DEPOSIT OF MIST-CONCENTRATE SPRAY AS INFLUENCED BY DROPLET SIZE AIR VELOCITY, TEMPERATURE AND HUMIDITY

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ABSTRACT

In recent years, a new method of applying pesticides - namely mist-concentrate spraying - has been developed. With this method of spraying, the toxicant is suspended or dissolved in the liquid diluent at relatively high concentrations in the sprayer tank. This concentrated liquid is injected into a high velocity air stream and is carried to the treated surface in the form of mist droplets which usually range from 50 to 200 microns in diameter.

Although mist-concentrate spraying has many inherent advantages over dilute type application, certain problems remain to be solved. Of these problems, probably the most important is the relation of droplet size to overall deposit and pest control. The main objective of this study is to determine the optimum size of spray droplets for uniform distribution and maximum deposit of mist-concentrate sprays on plant surfaces under various climatic conditions.

A special air-driven rotating disk spray apparatus was constructed to produce uniformly sized droplets, adjustable from 50 to 150 microns diameter. In conjunction with this apparatus, a speed measuring device to measure and regulate the spinning top was designed, constructed and used. This latter device consisted of inserting a magnet in the rotor, and mounting pickup coils in close proximity to it. The coils were electrically connected to a cathode ray oscilloscope and the re-

sulting cycles generated were compared with an audio-frequency generator. A constant, low-pressure bubbler liquid feed and flowmeter were constructed and utilized to maintain a constant regulated pesticide flow to the spinning disk sprayer.

The spinning disk spray apparatus was mounted in a specially constructed spray stand in such a manner that some of the droplets produced were drawn into a vertical lucite wind tunnel. An insertion device was constructed in this tunnel that permitted leaf samples and droplet collecting slides to be exposed to the resulting mist of fairly uniformly sized droplets. Leaf samples were exposed to three different sized droplets, 50, 100 and 150 micron diameters, with varying parameters of temperature, relative humidity and air velocity.

Microprojection equipment was utilized to measure and count the spray droplets. Resulting spray deposits on the leaf samples were measured quantitatively by polarographic analysis and qualitatitively by a leaf printing technique.

Since a complete randomized block experiment was not practical for the quantitative tests, a split-split plot analysis of variance was used. The main plots were temperature variation, sub-plots were humidity differences, while droplet size and air velocities were randomized in the sub-sub plots. An analysis of data indicated that temperature, droplet size, air velocities and most interactions were highly significant while humidity was significant at the five percent level.

The 150 micron droplets were most effective at the lower temperatures.

In the qualitative analysis of deposit uniformity, the main plots were droplet size, sub-plots were air velocities, and sub-sub plots were leaf position in relation to the mist stream. Leaf surfaces, both top and bottom were analyzed in the sub-sub-sub plots. An analysis of data indicated that air velocities, leaf positions and surfaces as well as most interactions were significant.

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INTRODUCTION

Definition of the Problem

Protecting crops from losses caused by insects, diseases and weeds is one of the most important and costly operations in present day farming. Yet with no sizable acreage of new land available for agriculture and human population increasing at the rate of approximately 7,000 a day, it becomes vitally essential that these agricultural pests be controlled to obtain greater returns from the land now under cultivation. Though there have been improvements during and since World War II in the development of insecticides, fungicides and herbicides, in equipment for their application, and in skill in their use, much work remains to be done. The U.S. Department of Agriculture's latest estimates of annual losses crediting 2 1/2 billion dollars to plant diseases, 4 billion dollars to insect damage and 5 billion dollars to weeds emphasize the inadequacies of pest control.

In recent years, a new method of applying pesticides - namely mist-concentrate spraying - has been developed. This method was primarily instigated by the desire of various research workers to obtain more effective pest control procedures and at the same time lower the cost and labor requirements involved in applying pesticides.

With the mist-concentrate method of spraying, the toxicant is suspended or dissolved in the liquid diluent at relatively high concentrations in the sprayer tank. This concentrated liquid is injected into a high velocity air stream and is carried to the treated surface in the form of mist droplets which range from 50 to 200 microns[1] in diameter. Since this spray liquid is more concentrated with the active pesticide as compared to dilute sprays proportionately less total spray liquid is required to obtain the recommended dosage per acre or per tree. In actual practice, concentrations as high as 20X[2] have, in a few instances, been used successfully while concentrations of 4X are commonly used. Brann and Gunkel (1951) reported successful insect control in orchards at 10X concentration applied at 2 gallons per tree. Brann and Gunkel (1953) also reported successful bean-beetle and onion-thrip control at 10X concentration applied at 10 gallons per acre. Later tests with the same sprayer gave excellent control of early blight and anthracnose on tomatoes at 20 gallons per acre.

The mist-concentrate method has several inherent advantages over the dilute type spray application.

1. Less water is used, therefore fewer refills are required and field efficiency is increased. In some areas of limited water supply,

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[1]One micron = 10^{-6} meter
= 4×10^{-6} inch

[2]The concentration is expressed as so many times the standard or one X.

this saving of water is of paramount importance.

2. Less labor is required.

3. Lighter application equipment is involved.

4. In most cases, total deposit of toxicant is heavier for equal amounts of toxicants applied. This latter feature is explained by the fact that with mist sprays there is no runoff and a higher percentage of toxicant applied is actually deposited on the treated surface.

Although mist-concentrate spraying has many intrinsic advantages over dilute type spray application, certain problems remain to be solved. Of these problems, probably the most important is the relation of droplet size to overall deposit and resulting pest control.

Statement of the Thesis Problem

The four parts of the thesis problem are:

1. The design and construction of an apparatus for producing uniformly sized spray droplets.

2. The design and construction of a test stand for injecting these spray droplets into a moving air stream to produce a homogeneous mist cloud of uniformly sized spray droplets.

3. The exposure of leaf samples to the resulting mist spray with varying parameters of droplet size, air velocity, ambient air temperature and relative humidity.

4. Both quantitative and qualitative chemical analysis of leaf

samples for measuring uniformity and degree of spray deposit.

Objectives of the Thesis Study

The broad objective of this thesis study is to obtain more basic knowledge on the mode of mist spray deposits. The ultimate goal is the improvement of spray distribution, deposits, pest control, and resulting efficiencies of mist-concentrate sprayers. More specifically, the main objective of this study is to attempt to determine the optimum size of spray droplets for the most uniform distribution and maximum deposit of mist-concentrate sprays on foliage samples under various climatic conditions, and physical application characteristics.

REVIEW OF LITERATURE

Historical

During and since World War II, various types of aerosols and air-blower sprayers were introduced to help speed up and increase the efficiency of pest control applications. Next an interest in reducing the amount of diluent or carrier - water in this case - was aroused. Considerable work was undertaken to develop a better method of pest control and reduce the amount of liquid normally required. Mist-concentrate spraying and sprayers resulted from this work.

Effect of Droplet and Particle Size

Since the principle involved in mist-concentrate spraying is the coverage of a large area of treated surface with the smallest practical volume of liquid, it is axiomatic that the finer the droplets, the larger the area covered. As an illustration, consider droplets of 50 and 150 micron diameters.

$$V = \frac{4}{3} \pi r^3$$

$$= \frac{\pi}{6} D^3$$

Where:

V = volume in cubic microns

D = droplet diameter in microns

A 150 micron droplet has 1,767,150 cubic microns or 27 times the volume of a 50 micron droplet.

$$A = \pi (r\,K)^2$$
$$= \frac{\pi}{4} D^2 K^2$$

Where:

A = area covered in square microns

D = droplet diameter in microns

K = relation of stain diameter to droplet diameter. Courshee and Byass (1953) determined a value of 1.58:1 for droplets below 400 microns deposited on glass slides.

Considering K equal to unity, a 150 micron droplet can cover 17,671.5 square microns of leaf surface while the same volume of liquid in 27 droplets of 50 microns diameter can cover three times the area.

In addition to the area actually covered by a spray droplet, there is a zone of influence or effective cover surrounding each spray droplet. This zone of influence or halo of toxicity varies with the type of material used as well as the purpose of spray. For control of insects moving over the treated surface this zone is considerably larger than for disease control. Courshee, Daynes and Byass (1954) reported that the ratio between the effective cover unity and the actual cover is a maximum for a minimum value of droplet size based on the formula

$$R = \frac{(S + d)^2}{S^2}$$

Where:

R = ratio between effective cover and actual cover

S = resulting stain diameter

d = range of influence of a speck of deposit

Thus, a decrease in droplet size from 150 microns to 50 microns represents a possible increase of area coverage of 6 or 7 times.

Small droplets strike a slender plant surface more easily than a larger surface because the air stream is less diverted. Yeoman (1949) in his study of aerosol deposits based his D values on Sells' formula:

$$S'' = \frac{0.0005\ D^2 V}{S}$$

Where:

S" = efficiency (greatest when equal unity)

S = size of greatest width of object in inches

V = velocity in mph[1]

D = diameter of spray droplets in microns

Small droplets are also more satisfactory since they involve less danger of phytotoxic spotting of fruit and foliage.

Aside from the question of efficiency of impaction, the degree of residual deposit is very important. Potts (1946) indicated that although

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[1]mph is abbreviation for miles per hour.

fine atomization was necessary to obtain adequate distribution with low rates of application, the droplets had to be large enough to give a satisfactory deposit on fruit, foliage and insects. He further stated that there was practically no deposit of droplets less than 20 microns in diameter and very little deposit from droplets under 30 microns. Potts (1946) also believed that the optimum range for droplet diameters should be about 20 to 80 microns for ground application and about 70 to 100 microns for aerial application, both depending upon the density and type of insecticide, volatility of the carrier, plant growth, kind of insect, type of distributing device, and atmospheric conditions.

While no two researchers will agree as to what constitutes "adequate deposit", it is generally agreed that "complete coverage" implies leaving no part of the plant without adequate spray deposit so that insect and disease pest populations will not build up. How droplet size affects this deposit is not clear, but if one considers that a gallon of spray (3.785 x 10^{15} cubic microns) is dispersed in a homogeneous spray cloud and distributed uniformly over an acre of surface; a droplet diameter of 40 to 70 microns will result in a deposit of 17,931 to 3,354 droplets per square inch, and a droplet diameter of 80 to 100 microns will result in a deposit of 2,157 to 1,164 droplets per square inch. Thus for a given volume per acre, the smaller the droplets, the more uniform the distribution and deposit providing the atomization is not so fine as to prevent deposit.

Closely related to the study of droplet size is the investigation of particle size of the suspensions in liquid spray. Metcalf, et al (1944) reported a gradient in particle size as it affects mortality of different larval instars of mosquitoes. McNew and Burchfield (1950) reported that the activity of 2, 3-dichloro-1, 4-naphthoquinone as a foliage protectant against spores of Alternaria solani was dependent upon particle size. They found that on decreasing the mean radius from 24.5 micron to 0.5 micron only one-fortieth as much material was required to maintain equivalent blight control. Hamilton, Palmiter, and Mack (1943) and Heuberger and Horsfall (1939) reported similar results with copper; while Fiechtmeir (1949), Hamilton, Palmiter, and Mack (1943), and Wilcoxon, Frank and McCallan (1931), found the same results with sulfur. Burchfield and McNew (1950) further related the quantity of Phygon (2, 3-dichloro-1, 4-naphthoquinone) required to control tomato early blight versus the particle size. They reported that the quantity required was inversely proportional to the logarithm of the number of particles into which it is subdivided.

Other researchers worked on another phase of pest control; namely, the nature of a crystalline-type deposit as related to the mode of cuticular absorption of different sizes and shapes of these crystals onto the insect. McIntosh (1947-49) initiated these studies by comparing effects of an aqueous suspension and a colloidal DDT on Oryzaephilus surinamesis (lind) and Triboleum castaneous (H. P.) by dipping and placing insects on different surfaces previously sprayed. He further studied the effect of different crystal sizes and shapes in the resulting deposit. Malley (1953) attempted to find the interrelationship that existed between concentration of toxicant, its crystal size, and droplet size of spray deposits as a complex unit.

Methods of Measuring Droplet Size

Various methods have been used for measuring and recording droplet size. All the methods used can be roughly classified as direct or indirect measurements.

Indirect measurements. Some examples of this method are (1) microburette,(2) colorimeter, and (3) magnesium oxide.

The microburette forms a measured volume of liquid into drops of equal size; by counting the drops formed, the volume and diameter of each can be readily calculated. When these measured droplets are permitted to fall on a flat surface, the size of the resulting stain is proportional to the diameter of the drop causing the stain. Lenard (1904) and Niederdorfer (1932) used absorbent paper to catch the droplets. Walton and Prewett (1949) used a simplified method while other researchers used the blueprint paper method. Coons and French (1940) used clear glass slides to catch and measure spray droplets. Courshee and Byass (1953) indicated that this method was unsatisfactory for small droplets in that it was impossible to obtain uniform droplets of sufficiently small size and was subject to inaccuracies; these errors being due to varying volumes of measured liquid remaining in the instrument or evaporating before reaching the treated surface.

The colorimeter method also depends on measuring the total volume of a number of equal-sized drops, the total volume being estimated from the dye content of the stains. Courshee and Byass (1953) indicated that this method was also subject to errors from evaporation of the solution while it is being sprayed, with the results that the drops are smaller on impact than their dye content would indicate. More serious were the difficulties in obtaining an accurate calibration of the instrument. It was necessary to use almost saturated dye solutions and there appeared to be large variations of concentration in different samples from the same solution.

In the magnesium oxide method, a plate is covered with a thin layer of magnesium oxide layer by holding it over a burning magnesium ribbon. Carbon black or oleatis can also be used but in any case the thickness of the layer should be only as thick as the largest diameter droplet expected. Exposure to a spray results in drops landing on the plate and causing craters which bear a fixed relationship to the drop diameter. Courshee and Byass (1953) and Turner (1953) found it impossible to obtain a sufficient number of uniform craters from small droplets at their terminal velocities in air as most of them entered the oxide obliquely or bounced off.

Direct measurement. The direct measurement of droplets can be made by two different procedures.

In the first method the droplets are collected on microscopic slides coated with an oleophobic film. To determine the actual size of droplets, they can be considered as a plano-convex lens and the size of the original spherical drops can thus be obtained from the diameter and focal length of a liquid lens. May (1945) used this method while Davis (1949) used a modification of this method in conjunction with a photographic method for recording the size of spray droplets. Since some sprays evaporated rapidly it was essential that the droplet measurements be made immediately after exposure.

Farlow (1954) used an improved type of transparent halide ion-sensitive transparent film sampling surface for collecting and measuring droplets in the size range from 25 to 400 microns diameter. The droplets collected on this film contained a halide ion concentration greater than 0.5% by weight and on impact produced "spots" on the film surface. The size of these spots were then correlated with the diameter of the droplets producing them.

McGinn (1954) used a double image micrometer for particle size analysis. His method used a double image created by birefringent crystals so that every object in the field produced two images separated by a predetermined distance D. Since all droplets that appeared tangent in the field were of diameter D, the actual counting was much simplified.

Pui-Kum and LaMer (1954) used a forward angle, light scattering camera for determining size distributions in aerosols. In this procedure, the light scattered in the near forward direction from individual dioctyle phyhlate droplets, flowing in a thin stream of known thickness and illuminated by a high intensity electronic flash tube, was photographically recorded for the determination of number concentration, and size frequency distribution. The resulting photographs were then slightly off-focus so that pin-point images at focus were expanded into different diffraction patterns. The optical density of each pattern was used as a measure of its droplet size.

With the second "absolute method" of direct measurement, the droplets are collected on glass slides coated with a hydrophobic substance, thus preventing evaporation of the droplets. These droplets are suspended as true spheres and their diameter can be measured microscopically without the use of a correction factor. This latter technique was first used in Russia by Fuchs (1937) for the measurement of fog droplets. May (1945) published a modification of this technique for use in measuring water droplets from spray machines. Hurtig (1950) also used this technique. Courshee and Byass (1953) used several different coatings. In the drifilm method, they coated the glass cell with a water repellent film of a silicone. This cell was then filled with a non-viscus liquid, of a lower density than the spray, with which the spray droplets did not mix. The spray droplets sank to the bottom where they remained almost spherical. An alternative is to fill the slide cell with two oils immiscible with each other, one being more, and the other being less dense than the spray liquid. Drops penetrating the surface remain suspended at the interface of the two oils.

A third coating that can be used is a viscous grease mixture into which the droplets are impacted. They are then covered with another slide on which is a similar grease coating in a molten state which fuses with the first layer. The droplets are embedded in the grease between the two slides. Turner (1953) reported using a special slide mount with a hydrophobic material consisting of a mixture of two parts petrolatum and one part light mineral oil, the ratio depending upon the ambient temperature. In every case, the matrix was kept fairly soft, yet stiff enough to "set" solid in the special slide mount.

May (1945) successfully used the "Cascade Impacter" for measuring very fine droplets. Other researchers used improved versions of this instrument. Basically it consists of a series of tubes attached at right angles one to another. When the instrument was placed in a spray laden air stream, part of the mist was diverted through it. In circumventing the tortuous passage, the air decreased its velocity in each stage and deposited the spray droplets on slides. Turner (1953) found this instrument impractical for measuring large droplets.

Methods for Automatically Counting Droplets

Adler, et al (1954) devised an automatic counter for rapidly counting spray droplets from suitable negatives of droplet images. Their counter was based on the principle that in a random distribution of spots, there is a relationship between the length of chords and the number and size of spots. Their automatic counter incorporated a rotating drum on which was mounted the photographic negatives of spray droplets. These negatives were projected by an optical system and picked up by a phototube. The phototube then converted these light pulses to electric pulses and fed them into an electronic sorter-counter unit. Trickett and Courshee (1952) used a modification of this same relationship between chord lengths and droplet sizes in their automatic croplet counter. Their machine could count droplets directly on filter paper when sprayed by a Nigrosine dye.

Guyton (1946) reported on an analyzer based upon electrical pulses created upon interception of particles by a wire. The pulses were amplified, classified by size, and counted. His apparatus was intended for analysis of slow moving clouds, a sample of the suspension being aspirated through a tube and emitted at high velocity through a jet onto a wire. Apparently the particles became charged electrostatically as they moved through the tube, the charge being proportional to the square of the particle diameter. The wire was grounded except for a few inconclusive determinations, and the greatest success was obtained with nonconducting particles.

Recently Marconi Instruments Ltd, New York City have placed on the market a Cintel[1] Flying-Spot Particle Resolver for automatically counting and sizing microscopic particles. This instrument utilizes a scanning tube on which a 640 line diagonal sequential scan raster is produced on its face and which is imaged down through a conventional optical system of a microscope to scan that portion of a slide contained within the field of the objective lens used. The light passing through the slide is modulated according to the density and configurations of the object and these changes in light are then passed to a multiplier phototube where they are converted into an electrical signal. From here the signal is fed to a Video amplifier whose output modulates the monitor picture tube, the raster of which is synchronized with the original scanning raster. This arrangement permits magnification up to 8000 diameters with a resolution of 0.1 micron. The counter also counts the spots and sizes them automatically.

In October 1956, the author had an opportunity to use this machine

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[1]Manufactured by Cinema-Television Limited, Worsley Bridge Road, Lower Sydenham, London.

for counting spray droplets embedded in a mixture of petrolatum and light mineral oil and mounted on a glass slide. The droplets showed up exceptionally well on the picture tube but there was not enough contrast between droplets and surrounding media to obtain a count. Sufficient contrast could be obtained by using a dyed spray liquid or a green filter in the optical system of the microscope.

Dynamics of Droplet Formation and Methods of Producing Uniform Droplets

Spray droplets are formed by the break-up of a fluid into small particles and are produced by nozzles or other devices. Lord Rayleigh (1878) originated the basic theory of jet disintegration on which he based his theory of sound. Castleman (1931) indicated that a jet started as a solid stream but subdivided into smaller units. Basically, a column of liquid ejected into air can be considered as a cylindrical rod contained by a shell, this shell being the liquid's surface tension. The surface tension can be considered as potential energy and when there are no other forces acting on the liquid it tends to reach a constant state where the surface energy is minimum for the contained volume. This explanation accounts for the fact that liquids falling in space form spheres since a sphere has maximum volume per unit of surface area. A droplet falling in air however, tends to elongate and forms the conventional tear drop.

Break-up of the rod of liquid occurs because the surface energy of liquid is lower when the cross-section of the cylinder is larger. As the cylinder of liquid moves through air there is a tendency for the cross-sectional area at one point to become larger. As the cross-section becomes larger in one spot, there is a corresponding decrease in cross-section at another point. As the rod of liquid progresses, the undulation increases until the film of liquid breaks at the thin section and the detached liquid tends to form spheres. As the large drops, which have films collapsing on both sides, pull themselves into spherical form, isolated particles are town off and these subsequently form one, two or more smaller droplets called satellites. As most droplets are formed in this manner, conventional nozzles are incapable of producing a homogeneous spray of uniformly sized droplets.

Various types of commercial nozzles are available for producing liquid break-up. Liquid emerging from a swirl nozzle forms a circular hollow cone by virtue of the high tangential velocity imparted to the fluid by passing through sloping holes in the whirl plate. The discharged liquid forms a thin sheet and breaks up similarly to the rod of liquid but in two directions; one in the forward direction and the other at right angles due to the constantly increasing radius of the cone.

The impinging nozzle causes liquid break-up by directing two streams of liquid together in such a manner that the momentum towards each other is converted to a movement at right angles. The resulting liquid forms a flat fan-shaped pattern that increases in width proportional to the distance from the nozzle. Liquid break-up in this type nozzle also occurs in two dimensions.

A modification of the impinging jet nozzle is the type in which a jet of liquid is directed against a flat plate in such a manner that the liquid forms a circular fan pattern. Droplet formation with this type is identical with the impinging jet. Wark (1933) discussed the theory of this type of nozzle.

Another method of producing droplets is by means of air break-up. Von Ohnesarge (1936) claimed that he was able to produce uniformly sized droplets under one set of conditions with this method. A modification of the air break-up is obtained by installing a series of airfoils in the air stream. These cause the large droplets to be impinged on the airfoil while the smaller droplets are carried around it. The larger droplets are swept over the surface of the airfoil and are torn off the trailing edge. When this process is carried out in two directions, the size of the droplets is reduced and no large droplets are emitted into the air. To be effective, numerous airfoils are necessary which in turn offer considerable resistance to the air stream.

LaMer and Hochberg (1949) designed an aerosol generator in which the droplets were pre-sized by condensing liquid around nuclei produced by heating a nichrome wire coil. Yeomans (1949) was able to produce droplets from 0.33 to 33.7 microns with this method.

Dimmock (1950) devised a method of producing uniform droplets by utilizing a glass capillary vibrating at its resonance frequency by an electromagnetic arrangement. Streams of drops were thrown off at various points on the path of the reed tip. Ennis and James (1950) and Vonnegut and Neubauer (1951) employed a similar method but excited the capillary with an air blast. Davis (1951) described an apparatus that used a vibrating blade to tear off drops from the liquid feeding through a stationary capillary. The size of droplets emitted were controlled by: (1) the rate of liquid flow, (2) the frequency of the vibrator, and (3) the amplitude of the vibrating tip. Changing any one of these varied the size of the resulting droplets produced. Malley (1953) used a modification of the glass capillary to produce uniform droplets but found several drawbacks: (1) the number of droplets produced were few, and (2) the performance of the vibrating reed was very erratic. Rayner and Haliburton (1955) used a high speed rotating blade and capillary tube to shear off droplets. They reported their device produced uniform droplets in the diameter range of 50 to 700 microns and had a convenient adjustment for emission frequency that eliminated splatter.

The most successful method of producing uniform droplets so far devised appears to be the rotating cup or disk method. Walton and Prewett (1949) used an air driven rotating disk similar in principle to the rotating cup used by Beams (1937) and Hinze and Milborn (1949). Liquid breakup occurred when liquid was fed to the center of the rotating disk or cup and was centrifuged off the edge. In operation, the liquid flowing into the center of the disk spread into a thin sheet or spiral ligaments over the surface and was thrown out at the edge like the spokes of an open umbrella. These ligaments or rods broke into droplets at or near the edge of the disk. When breakup occurred, two sizes of droplets were produced: (1) large uniform droplets, and (2) smaller size but mixed diameters called "satellites", which were remnants of liquid ligaments or rods after breakup had occurred.

Walton and Prewett (1949) found that they could control the size of the main drops by regulating the rotative speed of the spinning disk and remove the satellite droplets with air suction. They were able to accomplish this differential removal of smaller droplets by virtue of the difference in projection distance from the rotor between the main and satellite drops. May (1949) further improved the apparatus by designing the spinning top to use the scavenged air to remove these satellite droplets. He reported excellent results with the improved apparatus.

Malley (1953) successfully used an electrically powered disk to obtain uniform droplets. By maintaining a constant speed and liquid pressure, he was able to produce uniform droplets together with the accompanying satellites. By utilizing the different trajectories of the two size ranges of the droplets produced, Malley (1953) was able to separate out and use the larger uniform droplets.

Methods of Determining and Controlling Speed of Disk Rotation

In the initial operation of an experimental air-driven spray apparatus used for producing uniform droplets, it was evident that some method had to be devised to determine and control the speed of rotation of the spinning disk. Regulating the driving air pressure did control the disk's speed of rotation, but a much more sensitive device had to be found to accurately determine and control this speed.

One method of measuring rotational speed is by means of a stroboscope. This instrument functions by emitting a cyclic light beam of adjustable, regulated frequency. When this light beam is focused on a rotating surface, the surface appears to "stop" when the light frequency is in resonance with the rotating object. The stroboscopic method of measuring rotational speeds has, however, several disadvantages. It is virtually impossible to directly distinguish between various related frequencies of rotation. For instance, a stroboscope adjusted to 1000 rpm[1] will "stop" an object which is turning at 500, 1000 and

[1] rpm = revolutions per minute.

2000 rpm as well as other related frequencies.

MacInnes (1943) described a method of using stroboscopic patterns for determining speeds of rotation. If a source of flashing light is used for illuminating a rotating disk on which there is painted a single radial band, and the speed of rotation of this disk is increased or decreased, a series of stroboscopic patterns are observed, each of which, when stationary, correspond to a definite speed of rotation. Similar patterns recur, however, at a series of different, but related speeds. For example, if a light flashing 3600 times per minute is directed on a disk rotating 400 rpm $= \frac{3600}{400} = 9$ bands — disk makes 1/9 revolution between flashes. Though the same pattern occurs at several different speeds, the actual speed of rotation can be calculated from a formula presented by the above author.

Other disadvantages of the stroboscopic method for measuring the speed of rotation of the spinning disk spray apparatus are the inaccessibility of the disk and the high rotational speeds attained. Most commercial instruments have a maximum range of approximately 10,000 revolutions per minute while speeds of 50,000 plus revolutions per minute are obtained with the spinning disk spray device.

The high rotational speed was not a serious problem since Wilson (1943) described a stroboscope made from a Hewlett audio oscillator and neon light. This instrument was capable of measuring speeds in the audio-frequency band or in excess of 10 KC.

The most difficult obstacle to surmount was the inaccessibility of the spinning disk to the beam of flashing light. Had not the top been so inaccessible, a speed indicator and control device similar to Kahler (1938) could have been used. His system utilized a stroboscope in connection with an electric air valve to control speed. A photo-electric cell in connection with the stroboscopic light measured the speed and controlled the air valve which in turn regulated the speed. Kahler's system controlled the speed of the top from 10 to 5000 cycles per second.

Since the stroboscopic principle could not be effectively utilized to control the rotating top, some other means had to be found. Beams, Linke and Sommers (1947) described a system of speed control for an air-driven centrifuge and this method seemed applicable to the spinning disk spray apparatus. In this system, a permanent magnet was attached to the centrifuge and a set of permanent coils was placed near the rotor. The coils were connected to a resistance and capacitor making a RCL[1] circuit. When the centrifuge and magnet rotated, an elecromotive force was induced in the circuit. Negligible current was generated at speeds below ciruit resonance. At resonant speed, however, the generated current abruptly increased and served to "brake" the centrifuge. By adjusting the capacitance, the speed of

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[1] RCL = resistance, capacitance and inductive

rotation was accurately controlled, while a cathode ray oscilloscope and Lissajous figures or comparing frequencies with an audio-frequency oscillator was used for measuring this speed.

Summary of Review of Literature

Various methods of producing uniform droplets in still air have been reviewed. Unfortunately no literature appears available relative to producing uniform droplets in a moving air stream. Malley (1954) indicated that he and several of his co-workers had attempted to do this but were forced to give it up because of unsatisfactory results. Druett and May (1952) reported using a 12 inch vertical wind tunnel and the rotating top to produce a homogeneous spray cloud. Unfortunately, the droplets produced were smaller than 60 microns and subsequent evaporation reduced them to 10-15 micron dry size. There is a possibility that Druett and May (1952) may have further unpublished work which is presently "classified".

APPARATUS AND METHODOLOGY

Equipment Used for Collecting, Measuring, and Counting Droplets

Droplet collection. After reviewing the merits of the various methods studied for measuring droplets a modification of the "absolute method" similar to the method of Turner (1953) was adapted. The principle of this technique consists of catching and rapidly embedding the droplets in a hydrophobic substance before evaporation occurs. Spray droplets are therefore suspended as true spheres in this matrix compound and their diameters are measured microscopically without the use of any correction factor.

The hydrophobic material used for trapping droplets was a mixture of one part white petrolatum to two parts prorrex-D oil by volume. Proportions were varied, depending upon the ambient temperature, to keep the matrix fairly soft but stiff enough to set solidly in concave cell microscopic slides. In practice, the hydrophobic material was melted in a double beaker and stirred well to obtain a thorough, even mixture. The water in the outer beaker also served to keep the matrix in solution while taking droplet samples. After the matrix was pipetted onto the slide and left to cool, the excess matrix was scraped off leaving an even thickness on the slide. It was observed that the viscosity of the matrix changed with repeated "heatings", therefore, a new batch of material was mixed for each run of samples.

Concave microscope slides were used in the initial study. In viewing under a microscope, it was found that each droplet had to be focused individually since they were on different planes. To alleviate this tiresome effort, slide mounts similar to those used by Turner (1953) were utilized (Fig. 1 and 2). These slide mounts were constructed of brass and were glued onto the glass slides using a special "cycleweld"[1] C-14 bonding material.

There are several ways of exposing the treated slides to a spray stream, but for the preliminary testing the so-called "hand method" was used. The prepared slide was held in one hand and covered with the other. At the testing position, the slide was quickly passed on a perpendicular plane through the spray stream. After the slide was exposed in this manner, melted matrix was pipetted on a cover slip and this in turn was immediately inverted and placed on top of the slide. The droplets embedded in the matrix in this manner were subsequently counted. Since evaporation of the droplets "caught" in the matrix was impossible, the actual "count" could be made days after with no appreciable error.

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[1] Chrysler Corporation -- Cycleweld Cement Product Division, Trenton Michigan.

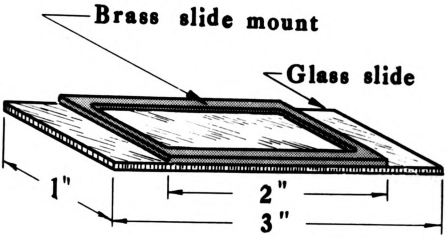

Figure 1. Diagram of special slide mount.

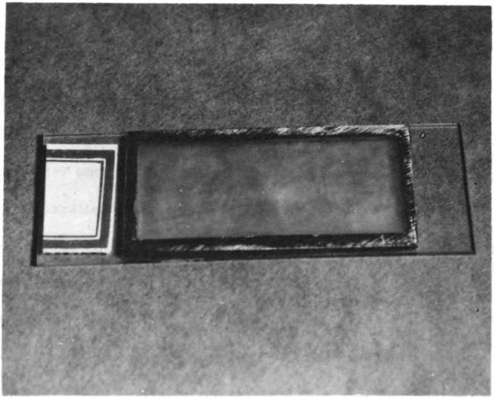

Figure 2. Microscope slide mount.

A 1" x 3" microscope slide with a special brass slide mount filled with matrix and used for collecting spray droplets.

Microprojection apparatus for measuring and counting droplets. Past experience indicated that microscopic measurement of droplets by direct observation would be both laborious and time consuming. Therefore, a "microprojection" method was used that increased both the accuracy and rapidity of measuring and counting droplets, and at the same time reduced physical fatigue. In conjunction with this method a special microprojection box was constructed (Fig. 3). This box was light-tight and had an adjustable vertical screen for focusing the projected images. The microscope, equipped with a commercially available prism mounted on the ocular, was placed in a special restraining mount on the front of the box. When a strong light was suitably directed on the adjusted mirror, the image of the microscope field was projected from the prism onto a calibrated screen in the projection box. Calibration of the screen was accomplished by projecting the image of a stage micrometer onto the screen and adjusting this screen so that the vertical ruled parallel lines on the screen corresponded to the projected image of the stage micrometer. For the present work, the lines on the screen were drawn in increments of 10 from 0 to 200 microns, and size ranges marked every 20 microns.

Since it was desirable to obtain photographs of some of the droplet samples, a commercial microprojection "Euscope"[1] was purchased (Fig. 4).

[1]Manufactured by Bausch & Lomb Optical Co., Rochester 2, New York

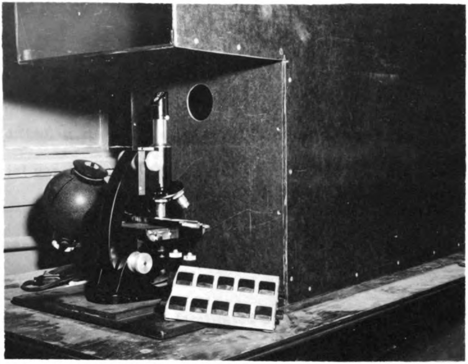

Figure 3. "Homemade" microprojection box.

This special box was constructed to facilitate the measuring of spray droplets.

Figure 4. Euscope microprojection apparatus.

The commercial microprojection apparatus was much more convenient to use.

This device consisted of an enclosed rectangular box fitted with a lens piece, reflecting prism, special metal screen and photographic attachment. In addition, a special ground glass viewing screen was provided. A special parallel wire grid was constructed for the white metal screen and calibrated in the same manner as the microprojection box previously described. The commercial unit was much more convenient to use than the "homemade" one.

Counting of the droplets was facilitated by the use of a mechanical stage on the microscope and a special ten-unit Veeder-Root[1] counter. Each counter was assigned a droplet class interval and as the slide was drawn lengthwise across the microscopic field, the droplets were classified and recorded in their correct class interval.

Methods Used for Sampling Droplets, Recording Droplet Frequency, and Determining Mean Size

Sampling droplets. Since each exposed slide contained hundreds of droplets, some unbiased method of selecting droplets had to be used. The sampling area of roughly two square inches per slide was divided into four evenly sized rectangular quarters of one by one-half inch, numbered clockwise from A to D, with A being the upper left-hand quarter. Each quarter in turn was subdivided into four equal parts, one-half by one-fourth inch, numbered clockwise from one to

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[1]Manufactured by Veeder-Root, Inc., Hartford, Connecticut.

four, one being the upper left hand section. Two dice were used to select the area, one for letter and the other for number. Since four 50 droplet counts were taken on each slide, and every quarter had to be included in the composite 200 droplet sample per slide, the dice shake was repeated if an impossible selection appeared.

Recording droplet frequency and determining mean size. Several methods have been used for determining a weighted mean diameter for a group of droplets that characterizes the droplet size of the entire spray. Of these, Sauter mean diameter and Mass mean diameter abbreviated S.m.d. and m.m.d. respectively - are most commonly used. Sauter mean diameter is the diameter of a droplet which has the same ratio of surface to volume as the entire spray.

$$\text{S.m.d.} = \frac{\sum D^3 \Delta n}{\sum D^2 \Delta n}$$

Where:

Δn = the number of droplets in each diameter - class D.

For this study mass median diameter was used. Mass median diameter of a number of droplets is defined as the diameter of a hypothetical droplet below which one-half of the total volume of droplets occur. The other half of the total volume of droplets will be above this diameter. Of necessity, mass median diameter is a weighted average and gives a clearer picture of "average" size than would mean or a numerical average droplet size. In reality, it is possible that there are no droplets in a sample that are exactly the mass median diameter.

Mass median diameter was determined by dividing the volume of droplets in each class interval by the total volume in all class intervals in order to obtain the percent total volume in each class interval. The cumulative percent volume was then plotted on logarithmic probability paper and a straight line drawn to connect the resulting points. The diameter corresponding to the 50% cumulative percent volume was the mass median diameter of the group of droplets. Of course, to utilize this method, one has to assume that the increments from minimum to maximum size in any class interval fall in a straight line.

In practice, the volume of the droplets was calculated from the formula for the volume of a sphere:

$$v = 1/6\, \pi D^3$$

Where:

D = diameter of the largest droplet occurring in a specific size range.

Again this procedure is arbitrary, but it does give a weighted average since a few droplets above a specific size range usually contain more volume than all those droplets below this diameter.

To prove the validity of using this procedure, several droplet samples were collected from a homogeneous spray cloud of uniformly sized droplets produced by an air driven spinning disk sprayer. Details of this apparatus will be discussed later.

TABLE I

FREQUENCY DISTRIBUTION AND CALCULATED MASS MEAN DIAMETER OF THREE DIFFERENT SIZED DROPLET SAMPLES

Droplet Size in Microns	Number of Droplets in Each Sample			
	100	100	300	500[1]
90	0	0	2	2
91	1	1	5	7
92	2	3	4	9
93	1	1	6	8
94	1	2	12	15
95	1	4	5	10
96	5	5	12	22
97	4	4	15	23
98	6	8	27	41
99	14	11	24	49
100	29	31	80	140
101	13	12	34	59
102	7	9	24	40
103	7	4	16	27
104	3	2	10	15
105	3	3	8	14
106	1	0	8	9
107	1	0	4	5
108	1	0	3	4
109	0	0	1	1
110	0	0	0	0
m.m.d.	100 microns	99 1/2 microns	100 microns	100 microns

[1]Accumulative sample of other three.

When the droplet frequency distribution in the above 300 group sample was divided into four groups namely: 91-95 microns, 96-100 microns, 101-105 microns, and 106-110 microns, the calculated mass mean diameter was 99 microns. On the other hand, when this same distribution was divided into four groups of 90-94 microns, 95-99 microns, 100-104 microns, and 105-109 microns the calculated mass mean diameter equaled 100 microns. Since the latter method of grouping more nearly approximated the acutal mass median diameter, that method of calculation was used for subsequent determinations.

Commercial Equipment Tested

From past experience, it was known that a conventional nozzle would not produce uniform droplets in a moving air stream. Therefore, some device had to be purchased or constructed that would produce uniform droplets.

Test of a commercial unit. It was thought that a commercially available, spinning disk aerosol generator might produce a homogeneous cloud of uniform droplets. Therefore, a Model #202 Microsol Generator[1] was obtained on loan and subsequently tested. This unit is illustrated schematically in Fig. 5 and shown in Fig. 6. The two concave

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[1]Manufactured by Silver Creek Precision Corp., Silver Creek, New York

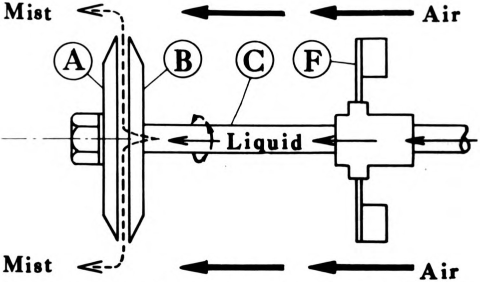

Figure 5. Schematic diagram of spinning disk sprayer.

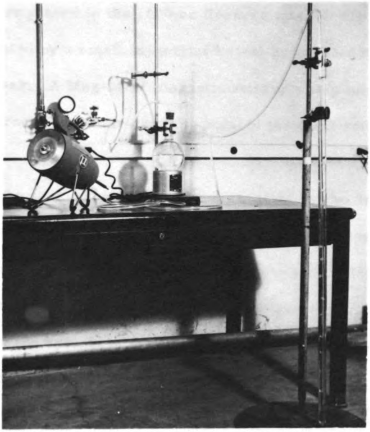

Figure 6. Liquid pesticide flow system.

The magnetic stirrer keeps the pesticide in suspension while the constant-feed bubbler system maintains an even, positive feed to the spray apparatus.

disks A and B (Fig. 5) turned at approximately 16,000 revolutions per minute with the hollow shaft C and powered with an armature not shown. The strong centrifugal force expelled the liquid between the disk rims, where the small droplets were sheared off and blown forward by air currents produced from blower F. For preliminary testing, the original tank was removed and a constant feed bubbler and pesticide flow system was constructed.

Pesticide flow system. To ensure continuous agitation and a uniform, controlled flow, the system shown in Fig. 6 was constructed. The spray materials were placed in the 1000 cc florence wash bottle where they were kept agitated by a small magnetized steel rod sealed in glass and placed in the flask. A Mag-Mix[1] magnetic stirrer was placed below the flask and through magnetic coupling rotated the steel rod agitator.

Liquid flow to the sprayer was maintained constant by the device shown in Fig. 6. A 1/4 inch glass rod 4 foot long was placed inside a 1 1/2 inch glass tube sealed at one end, and the larger tube filled with water. This device worked on the principle of a bubbler system where the pressure head in the system is very nearly equal to the height of the water column above the bubble emitter tube. As air passed to the

[1]Manufactured by Precision Scientific Co., Chicago, Illinois.

florence flask, it was allowed to go either into the flask or escaped down through the small tube into the liquid and bubbled to the surface. By moving the tube up or down thereby increasing or decreasing the head, the pressure was controlled from zero to approximately two pounds per square inch.

Since the commercial aerosol generator described was not satisfactory, another device had to be utilized.

An Experimental Apparatus for Producing Uniform Droplets in an Air Stream

Construction of an air-driven spray device. In order to produce a homogeneous spray cloud of uniform droplets, a special air-driven, spinning disk spray apparatus similar to that used by May (1949) was constructed. This device produced two size ranges of droplets, but it was so designed that the smaller satellite droplets were removed with the scavenged air, leaving only the uniform droplets in the spray stream. The construction of this spray device was considered essential to a basic approach to the problem of liquid spray deposit.

The experimental spinning disk sprayer, Fig. 7 and 8, essentially consists of:

(1) Special rotor with milled flutes and ground glass top. (Fig. 8)

(2) A brass stator assembly for supporting the rotor with suitable holes for directing the compressed air against the rotor flutes to produce rotation.

(3) A liquid feed assembly consisting of a removable stem and hypodermic needle tip for directing the liquid to the center of the spinning top.

(4) An aluminum body and stainless steel cap with intake and exhaust ports for admitting and discharging the compressed air.

(5) Special lucite plastic annular rings for increasing the exit diameter and consequent satellite droplet removal.

Mode of operation of spinning disk. When compressed air is admitted to the stator assembly, it escapes through the four holes in the stator cone and strikes the flutes of the rotor at approximately right angles causing the rotor to rise slightly from the stator cone and rotate on a film of air. The Bernoulli suction effect within the stator holds down the rotor and prevents it from leaving the stator cup. Working air escapes from the top of the cup and flows between the cap piece and the rim of the stator. This high velocity scavenged air causes an ejection or venturi effect that sucks air into the annular gap between the spinning top and cap. The inward flow of air draws back the fine, unwanted satellite droplets and by virtue of the greater projection distance of the larger homogeneous droplets allows only the latter to escape from the apparatus. By this method the satellites are automatically separated from the main droplets and are entrained in the spent working air. The majority are impacted on the internal surfaces of the apparatus while the remaining are carried out of the

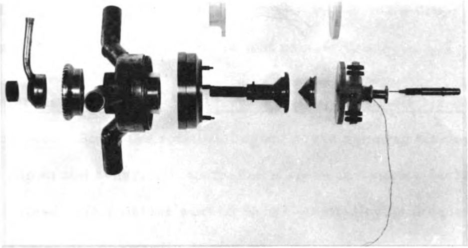

Figure 7. Exploded view of air-driven experimental spray apparatus.

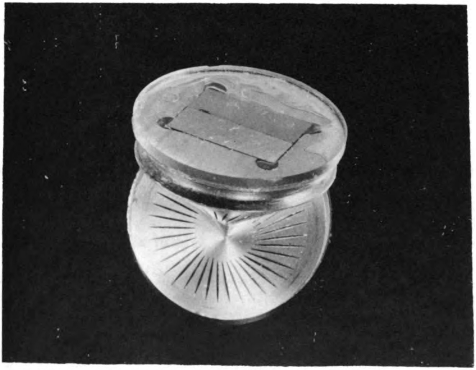

Figure 8. otor with magnets.

Photograph of rotor on a irror surface showing illed flutes on the cone and installed magnets in the top surface.

exhaust ports by the air stream. As satellite droplets are only about one-quarter the diameter of the "main" droplets, and at moderate rates of liquid feed there are about four satellites per main drop, less than ten percent by volume of liquid is lost as satellites.

Design and construction of a speed measuring device for the air-driven spray apparatus. Since the rotational speed of the spinning disk sprayer had to be known and accurately controlled a speed measuring device was constructed. This device worked on the electric cycle frequency measuring principle previously described.

The first step in its construction was the installation of magnets in the rotor (Fig. 8). Four permanent rectangular Alnico[1] magnets were inserted into a recess milled in the top surface of the non-magnetic stainless steel rotor. An accurately ground glass disk was then glued concentrically over the flat top surface using Cycleweld C-14 bonding material. This glass surface was readily wettable and when dirty, was very easily renovated by a few seconds regrinding on a flat glass plate.

After concealing the magnets within the rotor, it was then necessary to install a set of coils to pick up the induced electrical impulses from the rotating magnets. These coils had to be mounted in close proximity to the rotor and yet not interfere with the operation of the

[1]Manufactured by International Nickel Co., New York 5, New York.

top. Two coils of 7 1/2 millihenery inductance were connected in series and attached to the aluminum stator inside the body proper (Fig. 9). A metal core of soft iron pieces was inserted in the center of each coil to increase their inductance. Lead wires were connected to the coils and were inserted through one of the legs of the spray apparatus.

In actual operation, it was found that these coils caused a turbulence in the scavenged air, resulting in an unstable spinning top and consequent droplet production. Therefore, it was necessary to relocate the coils from the stator to the hypodermic needle support. This external mounting (Fig. 10), proved entirely satisfactory and was subsequently used for speed measurements.

The other end of the coil lead wires were connected to the vertical plates of a cathode ray oscilloscope, while the horizontal plates were energized by an audio-frequency generator (Fig. 11). In operation, the dial of the audio-frequency generator was adjusted until its frequency matched the frequency of the impulses from the rotating top. At "matched" frequency, a circle appeared on the cathode ray screen, and the speed of rotation was read directly from the audio-frequency generator dial.

In the original design of the speed measuring device, it was intended that a capacitor and resistance would be included in the circuit to provide a magnetic speed control similar to the one described by Beams, Linke and Sommers (1947). When tested however, it was found

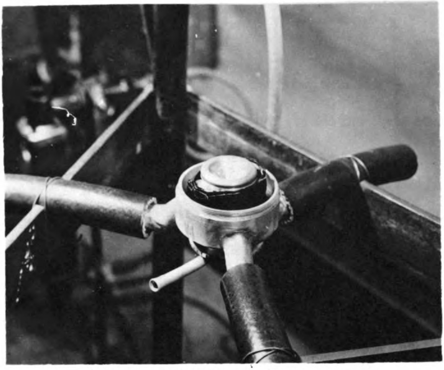

Figure 9. Coils mounted on stator.

Note that the coils are covered with tape and sprayed with a waterproofing lacquer.

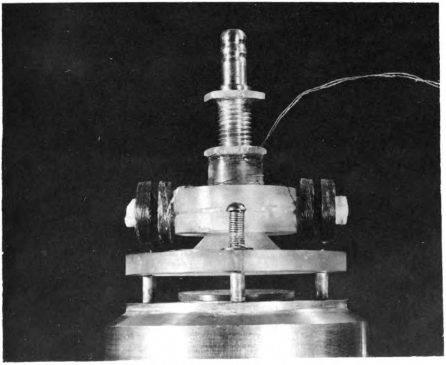

Figure 10. Pickup coils mounted on hypodermic needle support.

This external mounting of the coils was necessary to prevent turbulence within the sprayer body.

that the speed of the top could be held constant within one percent with the air pressure regulator and needle valve. In all the tests therefore, it was unnecessary to utilize the magnetic brake feature.

Liquid flow system. In addition to the constant-feed bubbler system previously described in connection with the Microsol Generator, a Fisher and Porter[1] flowmeter was installed to accurately measure the rate of flow (Fig. 12). The feed rate was controlled by raising or lowering the glass tube in bubbler, which in turn decreased or increased the "head" on the pesticide flask.

Construction of a suitable test stand. In order to produce a homogeneous spray cloud of uniform droplets in an air stream and using the spinning disk spray apparatus; a special preliminary test stand was constructed (Fig. 13). A top view of the stand is also shown in Fig. 9.

This stand consisted of three tubular legs with a triangular top of flat iron notched to position the supports of the spray apparatus. Three short lengths of flexible rubber hose were slipped over these supports and were then securely fastened to the triangular top of the test stand. A six-bladed, electrically powered axial flow fan cushioned with sponge rubber was mounted between the three legs in such a way that the fan

[1]Manufactured by Fisher and Porter Co., Hatboro, Pennsylvania.

Figure 11. Cathod ray oscilloscope and audio-frequency generator.

When a circle appeared on the oscilloscope, the frequency of the spinning top was matched with the audio-frequency generator.

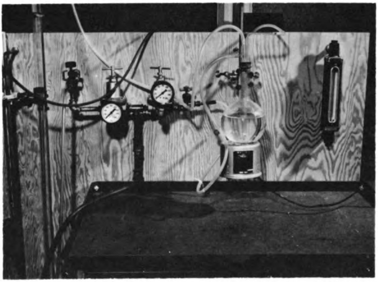

Figure 12. Liquid pesticide flow system.

The magnetic stirrer kept the pesticide in suspension while the constant-feed bubbler system maintained a constant measured feed to the spray apparatus.

could be raised or lowered to produce a constant, adjustable flow of vertically rising air.

Preliminary testing of this device indicated that the spinning top spray apparatus could be successfully used for producing fairly uniform droplets in an air stream. Unfortunately, the updrought of rising air caused the spinning top to be slightly unstable. Also, it was impossible to control or direct the mist-laden air stream.

The next logical approach was to allow the droplets to fall vertically into a downwardly moving air stream where the mist-laden air could be directed into a suitable collecting device. Once the mist was so restrained, it could then be directed through a wind tunnel where the leaf samples could be exposed to the spray.

On this premise, a second spray stand was constructed (Fig. 14). This stand consisted of a large 36 inch diameter funnel with an included apex angle of 60 degrees and supported on three pipe legs. These three legs also supported a vertical, six-inch lucite wind tunnel. Three lengths of flexible rubber hose were slipped over the legs of the spray apparatus in such a way that it was suspended directly over the center of the collecting funnel. The lucite wind tunnel was connected to the intake side of a centrifugal fan by means of a flexible hose. The fan was then provided with three removable orifice plates calibrated to give a wind tunnel air velocity of 10, 20 and 30 miles per hour respectively.

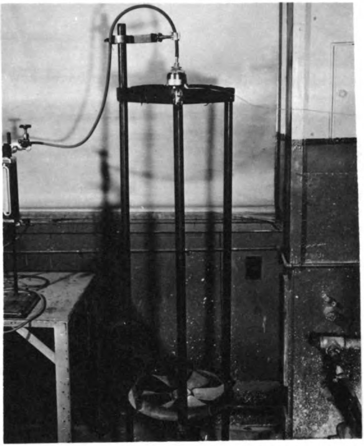

Figure 13. Preliminary test stand.

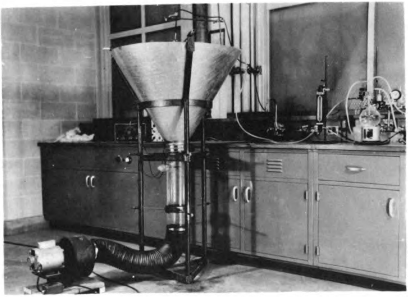

Figure 14. Test stand with funnel-shaped collecting device.

In operation it was found that such an air collecting device caused very little air turbulence near the spinning top, and consequent stable operating conditions. Unfortunately, the low air velocity occurring near the top of the funnel was not sufficient to support the spray droplets, hence they dropped vertically and were impacted against the sides of the funnel.

The next and final approach was to allow the droplets to be directed horizontally over a circular flat surface; permitting only a certain percentage of these droplets to fall through a suitable opening. Directly below the opening was positioned a vertical lucite wind tunnel for collecting those droplets that fell through the opening.

The spray stand, shown in Fig. 15 was then constructed. This consisted of two separate parts: (1) a rigid pedestal of three-inch pipe supported by a heavy base for mounting the spray apparatus and mounted concentrically within (2) a three-foot circular metal plate with a four-inch flange supported on a four-inch pipe and four adjustable legs. A 20-degree pie-shaped section was removed to permit some of the droplets to fall through into the wind tunnel. This opening was then equipped with a swinging gate type shutter operated by an electric solenoid. Connected electrically parallel with the solenoid was a mercury-electric counter. The solenoid was operated through a regular photographic interval timer in such a way that the length of shutter opening and consequent leaf exposure could be conveniently

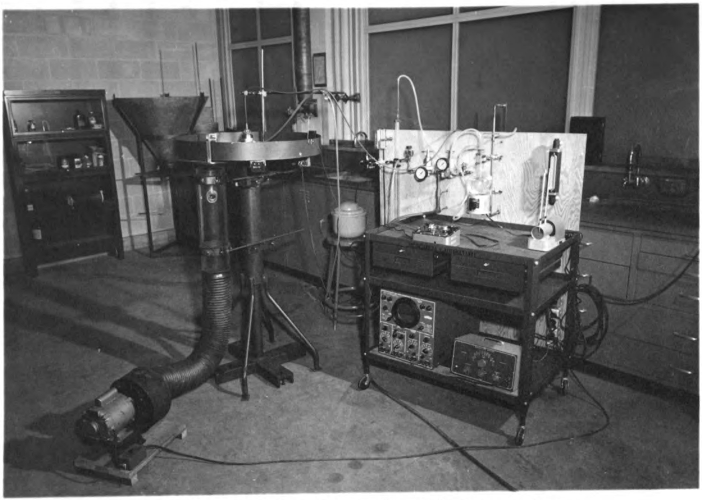

Figure 15. Complete spray stand used in the experiments.

Note the funnel-shaped collection device in the background.

adjusted and regulated.

The lucite wind tunnel, six inches in diameter was supported on two horizontal one-half inch rods attached to the outside stand. This arrangement permitted the adjustment of the wind tunnel without disturbing the spray apparatus. The lower end of the wind tunnel was connected to a centrifugal type fan equipped with three removable orifice plates previously described. The air velocity through the tunnel could thus be changed from 10, 20 and 30 miles per hour respectively by inserting the proper orifice plate.

Approximately six inches from the top of the lucite wind tunnel was positioned a four inch length of a two-inch diameter lucite tube, glued at right angles to the main tube. This tube was used for inserting (1) leaf samples to be exposed to the spray stream, and (2) slides for collecting droplet samples.

The size of the actual wind tunnel was quite critical since it had to be large enough to prevent air restriction around the inserted leaf sample and consequent boundry effect. Conversely it had to be small enough to prevent air turbulence near the spray apparatus and resulting unstable operation. A mathematical justification of the tunnel size that was used is given in the APPENDIX. As a further test, smoke was injected into the air stream entering the wind tunnel. Visual observation of the area surrounding the leaf sample showed that the air flow lines were straight near the internal tunnel wall.

Test Procedure

Operation of spinning disk spray apparatus and spray stand. A specially prepared mixture consisting of ten milligrams of unflavored gelatine and a drop of Triton X-100 per gram of distilled water was brushed on the top surface of the spray apparatus to make it readily wettable to the spray liquid. The spinning top was then started by slowly opening the air needle valve. After picking up rotor speed, the needle valve and air pressure regulator were adjusted to give the pre-determined operational speed. The hypodermic needle was then inserted in its holder and the liquid flow valve turned on.

Rate of liquid flow was then correctly adjusted through the flow-meter by vertically moving the inner glass tube in the constant-feed bubbler system. Once the flow was set correctly, it seldom had to be adjusted during the test. There was however, a definite relationship between rate of liquid flow and speed of top rotation. In other words, a change in flow rate changed the speed of rotation and conversely, a change in rotational speed affected the rate of flow. In practice, the flow rate and speed adjustments were made simultaneously, and no difficulty was experienced.

In operation, the spinning disk spray apparatus produced uniform droplets, and projected these droplets out in a horizontal sheet, 360 degrees around the periphery of the top. Since each droplet was the same size and had the same kenetic energy imparted to it, all the droplets had the same projection distance before they dropped vertically due to gravity. This phenomenon was evident when the sprayer was running, since the projected droplets on being arrested by air resistance appeared as a well-defined concentric ring-in-space around the apparatus. The radius of this ring varied little according to the liquid sprayed, but it was directly proportional to the droplet size. In fact, for the spray solution used, the radius of this ring measured in inches was approximately one tenth the droplet diameter measured in microns forming this ring. Thus for 100 micron droplets, the radius of this ring was 10 inches.

The vertical wind tunnel was adjusted horizontally so that the resulting droplets produced would fall through the center section of the tube. Once the tunnel was adjusted correctly, the appropriate orifice was inserted into the blower outlet and the fan turned on.

Method of exposing leaf samples. Circular samples, 1 1/4 inch in diameter, were taken from the terminal leaves of month old Red Kidney Bean plants. The leaves were collected from the plant and placed on a hard rubber mat where the leaf samples were punched out using a hollow stainless steel tube 1 1/4 inch in diameter, sharpened on one end and capped on the other (Fig. 16). After cutting, the leaf sample was picked up with a tweezer and inserted into a spring loaded clamp of the positioning device (Fig. 17). The internal diameter of this clamp was slightly less than one inch, calculated so the leaf surface exposed was exactly five square centimeters per side or a total of ten square centimeters per leaf sample counting both sides. Each leaf sample was exposed to the mist for one minute.

Cognizance of the fact that in an actual spraying operation, not all leaves are positioned at right angles to the spray stream necessitated the taking of several leaf punches per composite sample. Each composite sample therefore consisted of eight leaf punches, one punch taken every 45 degrees; the first from number one position or at right angles to the mist stream, the second from number two position or turned 45 degrees to the mist stream, the third from number three position or parallel to the mist stream, and so on around the axis of the positioning device. The index mark on the insertion tube and the station marks on the positioning device can be seen in Fig. 17.

Collecting droplet samples. A special spoon for holding and inserting the droplet collecting slides into the wind tunnel was constructed (Fig. 18). A droplet sample index slide was exposed to the mist stream, covered and labeled immediately after collecting each composite leaf sample. After running a series of tests, two hundred droplets were counted on each index slide and the mass median diameter calculated. If this mass mean diameter varied more than plus or minus four from the intended size, its corresponding composite leaf sample was discarded and a new test run.

Environmental control. Two temperatures, 75 degrees and 45 degrees Fahrenheit and two humidities, 70 percent and 40 percent relative humidity respectively were used for the tests. A Sargent motor ventilated wet and dry hygrometer[1] was used for continuous measurement of the temperature and humidity. Frequent spot tests were also made during the actual running of the tests using a Friez[2] bulb aspirator type hygrometer.

Deposit study tests were run in a regular themostatically controlled room for the 75 degree Fahrenheit temperatures, but a special controlled environmental room was used for those tests run at 45 degrees Fahrenheit. In both rooms, the termperature was accurately controlled to within a plus or minus one degree Fahrenheit.

Humidity control was more difficult. In the 75 degree room, the natural humidity was 40 percent on the test days, and varied less than one percent during the tests. For the high 70 percent relative humidity however, special equipment had to be used (Fig. 19). This special equipment included the aerosol generator previously described, augmented by a regular dome Walton humidifier[3] controlled through a

[1]Manufactured by E.H. Sargent Co., Chicago, Illinois.

[2]Manufactured by Friez Instrument Division, Bendix Aviation Corporation, Baltimore, Maryland.

[3]Manufactured by Walton Laboratories Inc., 1186 Grove Street, Irvington 11, New Jersey.

Figure 16. Equipment for punching and collecting leaf samples.

Figure 17. Positioning device for exposing leaf sample to mist.

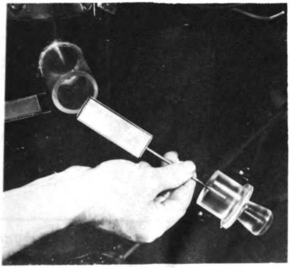

Figure 18. Spoon for holding glass slide when collecting droplets.

Honeywell humidistat[1]. During the tests, the aerosol generator ran continuously while the humidifier, adjusted to 70 percent humidity, operated intermittently. The actual relative humidity of the air entering the wind tunnel varied two to three percent.

In the cold room the natural humidity ran approximately 70 percent and stayed constant during the running of the tests. Obtaining the 40 percent relative humidity at this low temperature was more difficult however. Special trays of corrugated aluminum roofing were assembled in the cold room, fitted with drain channels and covered with calcium chloride (Fig. 20). The temperature was then lowered to approximately 32 degrees Fahrenheit and kept there for several days. An hour before the tests, the thermostat was readjusted to 45 degrees Fahrenheit and the tests were run. During the course of a series of tests, the humidity would increase as much as four to five percent.

Quantitative deposit measurements. The spray liquid used for the deposit studies consisted of 50 grams of copper sulphate, $CuSO_4 \cdot 5H_2O$ per liter of distilled water. Each composite sample of eight leaf punches or 80 square centimeters was quantitatively measured for copper

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[1] Manufactured by Minneapolis-Honeywell Regulator Co., Minneapolis Minnesota.

Figure 19. Special equipment used to control the relative humidity in the 75 degree Fahrenheit room.

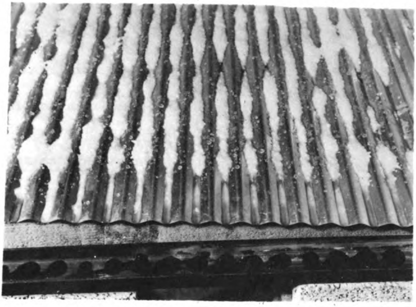

Figure 20. Moisture absorbing pan used to lower humidity in the 45 degree Fahrenheit room.

deposit using the polarographic method of analysis similar to that described by Ban and Carleton (1955).

The leaf punches in each sample were leached in 25 cc of .4 normal solution of K_2SO_4 with intermittent shaking every 20 minutes. A 20 cc aliquot of this leaching solution with the copper residue was pipetted into the polarographic cell. One milliliter of 1.3×10^{-2} m "Versene", and .2 milliliter of Triton X-100 were added. Nitrogen was then bubbled through the solution for ten minutes to remove the oxygen and the nitrogen was allowed to continuously sweep over the solution during the analysis. The solution was scanned from -0.1 to -1.1 volt with a Recording Leeds and Northrup Model E, Electro-Chemograph[1]. The half-wave potential was calculated from the resulting graph using a slope-intercept method and compared with standard solutions previously prepared from the $CuSO_4 \cdot 5H_2O$ salt. Results were recorded in parts per million of copper per 20 milliliter of solution and converted to micrograms per square centimeter of leaf area.

Qualitative measurements of deposit. Since the polarographic method of quantitative measurement of copper deposit could not yield any information as to either the uniformity of deposit or distinguish between upper and lower leaf surfaces, some other method had to be used for

[1]Manufactured by Leeds and Northrup, Philadelphia, Pennsylvania.

this part of the study.

A leaf printing technique of Blodgett and Mader (1934) proved to be ideally suited for this type of analysis and was therefore used.

(1) A top quality bond paper was submerged in a two percent sodium hydroxide solution for ten minutes to remove the sizing.

(2) The paper was then washed for ten minutes and was transferred to an acidified solution of potassium ferrocynide consisting of two grams of potassium ferrocynide, five milliliters of acetic acid per 100 milliliters of distilled water.

(3) After ten minutes of soaking, the paper was removed, placed on blotters and the excess solution rolled off using a photographic type roller.

(4) The exposed leaf samples were then placed, top down on the treated paper and covered with a second treated paper. On top of this was placed a blotter and sponge rubber pad, and the whole sandwich compressed in a suitable press for five minutes.

(5) The paper was then removed from the press and washed for twenty minutes in tap water. After removing from the rinse, the paper was placed on paper towels and allowed to dry. Just before the prints became absolutely dry, they were placed in a press for several hours to remove the wrinkles.

After drying, the prints, upper and lower surfaces separately, were visually indexed or classified from zero to ten depending upon uniformity and degree of coverage. An index of zero was given to no coverage and ten to complete coverage. Figure 21 illustrates the type of leaf print obtained by this method.

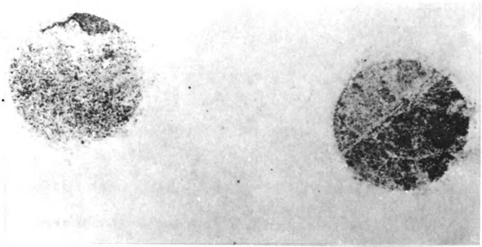

Figure 21. Qualitative print of leaf sample obtained and used to measure uniformity of deposit.

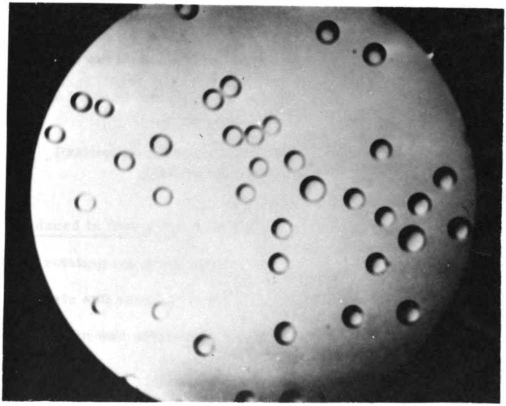

Figure 22. Photograph of 100 micron diameter spray droplets collected in a 30 miles per hour mist spray.

RESULTS AND INTERPRETATION

Test of Mechanical Aerosol Generator

The commercial aerosol generator previously described was tested to determine if it could produce uniform droplets. A variable voltage device was used to control the speed of rotation while the liquid feed bubbler and flowmeter regulated the rate of discharge of the spray liquid.

At 16,000 rpm the droplets varied from 10 to 200 microns with a mean diamter varying with the rate of liquid feed. Since all of the droplets produced were not uniform within very close limits, the apparatus couldn't be used for the desired tests.

Preliminary Tests of Air Driven, Spinning Disk Spray Apparatus

Droplets produced in free air. A series of runs was made with the experimental rotating top spray apparatus in still air to determine the effect of flow rate and speed of rotation on droplet size. After several trial runs, a series was obtained in the 50 micron diameter range.

TABLE II

EXPERIMENTAL SPRAY APPARATUS
PRODUCING DROPLETS
IN STILL AIR

Approximate operating pressure psi	Speed of rotation rps[1]	Flow rate cc/min.	Mass mean diameter microns
4.5	400	0.70	50
4.5	400	0.49	46
4.0	300	0.51	55

[1]Revolutions per second.

Droplets produced in flowing air. A second series of test runs was made with the experimental rotating disk sprayer in which the droplets were injected into a 15 mph updraught of air. The droplets were collected approximately six inches from the rotor surface. Also, in every case the plastic rings to increase the diameter of the exit annulus above two inches were not used.

TABLE III

EXPERIMENTAL SPRAY APPARATUS
PRODUCING DROPLETS IN A
15 MILES PER HOUR AIR STREAM

Approximate operating pressure psi	Speed of rotation rps	Flow rate cc/min.	Mass mean diameter microns
4.5	410	0.70	50
4.0	300	0.51	53
3.0	200	0.75	73

An examination and comparison of Tables II and III shows that there is very little difference in the droplet size at constant speed and feed rate, irrespective if the droplets are injected into free or flowing air. However, since all of the droplets were collected within six inches of the rotor surface one would not expect much decrease in size owing to evaporation. In later tests, where the droplets were collected over two foot distance from the rotor surface, there was a considerable decrease in size owing to evaporation.

Uniformity of Droplets Produced by the Air Driven Spinning Disk Spray Apparatus

Droplets produced in still air. After the spray stand, Fig. 15 was completed, the experimental spray apparatus was operated at 290 revolutions per second, air temperature 75 degrees Fahrenheit, and 40 percent relative humidity. 500 droplets were collected in still air. Fig. 23 illustrates the amazing uniformity of resulting droplets, with a mass mean diameter of 100 microns.

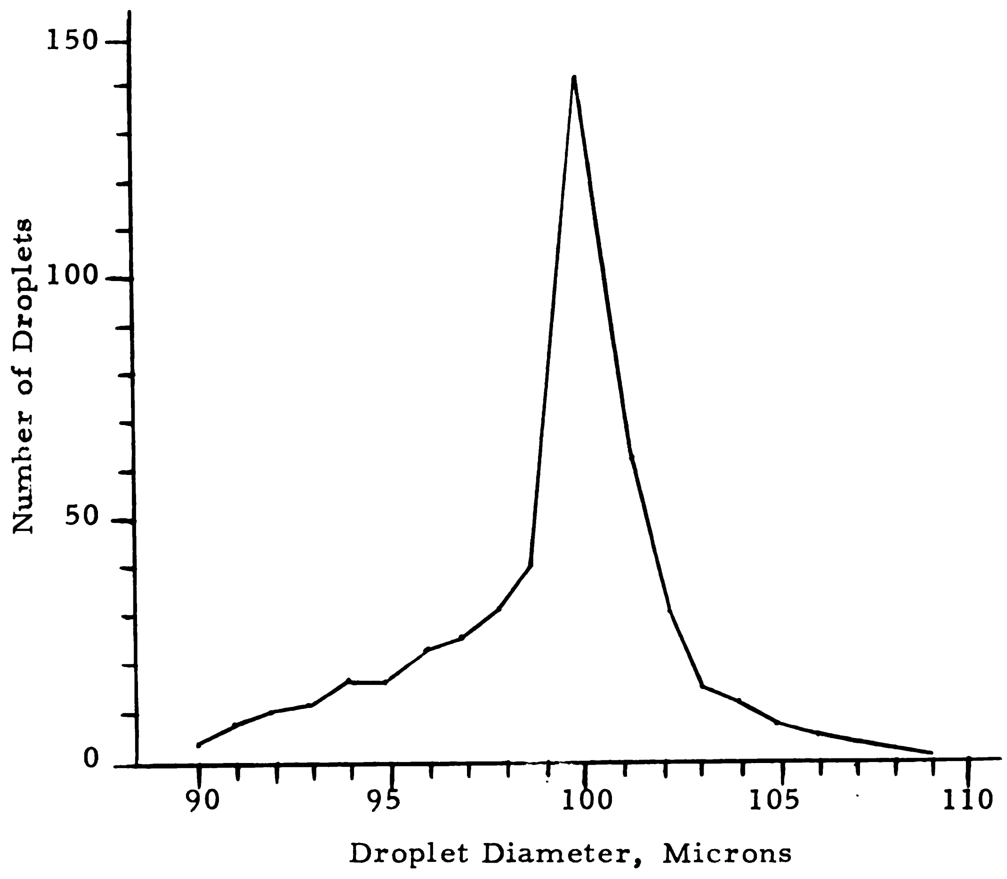

Figure 23. 500 droplets produced in still air.

Droplets produced in flowing air. The final test stand was also utilized to determine the uniformity of droplets produced in flowing air. The glass collecting slides were inserted into the wind tunnel illustrated in Fig. 18 and the droplets collected. Since some evaporation and consequent decrease in droplet size was expected, the spinning top was operated at 290 revolutions per second in a 75 degree Fahrenheit temperature and a 40 percent relative humidity. Fig. 24 illustrates the range of droplet size produced. Fig. 22 is a photograph of the actual spray droplets.

The mass median diameter in the 10 mile per hour air stream was 90 microns, in the 20 mile per hour air stream was 94 microns while in the 30 mile per hour air stream the mass mean diameter was 95 microns. In all cases, the liquid flow rate was 1.1 cc per minute.

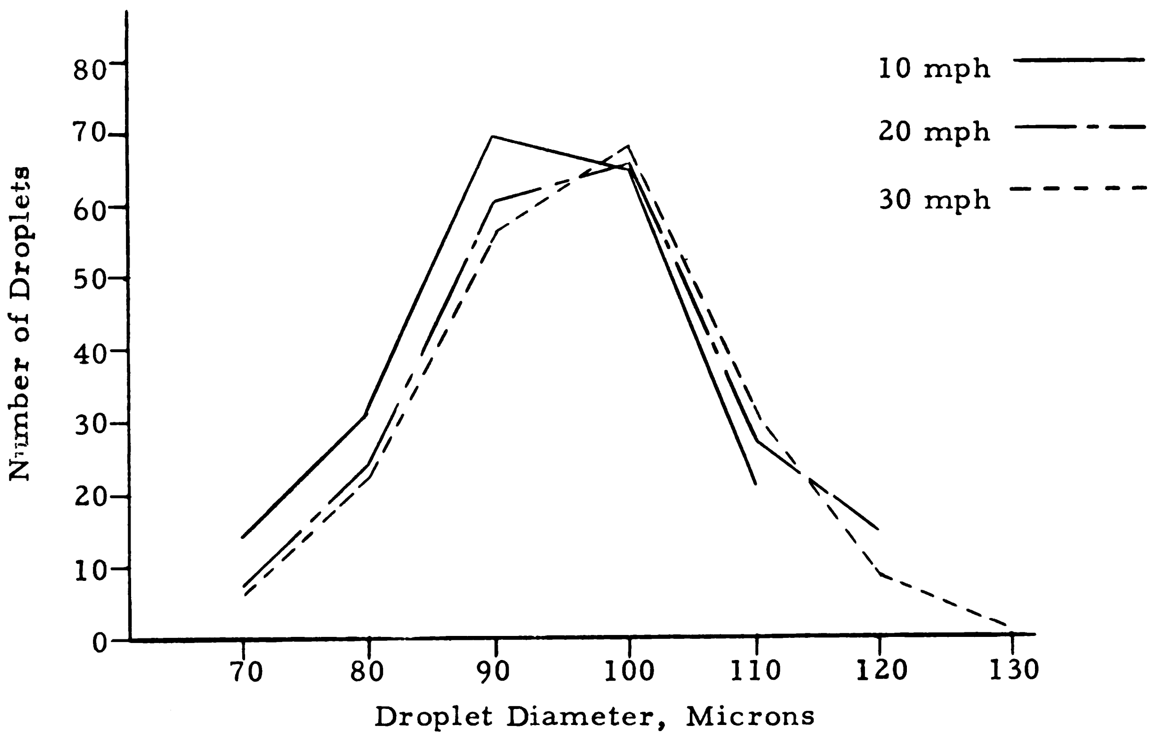

Figure 24. 200 droplets produced in flowing air.

Quantitative Spray Deposit Studies of Droplet Size versus Temperature, Relative Humidity and Air Velocity

Statistical design. Since it was physically impractical to change temperature and relative humidity in a completely randomized manner, a split-split plot design was used. The experiment consisted of 36 treatments with 2 replications. Main plots were temperature variation, 75 degrees and 45 degrees Fahrenheit, while the sub-plots were humidities, 70 percent and 40 percent respectively. Droplet sizes 150, 100 and 50 microns diameter and air velocities of 10, 20 and 30 miles per hour were randomized in the sub-sub plots.

As indicated previously, the mass mean diameter varied less than a plus or minus four microns with the range of droplets in any one size group varying less than a plus or minus thirty microns. In most cases, especially in the 50 micron size, the range was considerably less -- more nearly plus or minus fifteen. Table IV gives the resulting deposit.

TABLE IV

DEPOSIT OF MIST-CONCENTRATE SPRAY WITH VARYING PARAMETERS OF DROPLET SIZE, AIR VELOCITY, TEMPERATURE AND HUMIDITY

Air temp. deg. F	Rel. hum. %	Droplet size μ[1] mmd	Air vel. mph	Spray Deposit Replication I μ gms/cm²	Spray Deposit Replication II μ gms/cm²
75	40	50	10	6.75	6.81
75	40	50	20	12.25	12.31
75	40	50	30	14.81	14.50
75	40	100	10	13.19	14.38
75	40	100	20	14.75	16.38
75	40	100	30	17.00	17.25
75	40	150	10	5.25	4.38
75	40	150	20	11.69	9.81
75	40	150	30	13.44	13.75
75	70	50	10	6.19	5.75
75	70	50	20	12.81	13.44
75	70	50	30	18.13	16.50
75	70	100	10	13.00	13.50
75	70	100	20	16.13	16.56
75	70	100	30	17.06	17.25
75	70	150	10	6.31	5.69
75	70	150	20	9.97	9.88
75	70	150	30	14.94	14.69
45	40	50	10	2.09	2.63
45	40	50	20	4.44	4.47
45	40	50	30	5.78	6.28
45	40	100	10	3.63	3.94
45	40	100	20	4.75	5.03
45	40	100	30	5.81	6.03
45	40	150	10	5.03	5.38
45	40	150	20	6.28	6.34
45	40	150	30	8.97	8.03
45	70	50	10	3.19	3.53
45	70	50	20	5.09	5.31
45	70	50	30	6.72	5.63
45	70	100	10	3.78	3.81
45	70	100	20	4.81	5.00
45	70	100	30	7.66	8.41
45	70	150	10	5.41	5.75
45	70	150	20	6.97	6.84
45	70	150	30	9.66	8.94

[1] Abbreviation for microns, or micrograms.

Split-split plot analysis. The split-split plot analysis together with the f test of significance of temperature, relative humidity, air velocity, and droplet size as well as interactions is shown in Table V.

TABLE V

SPLIT-SPLIT PLOT ANALYSIS OF DEPOSITS

Source of variation	Degrees freedom	Sums of squares	Mean square	f value
Total	71	1534.8287		
Whole Plots	(3)	834.2902		
Replication	1	.0027	.0027	.04
Temperature	1	834.2251	834.2251	13,368.99[1]
Error A	1	.0624	0.0624	
Sub-Plots	(4)	6.1762		
Relative Humidity (R.H.)	1	5.9512	5.9512	86.13[2]
R.H. x Temp.	1	.0868	.0868	1.26
Error B	2	.1382	.0691	
Sub-Sub Plots	(64)	694.3623		
Droplet Size	2	69.9574	34.9787	133.41[1]
Air Velocity	2	342.4203	171.2102	652.98[1]
Size x Vel.	4	25.2381	6.3095	24.06[1]
Size x Temp.	2	160.5546	80.2773	306.17[1]
Size x R.H.	2	.3950	.1975	0.75
Vel. x Temp.	2	53.7568	26.8784	102.51[1]
Vel. x R.H.	2	3.1698	1.5849	6.05[1]
Size x Temp. x R.H.	2	0.6069	.3036	1.16
Vel. x Temp. x R.H.	2	0.4826	.2413	0.92
Size x Vel. x Temp.	4	19.9831	4.9958	19.05[1]
Size x Vel. x R.H.	4	1.7379	0.4345	1.66
Size x Vel. x Temp. x R.H.	4	7.6685	1.9171	7.31[1]
Error C	32	8.3913	0.2622	

[1]Significant at 1 percent level.

[2]Significant at 5 percent level.

Contrary to expectations, the error mean square of the sub-sub plots, error C, was larger than either error A or error B. Since this was improbable, because error A is usually sacrificed or made larger in order to obtain greater precision in error C of a split-split plot design, a check was made of the error terms:

Error Sums of Squares A + B + C =

$$.0624 + .1382 + 8.3913 = \underline{8.5919}$$

Total Error Sums of Squares

$$= \frac{\sum \text{Treat. (Repl. I - Repl. II)}^2}{2}$$

$$= \frac{(6.81-6.75)^2 + \cdots + (9.66-8.94)^2}{2}$$

$$= \underline{8.5886}$$

Therefore it was concluded that the calculations were correct.

Since some questions might arise as to the feasibility of carrying the analysis to four significant figures, its justification lies in the fact that there was almost complete control of all of the parameters and duplicate results could be expected in each replication. Also since the error terms were so small, four significant figures were necessary to obtain significance in the treatments.

Effect of temperature and droplet size on deposit. Fig. 25 illustrates the inter-relation of temperature and droplet size. A careful scrutiny shows that at all air velocities and humidities the 100 micron diameter droplet gave more deposit at the 75 degree Fahrenheit temperature while the 150 micron droplet gave superior deposit at the lower, 45 degree Fahrenheit temperature.

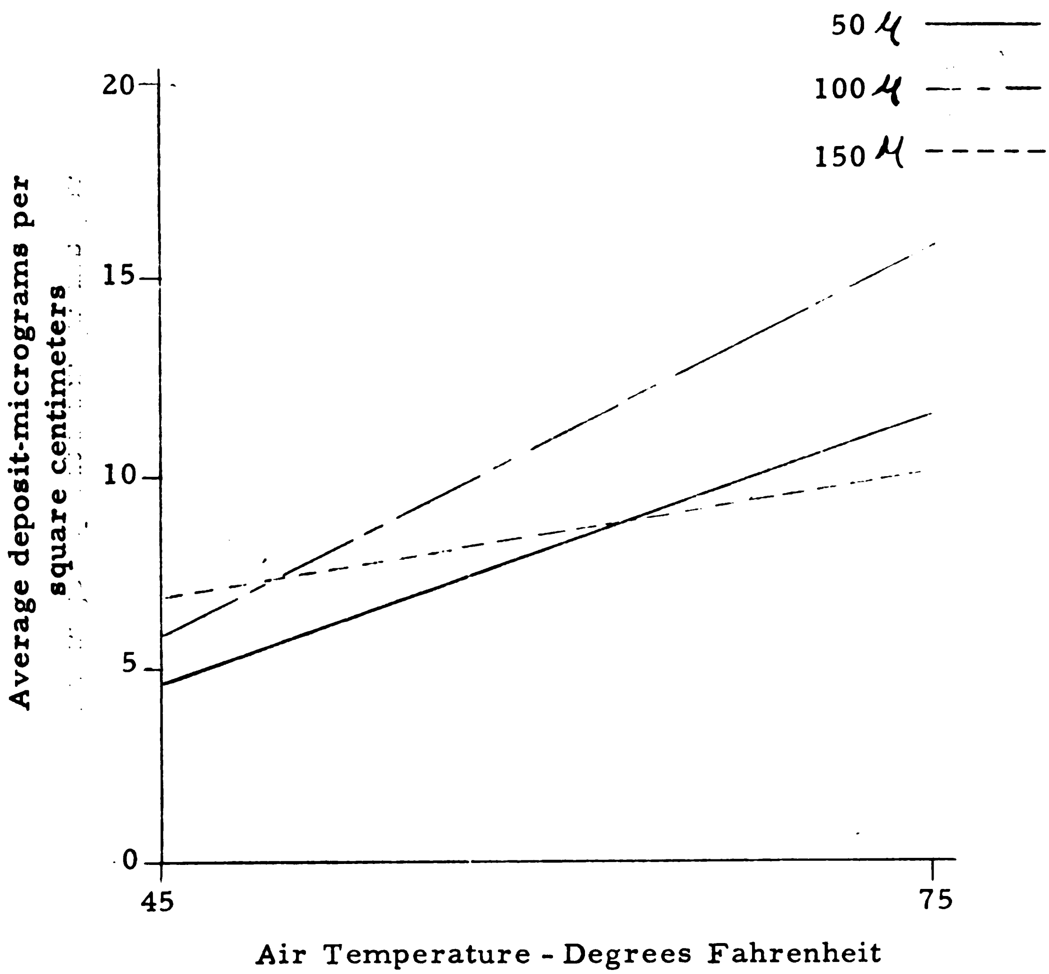

Figure 25. Temperature versus droplet size.

Effect of air velocity and droplet size on deposit. A cursory glance at Fig. 26 shows that in every case, the higher the air velocity, the greater the deposit. The 100 micron diameter droplets gave the highest deposit in every case, with the 150 micron diameter droplets giving the next highest deposit.

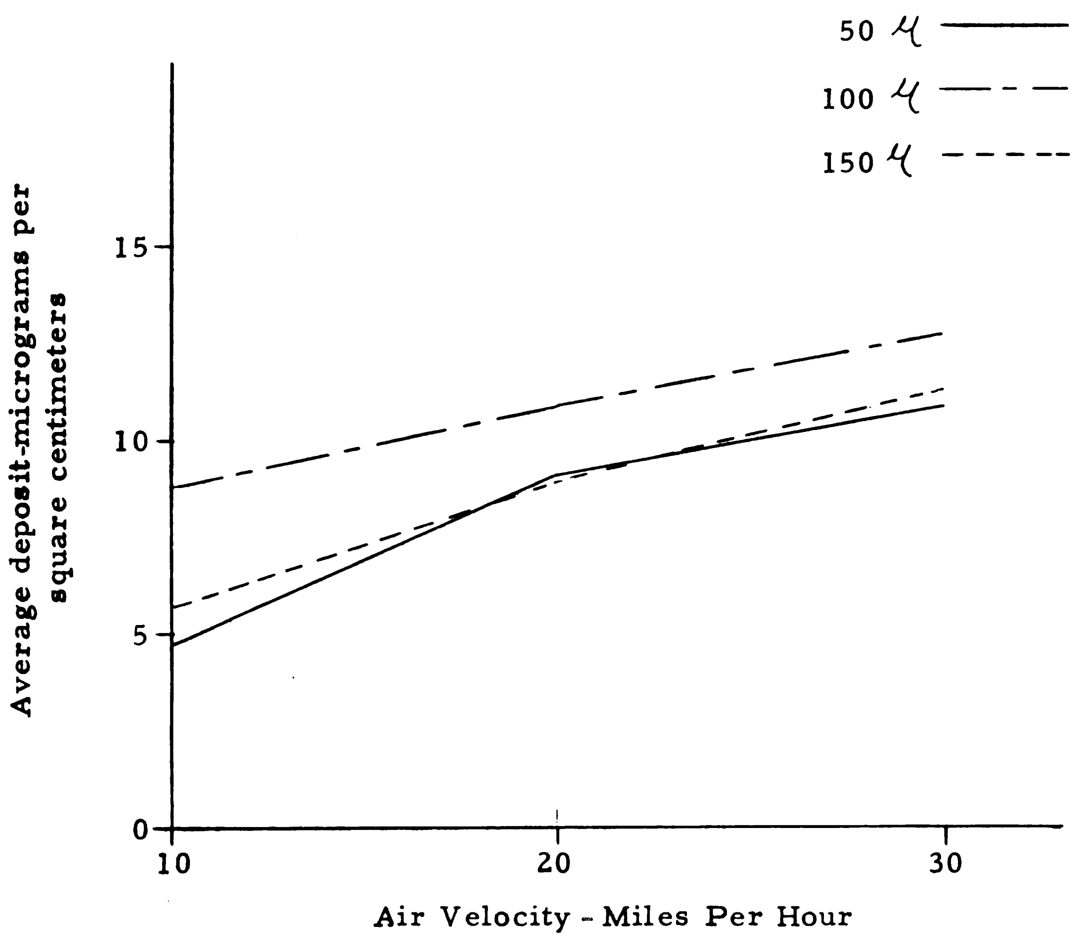

Figure 26. Air velocity versus droplet size.

Effect of relative humidity and droplet size on deposit. Fig. 27 illustrates the effect of relative humidity and droplet size on deposit. In every case, the 70 percent relative humidity gave a higher average deposit than did the 40 percent relative humidity. Also, the 100 micron diameter droplets gave the highest deposit at both humidities with 150 micron diameter droplets giving the next highest deposit.

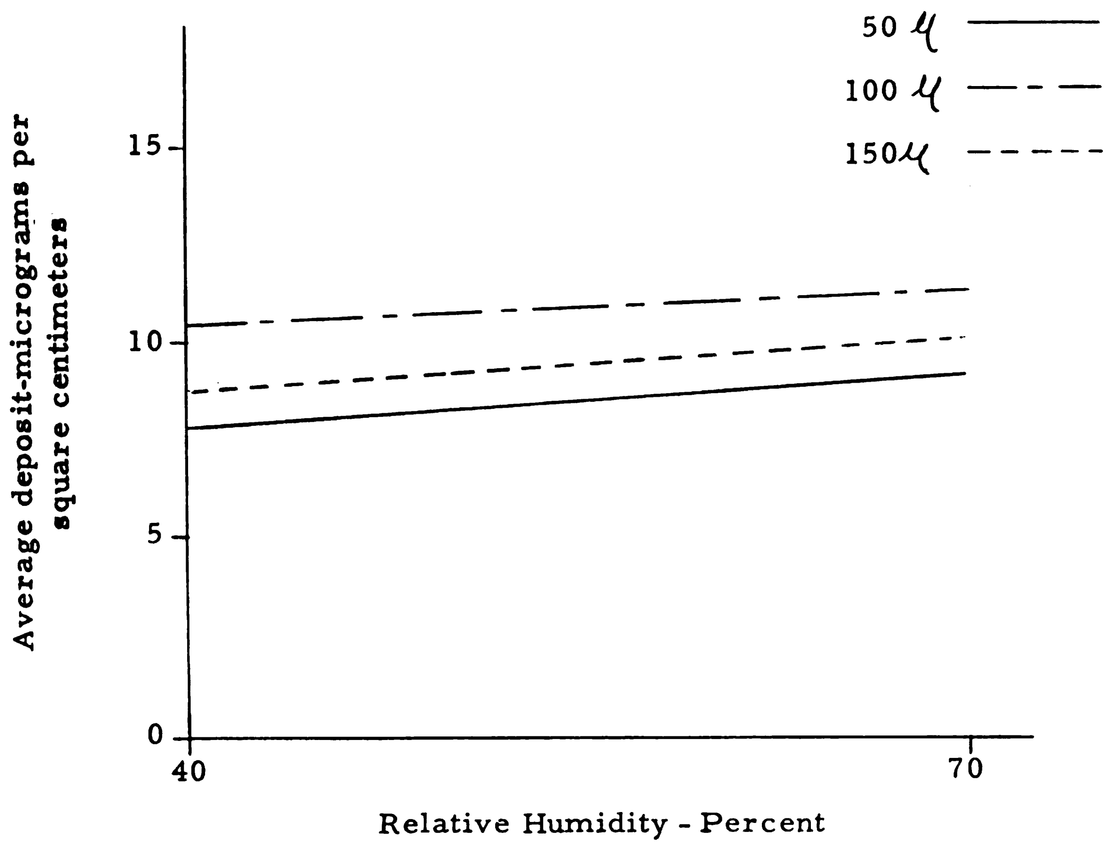

Figure 27. Relative humidity versus droplet size.

Qualitative Spray Deposit Studies of Droplet Size Versus Air Velocity, Leaf Position and Leaf Surface

Statistical design. All of the tests run in this part of the experiment were conducted at 75 degrees Fahrenheit and 40 percent relative humidity. Also, since it was found to be physically impractical to change droplet size, air velocity and leaf position in a completely randomized manner, a split-split-split plot design was utilized. This experiment consisted of 144 treatments with 2 replications. Main plots were droplet sizes 50, 100 and 150 microns diameter; sub-plots were air velocities, 10, 20 and 30 miles per hour; while sub-sub plots were positions, 1, 2, 3, 4, 5, 6, 7 and 8. Leaf surfaces, top and bottom, were analyzed from these eight positions using the leaf printing technique previously described. The results of this experiment are presented in Table VI.

TABLE VI

UNIFORMITY OF MIST-CONCENTRATE SPRAY DEPOSIT WITH VARYING PARAMETERS OF DROPLET SIZE, AIR VELOCITY, LEAF POSITION, AND LEAF SURFACE[1]

Droplet size μ	Air vel. mph	Position	Leaf Surface: Replication I Top	Leaf Surface: Replication I Bottom	Leaf Surface: Replication II Top	Leaf Surface: Replication II Bottom
50	10	1	6	1	5	1
50	10	2	5	1	5	1
50	10	3	1	2	1	1
50	10	4	1	5	1	4
50	10	5	1	5	1	5
50	10	6	1	3	1	4
50	10	7	1	1	1	1
50	10	8	5	1	5	1
100	10	1	7	1	6	1
100	10	2	5	2	5	2
100	10	3	1	1	1	1
100	10	4	2	4	2	5
100	10	5	1	6	1	6
100	10	6	2	5	2	5
100	10	7	1	1	1	1
100	10	8	6	1	5	1
150	10	1	5	1	5	1
150	10	2	4	1	5	1
150	10	3	1	1	1	1
150	10	4	1	5	1	4
150	10	5	1	5	1	5
150	10	6	2	4	1	4
150	10	7	1	1	1	1
150	10	8	6	1	6	1

[1]Morphologically the top surface of the leaf refers to the abaxial while the bottom to the adaxial surface.

TABLE VI (continued)

Droplet size μ	Air vel. mph	Position	Leaf Surface			
			Replication I		Replication II	
			Top	Bottom	Top	Bottom
50	20	1	7	1	7	1
50	20	2	6	1	5	1
50	20	3	1	2	1	1
50	20	4	1	4	1	5
50	20	5	1	5	1	5
50	20	6	1	6	1	5
50	20	7	1	1	1	1
50	20	8	6	1	5	1
100	20	1	8	1	8	1
100	20	2	6	1	6	1
100	20	3	2	1	1	1
100	20	4	1	6	1	6
100	20	5	1	6	1	6
100	20	6	1	5	1	4
100	20	7	1	2	1	1
100	20	8	7	1	6	1
150	20	1	6	1	6	2
150	20	2	5	1	5	1
150	20	3	1	1	1	1
150	20	4	1	5	1	5
150	20	5	1	6	1	6
150	20	6	1	5	1	5
150	20	7	1	1	1	2
150	20	8	6	1	6	1

TABLE VI (continued)

Droplet size μ	Air vel. mph	Position	Leaf Surface Replication I Top	Leaf Surface Replication I Bottom	Leaf Surface Replication II Top	Leaf Surface Replication II Bottom
50	30	1	7	1	8	1
50	30	2	6	1	6	1
50	30	3	1	2	1	1
50	30	4	2	7	2	7
50	30	5	1	7	1	7
50	30	6	1	6	1	6
50	30	7	1	2	2	2
50	30	8	7	1	7	1
100	30	1	8	1	7	1
100	30	2	7	2	7	2
100	30	3	1	2	1	2
100	30	4	3	7	2	7
100	30	5	1	7	1	7
100	30	6	2	6	2	6
100	30	7	2	2	2	1
100	30	8	8	1	7	1
150	30	1	7	1	7	1
150	30	2	6	1	6	1
150	30	3	1	1	1	1
150	30	4	1	6	1	6
150	30	5	1	7	1	7
150	30	6	1	6	1	6
150	30	7	1	1	1	2
150	30	8	7	1	7	1

Split-split-split plot analysis. The split-split-split plot analysis together with the f test of significance of droplet size, air velocity, leaf position, leaf surface and all interactions is illustrated in Table VII.

TABLE VII

SPLIT-SPLIT-SPLIT PLOT ANALYSIS

Source of variation	Degrees freedom	Sums of squares	Mean square	f value
Total	287	1605.2		
Whole Plots	(5)	9.3		
Replication	1	0.5	0.5	1.7
Droplet Size	2	8.3	4.2	14.0
Error A	2	0.5	0.3	
Sub Plots	(12)	31.6		
Velocity	2	29.9	15.0	150.0[1]
Vel. x D.S.	4	1.0	0.3	3.0
Error B	6	0.7	0.1	
Sub-Sub Plots	(126)	315.8		
Position	7	291.3	41.6	416.0[1]
Pos. x D.S.	14	4.2	0.3	3.0[1]
Pos. x Vel.	14	7.6	0.5	5.0[1]
Pos. x Vel. x D.S.	28	7.2	0.3	3.0[1]
Error C	63	5.5	0.1	
Sub-Sub-Sub Plots	(144)	1248.5		
Surface	1	4.3	4.3	43.0[1]
Surf. x D.S.	2	0.8	0.4	4.0[2]
Surf. x Vel.	2	0.2	0.1	1.0
Surf. x Vel. x D.S.	4	0.8	0.2	2.0
Surf. x Pos.	7	1195.7	170.8	1708.0[1]
Surf. x Pos. x D.S.	14	5.1	0.4	4.0[1]
Surf. x Pos. x Vel.	14	27.7	2.0	20.0[1]
Surf. x Pos. x Vel. x D.S.	28	4.6	0.2	2.0[2]
Error D	72	9.3	0.1	

[1]Significant at 1 percent level.

[2]Significant at 5 percent level.

A check of the error terms indicates that:

$$\text{Error sums of squares} = A + B + C + D = 16.0$$

$$\text{Total error sums of squares} = \frac{\sum \text{Treat.}(\text{Repl. I-Repl. II})^2}{2}$$

$$= 14.6$$

Since the error terms closely agreed, it was concluded that the calculations were correct.

Effect of droplet size on uniformity of deposit. A cursory examination of Table VII reveals that droplet size is not significant for uniformity of coverage, whereas in the previous experiment it was significant from a quantitative standpoint. However, since droplet size is the first main split, some precision is sacrificed in error A in favor of the succeeding errors B, C, and D. Also, most of the subsequent droplet size two, three and four way interactions are significant.

<u>Effect of air velocity and droplet size on uniformity of deposit.</u> An examination of Fig. 28 shows that in every droplet size range, the higher the velocity, the more uniform the deposit.

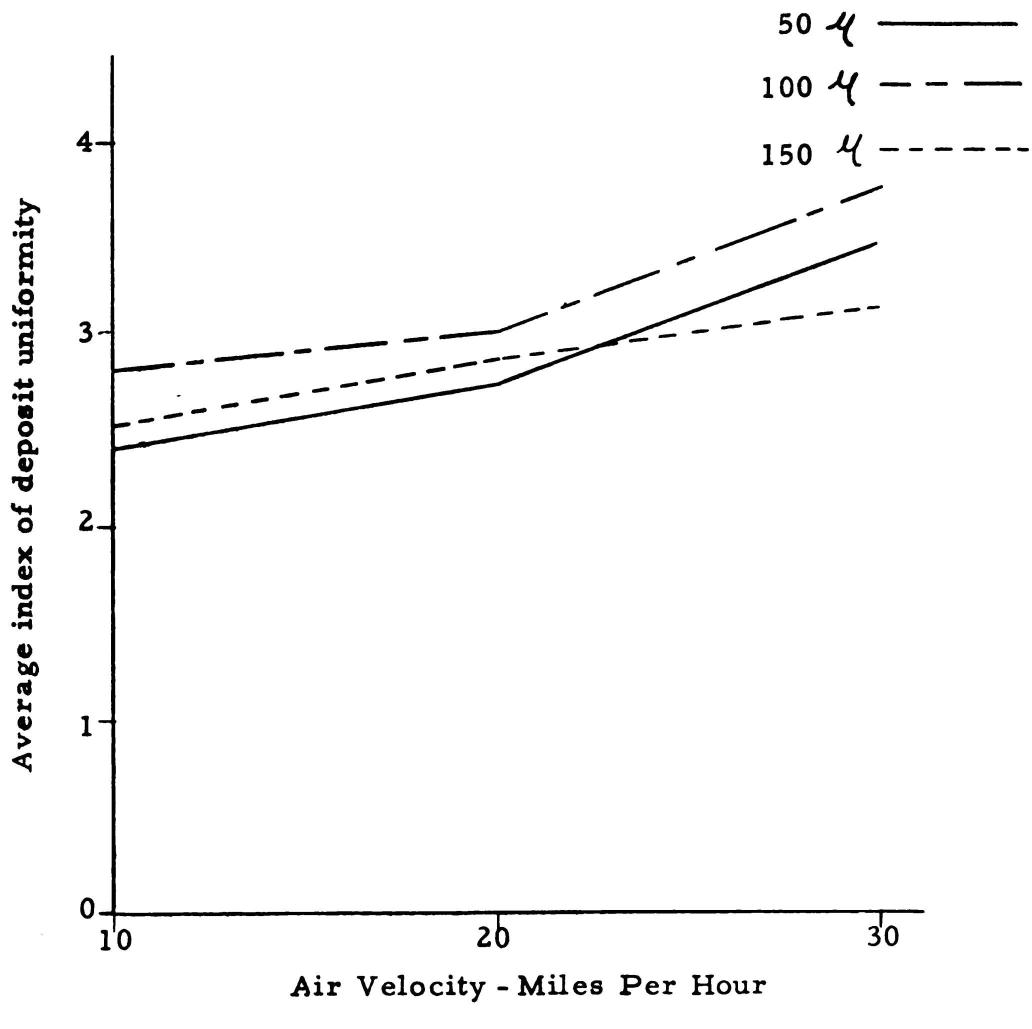

Figure 28. Air velocity versus droplet size on uniformity of deposit.

Effect of droplet size and leaf position on uniformity of deposit. It was anticipated that a smaller droplet would provide a more uniform deposit on leaves not at right angles to the direction of the mist stream. A careful examination of Fig. 29 vividly illustrates the falacy of this assumption.

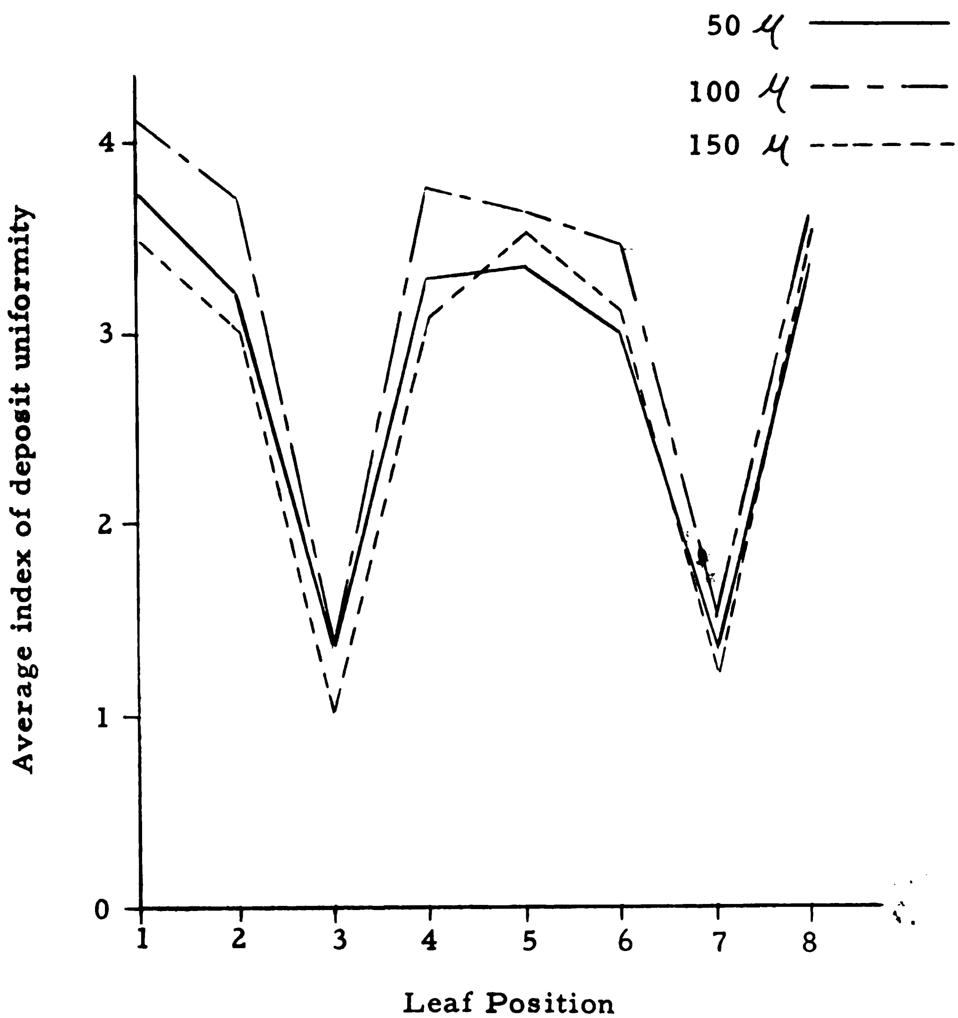

Figure 29. Droplet size versus leaf position on uniformity of deposit.

Effect of air velocity and leaf position on uniformity of deposit. It was also anticipated that a lower air velocity would provide a more uniform deposit on leaves not at right angles to the direction of the mist stream. Fig. 30 shows the exact opposite. A high air velocity gives the most uniform deposit.

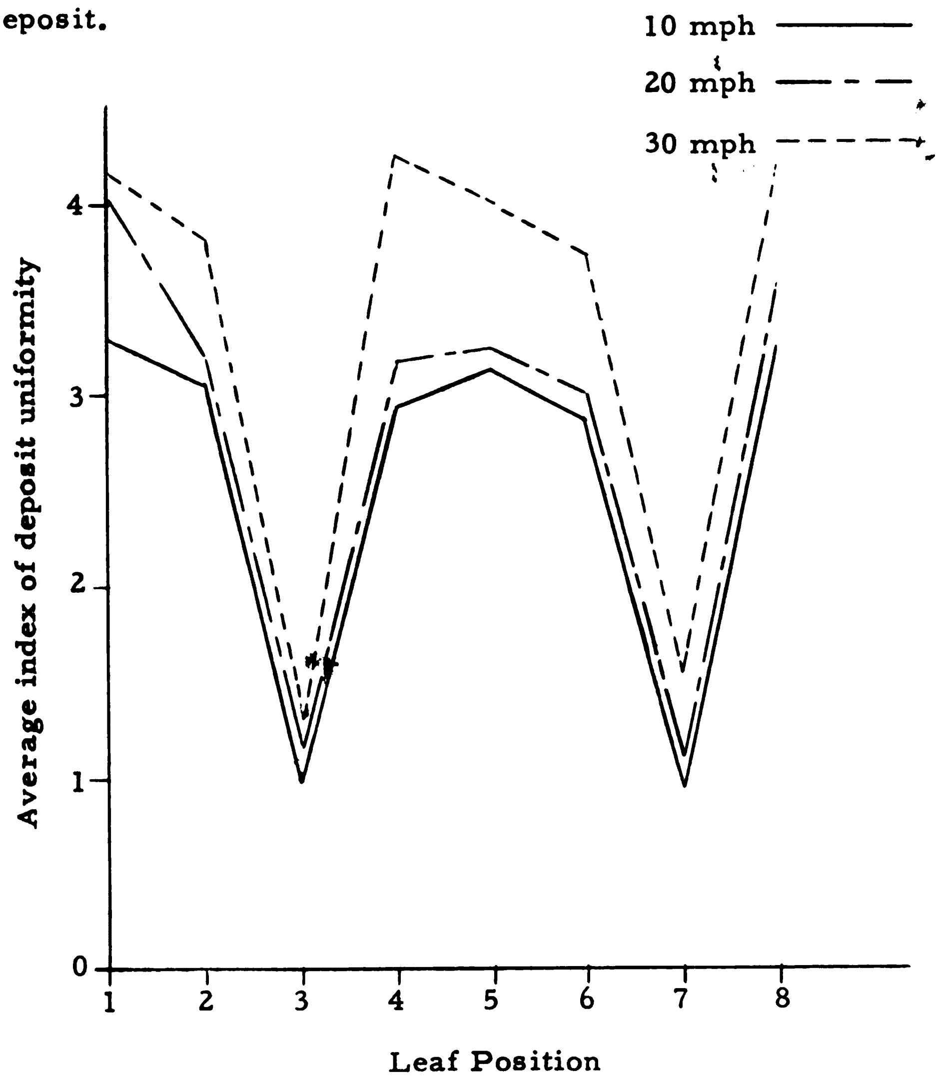

Figure 30. Air velocity versus leaf position on uniformity of deposit.

Effect of leaf position and surface on uniformity of deposit. Fig. 31 illustrates the effect of deposit on upper and lower surfaces of the leaf samples for various positions in relation to the air stream. Actually the top surface of the leaf was superior to the lower surface as measured by uniformity of deposit.

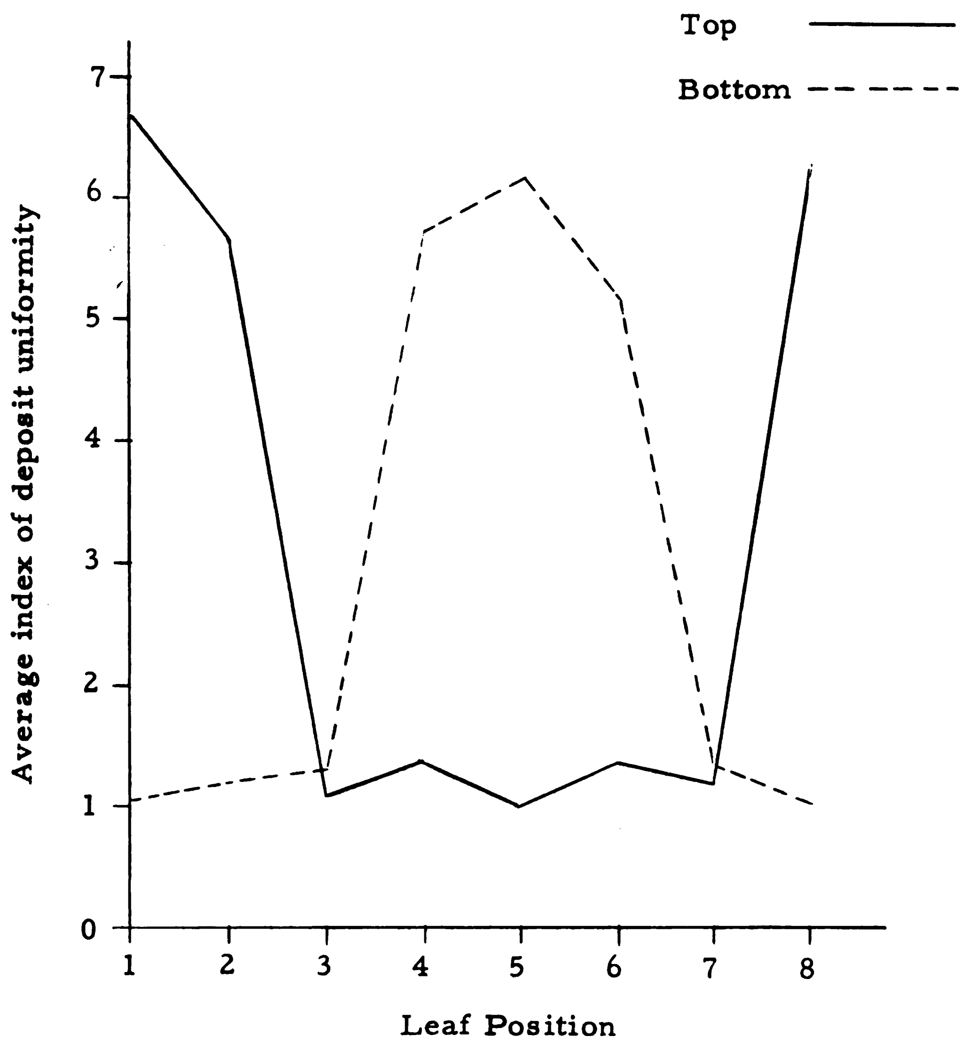

Figure 31. Leaf position versus top and bottom leaf surface.

SUMMARY AND CONCLUSIONS

The advent of mist-concentrate spraying greatly increased the efficiency and reduced the labor of the spray operation. Further attempts to improve the efficiency of mist-concentrate spraying created an acute demand for more basic information and knowledge relative to the mode of spray deposits. Of this information required, probably the most important is the relation of droplet size to overall deposit.

This investigation consisted of a quantitative study of spray deposit on leaf samples with varying parameters of:

(1) droplet sizes - 50, 100 and 150 microns

(2) air velocities - 10, 20 and 30 miles per hour

(3) temperatures - 45 and 75 degrees Fahrenheit

(4) relative humidities - 40 and 70 percent

It also consisted of a qualitative study of uniformity of spray deposit with varying parameters of:

(1) droplet sizes - 50, 100 and 150 microns.

(2) air velocities - 10, 20 and 30 miles per hour

(3) leaf position in relation to the mist stream

(4) leaf surfaces, both top and bottom

Results of the quantitative study indicated the following facts:

1. Temperatures were highly significant. The resulting deposits were consistantly higher at 75 degrees than at the lower 45 degrees

Fahrenheit temperature.

2. Humidities were significantly different. The deposits obtained at 70 percent relative humidity were noticeably higher than those obtained at the lower 40 percent humidity. At the higher 75 degree temperature, the effects of humidity were more noticeable than at the lower temperature.

3. Air velocities were highly significant. In all cases the higher the air velocities, the greater the residual deposits on the leaf samples.

4. Droplet sizes were highly significant. At all air velocities and humidities the 100 micron droplets gave more deposit at the 75 degree Fahrenheit temperature while the 150 micron droplets gave greater deposits at the lower 45 degree temperature.

Results of the qualitative tests of uniformity of deposits indicated the following facts:

1. Droplet sizes were not significantly different. In other words, the smaller droplets were no more uniformly deposited than were the larger droplets. This was in direct contrast to the previous tests relative to the quantity of residual deposits. However, the latter tests were run at only one temperature and humidity while the previous experiment was conducted at two temperatures and two humidities. Also, since droplet size was the first split, some precision was sacrificed in favor of the succeeding splits.

2. Air velocities were highly significant. Again the higher air velocities gave the most uniform deposits. The 100 micron droplets gave the highest index of deposit uniformity for all air velocities.

3. Positions of the leaf were highly significant. Positions number one and eight or at right angles to the mist had the highest index of uniformity. Positions three and seven or parallel to the mist had the lowest index of uniformity. This was the case for all air velocities and all droplet sizes.

4. Leaf surfaces were also highly significant. In all cases, the deposits were more uniform on the top surfaces of the leaves.

From a practical viewpoint, the overall results of these experiments indicate that the efficiency of mist-concentrate spraying can be substantially increased. First, if the mist-sprayers were designed to give a higher air velocity near the fruit or foliage surfaces being treated, the overall deposit as well as uniformity of deposit would be greatly improved. Secondly, spraying with the 150 micron droplets in cold spring weather and changing to the 100 micron size later in the season would further improve the resulting deposits. Of course, before this could be done a nozzle would have to be designed to permit adjustment for droplet size. Finally spraying during periods of high humidity would also improve the coverage and deposit. Ordinarily these periods occur during the early mornings and late afternoons and evenings.

Though many improvements have been made in spraying equipment, much research and testing remains to be accomplished. Devising a simple nozzle that will produce a fairly homogeneous mist cloud of controllable droplet size is urgently needed. Until such advancements are made, the sprayer operator is somewhat limited in increasing the efficiency of application.

APPENDIX

Wind Tunnel Size

The presence of the leaf sample in the wind tunnel effectively reduces the area through which the air must pass and hence increases the velocity of the air that flows past it. Since it is desirable to nearly approximate free air and thus reduce the blocking effect, the wind tunnel size is important.

As air passes the leaf sample a wake is formed behind it. In order to compute this wake effect and consequent increase in air velocity past it, we must first mathematically simulate the wake and tunnel boundaries. Pope[1] discusses this problem and presents the following formulas for wake corrections.

In a three dimensional case a source at the edge of our sample disk emitting, say a "blue" fluid will result in a "blue" region quite similar to a wake. Since the only drag existent is represented by this wake, the proper quantity Q to be emitted may be determined by:

$$Q = \frac{D}{\rho V}$$

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[1] Pope, Alan. Wind-Tunnel Testing. John Wiley & Sons, Inc. New York. 2nd ed. pp. 280-291, 1954.

Where:

Q = quantity of fluid emitted

D = drag

ρ = density

V = velocity of air

Thus the wake is simulated by a source of strength Q which is matched by a downstream sink. The image system consists of a double infinite source - sink system spaced a tunnel height h apart vertically and a tunnel width B horizontally. In our case, B = h = inside diameter of wind tunnel = 5 1/2 inches.

The axial velocity induced at the leaf sample by the image source system is zero, but that due to the image sink system is

$$\Delta V = \frac{1}{2} Q / Bh$$

Where:

ΔV = axial velocity

The incremental velocity is then:

$$\epsilon_{wb} = \Delta V / Vu$$

$$= \left(\frac{1}{4} \; S/C \right) C_{Du}$$

Where:

ϵ_{wb} = incremental or correction velocity factor for wake blocking to be added to free tunnel velocity

Vu = average uncorrected velocity past leaf sample

S = cross-sectional area of leaf sample and holder

C = cross-sectional area of wind tunnel

C_{Du} = uncorrected coefficient of drag

= 1.33[1]

For our tunnel of 5 1/2 inches inside diameter and leaf sample of 1 1/4 inch outside diameter

$$S = \frac{\pi d^2}{4}$$

$$= \frac{\pi (1\ 1/4)^2}{4}$$

$$C = \frac{\pi d^2}{4}$$

$$= \pi \frac{(5\ 1/2)^2}{4}$$

$$\epsilon_{wb} = \frac{1.33}{4} \left[\frac{(1\ 1/4)^2}{(5\ 1/2)^2} \right]$$

$$= \frac{1}{3} \left[\frac{1\ 1/4}{5\ 1/2} \right]^2$$

$$= \frac{1}{3} \left[0.0518 \right]$$

$$= \underline{\underline{0.0173}}$$

Since this correction factor is so small it can be assumed that the boundary effect in the wind tunnel used was negligible.

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[1]Calculated for our wind tunnel and leaf sample.

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