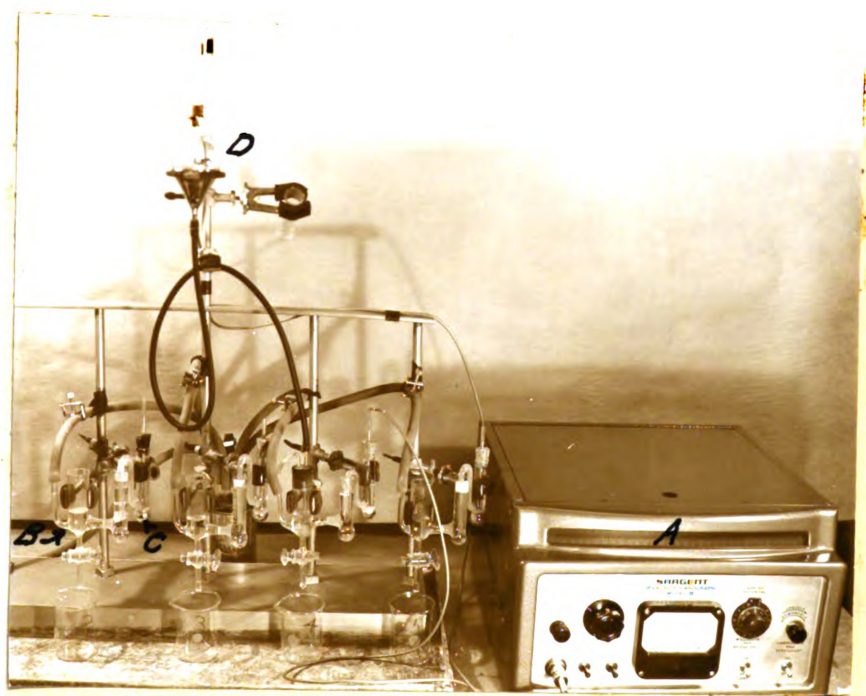


Fig. 27. Apparatus for polarographic analysis. The equipment indicated by letters is the following:

- A. Polarograph
- B. "H" type polarographic cell
- C. Calomel electrode
- D. Mercury reservoir for dropping mercury electrode

2. Versatility. The polarograph is suitable for analyzing a wide variety of materials. At this writing it has been used only for copper in deposit evaluation, but it potentially could be used for a wide variety of materials including organic chemicals.
3. Rapidity. Approximately seven minutes per analysis is required to analyze a group of wash solutions. However approximately 15 minutes is needed to analyze a single solution.
4. Relative simplicity. The polarographic analysis is decidedly more complex than the volumetric copper titration previously described. However, it is simple enough to be conducted outside of the chemistry laboratory by semi-skilled technicians.
5. Portability. It is possible, though somewhat difficult, to make the polarograph portable enough to take to the field.
6. Cost. The equipment necessary for the polarographic evaluation is decidedly more costly than that required for the titrimetric method.

PLANT LEAF-SURFACE EXPERIMENT

Equipment and Technique

Surfaces

Leaf surfaces to be used in this experiment were chosen which were typical of vegetable crops to which pesticidal dusts were commonly applied. Leaves from three species of plants -- bean, tomato, and lettuce -- were used. Both the top and bottom surfaces of these leaves were investigated. Thus a total of six leaf surfaces was included in the experiment.

The characteristics of leaf surfaces vary widely, even for a particular species or variety. Those used in this experiment are described below.

Bean leaves. The tops of bean leaves were somewhat rough and moderately pubescent. The venation stood out slightly and produced a somewhat random pattern as can be seen in Figure 28. The bottoms of the leaves were rather smooth except for the prominent veins. As can be seen in Figure 29 a large part of the pubescence was located along the veins.

The bean leaves used in this experiment were from mature plants grown in flower pots in a greenhouse. They were left

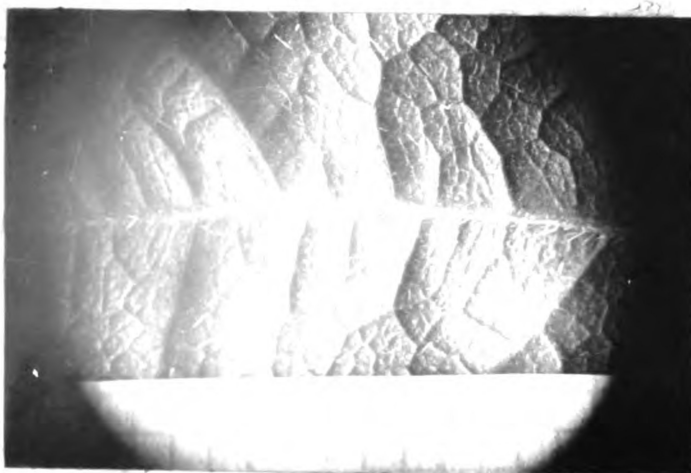


Fig. 28. Top of bean leaf magnified four times. The coordinate paper in the lower part of the picture was used to determine the magnification. It had twenty lines per inch.

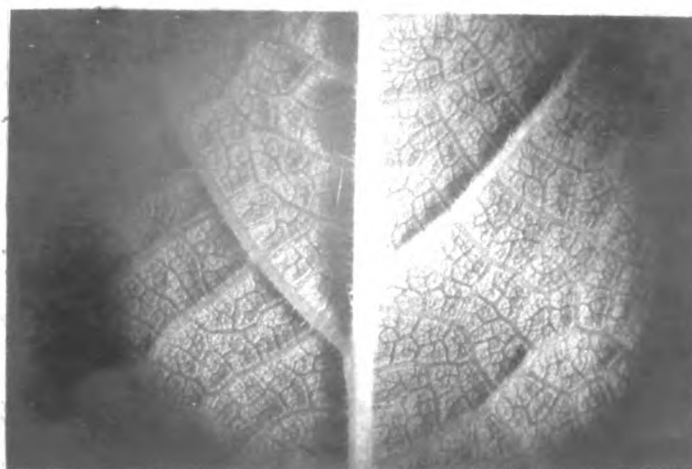


Fig. 29. Bottom of bean leaf magnified four times.

on the plant until immediately before use. The bean variety was Burpees Stringless Green Pod.

Tomato leaves. As is evident in Figures 30 and 31, the tomato leaves were smoother than the bean leaves, except that the larger veins were very pronounced. These leaves were also somewhat more pubescent than the bean leaves.

The tomato leaves used in the experiment were from mature plants in the field. They were of the Long Red variety. In general, the older leaves were used in order to get leaves large enough for test purposes. The stems of the tomato leaves were placed in water to prevent wilting before using.

Lettuce leaves. The lettuce leaves had rather smooth waxy surfaces with no pubescence. However, they were wrinkled into very uneven contours as can be seen in Figures 32 and 33.

The lettuce was grown in flower pots in a greenhouse, and the more mature leaves were selected for experimental work. The Grand Rapids variety of lettuce was used. The leaves were left on the plant until immediately before use.

Mounting of Surfaces

The leaves to be used in the experiment were mounted in frames in such a way that only one side of the leaf was exposed to dust. The frame also held the leaf flat and



Fig. 30. Top of tomato leaf magnified four times.



Fig. 31. Bottom of tomato leaf magnified four times.

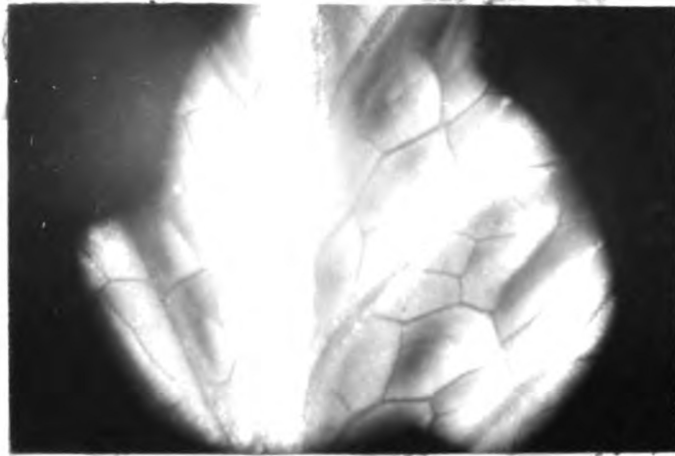


Fig. 32 . Top of lettuce leaf magnified four times.



Fig. 33 . Bottom of lettuce leaf magnified four times.

permitted it to be oriented at any angle with respect to the incident aerosol.

The two types of leaf frames which were used are shown in Figure 34. The leaf was placed between the solid sheet-metal plate at the top of the picture and one of the plates at the bottom which had holes cut in them. The spring clips at left were used to hold the frames together. A bean leaf in a frame can be seen in Figure 36.

The frame at the right in Figure 34 was the type used for bean and lettuce leaves. It had an opening one and one-fourth inches square. However, this opening was too large for use with tomato leaves. Consequently the frame at the left in the picture was constructed in order that two tomato leaves could be dusted at once. In this way the same leaf area could be dusted on each test for all types of leaves.

The leaf area which was sampled on each test was one square inch. However, the frames were large enough to allow a one-eighth inch margin between the sampled area and the frame in order to eliminate edge effects caused by the thickness of the frame.

The leaf sample was taken by cutting a one square inch leaf area directly out of the frame with a razor blade as shown in Figure 35. The scribed lines which are visible on the frames in Figure 36 marked the boundary of the one square inch area.

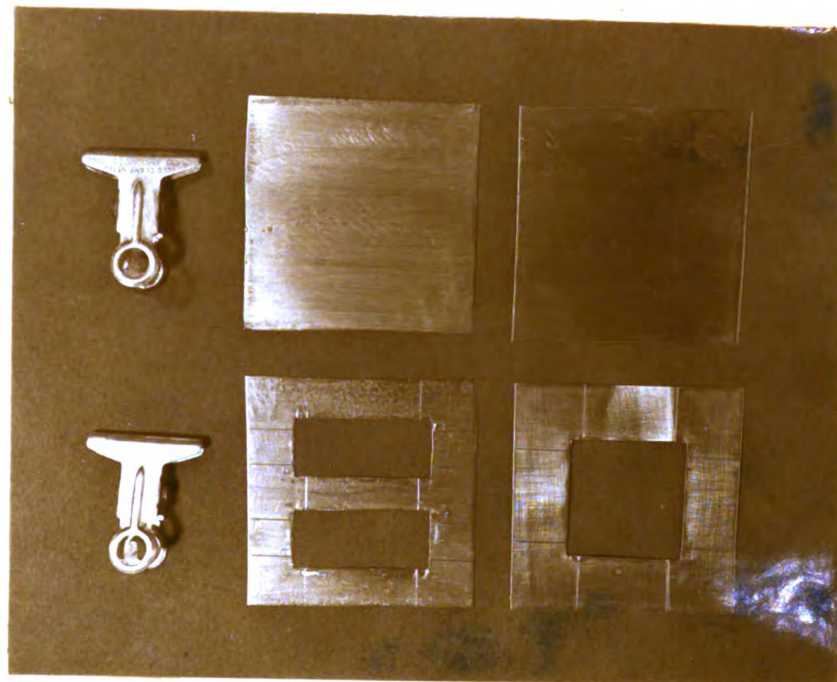


Fig. 34. Leaf frames. The leaves were held in position to be dusted by these metal frames. The leaf was placed between the two pieces of metal and the portion to be dusted was exposed through the opening. The frame was held together by the clips at the left. The frame at the right with the single opening was used for bean and lettuce leaves. The frame with two rectangular openings was used for tomato leaves.



Fig. 35. Cutting leaf sample from frame. Lines scribed on the frame marked the boundaries of the leaf samples.

Leaf Angles

In most of the previous study of dust deposition at Michigan State College it was assumed that the surface to be dusted was perpendicular to the aerosol stream striking it. However, in field dusting work the leaf orientation may be quite variable. Indeed, the high velocity air stream of the field duster tends to deflect any leaves which may be perpendicular to it.

For these reasons tests were included in this experiment in which the leaf surface was oriented at three angles to the incident, dust-laden air stream. The surface was placed perpendicular to, at a 45 degree angle to, and parallel to the incident aerosol stream.

A special holder for the leaf frames was built which could be quickly and accurately set to hold the leaf in any of these positions. This leaf frame holder is pictured in Figure 36.

Air Velocities

Air velocities at the surface to be dusted of 300, 900 and 1500 feet per minute were used in the plant leaf-surface experiment. As in the artificial leaf-surface experiment, these velocities were selected to give a range from a velocity typical of that at a leaf directly in the path of the air stream of a field duster to a low velocity such as might strike a "sheltered" leaf in the field.



Fig. 36.. Leaf frame holder. This holder could be adjusted to hold the frame at an angle of ninety, forty-five, or zero degrees with respect to the incident air stream.

Deposit Evaluation Method

The dust deposits were evaluated by the polarographic method as described under "Polarographic Evaluation" beginning on page 61 . Preliminary tests indicated that the simpler volumetric copper titration technique was not sufficiently sensitive.

Dusting Material

Only one dusting material, micronized hydrated copper sulfate, was used in the plant leaf-surface experiment. This dust is described under "Micronized Copper Sulfate" on page 32 and a size distribution is given in Table I.

Experimental Design

A randomized block experimental design was used for the plant leaf-surface experiment. There were six surfaces, three leaf angles, and three air velocities. The experiment was replicated four times, resulting in a total of 216 tests.

Within each replication all the tests with each surface were run in a group to facilitate the conduct of the experiment. Otherwise all tests were completely randomized.

Experimental Procedure

Arrangement of equipment. The arrangement of the experimental equipment is shown in Figure 37. This arrangement was designed in such a way as to give a definite flow pattern for the materials used in the conduct of the experiment.



Fig. 37. Arrangement of equipment for the plant leaf-surface experiment. The equipment indicated by letters is the following:

- A. Dusting chamber
- B. Table with analytical balance and data book
- C. Table for leaf washing jars.
- D. Balance for weighing dust for feeding.

Such a pattern had two primary purposes -- (1) to reduce confusion and the accompanying likelihood of error and (2) to minimize the possibility of the leaves being exposed to stray copper sulfate outside the dusting chamber.

The flow pattern for the experimental leaves began on a table (not in picture) to the right of the equipment shown in Figure 37. On this table leaves were kept in readiness for use. Also on this table the leaves were placed in the frames. From here the frames were moved to table B in the picture where they were ready to be placed in the dusting chamber, A. After being exposed to dust in the dusting chamber, the leaf frames were placed on table C where the sample was cut from the frame and placed in the wash solution jars. The empty frames were cleaned on the right end of table C and then returned to the table to the right on which the leaves were kept. This completed the cycle.

The membrane filters were moved from the vicinity of the balances on table, B, to the dusting chamber, A.

The dust was kept to the left of the equipment in the picture. It was weighed on the balance, D, and placed in the dust-feed chamber also to the left of the picture.

Experimental conditions. The conditions under which the experiment was run were the following:

1. Relative humidity. The relative humidity was maintained at 60 percent plus or minus three percent.

2. Temperature. The temperature in the dusting chamber varied between 80 and 98 degrees Fahrenheit.
3. Dust feed. Twenty grams of micronized hydrated copper sulfate dust were fed into the system during each test.

Cleaning procedure. The inertial fan was cleaned before each test as described under "Clumping in the Inertial Fan" (page 20).

The cleaning procedure for the feeding system varied somewhat during the experiment. During the first two replications the system was not cleaned. It was hoped that by this means the low aerosol densities immediately after cleaning which were observed in the artificial leaf-surface experiment would be avoided. However, it became obvious that the aerosol density was not being satisfactorily controlled, and the system was cleaned at several points as indicated on Figure 38.. (The degree of control of the aerosol density will be discussed under "Correction for Variation in Dust-Feed Rate" on page 86).

A special cleaning problem which developed involved an accumulation of dust on the vertical wall of the dust-feed chute (see Fig. 1) immediately in front of the dust-feed brush. This accumulation of dust, which is discussed under "Irregularity of Dust-Feed Rate" on page 18 , caused serious inconsistencies in the aerosol density. After it was discovered in the fourth replication, the accumulated dust was

cleaned off before each test for 14 tests. Then the dust-feed brush was removed, thus eliminating the cause of the accumulation.

The leaf frames were cleaned after each use by thoroughly wiping the dust from them with a cloth.

Aerosol sampling. An aerosol sample was taken from the dusting chamber on a membrane filter once every fourth test. Since the tests naturally divided themselves into groups of nine, a filter sample was taken on the first, the fifth, and the ninth tests.

For each sample 1.4 cubic feet of air was drawn through the membrane filter. This required the vacuum pump to be operated two minutes.

Order of procedure. The procedure for conducting the experiment had two distinct parts. First, the leaf was exposed to the dust, and the sample for analysis was placed in the wash solution. Second, the wash solution was analyzed polarographically. This second part of the test procedure was carried out in another building and is described in detail in Appendix B.

The following is a step-by-step description of the operation of the experimental dusting equipment:

1. A leaf was mounted in a frame while the previous test was being run.
2. When the previous test was completed the outlet tube of the inertial fan was cleaned with a brush and the

fan was run at full speed for approximately thirty seconds.

3. A twenty gram sample of micronized hydrated copper sulfate was weighed out and placed in a four and one-half inch band on the dust feed belt.
4. The frame containing the test leaf was placed in the dusting chamber. The leaf-frame holder was set at the proper angle and the setting was entered in the data book.
5. The air velocity was adjusted by means of the auto-transformer and this was entered in the data book.
6. The relative humidity reading was taken and entered in the data book.
7. An automatic time switch which controlled the inertial fan, dust-feed belt, and dust-feed brush was set for two minutes. This turned the equipment on and started the test.
8. While the equipment was running, the leaf frame used on the previous test was cleaned and the leaf for the following test was placed in a frame.
9. When the time switch turned the equipment off, the leaf frame was removed from the chamber and any unusual features of the dust deposit were noted and entered in the data book.
10. The leaf sample was cut from the frame and placed in the jar containing wash solution by means of forceps.

The feeding fan and exhaust fans were allowed to run continuously.

On tests during which an aerosol sample was taken, a membrane filter was placed in the filter holder before the test was begun, and a switch was thrown which allowed the vacuum pump to be operated by the time switch also. Thus the vacuum pump operated simultaneously with the inertial fan.

Results of Plant Leaf-Surface Experiment

Correction for Variation in Dust-Feed Rate

Variation. In some instances the amount of dust which entered the dusting chamber per test during this experiment varied by a factor of almost three*. As can be seen in Figure 38 the aerosol sample dust weights varied from 11.1 to 28.0 milligrams in 1.4 cubic feet of air. Since the amount of dust deposited on the surface appears to be directly dependent upon the quantity of dust directed at the surface, this lack of control seriously limits the value of the experiment. In order to obtain the maximum amount of information, an attempt was made to apply a correction factor to the deposit data based on the aerosol-sample dust weights.

Assumptions necessary for correction. Two assumptions were necessary in order to correct the dust deposit data according to aerosol density.

* See "Irregularity of Dust-Feed Rate", page 18; and "Cleaning Procedure", page 83.

First, the dust deposit must be assumed to be proportional to the aerosol density. The degree of error which might be caused by this assumption is not known, but it would appear that the assumption would be a good approximation. It is obvious that the amount of dust incident upon the test surface was dependent upon the aerosol density. It would appear that the amount of dust deposited might be proportional to the amount of dust striking a surface unless the increased quantity of dust caused increased erosion.

It was also necessary to assume that the dust-feed rate varied linearly from test to test during the intervals of four tests during which no aerosol samples were taken. This assumption was necessary in order to obtain a value for the aerosol-sample dust weights for the two-thirds of the tests for which no such data was taken. These values were obtained by graphical interpolation from Figure 38. It is evident from the figure that the dust-feed rate did not vary linearly from test to test. (It is assumed that the dust-feed rate and the aerosol density are proportional). However, certain trends are evident. During the first replication most of the weights are above 20.0 milligrams, while during the second replication the weights were largely below that value. The third replication was more random, but even here the weights for the individual groups of tests are rather close to the straight lines. After the brush was removed in the

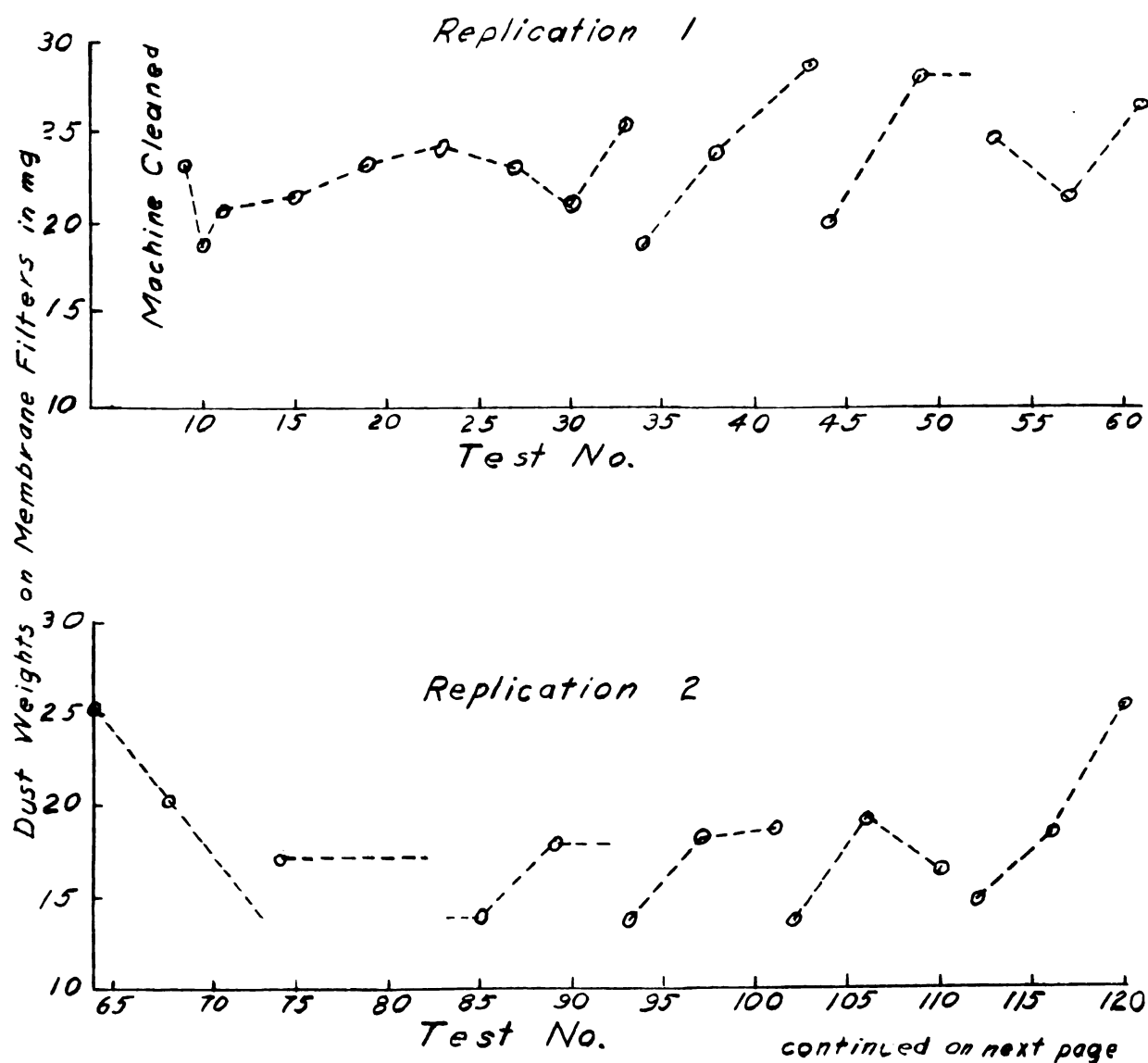


Fig. 38. Variation of aerosol-sample dust weights by consecutive tests during plant leaf-surface experiment. Dotted lines connect the points representing tests run in a group. Aerosol-sample dust weights for tests for which no sample was taken were read from this graph as discussed on page 90. In certain instances it was necessary to extrapolate lines in order to get aerosol-sample data for all tests. The aerosol density was assumed proportional to the aerosol-sample dust weights.

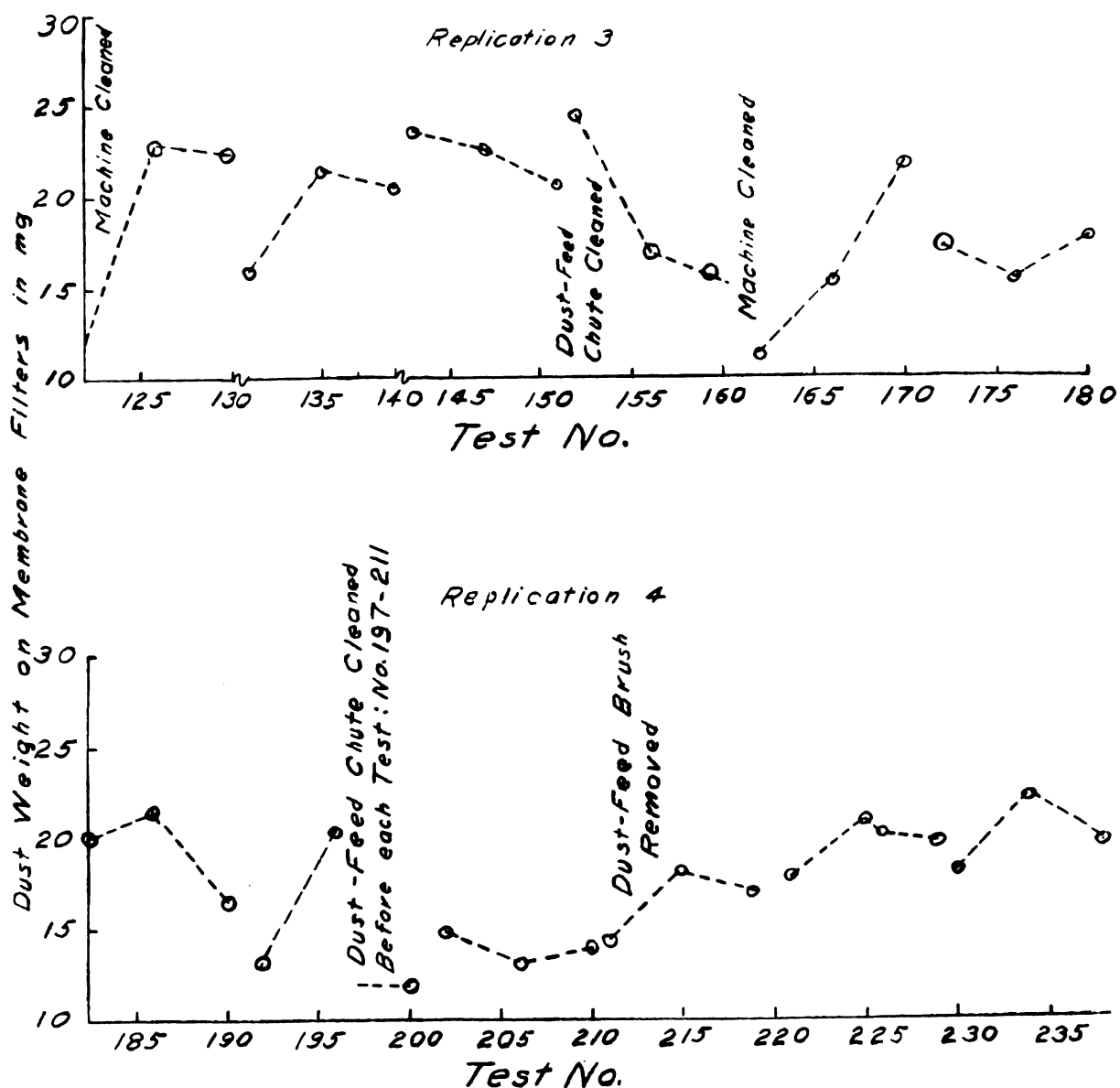


Fig. 38. (Continued)

The points at which the machine was cleaned are included on Figure 38. The cleaning procedure is discussed on page 83.

fourth replication the aerosol-sample dust weights followed a rather consistent trend. For these reasons it was felt that the aerosol-sample dust weights obtained by linear interpolation were of some value, and would serve as a basis for correction of the dust deposit data.

Calculation of correction factor. The dust deposit data was corrected to a base aerosol density of 14.3 milligrams dust per cubic foot of air. This corresponded to an aerosol-sample dust weight of 20.0 milligrams in the 1.4 cubic feet drawn through the membrane filters.

The deposit weight, d, was multiplied by a correction factor, c, which was obtained as follows:

$$c = \frac{a}{20.0}$$

where a is the aerosol-sample dust weight in milligrams for the test being corrected. Thus the corrected dust deposit, D, is

$$D = cd = \frac{ad}{20.0}$$

Table A-II contains the original dust deposit data while Table A-III contains the corrected data. The analysis of the results is based on the corrected data.

Missing Value Calculation

The value in the original deposit data for the deposit on the top of a tomato leaf at an angle of 45 degrees, an air

velocity of 1500 feet per minute, and in the fourth replication differed from the other readings to such a degree that it was an obvious error. The least squares method of calculation of missing values was employed to calculate a new value to replace it in the data. Table A-III contains the calculated value.

Statistical Analysis

Inspection of the deposit data in Table A-III showed that there was clearly a significant difference between the three air velocities. For this reason a separate analysis of variance was made for the data for each of them. These are shown in Tables IV, V, and VI.

Each of the three analyses of variance showed significance at the one percent level for both surfaces and angles. In addition the surface-position interaction showed significance at the five percent level in the data for the 300 feet-per minute deposits. These results will be discussed below.

Replications was included as a classification in the analysis of variance. This was done because there were definite changes in conditions as the tests proceeded*.

A pooled error term is used in each of the analyses of variance. This term consists of the two interactions containing replications and the usual error term. In all cases this pooled error term gave a larger error mean square than the single error term.

* See "Cleaning Procedure", page 83 , and "Correction for Variation of Dust-Feed Rate", page 86. .

TABLE IV
ANALYSIS OF VARIANCE OF DUST DEPOSITION ON PLANT LEAF
SURFACES AT 300 FEET PER MINUTE

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F
Total	71	1.242987		
Replications	3	.249648		
Surfaces	5	.343729	.068746	11.83**
Angles	2	.220258	.110129	18.95**
Surfaces-Angles	10	.132975	.013298	2.23*
Error	51	.296377	.005811	

* Significant at 5% level

** Significant at 1% level

TABLE V
ANALYSIS OF VARIANCE OF DUST DEPOSITION ON PLANT LEAF
SURFACES AT 900 FEET PER MINUTE

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F
Total	71	24.327365		
Replications	3	4.261059		
Surfaces	5	5.286607	1.057321	7.41**
Angles	2	6.145219	3.072610	21.53**
Surfaces-Angles	10	1.355964	.135596	.95
Error	51	2.076080	.142716	

** Significant at 1% level

TABLE VI
ANALYSIS OF VARIANCE OF DUST DEPOSITION ON PLANT LEAF
SURFACES AT 1500 FEET PER MINUTE

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F
Total	70 ¹	326.198287		
Replications	3	42.294070		
Surfaces	5	59.178445	11.835689	4.66**
Angles	2	73.655233	36.827617	14.52**
Surfaces-Angles	10	24.210034	2.421003	.95
Error	50 ¹	126.860505	2.537210	

** Significant at 1% level

1 One degree of freedom subtracted because of one missing value.

Least significant differences were calculated for surfaces and angles for the three groups of data on the basis of the "t" test. These values are included on the charts on which the data are presented.

Effect of Leaf Surfaces

The average values for the dust deposits on the six surfaces at the three air velocities are plotted in Figure 39. Perhaps the most significant feature of this data is the fact that in all cases there was a larger deposit on the bottoms of leaves than on the tops. It is suggested that possibly the more prominent veins in the bottoms of the leaves had some connection with this increase. This possibility will be discussed further under "Effect of Positions".

It can also be seen from Figure 39 that while the deposit on the bean and tomato leaves was about equal, the deposit on the lettuce leaves was somewhat lower. This would seem to indicate that a pubescent surface might present more resistance to dust erosion than a smooth waxy surface, although other factors may be involved also.

It will be noted in Figure 39 that the deposits on the six surfaces vary in a similar manner for all three air velocities.

It should be pointed out that, in reference to Figure 39, the quantities of incident dust at 900 and 1500 feet per

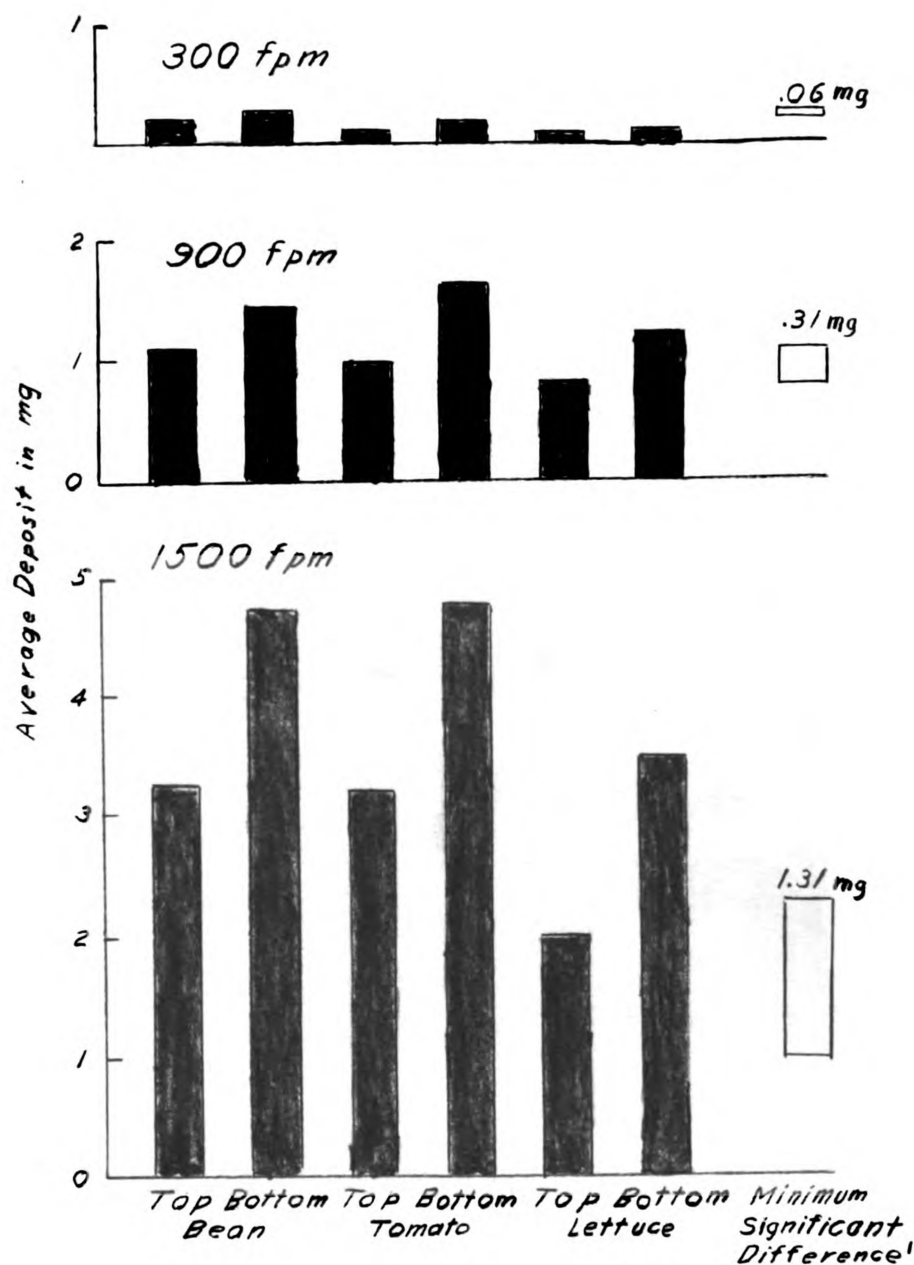


Fig. 39. The effect of plant surfaces on dust deposition at three air velocities. This graph represents the average of the deposits of "micronized" copper sulfate on surfaces at the three angles described on page 78. The graph is not a valid comparison between air velocities since no correction has been made for the variation of incident dust quantity with a variation in air velocity.

¹ The minimum significant difference is the smallest difference between two random deposits which would be significant at the five percent level. This value was determined from the "t" test as discussed on page 95.

minute were three times and five times, respectively, the quantity of incident dust at 300 feet per minute. This is explained under "Inertial Fan" (page 15). Corrected air velocity data will be discussed under "Effect of Air Velocities".

Effect of Leaf Angles

The average weights of dust deposited at the various angles are shown in Figure 40. It will be noted from this graph that the deposits on surfaces perpendicular to the air stream are rather close to the deposits on surfaces at a 45 degree angle to the air stream. This is even more interesting when the fact is considered that a surface of a given area will be struck by only 0.707 times as much dust when at an angle of 45 degrees as it will when it is at an angle of 90 degrees. This is due to the fact that the cross-sectional area of the dust stream which will strike a surface will be proportional to the sine of the angle the surface makes with the air stream. It would appear, then, that a larger part of the incident dust was deposited at an angle of 45 degrees than at an angle of 90 degrees.

A surface parallel to the dust stream would have no dust striking it at all according to the relationship expressed above. However, turbulence in the air stream and surface irregularities would cause dust to strike a parallel surface and a deposit was recorded.

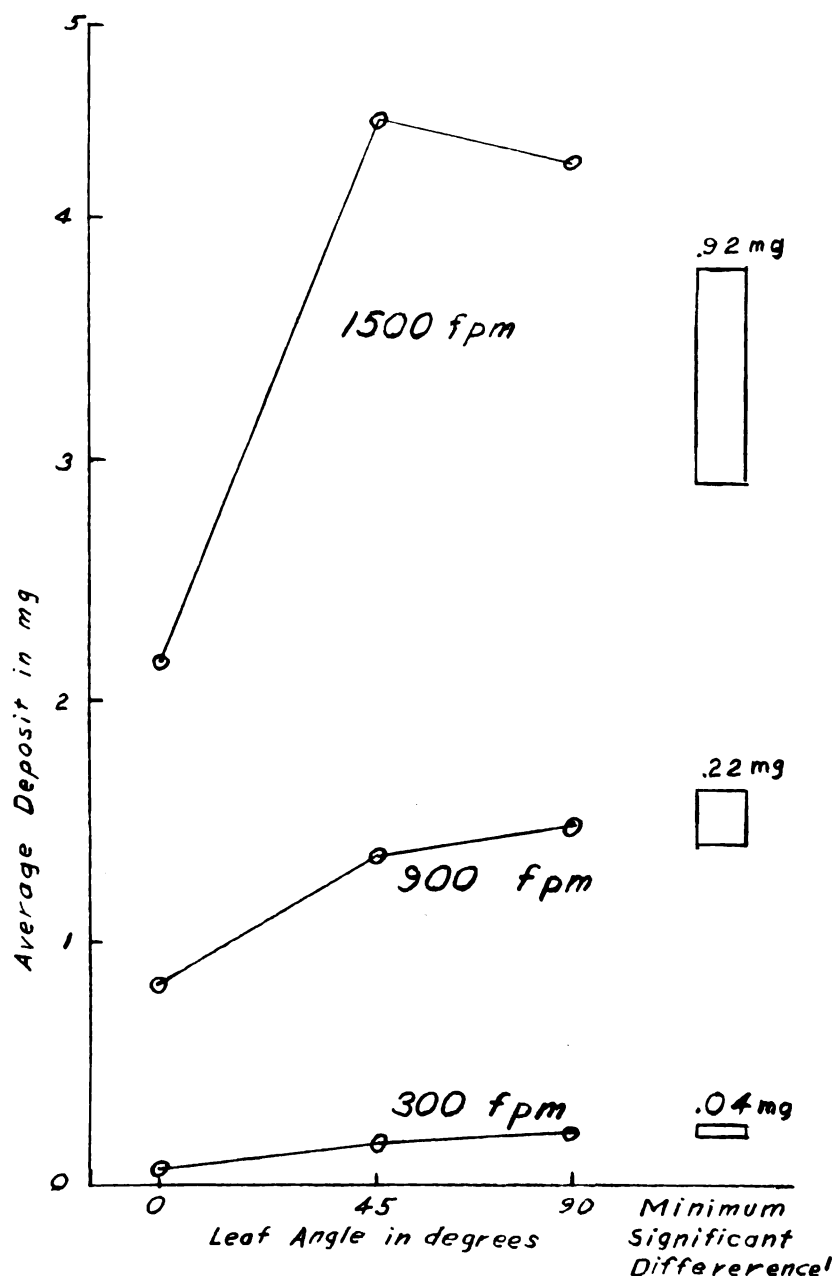


Fig. 40. The effect of angle with respect to air stream on dust deposition at three air velocities. This graph represents the averages of the deposits on the six leaf surfaces described on pages 23-27. The graph is not a valid comparison between air velocities since no correction has been made for the variation of incident dust quantity with a variation in air velocity.

¹ The minimum significant difference is the smallest difference between two random deposits which would be significant at the five percent level. This value was determined from the "t" test as discussed on page 95.

Effect of Surface-Angle Interaction

In the analysis of variance of the deposit data for 300 feet per minute, significance was shown for the surface-angle interaction. The reason for this significance is obvious from Figure 41. The relative deposit at the 45 degree angle for leaf bottoms was much greater than for leaf tops. Thus the angle-deposit curve was distinctly different for the bottoms and tops of leaves.

Reference to Figures 42 and 43 will show that the same tendency was present for air velocities of 900 and 1500 feet per minute also, although the interaction was not significant at the five percent level.

Perhaps the most obvious difference between the surfaces of the bottoms and the tops of leaves is the fact that the veins are more prominent on the bottoms. The pictures of the dusted leaf surfaces -- Figures 44 through 48 -- show that when leaf bottoms were dusted at an angle of 45 degrees there was a relatively large accumulation of dust on the windward side of the protruding veins. It is possible, then, that large surface irregularities such as protruding veins are more important in dust deposition when the surface is at an angle to the incident aerosol stream, than when it is perpendicular.

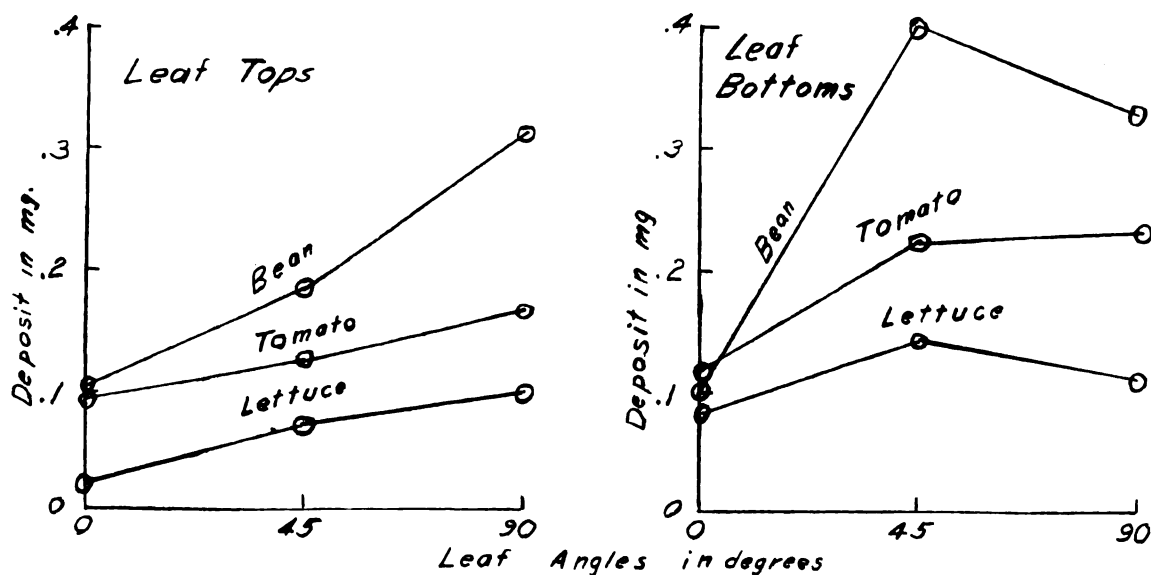


Fig. 41. The effect of plant leaf surfaces and leaf angles on "micronized" copper sulfate dust deposition at a 300 fpm air velocity. The analysis of variance showed the surface-angle interaction to be significant at the five percent level. Table I is a size distribution of the dust particles and the experimental conditions are described on pages 70-84.

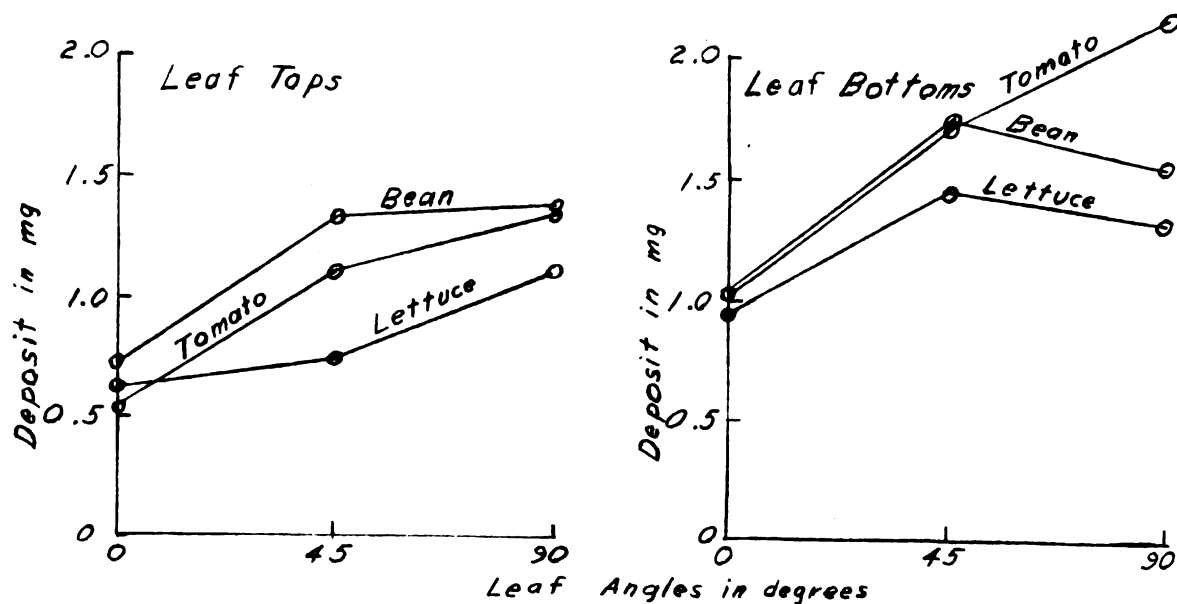


Fig. 42. The effect of plant leaf surfaces and leaf angles on "micronized" copper sulfate dust deposition at a 900 fpm air velocity. The analysis of variance showed the surface-angle interaction to be non-significant at the five percent level. Table I is a size distribution of the dust particles and the experimental conditions are described on pages 70-84.

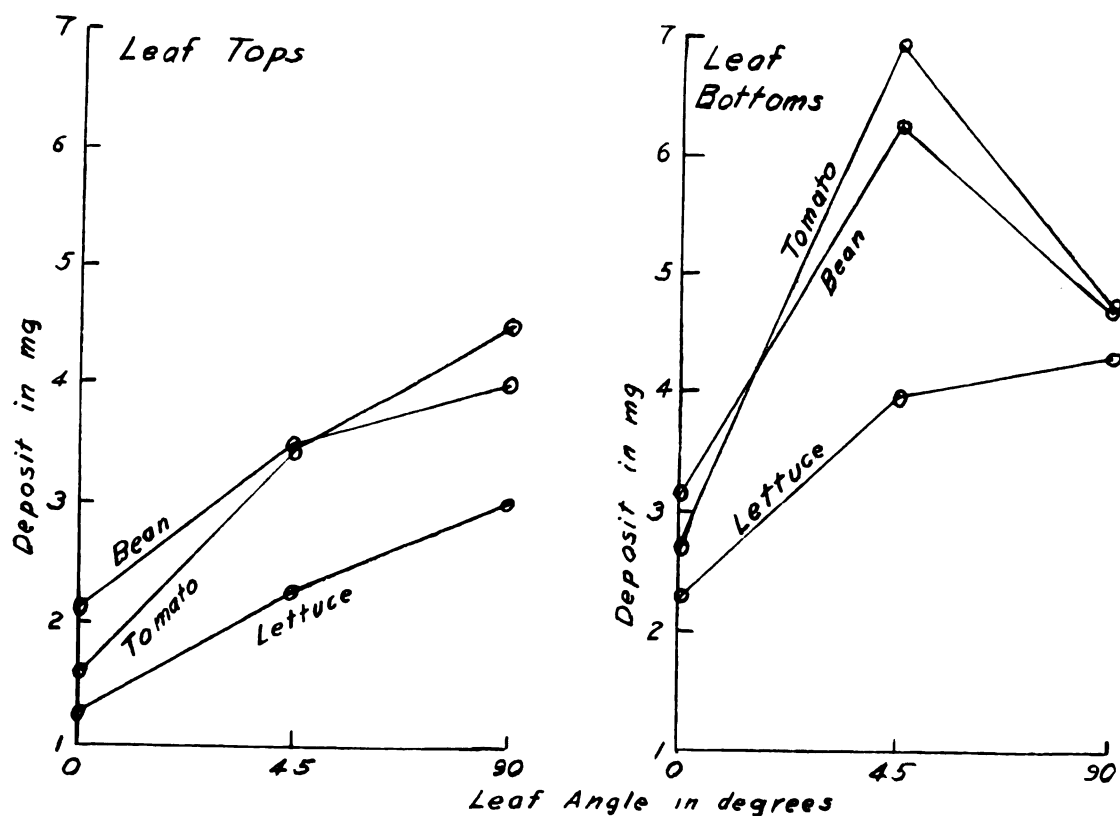


Fig. 43. The effect of plant leaf surfaces and leaf angles on "micronized" copper sulfate dust deposition at a 1500 fpm air velocity. The analysis of variance showed the surface-angle interaction to be non-significant at the five percent level. Table I is a size distribution of the dust particles and the experimental conditions are described on pages 70-84.

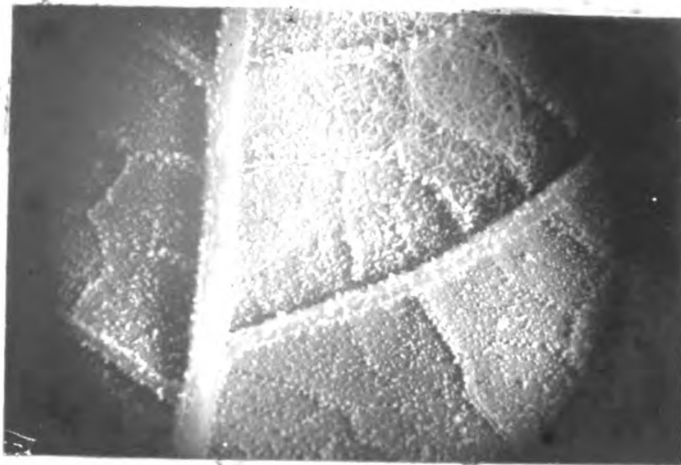


Fig. 44. Dust deposit on bottom of bean leaf. The air velocity was 1500 fpm at an angle of 90 degrees. There was a 3.62 mg dust deposit. (Magnification four). The webbing in the upper right was on the leaf previous to dusting, but was almost invisible without dust on it. It was observed occasionally during the experiment.

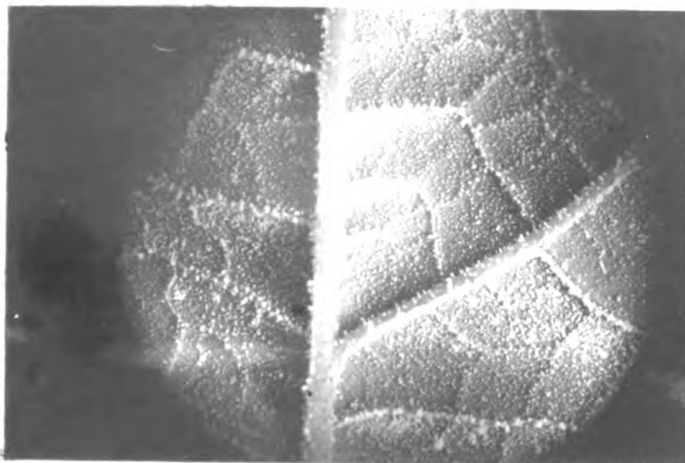


Fig. 45. Dust deposit on bottom of bean leaf. The air velocity was 1500 fpm at a 45 degree angle. There was a 3.72 mg dust deposit. (Magnification four)



Fig. 46. Dust deposit on top of tomato leaf. The air velocity was 900 fpm at an angle of 45 degrees. There was an 0.60 mg dust deposit. (Magnification four)



Fig. 47. Dust deposit on bottom of tomato leaf. The air velocity was 900 fpm at an angle of 45 degrees. There was a dust deposit of 1.22 mg. (Magnification four)

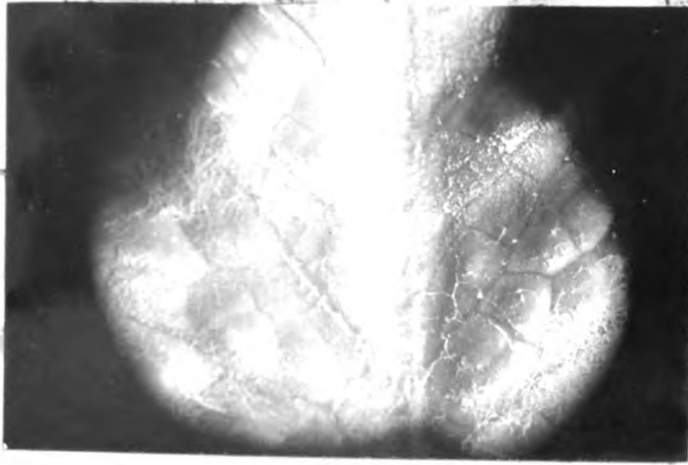


Fig. 48. Dust deposit on top of lettuce leaf. The air velocity was 1500 fpm at an angle of zero degrees. There was a deposit of 1.35 mg. (Magnification four) Some of the webbing which was visible in Figure 44 can be seen in this picture also.

Effect of Air Velocities

The effect of air velocities on dust deposit is shown in Figure 49. This curve was plotted from data which had been corrected to a constant quantity of incident dust for all velocities as explained in Appendix A. (This is in addition to the correction for the non-uniform dust-feed rate.)

It will be seen that, as was the case with the artificial leaf surfaces, the velocity-deposit curve is very close to a straight line. This line has a positive slope as was the case with the micronized dust in the artificial leaf-surface experiment.

Percent of Incident Dust Deposited

From .17 to 1.7 percent of the dust which was directed at the leaf surface was deposited according to the aerosol density calculations in Appendix A. At 300 feet per minute approximately 60 milligrams of dust were directed at the leaf surface, but only from 0.1 to 1.0 milligrams was deposited. These calculations apply to an average aerosol density of 14.3 milligrams dust per cubic feet of air.

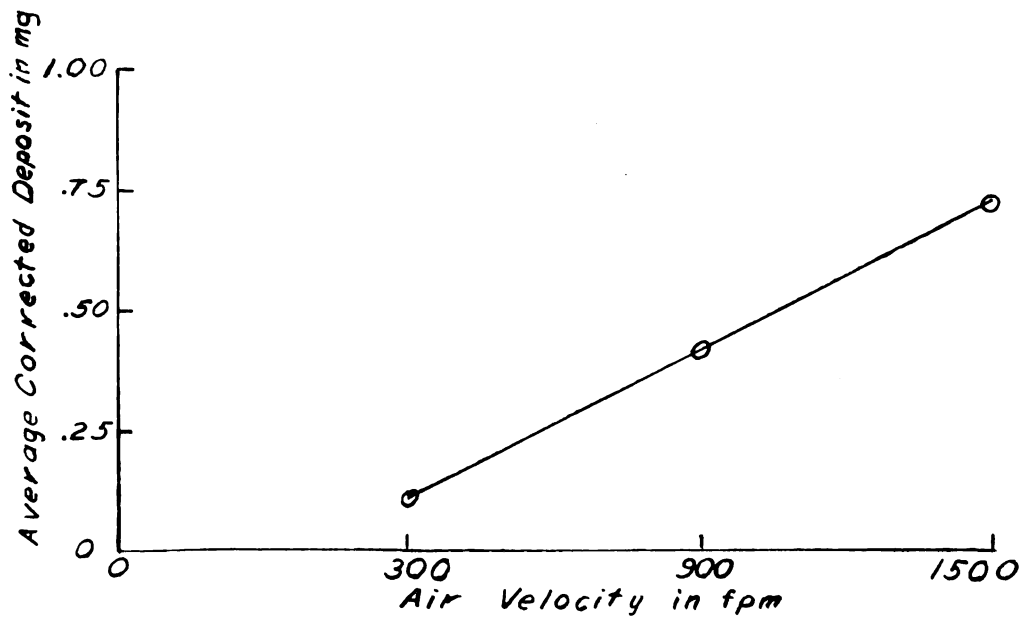


Fig. 49. The effect of air velocity on dust deposition during the plant leaf-surface experiment. This graph represents an average of all surfaces and positions used in the experiment as described on pages 70 to 78. The data has been corrected for variation in incident dust quantity with air velocity as described in Appendix A.

SUMMARY AND CONCLUSIONS

In this study an attempt was made to learn the manner in which the nature of plant surfaces affects the deposition of pesticidal dusts. The approach used to the problem was that of actually depositing dust on a group of representative surfaces under controlled conditions.

Two general types of surfaces were used in the experimental work. First, an experiment using artificial leaf surfaces was conducted. These surfaces were smooth aluminum, sandblasted aluminum, wax coated aluminum, and petroleum-jelly coated aluminum. The conditions varied were dust particle size and air velocity.

The second experiment involved the use of actual plant leaf surfaces. The surfaces used were the tops and bottoms of bean, lettuce, and tomato leaves. The angle of the surfaces with respect to the air stream and the velocity of the air stream were varied, while it was attempted to hold other conditions constant.

The precision of the results was reduced by a rather high degree of irregularity in the dust feeding system. However, statistical analyses which were applied to the results of the experiments indicated that surface types, dust particle size, air velocities, surface angles, and

certain interactions all caused significant differences in deposition. Since the precision of the tests was rather low and a number of assumptions were involved in the analysis of the results, it was felt that no conclusive generalizations could be made. The important results of experiments were the following:

1. There was a somewhat higher deposit of dust on the bean and tomato leaves, both of which are pubescent, than there was on the non-pubescent lettuce leaves.
2. There were distinctly larger deposits on the bottoms of each of the three plant leaves than on the tops. This was particularly true at the 45-degree leaf angle. At this angle large localized deposits were observed along the prominent veins on the bottoms of the leaves.
3. Leaves making an acute angle to the incident air stream held a distinctly larger deposit of dust than those which were perpendicular. This was especially true of leaf bottoms.
4. There was no significant difference between the deposits on smooth aluminum surfaces and sandblasted aluminum surfaces. Wax and petroleum-jelly surfaces received large, highly significant increases in deposit over the aluminum surfaces.
5. On aluminum surfaces there was a larger deposit of "micronized" dust than of the "standard" dust which

had larger particles. However, on the softer wax and petroleum jelly surfaces the "standard" dust gave the larger deposit.

6. The deposit of micronized dust increased with an increase in air velocity, but the deposit of standard dust decreased as the air velocity increased. In both cases there was a nearly linear relationship between the two for the three air velocities used.

It is believed that the information gained in this study may prove valuable as a step toward an understanding of the basic factors involved in the deposition of pesticidal dusts.

RECOMMENDATIONS FOR FURTHER STUDY

It is felt that before the efficiency of the pesticidal dusting operation can be materially improved, it will be necessary to better understand the manner in which dusts behave while they are in the dusting machine and while they are being deposited on the plant. The following suggestions for further study are recommended as means toward this end.

1. A study should be made of the physical characteristics of various dusting materials. This should include the effects of the material, the particle size, and the moisture content on both handling and dusting. The study might include the following:

- a. A system for classifying dusts according to their physical properties so that their behavior could be predicted.
- b. The determination of optimum moisture contents for various dusting materials, and the possibility of storing such dusts in sealed containers until ready for use.
- c. Determination of optimum particle sizes of dusting materials considering plant coverage, dusting efficiency, and handling problems.

- d. Determination of optimum air velocities for maximum dusting efficiency with certain materials of certain particle sizes.
2. A basic study of the manner in which dust is deposited should be made utilizing the previous studies at Michigan State College. It is felt that this previous work should be brought together and the results generalized if possible. Additional analytical and experimental studies could then be carried on to test these generalizations.
3. The experimental dusting equipment at Michigan State College should be improved as suggested under "Recommendations for Change" on page 21 .
4. The polarographic evaluation method should be developed for additional materials.
5. The volumetric copper titration method of evaluation should be perfected for field use and tested in the field.

APPENDIX A:
ARTIFICIAL LEAF-SURFACE DATA AND CALCULATIONS

Calculation of Dust Quantity Directed Toward Test Surface

The quantity of dust directed at the test surface was dependent upon the aerosol density and the quantity of this aerosol striking the test surface.

The aerosol density was calculated from the aerosol-sample dust weight data. The average weight of dust collected as 1.4 cubic feet of air was drawn through a membrane filter was approximately twenty milligrams. (The vacuum pump drew .70 cubic feet of air through the filter per minute for two minutes.) Therefore, the average aerosol density was approximately $20/1.4$ or 14.3 milligrams dust per cubic foot of air.

The quantity of aerosol striking the test surface was proportional to the velocity of the aerosol and the area of the surface it struck according to the relationship

$$Q = Av$$

where Q was the quantity of aerosol, A was the cross sectional area of the aerosol stream striking the surface, and v was the velocity of the aerosol.

Where z was the aerosol density, the total quantity of dust directed toward the test surface, t , was expressed by

$$t = zQ = zAv$$

It will be seen then that when the aerosol density was 14.3 milligrams dust per cubic foot of air and the air

velocity was 300 feet per minute the quantity of dust striking a one square inch surface was 59.6 milligrams. Under the same conditions the quantity of dust striking a perpendicular disk three inches in diameter would be 420 milligrams.

Deposit Correction for Incident Dust Variation with Air Velocity

It will be seen from the relationship

$$t = zAv$$

which was discussed above, that the quantity of incident dust, t , was proportional to air velocity, v . The assumption was made that the weight of the dust deposit was proportional to the weight of the dust directed at the surface. This made it possible to compare deposits at the various air velocities on the basis of the same quantity of incident dust. Thus

$$\frac{d_1}{d_2} = \frac{t_1}{t_2} = \frac{v_1}{v_2}$$

where $\underline{d}$ was the deposit weight. Therefore to correct a deposit, d , at a velocity, v , to a base with an incident dust equal to that at 300 feet per minute, the formula

$$d_c = \frac{300d}{v}$$

was used. The corrected deposit weight was represented by $\underline{d}_c$.

TABLE A-I
DUST DEPOSIT ON ARTIFICIAL LEAF SURFACES
(Deposit in milligrams)

Air Velocity	Replications	Surfaces					
		Polished Aluminum		Sandblasted Aluminum		Wax	
		Dust Standard	Dust Microized	Dust Standard	Dust Microized	Dust Standard	Dust Microized
300	1	3.4	3.3	6.1	2.6	25.6	5.1
	2	8.0	6.4	4.9	3.7	21.5	3.0
	3	8.6	4.4	7.4	3.0	26.0	5.4
	4	7.6	4.2	6.9	3.4	21.3	4.7
	Av.	6.90	4.58	6.33	3.18	23.60	4.55
900	1	8.7	15.1	9.4	10.9	50.7	17.3
	2	11.6	23.7	7.6	9.9	45.6	20.1
	3	8.8	16.2	7.4	14.6	43.7	27.2
	4	12.0	19.6	12.5	19.0	45.8	18.2
	Av.	10.28	18.65	9.23	13.60	46.45	20.70
1400	1	10.0	50.0	12.6	43.3	47.9	37.1
	2	12.8	46.1	10.4	28.1	57.6	38.4
	3	7.8	28.6	7.5	49.0	53.3	30.4
	4	12.7	31.6	12.3	39.1	44.3	28.5
	Av.	10.83	39.08	10.70	39.88	50.78	33.60
						105.10	74.40
						91.6	60.8
						102.7	84.9
						120.4	74.9
						107.5	77.0
						88.83	33.73
						89.8	41.3
						101.0	29.3
						103.4	28.2
						61.1	36.1

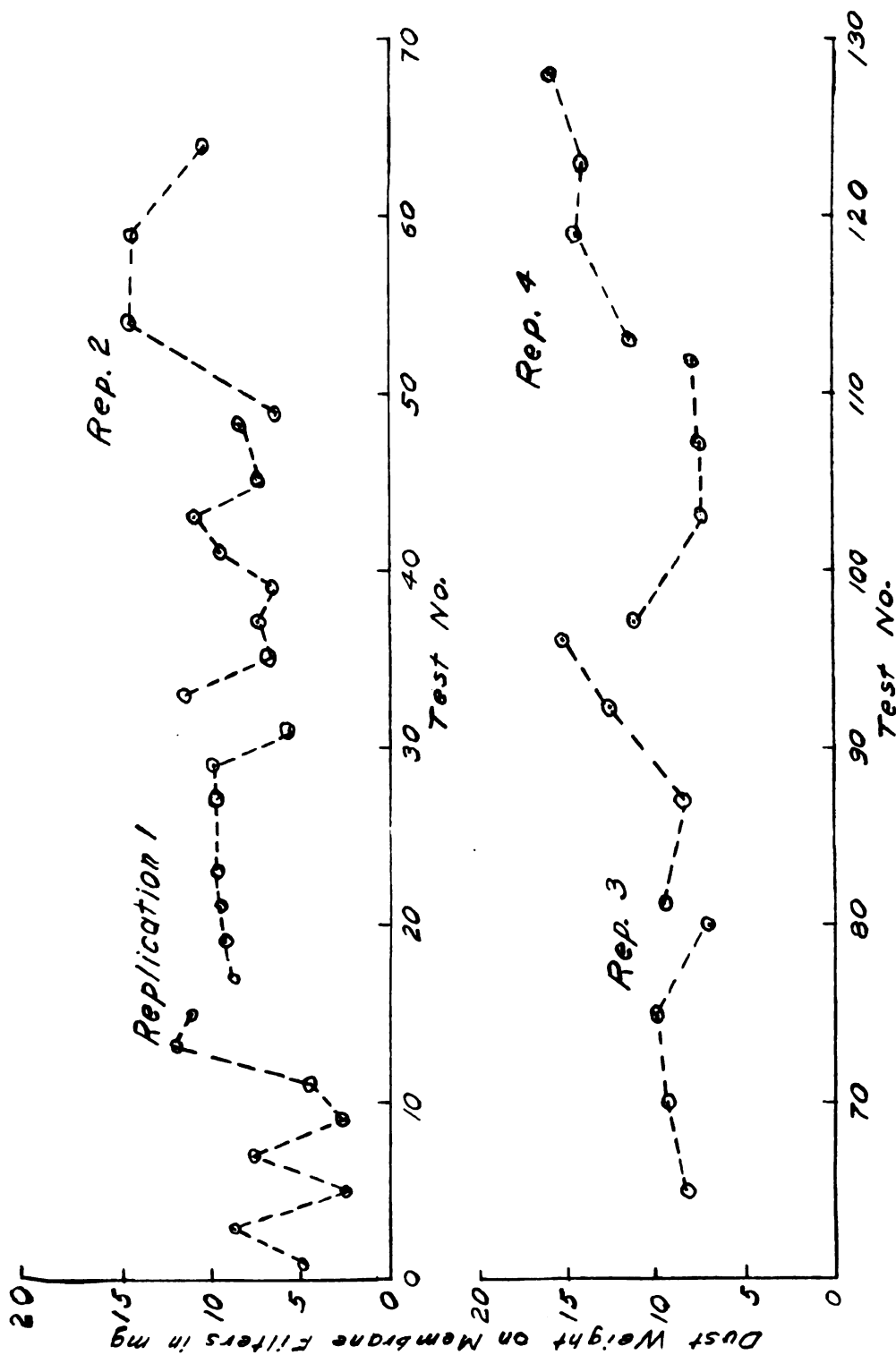


Fig. A-1. Variation of aerosol-sample dust weights by consecutive tests during the artificial leaf-surface experiment. Dotted lines connect points representing tests run in a group. The aerosol density was assumed proportional to the aerosol-sample weight.

Note: The time at which the vacuum pump was turned on to take an aerosol sample was changed from the one minute point to the one-half minute point in the test beginning with test 49. The vacuum pump was run for one minute in taking all samples -- thus drawing 0.7 cubic feet of air through the filter.

APPENDIX B:
TECHNIQUES OF DEPOSIT EVALUATION

Equipment and Procedure for Titrimetric Evaluation

The equipment and procedure used in the preliminary testing of the titrimetric method of evaluating deposits of hydrated copper sulfate dust are outlined below. The procedure is somewhat more simplified than the one Brazee (3) recommended. However, preliminary tests showed it to be accurate to within plus or minus 0.05 milligrams of copper. The equipment and materials necessary for the procedure are the following:

1. One burette, five milliliters capacity.
2. One burette, 25 milliliters capacity.
3. One medicine dropper.
4. Miscellaneous beakers, stirring rods, bottles, etc.
5. A number of one-half pint "fruit jars".
6. A sodium thiosulfate solution containing approximately 0.0036 grams of $\text{Na}_2\text{S}_2\text{O}_4$ per milliliter of solution.
7. A standard copper solution containing 1.00 milligram of copper per milliliter of solution. (See thesis by Brazee (3) for details of the preparation of the standard solution.)
8. A thirty percent solution of potassium iodide (43 grams of KI per 100 milliliters of water).
9. A one percent starch solution. This solution was prepared by dissolving one gram of soluble starch in 100

milliliters of water and boiling the solution. The starch solution must be made fresh every two weeks.

10. Distilled water. (Distilled water was used throughout the procedure.

The detailed procedure for performing the titrimetric evaluation was the following:

1. The leaf sample was placed in a one-half pint "fruit jar" containing fifty milliliters of water and agitated for at least thirty seconds. The leaf sample was then removed from the solution.
2. The analysis was begun by adding five milliliters of thirty percent potassium iodide solution to the wash solution from a 25 milliliter burette. In general, one part of potassium iodide solution was added per ten parts of unknown solution. If copper was present, the potassium iodide would cause a yellow color to appear in the unknown solution.
3. Sodium thiosulfate solution was added to the unknown solution with constant stirring until the yellow color almost but not quite disappeared. A five milliliter burette was used to measure the sodium thiosulfate.
4. Approximately five drops of starch solution were added to the unknown solution. If copper was present, a blue color now appeared.

5. Additional sodium thiosulfate was added to the unknown solution with constant stirring until the blue color just disappeared. This was the end point. The total amount of sodium thiosulfate solution added multiplied by a calibration constant gave the weight of copper present in the solution.

The calibration constant for the sodium thiosulfate titration solution was determined by simply analyzing solutions of known concentrations. In this way the quantity of the titration solution required to titrate a given quantity of copper in solution was determined. The calibration for the sodium thiosulfate solution of the concentration used was approximately one milligram of copper titrated for each milliliter of solution.

Equipment and Procedure for the Polarographic Analysis

The polarographic equipment and technique used in the evaluation of hydrated copper sulfate dust deposits on plant leaves are outlined below. For a more detailed description of the equipment the reader is referred to the thesis by Ban (4). A list of the primary equipment used is the following:

1. One polarograph, a Sargent Model III which is manually operated.
2. Three "H" type polarographic cells.
3. Three calomel electrodes.
4. One dropping mercury electrode.
5. A frame for supporting the polarographic cells and electrodes.
6. A potassium sulfate solution containing 0.071 grams K_2SO_4 per milliliter of solution.
7. A one percent solution of gelatin.
8. A standard copper sulfate solution containing 1.00 milligram of copper per milliliter of solution.
9. A cylinder of commercial "oil pump" nitrogen and a pressure regulator.
10. Miscellaneous glassware.

The procedure followed in a polarographic analysis was the following:

1. The dust deposit was dissolved in 24 1/2 milliliters of potassium sulfate solution as discussed on page 65 . One-half milliliter of gelatin solution was added just before the analysis. This gave a solution containing 0.4 normal K_2SO_4 and 0.02 percent gelatin as well as the unknown $CuSO_4$.
2. Approximately twenty milliliters of the solution to be analyzed were placed in the "H" type polarographic cell after the cell had been rinsed with distilled water.
3. Nitrogen was bubbled through the solution in the cell for from ten to fifteen minutes in order to remove the dissolved oxygen. While this was in progress other solutions in the other two cells were being analyzed by the operator.
4. The nitrogen hose was disconnected from the cell and the positive lead from the polarograph was connected to the calomel electrode.
5. An average galvanometer reading was taken at a potential of 0.400 volts. The galvanometer sensitivity was set in such a way as to get a scale deflection of less than 20 centimeters.
6. Another galvanometer reading was taken with a zero potential across the electrodes. This reading was subtracted from the first reading to give a net galvanometer deflection for 0.400 volts.

7. The weight of the copper sulfate in the total 25 milliliters of the solution was read from the calibration curve, Figure 29.

The calibration curve was plotted from experimental data obtained by analyzing solutions of known concentration. This calibration was replicated three times.

The dropping rate of the dropping mercury electrode was one drop every 3.2 seconds. The average temperature at which the analyses were made was eighty degrees Fahrenheit.

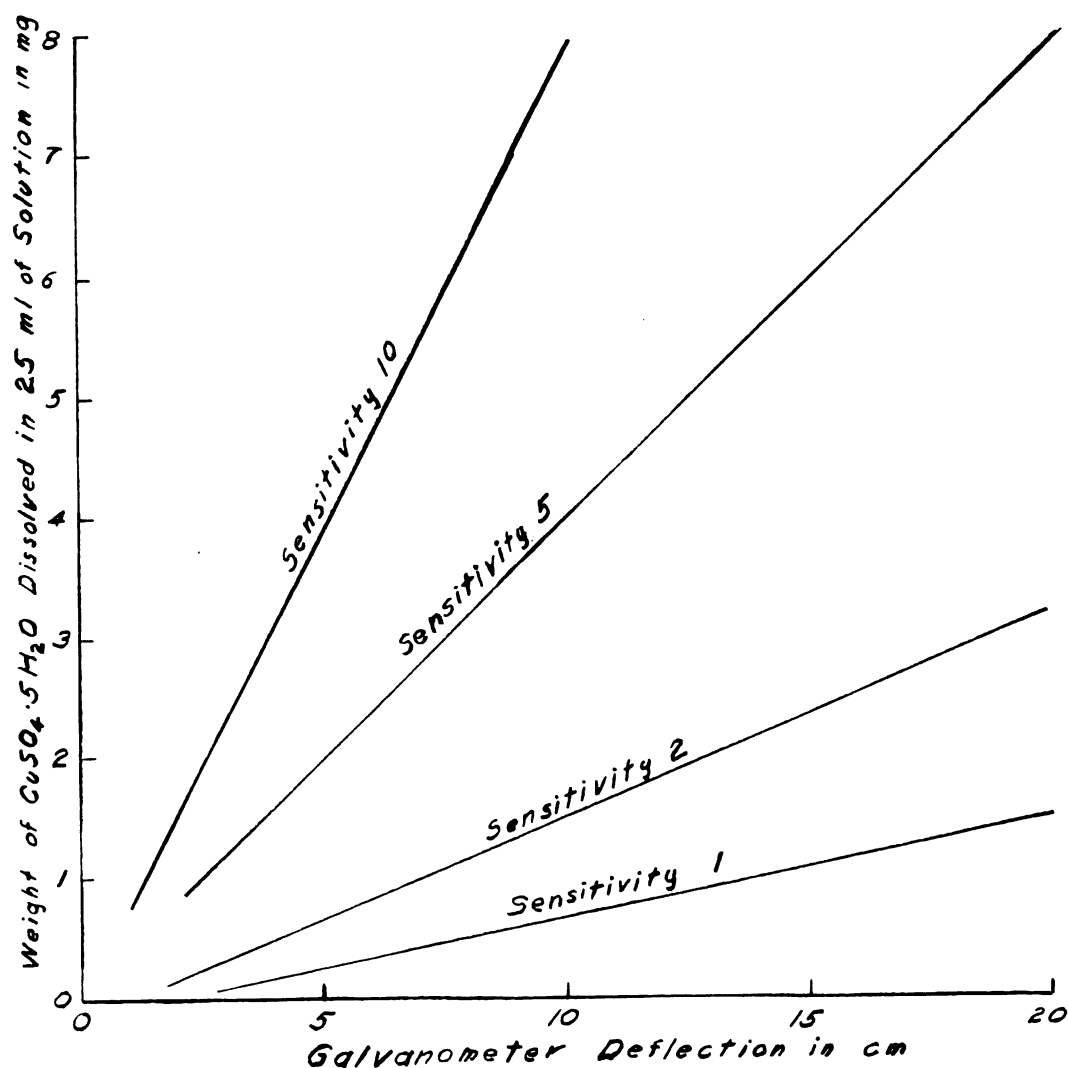


Fig. A-2. Polarographic calibration curves for 0.4 volts applied potential. This graph was plotted from experimental data and permitted the direct conversion of galvanometer deflection into deposit weight. The four lines represent four galvanometer sensitivity settings on the polarograph. The conditions for the calibration are applied potential, 0.4 volts; electrolyte, 0.4 normal potassium sulfate and 0.02 percent gelatin; interval between mercury drops, 3.2 seconds; and temperature, approximately 80 degrees Fahrenheit.

Note: This is a calibration of total current; that is, diffusion current plus residual current.

APPENDIX C:

PLANT LEAF-SURFACE DATA

TABLE A-II

DUST DEPOSIT ON PLANT LEAF SURFACES, ORIGINAL DATA
(Deposit in milligrams)

Air Velocities f.p.m.	Replications	Leaf Surfaces											
		Bean Top				Bean Bottom				Tomato Top			
		Angle*		Angle*		Angle*		Angle*		Angle*		Angle*	
		90°	45°	0°	90°	45°	0°	90°	45°	0°	90°	45°	0°
300	1	.37	.34	.20	.34	.51	.19	.09	.18	.06			
	2	.43	.23	.05	.30	.43	.07	.27	.14	.18			
	3	.38	.16	.12	.45	.55	.09	.14	.11	.07			
	4	.13	.11	.04	.18	.13	.07	.04	.04	.02			
	Av.	.33	.21	.10	.32	.41	.11	.14	.12	.08			
900	1	2.23	1.88	.77	2.25	2.80	1.54	1.23	1.17	.58			
	2	1.81	1.27	.60	1.17	1.70	1.06	1.11	.81	.44			
	3	1.30	1.33	.75	2.20	1.82	1.04	1.27	1.11	.41			
	4	1.13	1.00	.59	1.22	1.24	.83	.72	1.03	.38			
	Av.	1.62	1.37	.68	1.71	1.89	1.12	1.08	1.03	.45			
1500	1	5.43	4.00	1.69	6.68	13.30	5.07	7.02	4.40	1.70			
	2	2.65	3.03	2.62	3.89	4.12	2.20	4.33	2.63	1.49			
	3	4.74	2.11	2.68	5.43	4.58	2.54	3.10	3.39	1.39			
	4	4.08	3.24	1.80	3.38	4.17	2.45	1.50	.83	1.01			
	Av.	4.23	3.10	2.20	4.85	6.54	3.07	3.96	2.81	1.40			

(Continued on next page)

TABLE A-II, CONTINUED
(Deposit in milligrams)

Air Velocities f.p.m.	Replications	Leaf Surfaces									
		Tomato Bottom			Lettuce Top			Lettuce Bottom			Angle*
		90°	45°	0°	90°	45°	0°	90°	45°	0°	
300	1	.37	.57	.25	.14	.11	.10	.11	.23	.12	
	2	.29	.13	.05	.18	.13	.00	.14	.22	.14	
	3	.11	.14	.10	.05	.05	.00	.18	.11	.04	
	4	.08	.11	.04	.00	.00	.00	.00	.00	.00	
	Av.	.21	.24	.11	.09	.07	.03	.11	.14	.08	
900	1	3.36	2.18	.95	1.87	.71	1.06	1.75	1.08	1.31	
	2	3.37	2.38	1.34	.98	.81	.62	1.70	2.55	1.14	
	3	1.10	.87	.44	.61	.42	.30	.97	1.23	.78	
	4	1.28	1.45	.79	.88	.62	.47	.38	.47	.30	
	Av.	2.28	1.72	.88	1.09	.64	.61	1.20	1.33	.63	
1500	1	5.78	6.50	3.35	3.88	3.37	1.33	4.47	4.24	2.16	
	2	5.66	12.38	2.93	3.02	2.59	1.35	7.12	4.51	3.41	
	3	3.21	3.21	1.80	1.38	1.43	.61	3.63	3.68	1.47	
	4	2.78	3.67	2.13	2.54	2.08	.79	1.49	1.47	.95	
	Av.	4.36	6.44	2.55	2.71	2.37	1.02	4.18	3.48	2.00	

*Angles which leaf surfaces made with incident air stream.

TABLE A-III
DUST DEPOSIT ON PLANT LEAF SURFACES, CORRECTED DATA¹
(Deposit in milligrams)

Air Velocities f.p.m.	Re- plications	Leaf Surfaces											
		Bean Top			Bean Bottom			Tomato Top					
		Angle*			Angle*			Angle*					
		90°	45°	0°	90°	45°	0°	90°	45°	0°			
300	1	.37	.25	.14	.28	.46	.16	.09	.17	.05			
	2	.39	.23	.04	.40	.50	.09	.32	.16	.21			
	3	.34	.14	.16	.43	.51	.08	.17	.09	.06			
	4	.14	.10	.04	.19	.12	.08	.05	.07	.03			
	Av.	.31	.18	.10	.33	.40	.10	.16	.12	.09			
900	1	1.56	1.52	.82	1.71	2.34	1.23	1.23	1.13	.54			
	2	1.43	1.63	.72	1.43	1.92	1.11	1.31	.95	.52			
	3	1.50	1.17	.75	1.95	1.57	.93	1.67	1.34	.40			
	4	1.07	1.00	.55	1.24	1.23	.83	1.22	1.01	.64			
	Av.	1.39	1.33	.71	1.58	1.77	1.03	1.36	1.11	.53			
1500	1	4.22	3.74	1.50	5.81	11.77	4.74	6.62	4.19	1.81			
	2	3.60	3.46	2.85	4.23	4.63	3.26	5.09	3.09	1.75			
	3	4.19	3.52	2.38	5.30	4.18	2.23	4.00	4.03	1.49			
	4	4.04	3.39	1.84	3.40	4.32	2.49	2.54	2.55**	1.36			
	Av.	4.01	3.53	2.14	4.69	6.23	3.18	4.56	3.47	1.60			

(Continued on next page)

TABLE A-III, CONTINUED
(Deposit in milligrams)

Air Velocities f.p.m.	Repl litation	Leaf Surfaces									
		Tomato Bottom					Lettuce Top				
		Angle#		Angle#		Angle#		Angle#		Angle#	
		90°	45°	0°	90°	45°	0°	90°	45°	0°	90°
300	1	.33	.48	.20	.13	.08	.07	.10	.20	.10	.10
	2	.35	.10	.04	.20	.15	.00	.16	.24	.15	.15
	3	.14	.17	.13	.08	.05	.00	.18	.10	.05	.05
	4	.10	.13	.05	.00	.00	.00	.00	.00	.00	.00
	Av.	.23	.22	.11	.10	.07	.02	.11	.14	.08	.08
900	1	3.12	1.84	.91	1.34	.71	.80	1.46	.94	1.17	1.17
	2	2.81	2.36	1.76	1.42	1.03	.74	2.31	2.77	1.44	1.44
	3	1.28	.99	.51	.79	.63	.49	.92	1.33	.75	.75
	4	1.48	1.70	.88	.87	.60	.50	.55	.71	.45	.45
	Av.	2.17	1.72	1.02	1.11	.74	.63	1.31	1.44	.95	.95
1500	1	4.96	5.65	3.00	3.34	2.41	1.07	3.94	3.55	1.83	1.83
	2	5.96	13.99	2.72	4.38	2.91	1.83	7.70	6.63	4.03	4.03
	3	4.14	3.87	2.20	1.37	1.68	1.10	3.65	3.57	1.72	1.72
	4	3.94	4.34	2.54	2.89	2.07	.97	2.08	2.13	1.46	1.46
	Av.	4.75	6.96	2.62	3.00	2.27	1.24	4.34	3.97	2.26	2.26

*Angles which leaf surfaces made with incident air stream

1 Data corrected as explained on page 86.

**Value supplied by least squares method of missing value calculation.

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