ADA038826

(12)

OFFICE OF NAVAL RESEARCH

Contract N00014-70-A-0309-0003

Task No. NR136-977/5-9-74

ANNUAL REPORT NUMBER 2

(FINAL REPORT)

Standardization of Field Methods for Determination of Insecticide Spray Droplet Size

by

Richard McDaniel and Chester M. Himel

University of Georgia
Department of Entomology
Athens, Georgia 30602

15 March 1977

OFFICE OF NAVAL RESEARCH

~~Contract~~ N00014-70-A-0309-0003

Task No. NR136-977/5-9-74

ANNUAL REPORT ~~NUMBER~~ 2 (Final)

(FINAL REPORT)

Standardization of Field Methods for Determination of Insecticide Spray Droplet Size

by

Richard McDaniel ~~and~~ Chester M. Himel

University of Georgia
Department of Entomology
Athens, Georgia 30602

15 March 1977

Number of Copies

(1)	Commanding Officer U. S. Naval Medical Research Unit No. 2 Box 14 APO San Francisco 96263
(1)	Commanding Officer U. S. Naval Medical Research Unit No. 3 FPO New York 09527
(1)	Officer in Charge U. S. Naval Medical Research Unit No. 4 U. S. Naval Hospital Great Lakes, Illinois 60088
(1)	Officer in Charge Submarine Medical Research Laboratory U. S. Naval Submarine Base, New London Groton, Connecticut 06342
(1)	Scientific Library U. S. Naval Medical Field Research Laboratory Camp Lejeune, North Caroline 28542
(1)	Scientific Library Naval Biomedical Research Laboratory Naval Supply Center Oakland, California 94625
(1)	Scientific Library Naval Aerospace Medical Research Institute Naval Aerospace Medical Center Pensacola, Florida 32512
(1)	Commanding Officer U. S. Naval Air Development Center Attn: Aerospace Medical Research Department Johnsville, Warminster, Pennsylvania 18974
(1)	Commanding Officer U. S. Naval Unit Fort Detrick Frederick, Maryland 21701
(1)	Commanding General U. S. Army Medical Research & Development Command Forrestal Building Washington, D. C. 20314 ATTN: MEDDH-SR

OFFICE OF NAVAL RESEARCH
BIOLOGICAL & MEDICAL SCIENCES DIVISION
MICROBIOLOGY PROGRAM, Code 443
DISTRIBUTION LIST FOR TECHNICAL, ANNUAL AND FINAL REPORTS

Number of Copies	
(12)	Administrator, Defense Documentation Center Cameron Station Alexandria, Virginia 22314
(6)	Director, Naval Research Laboratory Attention: Technical Information Division Code 2027 Washington, D. C. 20390
(6)	Director, Naval Research Laboratory Attention: Library Code 2029 (ONRL) Washington, D. C. 20390
(3)	Office of Naval Research Department of the Navy Microbiology Program Director (Code 443) Arlington, Virginia 22217
(2)	Director, Research Division (Code 71) Bureau of Medicine and Surgery Department of the Navy Washington, D. C. 20390
(2)	Technical Reference Library Naval Medical Research Institute National Naval Medical Center Bethesda, Maryland 20014
(1)	Office of Naval Research Branch Office 495 Summer Street Boston, Massachusetts 02100
(1)	Office of Naval Research Branch Office 536 South Clark Street Chicago, Illinois 60605
(1)	Office of Naval Research Branch Office 1030 East Green Street Pasadena, California 91101
(1)	Office of Naval Research Contract Administrator - Southeastern Area 2110 G Street, NW Washington, D. C. 20007

Number of Copies	
(1)	Life Sciences Division Army Research Office 3045 Columbia Pike Arlington, Virginia 22204
(1)	Life Sciences Division Air Force Office of Scientific Research 1400 Wilson Boulevard Arlington, Virginia 22207
(1)	STIC-22 4301 Suitland Road Washington, D. C. 20390
(1)	Director Walter Reed Army Institute of Research Walter Reed Army Medical Center Washington, D. C. 20012

unclassified 1

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER Annual 2 (Final)	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Standardization of Field Methods for Determination of Insecticide Spray Droplet Size		5. TYPE OF REPORT & PERIOD COVERED 1 June 1975-1 October 1976 (Final)
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Richard G. McDaniel and Chester M. Himel		8. CONTRACT OR GRANT NUMBER(s) N00014-70-A-0309-0003
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Entomology University of Georgia Athens, Georgia 30602		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Task No NR 136-977/5-9-74
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Department of the Navy Arlington, Virginia 22217		12. REPORT DATE March 15, 1977
		13. NUMBER OF PAGES 57
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

This document has been approved for public release; its distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Monodisperse Sprays
Spray Droplet Size
Spray Spectra
Insecticide Spray Efficiency
Field Monitoring of Insecticide Sprays
Field Monitoring of Insecticide Sprayers
Spray Droplet Photographic Systems

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Spray droplet spectra determine insecticide efficiency, costs and the extent of ecosystem contamination. This research has developed new, significant analytical systems for spray spectra determination in the laboratory and field.

Key factors were (1) production of monodisperse (single size) droplets using a Berglund Liu sonic-type droplet generator, (2) development of a

over

spray droplet harp for zero critical impingement studies of spray droplets larger than 10 microns diameter, and (3) calibration studies of teflon coated slides useful as an adjunct impingement system.

Critical impingement velocity (CIV) considerations have been studied. Results show that static (low velocity) impingement of sprays (in the field or in the laboratory) on Kromecoat cards or glass 1x3 slides give analytical artifacts instead of viable spray distribution data. Where critical impingement velocity considerations are significant, low velocity (static) impingement data are misleading at best and at worst, are serious research artifacts. Such impingement artifacts foster spray systems which contribute mainly to gross insecticide application inefficiency.

Teflon coated slides are widely used in field and laboratory studies to determine insecticide spray spectra. Under static deposition conditions such data cannot be used for any quantitative analysis of droplets smaller than the range of 20-30 microns. Critical impingement velocities, target size and geometry, in-flight coalescence and multiple impingements on the target all contribute to the analytical problem.

A new spray droplet harp, using 5, 10, 15 micron and larger diameter wires for impingement at substantially zero critical, can be used with a newly developed photographic system. In conjunction with teflon coated slides, the total system represents an important new methodology in the fundamental study of sprays, and sprayers, as well as insecticide droplet transport and impingement. Droplet spectra data can be computer programmed.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES--Continued

LIST OF FIGURES

LIST OF FIGURES--Continued

1. General Statement

The field application of insecticides has been an empirical process. Insecticide delivery has lacked methods for the study of the processes by which insecticides are delivered to target insects. Until recent years need for analytical methods was mitigated by the relative cheapness of insecticides. The ecological problems facing us today reflect inadequate knowledge and use of empirical methods in insecticide spray applications.

Application of insecticides involves interrelationships between complex processes of transport, delivery, and impingement. There has been no available, analytical methodology by which these processes could be studied quantitatively. In the absence of quantitative data, insecticide application methods have been both empirical and controversial.

Ecological and economic problems are forcing changes in spray application. Stricter controls and higher costs have resulted in emphasis on efficiency in insect control operations. The actual efficiency of insecticide delivery has been unknown because the mechanism and mode of transport of insecticides to the target insect is unknown. Delivery of the insecticide to the target insect is an integral part of any insect control system. Efficient delivery is the transport of a lethal dose of insecticide through the environment to the target insect with minimal loss to the environment. Within this framework the concept of an optimum droplet size has arisen. Consideration has been given to the amount of insecticide needed for a lethal dose and to the most efficient size droplet that can be delivered through the environment to the insect.

In insecticide application, major importance is now placed on spray devices which produce sprays in the range of 1-50 microns diameter. Simple methods for unequivocal determination of droplet sizes in this range do not exist and cannot be extrapolated from the past. In these size ranges the factors, velocity and geometry of surface, are often ignored, yet they are critical in efficiency of impingement. When impaction devices are inefficient, data will be skewed toward larger sizes. As the collection surface becomes more efficient, small diameter droplets can be measured quantitatively, and data will be of increased significance.

These factors of spray droplet size and velocity at impingement have not been generally recognized as being of importance. Therefore, field scientists have developed no valid methods to determine the precise delivery of the sprays with which they work. Present emphasis on small droplet sprays represent a critical need for standardization of methodology. Simple and accurate spray droplet measurement devices must be found which are useful in the field. Insecticide spray efficiency of field use sprayers must be monitered to maintain optimum efficiency.

Impingement devices have resulted from years of field use but have not been studied to determine the nature of the mechanism of droplet action on impact or to determine whether their use represents fact or artifact. For the most part they were used in the field to collect large droplets traveling at terminal velocities of gravitational fall. For this size range, terminal velocities represent a type of standardization. That standardization does not carry over to present control methods which may involve sprays with 1-50 micron diameters and velocities from 1-100 miles per hour.

2. Scientific Background

Much controversy has arisen over the optimum droplet size, partially due to varied situations and methods of assessment. Laboratory and field studies have been carried out to determine the most effective droplet diameter for insect control. The concept of an optimum diameter range has been defined by several researchers (Lofgren 1970 and Uk 1975). Droplets of 5 to 20 microns have been found to be the only droplets that impinge efficiently on adult mosquitoes (Lofgren, Anthony, and Mount 1973 and Mount 1970). In forest insect control, sprays of 200-300 microns MMD (mass median diameter) have been reported to control defoliators best (Yeomans 1952 and Davis et. al. 1956). Burt et. al. (1970), Randall (1971), and Smith et. al. (1973) have reported on the effectiveness of narrow spectrum sprays in agriculture and forest control systems.

Himel, working with the fluorescent particle spray droplet method (Himel et. al. 1965 and Himel 1969), found that droplets of less than 50 microns had the greatest efficiency in reaching the target insect. These tests were conducted in both forest and agricultural situations (Himel and Moore 1967 and 1969). It was concluded that optimum size droplets were those size droplets small enough to be produced in maximum numbers to give maximum coverage, yet large enough to have a critical impingement velocity sufficient to give optimal impingement on the target insects. They found droplets in the range of 20 microns fulfilled these requirements (Himel 1969b,c).

The narrow spectrum small droplet (5-50 micron) spray concept, though still controversial, offers a partial solution to the economic and ecological problems facing insect control programs today. If the small droplet spray represets the optim spray droplet size, conventional sprays used in agriculture are operating at very low efficiencies, possibly as low as 1% (Himel 1969b). This leaves a large potential for reductions in the amount of chemical put into the environment.

The major argument against the use of small droplet sprays is drift of the droplets away from the target area and their failure to "get down" into the crop or forest canopy. The theoretical calculations of rates of fall and horizontal travel in cross winds have been reported by Potts (1958) for various droplet diameters. From his data, it has been argued that droplets below 100 microns could not reach the target insects within the canopy. Experimental, analytical evidence shows that these droplets not only get down into the canopy but are the only effective droplets (Himel and Moore 1967 and 1969). These statements do not include secondary control through contact insecticides where residues are important.

Contamination of the environment from small droplet sprays would be considerably less than from large droplet sprays. Conventional large droplet sprays have small diameter droplets (0-100 microns) as a component of their spectra. These are susceptable to drift by the same argument against small droplet sprays. Runoff with large droplet sprays results in major contamination to the environment which is usually ignored. If the amount of insecticide is reduced by 90% or more in ULV sprays, greatly reduced contamination would result, even recognizing drift.

It has been the lack of standard methods in the insecticide field that has led to many of the problems currently facing us. New concepts and old techniques are not compatable. Spray methodology operates under a wide range of conditions requiring methods to standardize the impaction devices for measurement of spray droplet size. To accomplish this, the effect of (1) nature of the spray liquid, (2) velocity at impact, (3) relative efficiency of collection of spray droplets as a function of size, and (4) geometry and surface factors during impingement must be determined (Frazier 1956, Orr 1966, Keathley 1972, and Fuchs 1964).

Many methods have been developed to count, size, and study airborne particles and spray droplets. Photographic techniques of actual suspended particles have been used for droplets from 1-100 microns (Cadle and Wiggins 1953 and Rathburn and Miserocchi 1967). Laser holographic techniques allow for direct measurement of droplets suspended in air (Roberts et. al. 1970 and Gabor 1972). These methods and other measure droplets as they are produced, but the cost of equipment and its complexity limit their potential for field use.

Other methods involve impingement of droplets in a liquid or on a surface. Of these two methods, only impingement on a surface has practical importance. Spray droplets follow the physical laws governing suspended particles. Suspended droplets have a critical impingement velocity, or the velocity at which a droplet of a given mass impacts on a surface. For very large droplets the critical impingement velocity approaches zero. As the mass of the droplet decreases, the critical impingement velocity increases. The critical impingement velocity is a function of size, shape, texture, temperature, and biological characteristics of the surface (Brooks 1947, Latta et. al. 1947, Yeomans 1949, Himel 1969, and Pieper 1972). The biological characteristics of insect surfaces act as efficient collectors of small diameter droplets. Evidence shows the optimum droplet size for deposition on insect surfaces to be 10-50 microns (Hadaway and Barlow 1965 and Yeomans et. al. 1949).

The shape of an object affects the air flow dynamics around its surface. When the direction of air flow around an object changes, droplets tend to resist the change in direction. The resistance is a function of the droplet mass, droplet velocity, and the surface. The probability of a droplet impinging on a surface increases as the diameter and the velocity increase, and decreases as the size of the object increases (Yeomans et. al. 1949, Gregory 1951, Gregory and Stedman 1953, Chamberlain 1967, Chamberlain and Chadwick 1971, and May and Clifford 1967).

There is an inverse relationship between the size of the object and the probability of a droplet impinging on a surface. Therefore, a small diameter wire would be an efficient collector of droplets. Rathburn (1970) showed the efficiency of wires vs. microscope slides. A wire of 80 microns had an efficiency of 87 percent for 12 micron droplets at 8 miles per hour. A microscope slide (1 x 3 inch) had a 10 percent efficiency for 10 micron droplets at 10 miles per hour, thus microscope slides and Kromecoat cards under static drop conditions are totally inadequate collection devices in the field.

Many surfaces are used to collect droplets for study. Droplets were impinged on mosquitoes and photographed with a scanning electron microscope. The scanning electron microscope provides direct observation and sizing of droplets on natural surfaces (Lofgren et. al. 1973).

The fluorescent particle spray droplet method is a statistical method based on the addition of a known number of fluorescent particles to the spray mixture. The droplets produced by the sprayer will contain a predicted number of fluorescent particles for a given droplet volume. Droplets impinged on insects and other surfaces can be sized by the number of grouped fluorescent particles (Himel 1969).

In general, these methods are complex and not easily adapted to general field use. Most droplet assessment methods use paper cards, such as kromekote cards, or glass slides coated with silicone, teflon, or magnesium oxide.

Droplet collection cards have an oil sensitive dye coating, or depend on a dye added to the spray solution. When a droplet impinges on a card, the droplet spreads causing a stain. The stain size must be related to the droplet size by a correction factor dependant on droplet size and coating.

Magnesium oxide (MgO) slides are prepared by collecting the oxide produced by burning a ribbon of magnesium. The oxide coating must be as thick as the largest droplet diameter to be collected. Impinging droplets create a crater slightly larger than the droplet diameter. A spread factor correction must be determined (a generally accepted value is 0.86). MgO slides are delicate and must be handled with care to keep from rubbing off the coating. The crater boundaries can be indistinct and difficult to measure (May 1949 and Rathburn 1970).

Silicone treatment of a glass slide leaves an oleophobic layer that prevents irregular spreading of droplets. An impinging droplet spreads into a lens shaped, round droplet. The spread factor must be determined to find the original droplet diameter. Various methods have been described for determination of spread factors for oleophobic coatings. Most methods involve measurement of lens height and base diameter (May 1945, Yeomans 1949, and Yeomans 1960).

Teflon surfaces can be coated on glass slides and are commercially available. The teflon surface is more oleophobic than silicone reducing the amount of spread. A spread factor can be found by a base to height relationship of the lens shaped droplet. Droplets of relatively non-volatile materials retain their shape and size on teflon for several days. The teflon coating is more permanent than silicone or MgO (Anderson and Schulte 1971).

3. Objectives

The purpose of this research was to study (1) the production of monodisperse droplets with the Berglund Liu Monodisperse Droplet Generator (Berglund and Liu 1973), (2) the impaction of these droplets by size, velocity, and substrate, (3) the critical impingement velocity, (4) spread factors, and (5) provide the fundamental data to develop a standard methodology for droplet detection in the field.

4. Materials and Methods

This research has dealt with impingement surfaces by which the size of spray droplets produced by a sprayer could be related to an optimum droplet size. Consideration has been given to (1) droplet production and size with the Berglund Liu generator, (2) effects of velocity, (3) spread factors, (4) nature and geometry of impaction surfaces, and (5) droplet impingement on insect surfaces in an effort to develop a standardized droplet detection system for field use.

The Berglund Liu Generator

The Berglund Liu Monodisperse Generator was the principal method used to atomize spray liquids in this study. Figure 1 is a schematic representation of the monodisperse aerosol generator system. This droplet generator produced single size droplets of controllable volume in the range of 1-100 microns. The generator system consisted of an orifice, a liquid delivery system, and a frequency generator. The orifice size was variable by exchanging the orifice disk. Orifice sizes of 5, 10, 20, and 50 microns were used in the tests. The liquid delivery system consisted of a motor driven syringe pump system geared to deliver a constant volume of spray liquid to the orifice. The volume was variable from 0.0004 to 77.0 ml/min. The frequency generator provided a sonic disturbance to the orifice assembly. The sonic disturbance, transmitted to a piezoelectric ceramic around the orifice, caused a controlled breakup of the liquid jet producing the droplets. In order to disperse and deliver the droplet cloud, nitrogen gas was used for dilution and dispersion (maximum dilution gas was 200 standard cubic feet per hour (SCFH) and maximum dispersion gas was 10 SCFH).

Glass lurlock syringes were used because of the action of many organic liquids on plastic materials and to prevent losses in flow rate due to leakage. The electrical connector cable contained within the dilution air chamber below the orifice assembly was protected by a teflon tape wrap.

Dioctyl phthalate (DOP) was used as the standard organic liquid for spray tests. A 50 to 60% solution of DOP in isopropanol was found to be the maximum with which a jet could be maintained. Neat DOP and concentrations above 60% welled up at the orifice opening forming a puddle. Other materials tried were a mineral oil, klerol; triethyl benzene; dimethylformamide; and dimethylsulfoxide, but success was limited with these as well. Fluorescent dye was added in some cases to make observations easier. This was especially helpful with MgO slides and on tests with insects. Solvents used for dilution were isopropanol, benzene, and hexane.

The constant volume drive of the syringe pump had a clutch which slipped at a predetermined pressure. This limited the viscosity of candidate spray liquids which could be driven through the 0.50 micron filter system and into the orifice with sufficient velocity to form a jet. Jet formation at the orifice was a critical requirement in the formation of monodisperse droplets by this device. A pressure bomb system was constructed to increase the available pressure (and thus the flow rate) on the liquid delivery system. Compressed nitrogen was used to put the liquid under pressure. Success with this system was limited, and maintenance of a constant flow was not achieved with efficiency. The constant flow of the syringe pump, recognizing viscosity limitations was found to be the preferable method of delivery.

In this sonic droplet formation device, frequency controlled the droplet size within limits of the orifice size (Berglund and Liu 1973):

$$D_d = \left(\frac{6Q}{\pi f}\right)^{1/3}$$

D_d = droplet diameter produced

Q = flow rate in ml/min

f = frequency

The frequencies used range between 20-200 kiloHertz (kH). At certain frequencies satellite droplets were produced. To check for these

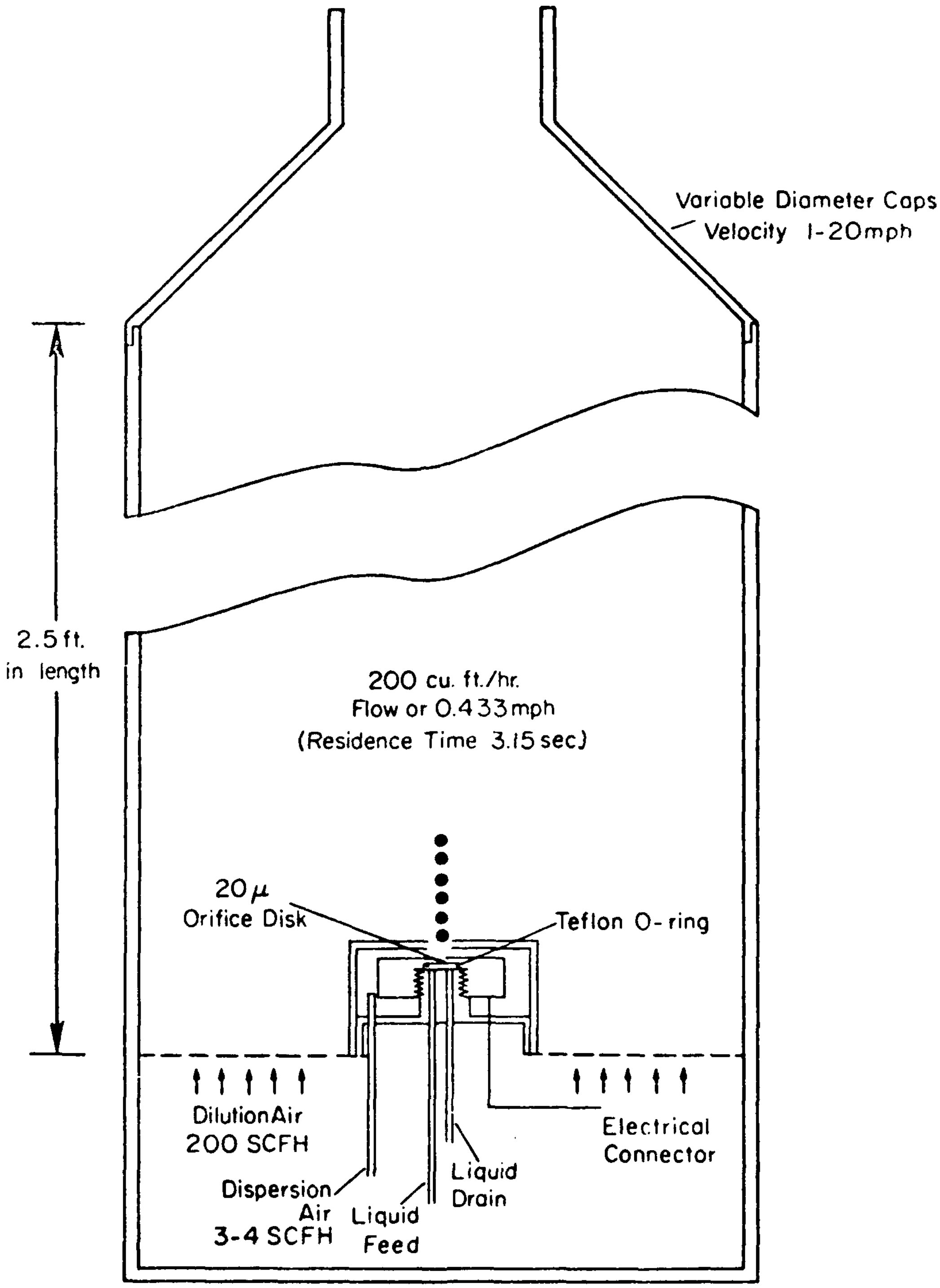


Figure I

SCHEMATIC FOR MONODISPERSE AEROSOL GENERATOR droplets a deflection nozzel was provided which fit into the dispersion air tube. The dispersion air stream was deflected perpendicular to the jet of droplets being produced. The droplets were deflected as a function of size (mass). For a uniform spectrum of droplets, the total stream was deflected by the same amount. If satellite droplets were produced, they were deflected by a greater amount due to their lower mass. When this condition existed two or more jets were observed. The frequency could be adjusted to compensate for this.

In general, the orifice produced a jet at flow rates which formed droplets within 20% of two times the orifice diameter. By changing the orifice diameter and the volume of volatile dilution liquid, virtually any size droplet could be produced. The droplet size produced after evaporation of the volatile diluent was calculated by the equation (Berglund and Liu 2973):

$$D_p = D_d(C)^{1/3}$$

D_p = diameter of the droplet produced

D_d = original diameter of the droplet at the moment of formation

C = concentration of volatile diluent in percent solute in solution

This equation was the correction factor for total evaporation of the volatile diluent. Table 1 gives the values for C13 of concentrations (C) used in these tests.

Table 1. $C^{1/3}$ values for various concentrations (C) of solute to solution.

% Solute/ Solution	$C^{1/3}$
1 (C=.01)	0.215
10	0.464
20	0.585
30	0.669
40	0.737
50	0.793
60	0.843
70	0.888
80	0.928
90	0.965
100	1.000

The dilution air system had a maximum total flow of 200 SCFH. This limited the size of droplets which could be carried upward through the dilution air column. In the upright position the maximum size droplet that could be lifted to the top of the column by the maximum dilution air was about 60 microns. Increased capacity of dilution air or inversion of the generator and dilution column for downward flow would allow for study of larger size droplets.

Velocity of impact

In order to study the effect of velocity on impingement, a series of varied diameter caps were designed for the top of the dilution air tube. The opening diameter of the cap was calculated to achieve the desired velocities at a standard air flow of 200 SCFH. Droplet velocities from under 1 mile per hour to 50 miles per hour were studied. Table 2 shows the tube diameters for the velocities used in these tests. The critical impingement velocities (the velocity above which droplets of a given size impinge on a surface) were determined for various droplet sizes on teflon slides. At velocities below the critical

Table 2. *Velocities of dilution air in miles per hour and the corresponding tube diameters required to achieve the velocity at 200 SCFH dilution air.*

MPH*	Tube Dia. (inches)
0.433	4.000
1	2.638
2	1.864
3	1.522
4	1.318
5	1.180
7	1.000
10	0.834
15	0.680
20	0.590
25	0.528
30	0.482
40	0.416
50	0.372

*Velocities were tested with a pietotube and found to be accurate.

impingement velocity, droplets are carried around the slide surface in the deflected air patterns. As the droplets pass around the slide some impinge on the back of the slide in the turbulent converging air pattern. Efficient impingement was determined by comparison of droplet numbers on the slide to the droplet impingement harp and the point at which all droplets impinged on the front surface and none on the back. At the critical impingement velocity for a given droplet size, these droplets and larger droplets impinge efficiently on the slide surface.

Spread factor determination

The Berglund Liu generator was also used to study spread factors on teflon and MgO slides. To determine spread factors, droplets on slides were compared to each other, the theoretical droplet size from the generator, and the droplet impingement harp. DOP; klerol; malathion; Pyrocide Fogging Concentrates 5628, 7052, and 7104; and Resmethrins DS-2MO, SBP-1382, DS40-007, DS18.5-007, and DS-2K were tested for their spread factor characteristics.

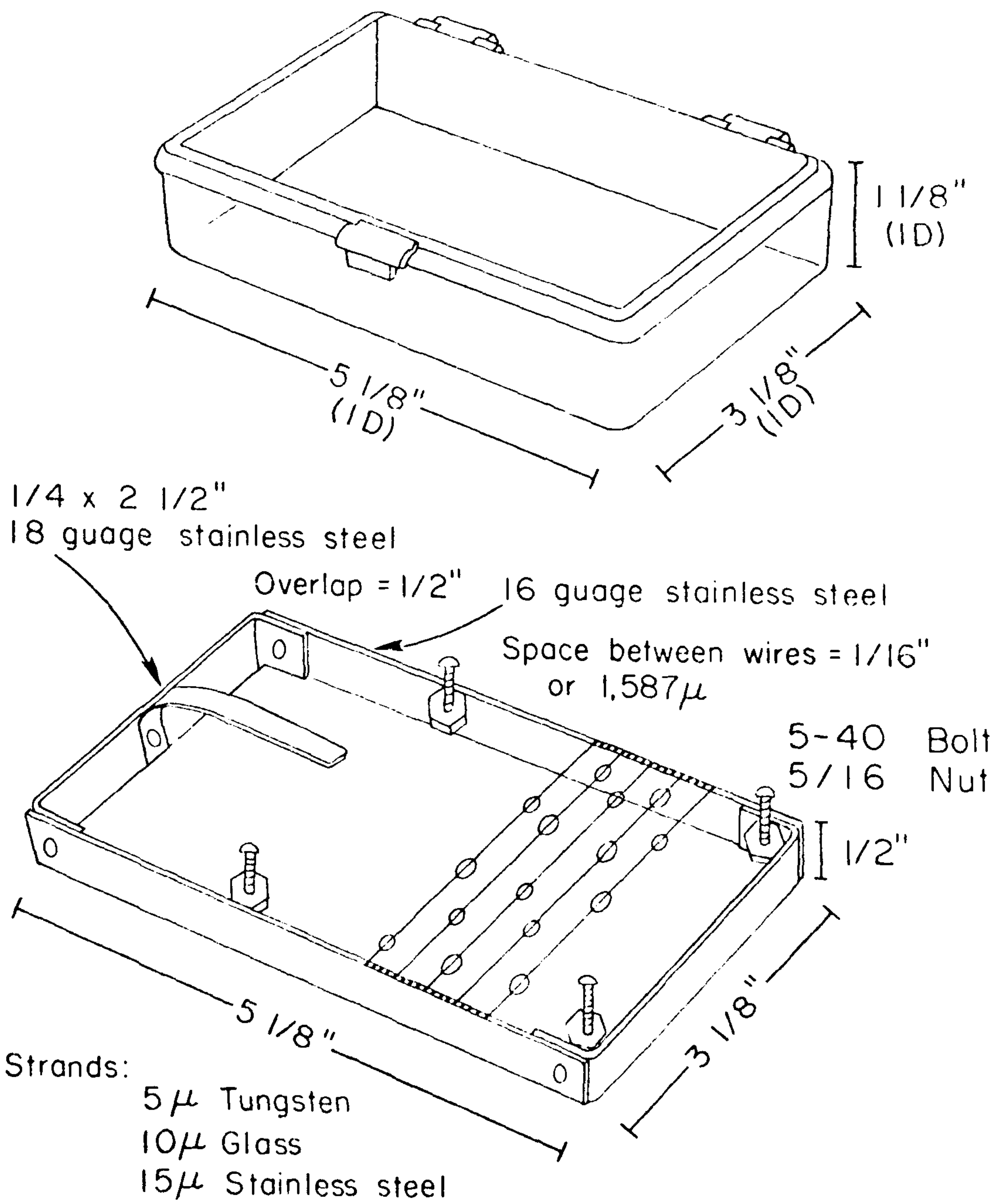
Droplet Impingement Harp

Impingement devices studied included magnesium oxide slides, teflon coated slides, and a specially designed "droplet impingement harp", shown in Figure 2. The harp was designed to fit snugly in a plastic box to protect the strands. On the droplet impingement harp, strands of various materials were used as collection strands.

The specially constructed harp was developed as a field reliable impingement device. Various materials have been tested for their impingement efficiency (silkworm threads, spider web strands, small diameter wires, and glass wool fibers). Strands of 5 micron tungsten wire, 10 micron glass fibers, and 15 micron stainless steel were used for the collection of droplets at high and low air velocities. The droplets collected on the strands were sized under a microscope with an eye-splitter attachment with an accuracy within ± 2 microns. The properties of the three materials were compared for their efficiency based on material and diameter of the strand. The glass fibers had to be individually picked from a mass of varying lengths. A mandrel was designed for the prespooled 5 and 15 micron wires.

The final design of the droplet impingement harp was made to hold 16 strands, 1/16 inch apart. The shape and construction offered minimal resistance to air flow. The strands were positioned in the grooves on the top of the harp and bent over the sides where double sided scotch tape was used to hold them in place. The grooves were included to serve as a guide to line the strands up and keep them equally spaced. Positioning and handling of the material was the greatest problem due to the delicate nature of the strand materials. The 5 micron wire was used in most tests. The strands had to be taut to prevent strands from crossing over and destroying the droplets impinged on adjacent strands. Once the wires were in place on the double stick tape, a piece of one sided tape was applied over the tape and strands to prevent slipping of the strands. Then, epoxy or a similar solvent resistant glue was placed in a thin line over the grooves which partitioned the strands. This made the harp relatively permanent. The harp could be strung, used, and then washed by

Figure 2. Droplet impingement harp and the protective plastic box.



gentle use of a solvent spray.

The droplets impinged in an ellipse on the strands, so that a measure of the long and short axis was taken with the droplet volume:

$$V = 4/3\ \pi ab^2$$

a = long axis radius
b = short axis radius

The cylinder volume of the strand had to be substracted:

$$V_{cylinder} = \pi r^2 h$$

r = strand radius
h = strand length (2a)

The eye splitter attachment for a microscope was used to measure the droplet diameters on the strand. As the droplet approached the strand at the long ends of the ellipse a subjective judgement had to be made as to the actual length of the droplet. Therefore the long axis measurement was less exact than the short axis. This was more apparent on wire strands, since the metal transmits less light than glass, and the droplet boundary merged into the dark background of the wire.

To study the nature of the droplets along the strand, "silanized" glass wool (used in Gas-Liquid Chromotography), silicone, and Vydax treatments of the fibers were tested. (The silicone treatment was Pierce Dri-Film SC-87 and Vydax is a fluorocarbon coating material available from Du Pont Co.) The "silanized" glass wool was placed on the harp in the same way as untreated glass fibers. Vydax and silicone treatments were made by dipping the strands in solutions of the materials and by a wipe on treatment of the strands. Various concentrations of the coatings were used to determine the effect on impingement.

To facilitate counting and sizing of droplets on the harp with a microscope, a plexiglass table was designed to fit over the microscope stage. This work table increased the area for easier handling of the harp. The clear plastic material allowed for light from underneath. See Figure 3.

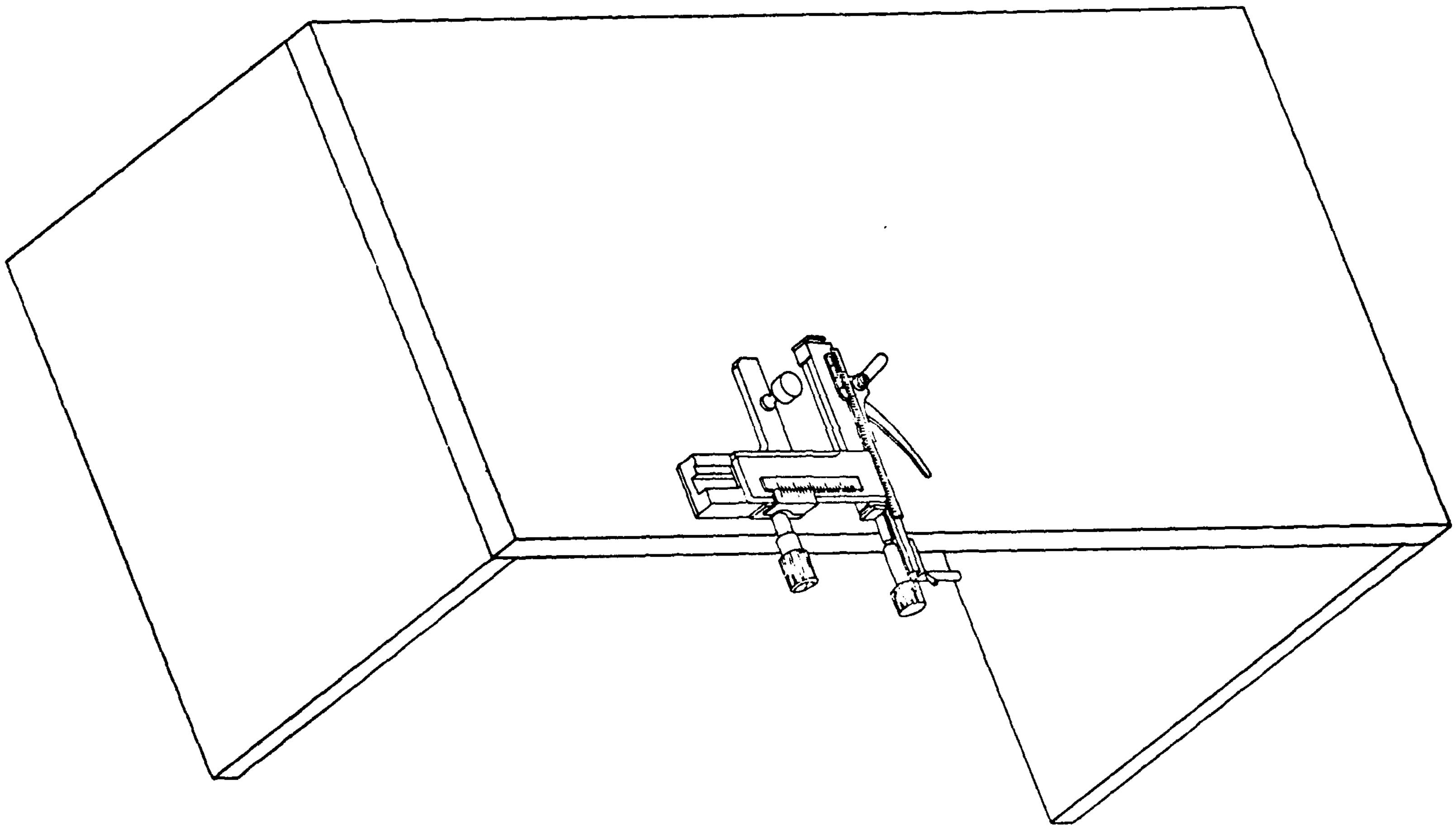
The stage mover was modified by the addition of attachments which fit the sides of the harp and were tightened by a thumbscrew. The harp was placed under the microscope and slowly moved through the field of vision. See Figure 4.

Photographic technique

The photographic method* is both simple and highly effective. A

*Developed by Professor Henry R. Hermann

Figure 3. Plexiglass work table designed to fit over the microscope stage with stage mover attached.



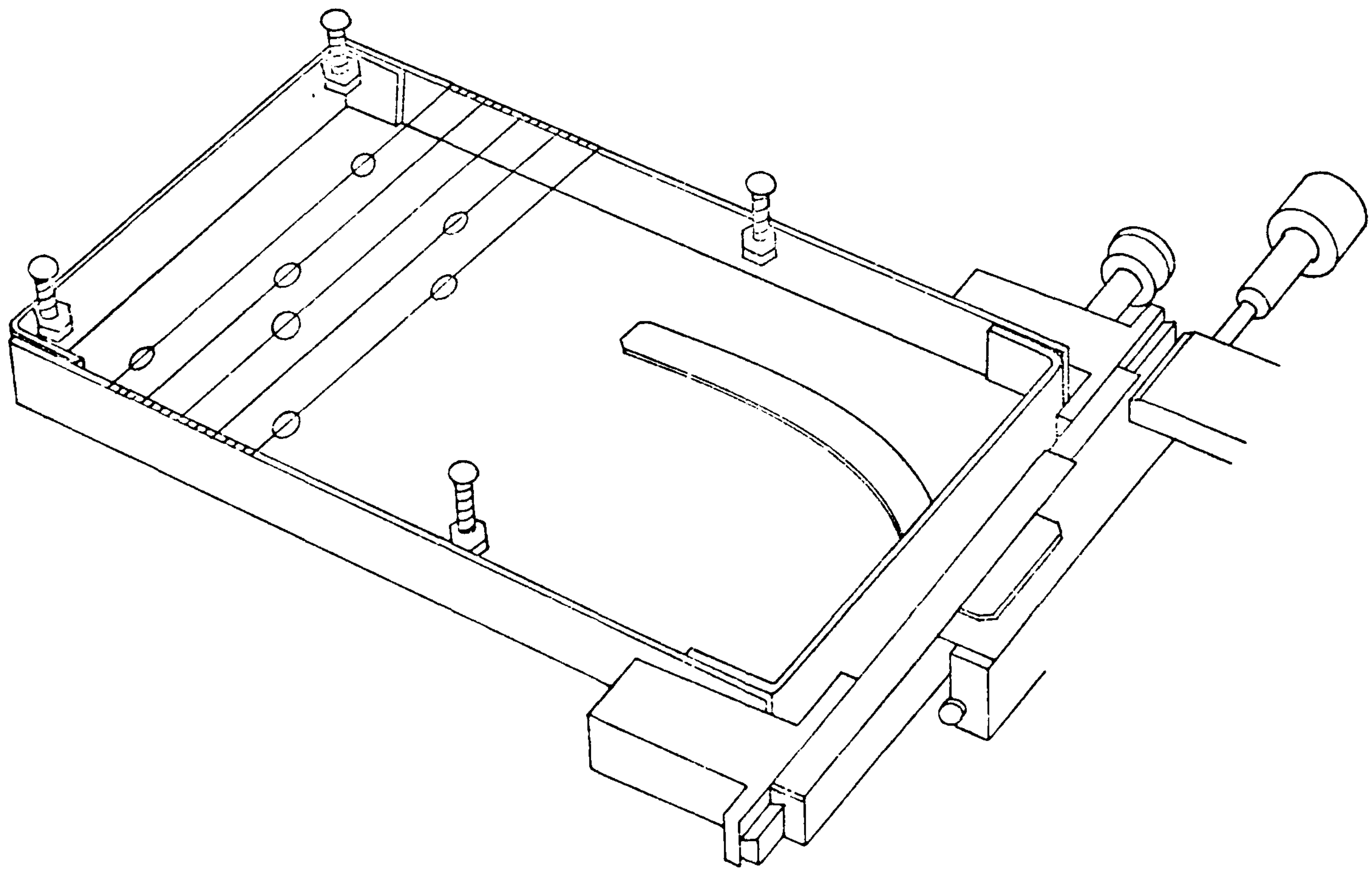


Figure 4. Stage mover modification to fit the sides of the droplet impingement harp for calibrated movement under the microscope.

commercial 4 x 5 inch photoenlarger was modified with a metal negative holder with a 1.5 x 1.5 inch opening. The harp or teflon slide was placed in the enlarger, over the opening. The enlarger was adjusted to project the image to precisely fill the 10 inch length of the paper. This gave a 6.5 fold enlargement. The slide or harp picture was then focused exactly using a magnifying glass. The f. stop was then reduced to f16 or f22. The image was photographed directly onto Afga #5 contrast enlarging paper for maximum resolution and image contrast. The droplets appeared white on a black background. The diameter of the wire strands used (5 and 15 micron diameters) allowed internal standards for calculation of total enlargement.

With teflon slides the same technique was used, i.e. the slide was placed directly over the open area in the holder. After precision enlargement to exactly 10 inches (long side), and focusing, the photo image was obtained as above. Correct exposure time is important in obtaining maximum resolution. After exposure, requisite identification data was written in pencil on the back of each 8 x 10 inch sheet (before processing). The print could then be used for droplet counts or stored for later use. This method gave a permanent record of the droplets collected which could be measured and counted later. It was a quick and relatively easy procedure that could be set up in the field with minimum equipment.

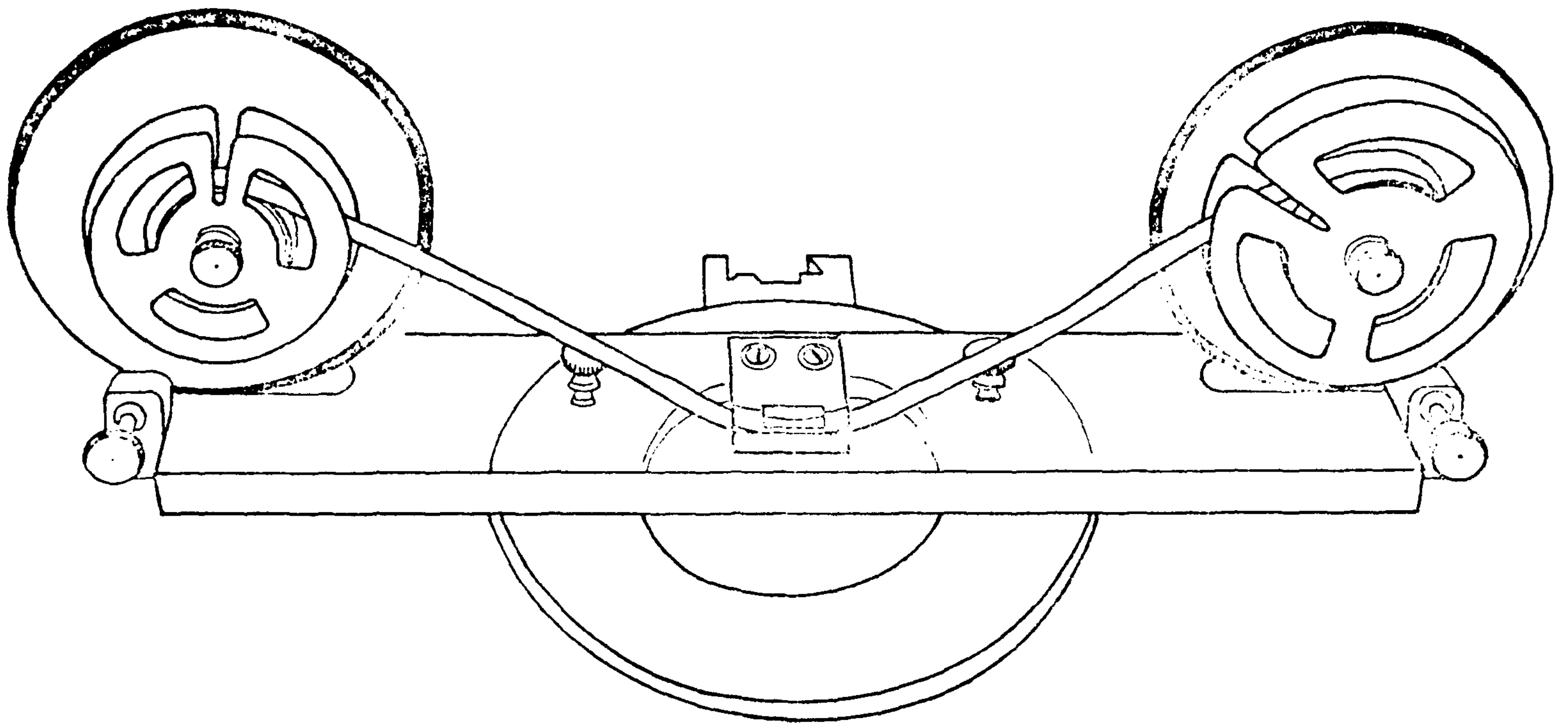
The prints were observed directly under a microscope using a precalibrated reticle. The resolution of the prints was sufficient to use about 200X magnification. To make observations of the prints easier, a photoreel moving and viewing device for the microscope was designed to run strips cut from the 8 x 10 prints through the field of vision of the microscope. See Figure 5. The prints were cut in ¼ inch strips and spliced end to end. The strips were threaded on a reel to reel recorder spool. The microscope attachment was designed to hold two spools, one containing the strip and one for uptake of the strip as it passed through the microscope. The prints were individually threaded on spools and retained on a permanent basis. A pair of knurled knobs, which turned the spools on a reduced gear basis, allowed the observer to slowly run the strips through the microscope field of view and size the droplets.

Droplet impingement on insect surfaces

Impingement of spray droplets was also observed on insects. Using *Musca domestica* adults and *Heliothis virescens* larvae, spray droplets were observed for location and number impinging. Fluorescent dye was added to the spray liquid, DOP, to make the droplets visible under ultra violet light. The Berglund Liu generator was used to generate the droplets.

Tethered flies, flies with small diameter threads attached to the thorax, were placed in the air stream laden with droplets. When tethered and no base to rest on, the flies were forced to fly. Flies were also placed in wire cages so that they were not forced to fly. Droplet

Figure 5. Photoreel moving and viewing device for counting and sizing strips cut from 8 x 10 prints of harp and teflon slides under the microscope.



number and location were observed.

The larvae of H. virescens were placed on screen wire and put in the air stream carrying the droplets. Various droplet sizes within 10-50 microns were sprayed.

Spray spectra determination

In addition to the Berglund Liu sprayer, several different sprayers were tested for their spectra on different collection devices. A Micro Gen SW-1 sprayer was used to spray artificial surfaces (teflon and MgO) in an enclosed spray room. The spray room eliminated air movements and external factors. The dimensions inside the room were 10 feet wide by 15 feet long by 10 feet high. The sprayer was positioned in a window port, 12 inches x 12 inches at a height of 8 feet above the floor. Teflon and MgO slides were arranged at varying distances from the spray source on elevated surfaces 2.5 feet from the floor. The sprayer was operated at 1/3 cc/min for different intervals of time to change the total amount sprayed. The slides were recovered after 8 to 10 min.

A Beeco Mist sprayer was tested outside using two vane axial fans to dilute and carry the droplet cloud. The fans were arranged one on the top of the other, and the sprayer was positioned in the center of the air blast about 1 foot from the fans. One cc of DOP was injected with a syringe into the sprayer. Impingement devices, teflon slides and harps, were clamped on ring stands at a distance of 10 to 12 feet from the fans (the point at which the velocity of the air stream was 10 miles per hour). The air velocity was determined with a pietotube. The slides and harps were immediately collected and returned to the lab for observation.

Tests with a freon pressure sprayer by Cessco Corporation were conducted in a dynamic fan system. The fan was set up in a large storage barn to eliminate effects of external wind. The dimensions of the room were 50 feet x 75 feet x 12 feet. The sprayer nozzel was clamped one foot in front of the fan. Teflon slides and harps were passed through the air stream at the point where the air velocity was 10-12 miles per hour. The sprayer was tested at pressures of 30, 40, and 50 psi, controlled by an adjustable value on the unit. Two orifice sizes were tested: (1) a 0.030 inch brass orifice and (2) a 0.018 inch plastic orifice. A pyrethrin formulation in freon was the spray liquid used.

Another model Micro Gen sprayer, model HCS1-2AA, was tested in the same dynamic system as with the Cessco sprayer. Teflon slides and harps were hand held and passed through the droplet cloud in a sweeping motion with an exposure of one second. Three flow rates using DOP were tested.

The Micro Gen model HCS1-2AA was tested in an abandoned field where foliage height was approximately 3 feet. Harps and teflon slides were placed in different locations. The sprayer was attached to a tractor boom adjusted to a height of 16 inches above the collection devices. The sprayer was driven over the collection devices at a rate sufficient to deliver 1 gallon per acre coverage. DOP was used as the spray liquid. Four different types of conditions were defined: (1) no cover where there was no foliage between the spray nozzel and the harps and slides, (2) grass cover where heavy grass covered the harps and slides, (3) dense cover I where heavy plant growth covered the devices at a distance of 36 inches from the spray nozzel.

Data analysis

The spray spectrum data was analyzed by a computer program, WTREG/UN=STAREBI. The program was a probit analysis adjusted to analyse droplet spectra based on volume. The data collected was grouped into 5-12 groups based on volume per drop. For each group the cumulative percent (cumulated percent volume calculated from the volume of droplets observed at a given size divided by the total volume of all droplets collected) was fed into the computer. The program gave the predicted curve of the spectra and values for 5%, 50%, and 95% of the volume. The 50% value corresponded to the VMD of the spray spectra. (VMD, median diameter one half of the total volume is produced by droplets of this size or smaller) The 95% value predicted the Dmax of the spectra. (Dmax, 95% of the volume is found in droplets of this size and smaller) With the 5% and 95% values, the range between which 90% of the volume was produced could be predicted.

5. RESULTS

The Berglund Liu Generator

The Berglund Liu generator required dilution of highly viscous organic liquids and insecticides to maintain constant jet formation. Through extensive testing the evaporation of volatile solvents was found to be complete or nearly so from spray solutions containing less than 90% solvent. The residence time (3.15 seconds) within the dilution air column allowed evaporation to cocur. Calculations of observed droplet sizes vs. theoretical and timed studies of droplets over long periods of time showed the volatile components had evaporated prior to impingement.

In the calibration studies of the aerosol generator, frequency and flow rates were found to vary droplet size as theorized by the operation formula for droplet diameter (D_d). As the flow rate increased droplet diameter increased, and as frequency increased droplet diameter decreased. Optimum operation conditions for flow rate with the 20 micron orifice and 60 percent DOP was found to be 0.15 cc/min. Changes in theorifice diameter or concentration of DOP increased or decreased the optimum conditions of flow rate. Within this range of flow rates, there was no clutch slippage of the syringe pump, and a jet was easily maintained.

It was found that the desired droplet size could be produced by changing the frequency or concentration of DOP (or insecticide). Adjustments in flow rates also changed droplet diameter, but generally the syringe pump was maintained at a flow rate that gave optimum operation conditions, i.e. constant flow without clutch slippage or leakage and a constant jet. For a given concentration and flow rate the droplet size could be varied by several microns with frequency changes. Actual values showing the relationship of frequency to the size of the droplets deposited on teflon slides are given in Table 3. The calculated value is the theoretical droplet diameter (D_p) produced by the monodisperse generator and the observed value is the droplet size on teflon slides with a spread factor correction of 0.63. For each frequency a minimum of 200 droplets per slide were sized and recorded.

Table 3. Sample data showing the effect of frequency with the Berglund Liu generator on droplet size in microns using DOP and other factors constant.

Frequency (X10kH)	Calculated Value	Observed Value*
4.0	31	34
5.0	29	30
6.0	27	28
7.0	26	26

*Observed size obtained by sizing a minimum of 200 droplets per slide. Droplets were monodisperse (one size) and accurate within ± 2 microns. Spread factor of 0.63 included.

Velocity of impact

Velocities of 1-50 miles per hour were used to impinge droplets on surfaces. Within this range of velocities there was no observable change in the spread factor of droplets impinging on collection surfaces. Table 4 is a sample set of data varying only the velocity of the dilution air leaving the column. It shows the size range of the observed droplets and the number of droplets at each size.

The majority of the droplets are of the size that was generated at all velocities from 1-50 miles per hour. The droplets at 60-68 microns are due to in flight coalescence, as this is the diameter for the coalescence of two, 52 micron droplets. The droplets observed at 72 and 76 microns are multiples of 3 droplets.

Table 4. Sample data showing the number of DOP droplets from the Berglund Liu generator in each size range up to 50 miles per hour. All droplets were generated at 52 microns diameter.*

					Multiplets				
	Single Droplets				Two Droplets			Three Droplets	
MPH	44	48	52	56	60	64	68	72	76
1	0	0	171	1	1	13	3	0	1
2	0	0	69	2	5	25	12	0	0
3	0	0	57	3	11	5	2	0	0
4	0	0	78	0	0	19	3	11	1
5	1	0	179	0	1	8	0	0	0
7	0	0	128	0	0	11	1	1	0
10	0	0	43	9	5	4	4	0	0
15	0	0	50	0	0	9	1	1	0
20	0	0	150	0	0	30	1	10	0
25	0	0	70	0	3	29	1	9	0
30	0	0	79	0	0	38	0	15	0
40	0	0	97	0	0	45	0	21	0
50	0	0	101	0	0	52	0	19	0

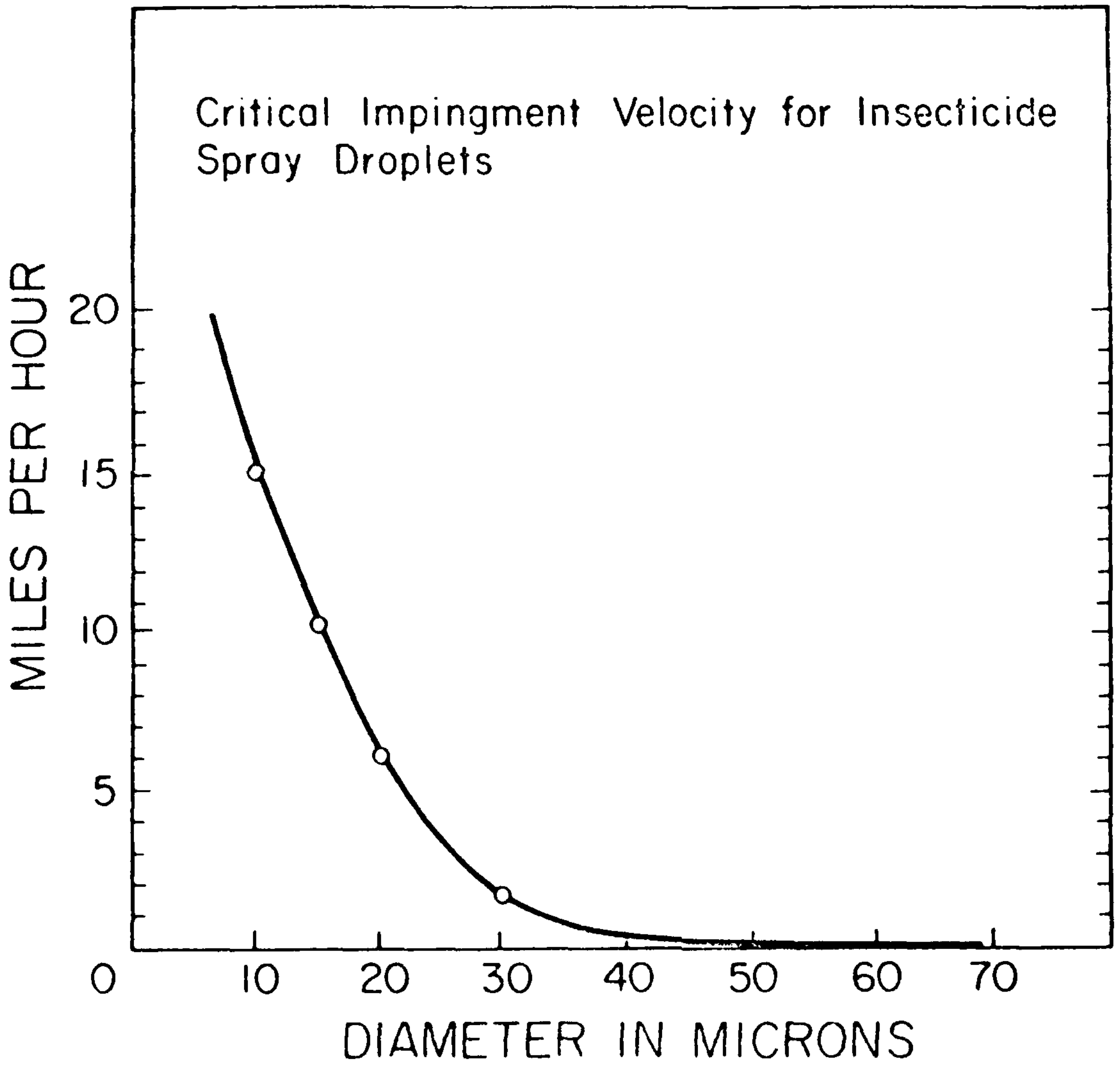
*Droplet diameters in microns at 4 micron increments. At each velocity the droplet count includes all droplets encountered in several passes across a teflon slide.

At velocities above 15 miles per hour the tube diameter was small, and large numbers of droplets were impinged in a small area on the slide. This caused large numbers of multiple impingements and misshapen droplets (only round, lens shaped droplets were considered in droplet counts).

By the use of the different diameter caps for the dilution air column, critical impingement velocities were determined for droplet sizes. With known droplet sizes produced by the Berglund Liu generator, the velocity was varied until droplets impinged efficiently on teflon slides. It was determined that 30 micron droplets had a critical impingement velocity of 1-2 miles per hour, above 30 microns the critical impingement velocity approached zero. Twenty micron droplets impinged at 5-7 miles per hour, 15 micron droplets at 10 miles per hour, and 10 micron droplets at 15 miles per hour. Figure 6 is a graphic representation of critical impingement velocities.

Spread factor determination

Figure 6. Critical impingement velocity in miles per hour related to droplet size in microns on teflon slides.



From extensive studies and tests the spread factors for teflon and MgO were found to be 0.63 and 0.86, respectively. These values were determined with DOP for droplets ranging from about 20 microns to 60 microns. The values were consistent with the theoretical values and in comparison to each other and the harp data. Tables 5 and 6 show observed vs. calculated droplet diameters for teflon and MgO, respectively, at different concentrations and frequencies of disturbance and the spread factors for each.

Table 5. Sample values of calculated and observed droplet diameters and the corresponding spread factors on teflon slides. The Berglund Liu generator was used to produce the droplets with DOP.

% solute/ solution	Freq. x10kH	Calculated (microns)	Observed (microns)*	Spread Factor#	Number of Observations*
10	5.0	21	32	.66	6
	6.0	20	29	.69	4
	7.0	19	26	.73	1
20	5.0	27	40	.68	2
	6.0	25	41	.61	4
	7.0	24	44	.55	1
30	4.0	33	52	.63	1
	5.0	31	46	.67	3
	6.0	29	38	.76	4
40	2.2	44	70	.63	2
	4.0	36	55	.65	2
	4.5	35	53	.66	3
	5.0	33	52	.63	2
	6.0	31	48	.65	3
50	4.0	39	60	.65	2
	5.0	36	56	.64	6
	6.0	34	52	.65	5

#All available data from this research (including data not tabulated here) gives an average spread factor of 0.63. The accuracy of measurement is ± 2 microns which accounts for the variation in the data above.

*A minimum of 200 droplets were counted and sized for each slide. Number of observations is number of slides counted. The spray was monodisperse so the 200 droplets were the same size within the accuracy of the microscope and eyesplitter device.

In addition to DOP, several insecticides and klerol were tested for spread factors on teflon slides. Teflon slides were found to have a spread factor range of 0.6 to 0.7 for materials tested. Table 7 lists materials tested and spread factors on teflon slides for each.

Table 6. Sample values of calculated and observed droplet diameters and the corresponding spread factors on MgO slides. The Berglund Liu generator was used to produce the droplets with DOP.

% solute/ solution	Freq. x10kH	Calculated (microns)	Observed (microns)*	Spread Factor#	Number of Observations
10	4.0	23	22	.95	1
	5.0	21	25	.84	6
	6.0	20	23	.87	3
	7.0	19	22	.86	1
20	5.0	27	30	.90	4
	6.0	25	32	.78	1
	7.0	24	30	.80	1
30	5.0	31	33	.93	3
	6.0	29	24	.83	2
40	5.0	33	31	.94	3
	6.0	31	36	.86	2
50	5.0	36	44	.82	2
	6.0	34	39	.87	2

#All available data from this research (including data not tabulated here) gives an average spread factor of 0.86. This is also the generally accepted value in the literature.

*A minimum of 200 droplets were counted and sized for each slide. Number of observations is number of slides counted. The spray was monodisperse so the 200 droplets were the same size within the accuracy of the microscope and eyesplitter device.

It was found with insecticide formulations which contained large amounts of volatile components such as kerosene, total evaporation of the solvent did not occur within the dilution air tube. The solvents in these formulations were not as volatile as those used in the tests with the Berglund Liu generator. When the droplets impinged on a teflon slide the droplet decreased in size on the slide as evaporation occured. The resmethrin and Pyrocide formulations all contained various percentages of volatile solvents. When the percentage of solvent was greater than 40-50 evaporation was not complete in the air dilution tube. With these materials the spread factor was not easily determined on the same basis as with non-volatile materials or formulations in which evaporation was complete. The solvent component of the formulation did not evaporate in the residence time within the tube, but evaporation occured after impingement on the slide. The apparent spread factor for these formulations ranged between 0.6 and 0.7 based on the size of the droplets due to non-volatile components. After 2 hours evaporations of volatile components approached completion and the droplet size remained constant. The same values were obtained by sizing droplets immediately after impingement and before evaporation produced a change in apparent size.

Droplet Impingement Harp

Droplets down to 10 microns and below impinged at very low critical impingement velocities on the droplet impingement harp. Droplets were measured directly on the strands of the harp without any "spread factor". Only droplets down to 10 microns could be sized due to inaccuracy in measurement of smaller droplets on 5 microns diameter wire. The

Table 7. Spread factors for various insecticides and organic liquids on teflon slides.

Material Tested	Spread Factor
DOP	.63
Klerol	.63
Malathion	.68
Pyrocide 7104	.59
Pyrocide 7052	*
Pyrocide 5628	*
Resmethrin DS-2MO	*
Resmethrin SBP-1382	*
Resmethrin DS40-007	*
Resmethrin DS18.5-007	*
Resmethrin DS-2K	*

*Spread factor not determinable due to volatile components contained in the formulations. Tests allowing volatile components to evaporate and sizing droplets remaining or sizing droplets immediately after impingement give spread factors for these formulations between 6 and 7.

boundaries of smaller droplets were not clear or measurable, and the formula for the volume approached a cylinder instead of an ellipse.

Droplets were collected on various strand materials. The diameters of the strands were important when collecting small diameter droplets. Droplets with diameters approaching the diameter of the strand impinged on the side of the strand or elongated along the strand such that the boundaries were indistinct. Therefore, the 5 micron tungsten wire was found to have the most acceptable impingement properties of the materials tested. With its small diameter, droplets of 10 microns and above could be sized, and did not adhere to the side of the wire. Also the strength of the five micron wire was greater than glass wool fibers. Droplets of 12-15 microns and above were measurable on the glass wool fibers.

The 15 micron stainless steel wire was much easier to handle than the 5 micron tungsten wire due to its greater strength, but its impingement properties for small droplets were less desirable. Droplets below 20 to 25 microns impinged on the side of the 15 micron wire and could not be sized. For larger spectra of droplets, the 15 micron wire was efficient and easier to use due to its greater strength.

At some point, large droplets are expected to hit the strand, shear, and go on by the wire strand. This would be a function of the droplet size, velocity, and wire diameter. With 5 micron wire droplets of 100-150 microns impinged without losses in volume. At some point, as droplet volume increases, the efficiency of impingement must be reduced. By the use of 15 micron wire or wires of larger diameter on the harp in conjunction with the 5 micron wire or alone, larger droplets could be detected and sized. With the availability of larger diameter wires, droplets of any size could be collected for study with no loss in efficiency.

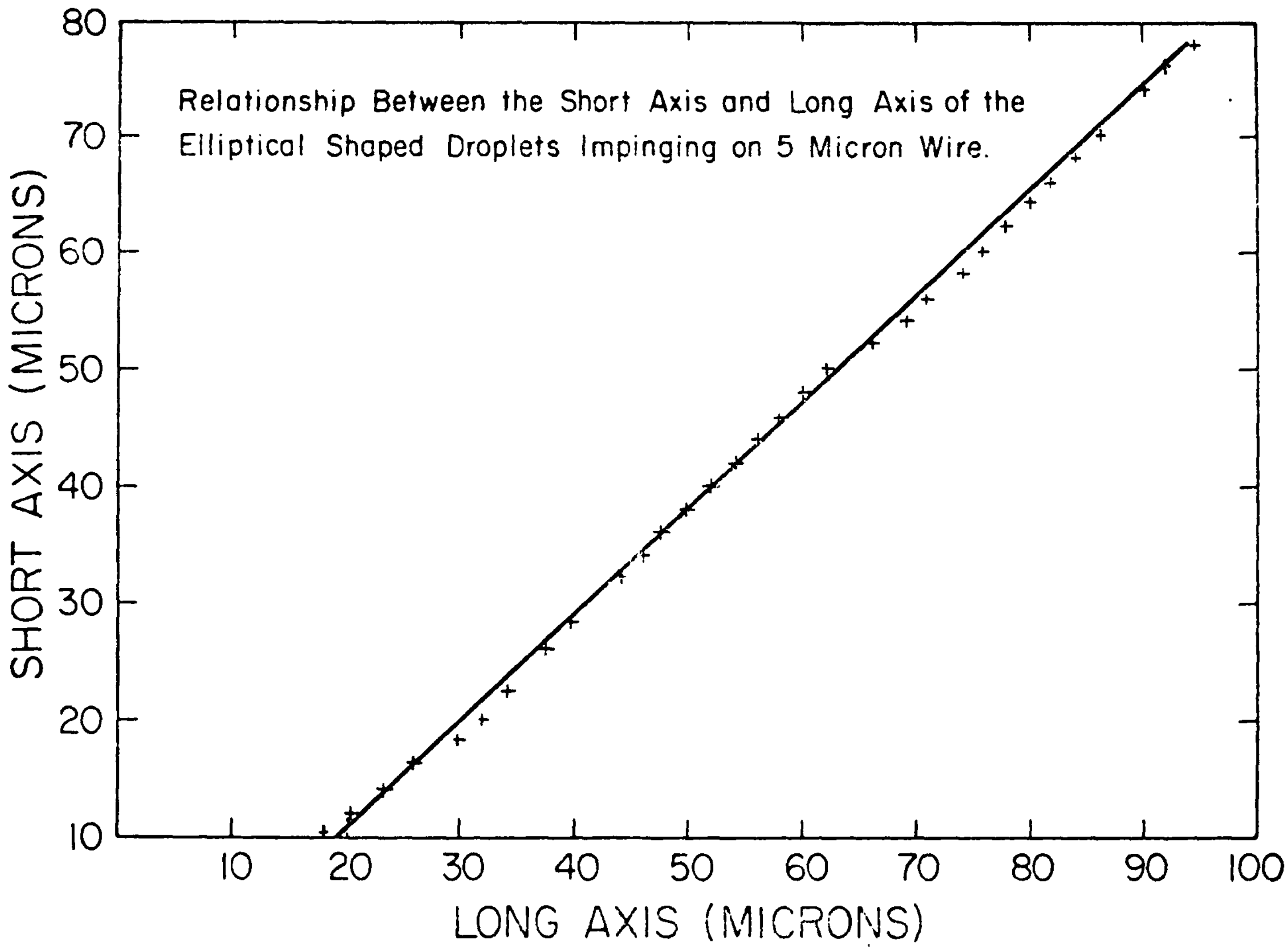
As the diameter of the strand decreased, the droplet shape approached a sphere, and as the size of the droplet increased the ratio of the short axis to the long axis approached one (a ratio of one represents a perfect sphere). The relationship of the long axis to the short axis found in these tests is shown in Figure 7.

Silanized glass wool was compared with non-treated glass wool strands. The impingement properties of the silanized glass fibers reduced the elliptical nature of impinging droplets, but the properties of strength and handling made it difficult to use.

The 5 and 15 micron wires were treated with silicone and Vydax. Both of these materials decreased the elliptical nature of impinging droplets, but the decrease was small (a difference of about 4 microns reduction in the long axis in most cases). With 5 micron wire the difference between treated and untreated strands was not sufficient to require treatment. With 15 micron stainless steel, the treatment decreased the number of smaller droplets that impinged on the side of the strands (instead they encircled the strand) as well as a small change in the elliptical nature of the droplet. The two treatments were equal in their effect.

The efficiency of the droplet impingement harp was found to be much

Figure 7. Relationship between the short axis and long axis of the elliptical shaped droplets impinging on 5 micron wire.



greater than glass slides. Tests showed the harp collected droplets with 10 times greater efficiency than teflon slides for small droplet spectra (less than 60 microns). The harp collected less total droplets than teflon slides due to the significant differences in collection area. A teflon slide had a collection surface area of 1.5 billion square microns. This compared to a harp area of 6 million square microns (sixteen five micron strands). Therefore, the harp area was 1/250 that of a teflon slide. In this respect the teflon slide under equal conditions had more total droplets, but it was less efficient by a factor of 10. This presented problems when using the harp and teflon slides together. Greater numbers of droplets were needed for a representative sample on the harp than was impinged under equal conditions with a teflon slide. This required a longer exposure time, or more strands either on the same harp or additional harps. Greater exposure times with teflon slides resulted in great numbers of multiple impingements due to too many droplets. The two devices were not easily compatable on this basis.

Photographic technique

The photographic method reduced time required in the field for counting and sizing droplets. The eight by ten prints gave a permanent record of droplet data for later use. After the prints were cut into strips they were easily stored on recorder spools and could be counted and sized with the photoreel moving and viewing device. With the precalibrated reticle the accuracy of droplet measurement was found to be within 4 microns at 200X magnification. The magnification could be increased, but the accuracy was not increased due to loss in resolution.

Droplet impingement on insect surfaces

In the tests with *M. domestica*, it was found that flies forced to fly in the droplet stream had significantly greater numbers of droplets impinged on the body surfaces, especially the wings, than was found on flies at rest. The greatest numbers of droplets were found on the wings of the tethered flies. Over the body surface impingement occured on the setae and other protuberances and not on the actual body surface. Table 8 gives the number and location of 50 micron droplets and flies, tethered and in cages, at five distances from the spray nozzel.

With *H. virescens* larvae, the droplets impinged on body setae and to a limited extent on the body surface. Impingement on the body surface was possibly a result of wriggling motions of the larvae. Droplets impinging on the screen wire rubbed off onto the larvae. Droplet sizes between 17 and 50 microns were sprayed with the Berglund Liu generator. Table 9 shows the number of droplets of DOP at several droplet sizes impinging on the larvae. The tests showed little difference in droplets from 20 to 50 microns. The number of 17 micron droplets impinging on the larvae was lower. The exposure time in all cases was two seconds.

Table 8. Number and location of 50 micron DOP spray droplets on *M. domestica* adults tethered and in cages at varying distances from the spray nozzel.

Distance from spray nozzel (feet)	Number of Droplets Head	Thorax	Abdomen	Wings
Tethered				
0.5	25	43	39	69*
1	21	42	45	58*
2	19	29	37	62*
3	7	25	10	40
5	3	7	15	30
In cages				
0.5	18	39	41	29
1	22	35	37	33
2	15	27	25	21
3	11	15	18	19
5	3	7	11	8

*Droplet counts were difficult because of patches of fluoresence from the coalesence of several droplets.

Table 9. Number of droplets impinging on *H. virescens* larvae at several droplet sizes from 17 to 50 microns. The Berglund Liu generator was used to produce the droplets using DOP. Five replicates were made with a 2 sec. exposure.

Replicate	Number of Droplets at Droplet Size (microns) 17	21	32	50
1	10	27	30	36
2	8	29	41	52
3	15	35	45	41
4	11	41	27	27
5	18	33	35	47
Average/larvae	12.4	33	35.6	40.6

Spray spectra determination

The initial spray spectra tests were conducted with a Micro Gen SW-1 sprayer within an enclosed spray room. The results of these tests were inconclusive. The collection devices showed the deposition pattern within the room was not uniform. The size of the droplets was a function of the location of the detection device and distance from the sprayer nozzel. Large droplets were found in line with the spray effluent at a distance of 6 to 8 feet. Small droplets were deposited around the room.

The Beeco Mist results from the tests in the dynamic fan system are shown in Table 10. The table gives the mass median diameters and Dmax values for each of the three sleeve types tested on both teflon slides and the harp. These values were obtained from the computer program predictions. The VMD values were in the range of 50-55 microns with Dmax values under 70 microns. With each sleeve, over 90% of the volume was found to be in a narrow range of 20 to 25 microns. Small droplets (0-30 microns) were present but contributed little (5% or less) to the total volume of the spray. Representative curves are given in Figures 8 and 9. Figure 8 is a probit plot from the predicted and observed values of the computer program. Figure 9 is the actual values of percent volume due to a given droplet diameters.

Table 10. Beeco Mist sprayer tests results showing the VMD and Dmax values in microns on teflon slides and the harp for three different sleeves. DOP was the spray liquid used.

Sleeve Material	Sleeve Pore Size (microns)	Collection Device	VMD*	Dmax*
Teflon	20			
		Harp	43	55
		Teflon	52	61
Polyethylene	40			
		Harp	52	67
		Teflon	57	66
Polyethylene	60			
		Harp	55	67
		Teflon	55	65

*Values were obtained from the computer program predictions. Based on average of two replicates with 200-500 droplets counted and sized for each replicate.

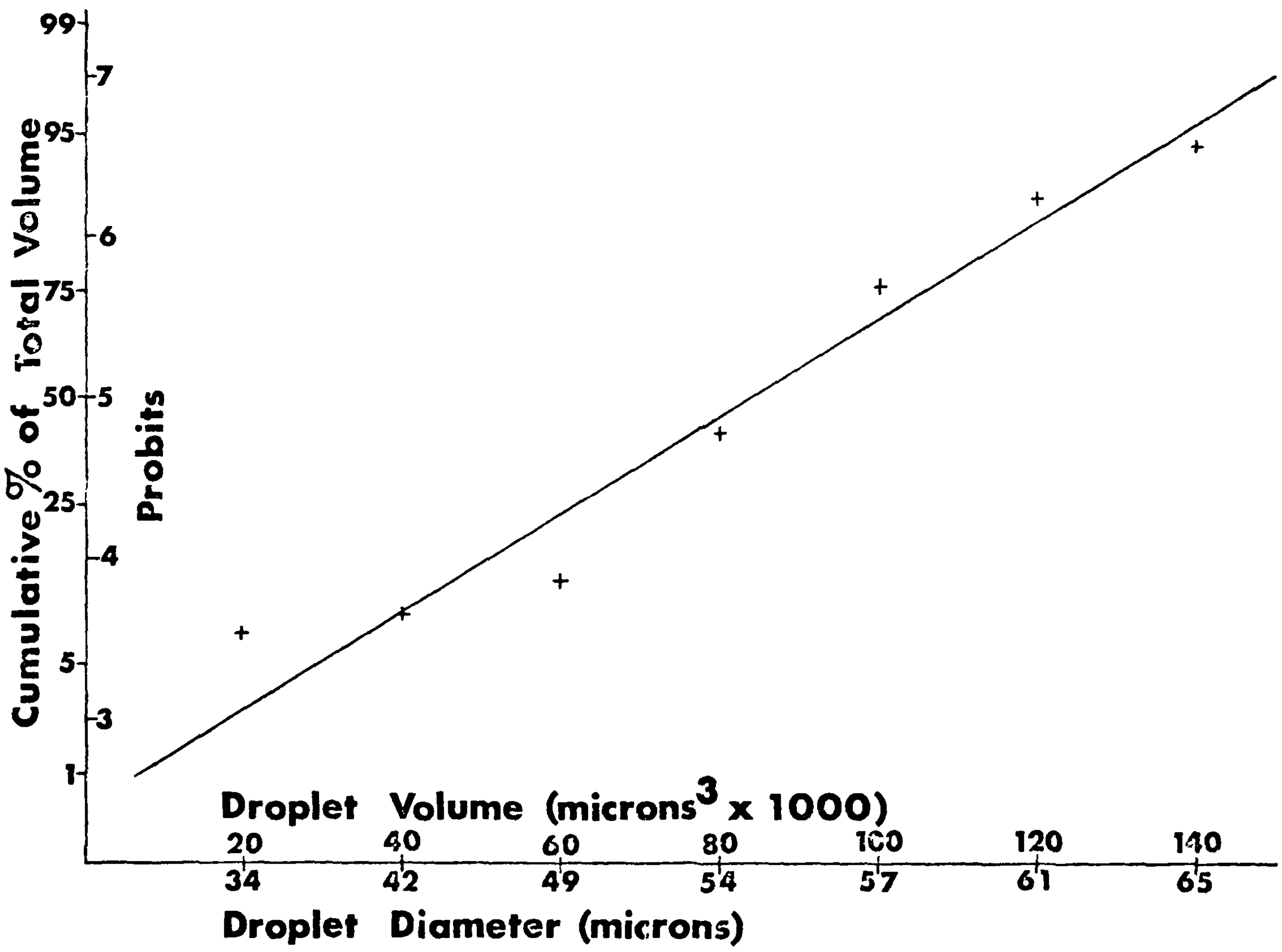
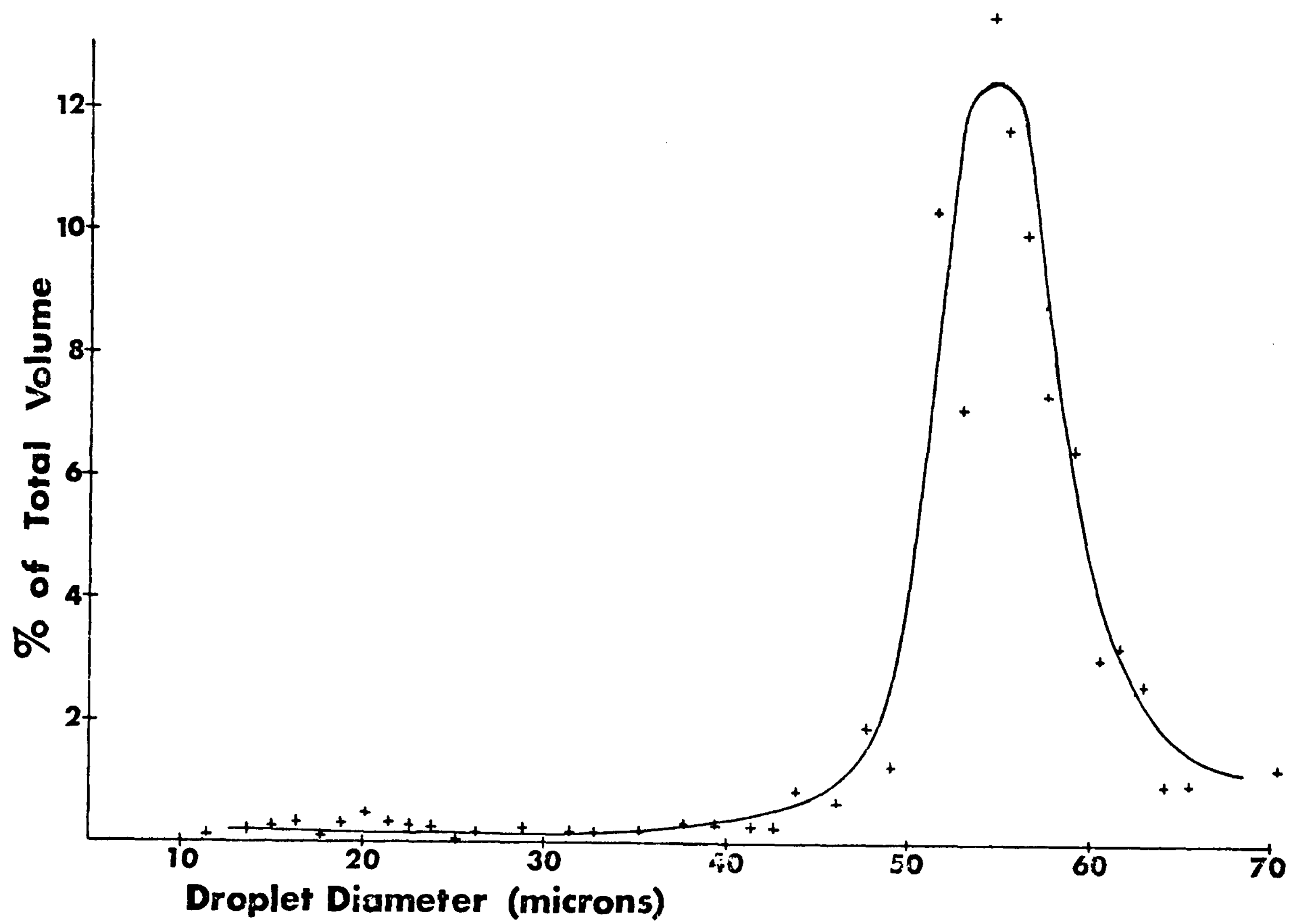


Figure 8. Representative probit plot for Beeco Mist Spray Spectra (60 micron polyethylene sleeve).

Figure 9. Beeco Mist spray spectra plot of actual values of percent volume accounted for by given droplet sizes in microns (60 micron polyethylene sleeve).



A Cessco pressure sprayer and Micro Gen HCS1-2AA sprayer were tested in a dynamic fan system within a large storage barn. The Cessco sprayer results are given in Table 11 for each nozzel at three pressure settings. The VMD values for all conditions were in the range of 20 microns. The Dmax values were generally around 30 microns. Representative plots are shown in Figures 10 and 11.

Table 11. Cessco sprayer tests results showing the VMD and Dmax values for nozzel sizes of 0.030 and 0.018 inches at three pressures on harps and teflon slides.**

Pressure	Collection Device	0.030 nozzel		0.018 nozzel	
		VMD*	Dmax*	VMD*	Dmax*
30 psi	Harp	14	27	12	24
	Teflon	22	29	19	27
40 psi	Harp	17	30	23	39
	Teflon	22	28	20	26
50 psi	Harp	15	31	21	30
	Teflon	25	31	20	26

*Values were obtained from the computer program predictions, based on average of two replicates with 200-500 droplets counted and sized for each replicate.
**Spray liquid was a pyrethrin formulation in freon.

The Micro Gen sprayer results are shown in Table 12. The VMD values were in the 25-30 micron range with Dmax values from 30 to 40 microns. Representative plots are shown in Figures 12 and 13.

The results of the field tests of the Micro Gen sprayer are given in Table 13. The only data collected for the harp was at the no cover location. At the other locations, due to the low rate of application and cover, insufficient number of droplets were collected on the harps to give a representative sample. The teflon slides had sufficient total droplets due to their greater collection surface. The no cover locations showed significant increases in the VMD and Dmax values over both grass and foliage covers.

Table 12. Micro Gen sprayer results for three flow rate settings using DOP and Harps and Teflon slides.

Flow Rate (oz/min)*	Collection Device	VMD**	Dmax**
0.5	Harp	29	37
	Teflon slide	28	36
1.0	Harp	22	28
	Teflon slide	28	36
1.5	Harp	24	35
	Teflon slide	29	37

*Flow rates calibrated for water; for DOP the flow rates were less.
**Values were obtained from the computer program predictions based on average of two replicates with 200-500 droplets counted and sized for each replicate. Values in Microns.

Table 13. Micro Gen tests in an abandoned field showing the penetration of droplets into the foliage, grass and open areas. DOP was the spray liquid; values are in microns, and are from the computer program and are based on 200-500 droplets per slide. Insufficient droplets were collected on the harps for a representative sample (at least 200 droplets) in the last three situations.

Location	Collection Device	VMD	Dmax
No cover	Teflon	49	65
	Harp	47	57
Grass cover	Teflon	17	23
Dense cover I*	Teflon	23	29
Dense cover II**	Teflon	13	17

*Dense cover I the collection device was about 16 inches from the spray nozzel.
**Dense cover II the collection device was about 36 inches from the spray nozzel.

Figure 10. Representative probit plot for Cessco spray spectra (0.018 inch nozzel and 50 psi).

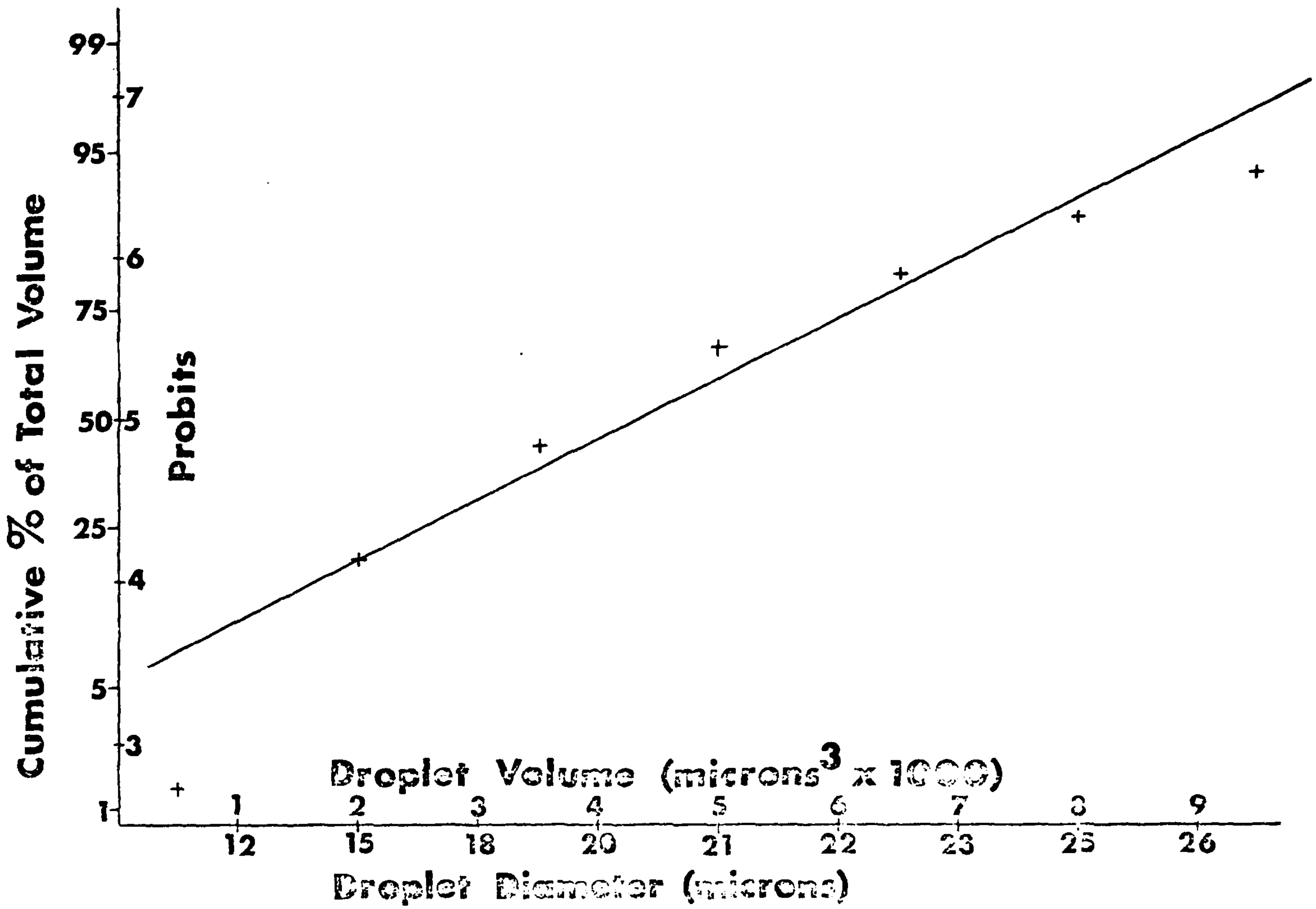


Figure 11. Cessco spray spectra plot of actual values of percent volume accounted for by given droplet sizes in microns (0.018 inch nozzel and 50 psi).

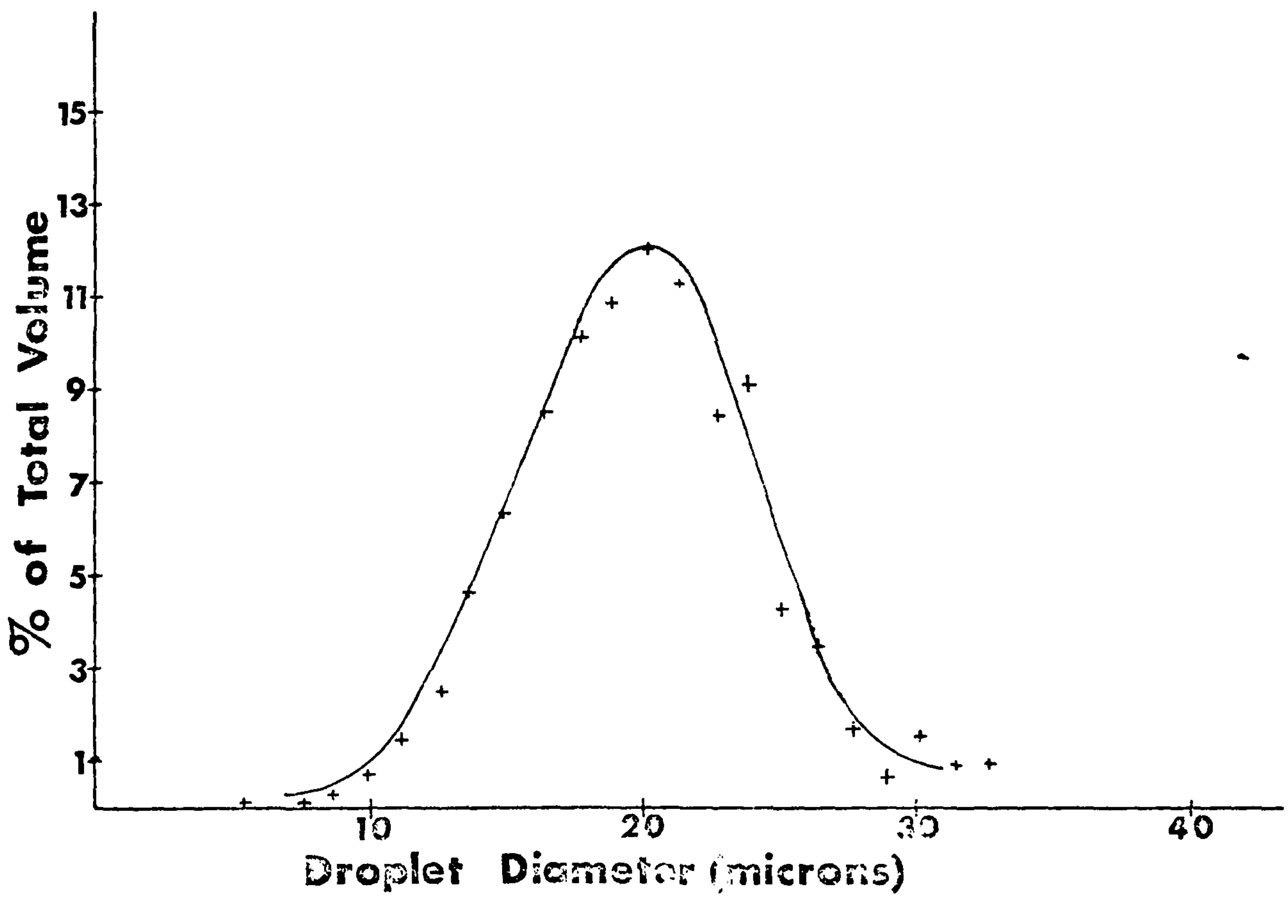
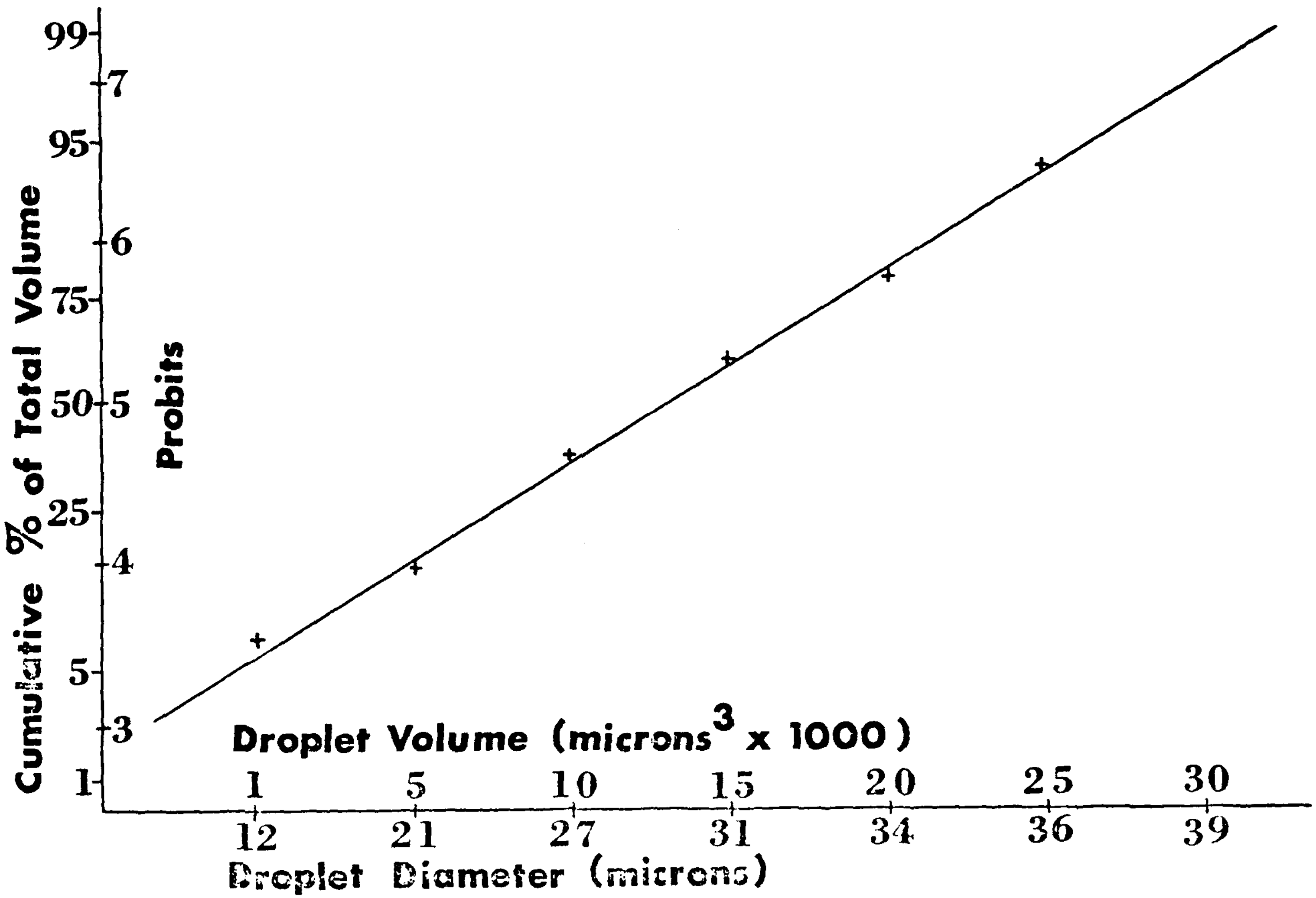


Figure 12. Representative probit plot for Micro Gen spray spectra (1.0 oz/min flow rate setting).



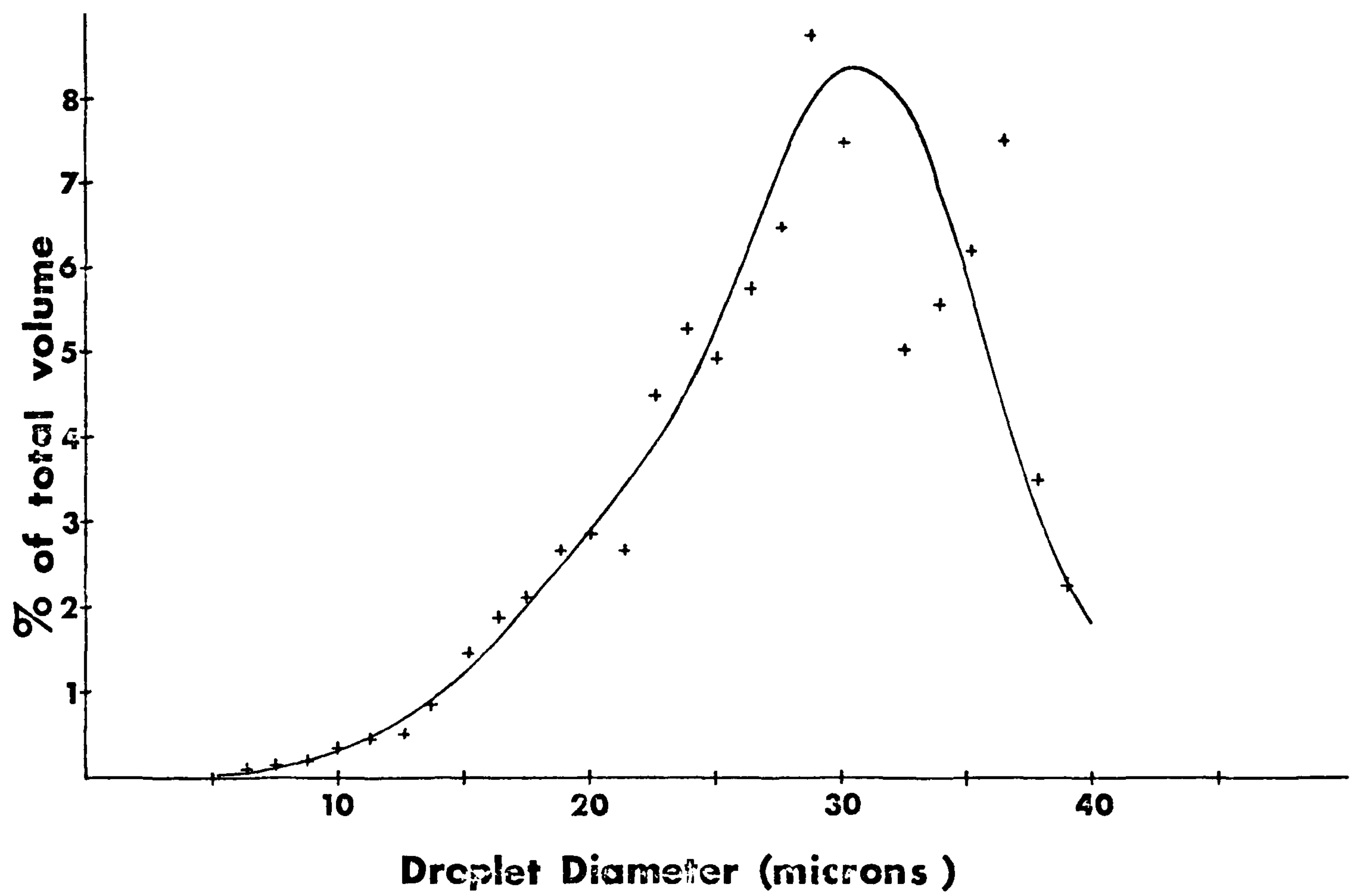


Figure 13. Micro Gen spray spectra plot of actual values of percent volume accounted for by given droplet sizes in microns (1.0 oz/min flow rate setting).

Discussion

The monodisperse droplets produced by the Berglund Liu generator made it possible to selectively study single size droplets of virtually any size. The impingement properties of individual size droplets could be determined. The production of monodisperse droplets has not been possible with normal spectra sprayers.

Spread factors are ambigious and a source of error in spray droplet studies. In these studies MgO slides were found to have a spread factor of 0.86. May (1949) reported the same value (0.86) for droplets above 20 microns. Teflon slides were found to have spread factors of 0.6 to 0.7 dependant on the spray liquid. Evans et. al. (1974) used 0.70 for malathion and 0.52 for klerol. These values compared to 0.68 and 0.63, respectively, in this research. Differences in spread factors and the need to determine the spread factor for each spray formulation and collection surface, emphasizes the need for standardization of detection devices.

Volatility of spray formulations was also found to affect spread factor determination. Most insecticide formulations contain volatile solvents such as water, kerosene, and petroleum distillates. The evaporation rate of these materials varies, so that some may evaporate before impingement occurs, while others evaporate on the impingement device. In the laboratory reasonable estimates of spread factors for formulations with volatile components by sizing droplets immediately after impingement, or by allowing evaporation to reach completion and basing the spread factor on the non-volatile portion of the formulation. In the field, droplets cannot be sized before evaporation occurs, so spread factors would have to be based on the non-volatile component of the formulation. Differences in volatility of solvents and insecticides are major factors in field evaluations of droplet size.

The effect of velocity on spread factors was tested from 1 mile per hour to 50 miles per hour. It was expected at some point, increasing velocity would increase the apparent droplet size. For droplets up to 60 microns, no effect on spread factor was observed on teflon slides.

As a check on the efficiency of droplet collection devices, the droplet impingement harp was designed as a zero critical impingement device. The strands and harp design offered no resistance to air flow. The strand diameter is less than the diameters of the impinging droplets, so that efficiency of impingement was maximized. The 5 micron wire due to its diameter and impingement properties and relative ease in handling was the most acceptable material found. The efficiency of small diamter wires is directly related to their size. Yeomans (1949) discussed the increased probability of particles striking an object as the object size decreases. Rathburn (1970) suggested the use of small diameter wires as a more efficient means of collecting droplets. Ranz and Wong (1952) determined the efficiency of wires from 80 to 9000 microns (0.08 to 9.0 mm). They found efficiencies approached 100% for

80 micron wire at wind speeds of 3-8 miles per hour. The droplet impingement harp with 5 micron strands allowed for direct sizing of droplets down to 10 microns with no spread factor correction.

The harp with 5 micron wire was efficient for small droplet impingement for droplets from 10 microns to over 50 microns. The uppper limit of the 5 micron wire was not found, but the harp could be used efficiently for virtually any size droplet by the addition of larger diameter wires. In the tests, 15 micron wires were found to be effective above 25 microns. Larger diameter wires, which are commercially available, used with 5 or 15 micron wire would detect the presence of droplets too large to impinge efficiently on the smaller wires.

The impingement harp is an effective way to test the efficiency of droplet collection devices for small droplet sprays (0-60 microns). In large scale field use, difficult and tedious preparation would limit its widespread use. For small droplet sprays, the droplet impingement device is the only field use device available to give a total representative sample of the spray spectra. Once strung, the harp can be used several times. With the photographic method, the harp is a valuable tool for checking the efficiency of field use devices and small spectrum spray studies.

The tests with insects showed the efficiency of insect surfaces in collection of droplets below 60 microns. Mount (1970) showed the increased efficiency in impingement of droplets in the range of 5-25 microns MMD on flying mosquitoes over mosquitoes at rest. Pieper (1972) showed small targets (of sizes similar to insects) collected droplets of less than 60 microns with greater efficiency than larger surfaces. Hadaway and Barlow (1965) found droplets up to 60 microns with greater efficiency than larger surfaces. Hadaway and Barlow (1965) found droplets up to 60 microns deposited more readily on tsetse flies than on other artificial surfaces. The efficiency of biological surfaces in collecting droplets has been well documented. Uk (1975) showed the increased number of droplets on cotton foliage and *Heliothis* larvae compared with artificial surfaces. The tests conducted in this research showed droplets readily impinged on setae and protuberances on insect surfaces and increased numbers of droplets on *M. domestica* adults that were forced to fly in an air stream over those at rest.

The tests conducted with the Micro Gen sprayer on penetration of droplets through foliage showed the foliage filtered droplets by size. The VMD of the droplets collected decreased as the spray penetrated through increased foliage. In heavy folaige only droplets of less than 30 microns were collected. Himel (1969), with the fluorescent particle method found forest canopies were efficient filters for droplet sprays. The conclusions of these studies were that droplets of less than 100 microns were the only droplets that could reach the protected habitats of insects within the forest canopy.

In the enclosed spray room tests, the non-uniform deposition patterns were a result of the effects of the room and sprayer position. Large droplets were collected as they fell out of the spray cloud due to the effects of gravity. Small droplets swirled around the room in the air blast from the sprayer. Mount (1972) used a settling room to sample droplets. He compared this method to impaction and hand-wave collection techniques. In the settling chamber, a sprayer was slowly passed by an open door, the door was shut, and the room sealed for 24 hours. It was concluded collection by settling chambers and impaction yielded unbiased droplet samples. Evans et. al. (1974) used teflon slides in settling chambers to collect droplets. Their results showed varibility inherent in the location of the slide within the chamber. Slides closest to the sprayer had the largest MMD and Dmax values and large droplets were found not to drift within the room.

From the results in this research it was concluded that enclosed settling chambers affect the impingement of droplets by the location of the collection device. Large droplets either fall out of the spray cloud in front of the sprayer or impinge on the wall opposite the sprayer as the air blast hits the wall. It is not possible to get a representative sample by this method.

After these test results became apparent, sprayers were tested in a moving air system in which the entire cloud was carried by a turbulent air mass. The turbulance mixed the cloud evenly within the air mass. The velocity was determined at varying distances from the spray nozzel. Collection devices were located at the point where the velocity was 10-15 miles per hour. This velocity was sufficient to impinge 10 micron droplets efficiently on teflon slides without any effect on spread factor.

At first the system was used outside, but it was found to be dependant on relatively calm conditions. External air influences caused swirling and difficulty in sampling. Therefore, the fan system was moved into a room large enough to minimize the effects of the enclosed spray room. An air mass, sufficient to carry and mix the total droplet spectrum with sufficient velocity to reach the impingement devices and efficiently impinge the total spectrum produced by the sprayer, is felt to be the most representative method to sample a spray droplet spectrum. A wind tunnel which would totally eliminate external effects, carry and mix the droplet cloud, and not introduce effects of its own would be the ultimate way to sample by this method.

The three sprayers tested were all found to have small droplet spectrums. The Beeco Mist sprayer had a spectrum which is representative of an optimum droplet size approach to insect control. Ninety percent or more of the mass produced by the sprayer was found in a narrow range of droplet sizes from 40-65 microns in diameter, large enough to eliminate much of the drift potential, yet small enough for penetration and impingement on the target insects.

The Micro Gen and Cessco sprayers are predominately used for interior pest control. The spectra of these sprayers were found to have very small droplet spectra well suited to interior control. The Cessco sprayer was found to have the lowest overall Dmax and VMD values.

A predictable amount of the volume of droplet spectra can be found in the size ranges which are generally not collected by present collection methods. With droplet spectra that have an VMD above 60 microns, the percentage of volume contained in droplets below 20 microns is negligible. Spray spectra with VMD values of 30-60 microns will have 5 percent or less of the volume below 20 microns. Spray spectra with VMD values below 30 microns have the majority of their volume in the 20 micron range. These approximations could be used in field use situations in which sampling devices are biased against small droplets (less than 20 microns).

Analysis of collected data is another source of controversy in droplet studies. Number average diameters, number means, and various other values have been used to describe spray spectra. The only way to compare spray spectra on a meaningful basis is by a Volume (mass) analysis of the data. Insecticidal control deals with delivery of insecticide on the basis of volume per acre. For efficient control, the majority of that volume must be contained within droplet diameters effective in delivery of a lethal dose to the insect. The sprayers tested in this study contained as many or more droplets in the 0-20 range, but these droplets accounted for less than 5 percent (except Cessco) of the total mass of the spray. Therefore, sprayer studies based on numbers of droplets indicate nothing about the efficiency of the sprayer. To characterize a sprayer, the volume median diameter must be determined, along with the maximum droplet size produced (Dmax), and the range in which a given percentage of the mass is contained.

For these reasons, the data was assembled, and then, to give a statistical comparison on which the various tests could be compared, the data was put into a computer program to find predicted values of VMD, Dmax, and a range between which 95% of the volume was found.

The bell shaped curves of the actual data are given in Chapter 3. Bell curve plots are commonly presented for droplet spectrums and show in picture form what the spectra look like. But the essential and meaningful information must be drawn from a plot which used a standard method to process the data. A statistically derived plot (as presented in the probit plots in Chapter 3) takes random variation and statistically predicts values by which the sprayer can be characterized.

Summary

The objectives of this research were to study factors affecting droplet impingement in order to develop fundamental data for a standardized methodology of field assessment for spray droplet size. The results have been:

(1) Monodisperse (single size) spray droplets were produced using

the Berglund Liu generator. These droplets were used to find spread factors for field use impingement devices, teflon slides (0.6 to 0.7 dependant on the spray liquid) and MgO slides (0.86). No effect on spread factor due to velocities of 1-50 miles per hour was found on teflon slides for droplets below 60 microns.

(2) Critical impingement velocities for droplets below 60 microns on teflon slides were found to be major factors in impingement of droplets on slides and impingement cards. Air velocities of 15 miles per hour were found to impinge 10 micron droplets on teflon slides. The critical impinge-velocity approaches zero as the droplet size increased.

(3) Teflon slides were found to be inefficient under static field conditions for droplets below about 25 microns. Dynamic conditions and impaction of small droplets at velocities equal to or above their critical impingement velocity were needed to sample spray spectra on teflon slides.

(4) A new collection device, the spray droplet impingement harp, was developed for zero critical impingement studies of spray droplets greater than 10 microns and calibration of field use devices. The harp employs small diameter strands (5 micron tungsten wire) to efficiently collect droplets measurable to 10 microns.

(5) A droplet sampling system, employing dynamic conditions and air mass to carry the droplet cloud at velocities sufficient to impact 10-15 micron droplets on teflon slides, was found to be the most representative method to study spray spectra. The droplet impingement harp was the only collection device that samples the total spectra of small droplet sprays. Teflon slides are the most efficient and easiest to use of conventional collection devices, if their inefficiency in collecting small droplets below 25 microns under static field conditions is recognized. If teflon coated 1 x 3 inch slides are used in field studies impaction velocities of 15 MPH are required. The use of the droplet impingement harp, in conjunction with teflon slides in a dynamic sampling system, gives a total unbiased insecticide spray spectra.

BIBLIOGRAPHY

Anderson, C. H. and W. Schulte. 1971. Teflon as a surface for deposition of aerosol droplets. Mosq. News 31(4): 497-504.

Berglund, R. and B. Liu. 1973. Generation of monodisperse aerosol standards. Environ. Sci. Technology 7: 147.

Brooks, F. A. 1947. Dynamic catch of aerosols by obstructions. Agr. Eng. 28: 233-8.

Burt, E. C., E. P. Lloyd, D. B. Smith, W. P. Scott, J. R. McCoy, and F. C. Tingle. 1970. Boll weevil control with insecticide applied in sprays with narrow-spectrum droplet sizes. J. Econ. Entomol. 63(2): 365-70.

Cadle, R. D. and E. J. Wiggins. 1953. Direct photomicrography of aerosol particles. Chem. Eng. News 31: 3074.

Chamberlain, A. C. 1967. Transport of Lycopodium spores and other small particles to rough surfaces. Proc. R. Soc. A. 296: 45-70.

Chamberlain, A. C. and R. C. Chadwick. 1972. Deposition of spores and other particles on vegetation and soil. Ann. Appl. Biol. 71: 141-158.

Davis, J. M., W. E. Waters, D. A. Isler, R. Martineau, and J. W. Marsh. 1956. Experimental airplane spraying for spruce budworm control. J. Econ. Entomol. 49(3): 388-41.

Evans, E. S., C. D. Davenport, J. H. Nelson, and N. E. Pennington. 1974. Preliminary assessment of practical alternates to the hand-wave method for the field collection of ULV size aerosol droplets. Proc. New Jersey Mosquito Extermination Assoc. 240-48.

Frazer, R. 1957. The fluid kinetics of application of pesticidal chemicals. Advances in Pest Control Research (Medcalf, R. Ed.) Interscience, New York.

Fuchs, N. A. 1964. The Mechanics of Aerosols. (Translation edited by Davies, C. N.) Pergamon Press, Oxford. 408p.

Gabor, D. 1972. Holography, 1948-1971. Science 177: 299-313.

Gregory, P. H. 1951. Deposition of airborne Lycopodium spores on cylinders. Ann. appl. Biol. 38: 357-76.

Gregory, P. H. and O. J. Stedman. 1953. Deposition of airborne Lycopodium spores on plane surfaces. Ann. appl. Biol. 40: 651-74.

Hadaway, A. B. and F. Barlow. 1965. Studies on the deposition of oil drops. Ann. appl. Biol. 55: 267-74.

Himel, C. M. 1974. Analytical methodology in ULV. Br. Crop Prot. Conc. Mongr. No. 11.

Himel, C. M. 1969a. The fluorescent particle spray droplet tracer method. J. Econ. Entomol. 62(4): 912-6.

Himel, C. M. 1969b. The optimum size for insecticide spray droplets. J. Econ. Entomol. 62(4): 919-25.

Himel, C. M. 1969c. The physics and biology of the control of cotton insect populations with insecticide sprays. J. Georgia Entomol. Soc. 4: 33-40.

Himel, C. M., and A. D. Moore. 1967. Spruce budworm mortality as a function of aerial spray droplet size. Science 156: 1250-1.

Himel, C. M., and A. D. Moore. 1969. Spray droplet size in the control of spruce budworm, boll weevil, bollworm, and cabbage looper. J. Econ. Entomol. 62(4): 916-8.

Himel, C. M., R. Vaughn, R. Miskus, and A. Moore. 1965. A new method for spray droplet assessment. U. S. Forest Service Res. Note PSW-87.

Keathley, J. 1972. Distribution of insecticide sprays and efficiency in application. PhD. Thesis, Department of Entomology, University of Georgia, Athens, Georgia.

Latta, R., L. D. Anderson, E. E. Rogers, V. K. LaMer, S. Hochberg, H. Lauterback, and I. Johnson. 1947. The effect of particle size and velocity of movement of DDT aerosols in a wind tunnel on the mortality of mosquitoes. J. Wash. Acad. Sci. 37(11): 397-407.

Lofgren, C. S. 1970. Ultra low volume applications of concentrated insecticides in medical and veterinary entomology. Ann. Rev. Entomol. 15: 321-42.

Lofgren, C. S., D. W. Anthony, and G. A. Mount. 1973. Size of aerosol droplets impinging on mosquitoes as determined with a scanning electron microscope. J. Econ. Entomol. 66(5): 1085-8.

May, K. R. 1945. The cascade impactor: an instrument for sampling coarse aerosols. Jour. Sci. Instrum. 22: 87-95.

May, K. R. 1949. The measurement of airborne droplets by the magnesium oxide method. Jour. Sci. Inst. 27: 128-30.

May, K. R. and R. Clifford. 1967. The impaction of aerosol particles on cylinders, spheres, ribbons and discs. Ann. Occup. Hyg. 10: 83-95.

Mount, G. A. 1970. Optimum droplet size for adult mosquito control with space sprays or aerosols of insecticides. Mosq. News 30: 70-75.

Mount, G. A. and N. W. Pierce. 1972. Droplet size of ultra-low volume ground aerosols as determined by three collection methods. Mosq. News 32: 587-9.

Orr, C. 1966. Particulate Technology. Macmillan Co., New York, 562p.

Pieper, G. R. 1972. Effect of target size and air movement on drop impingement efficiency and drop size distribution. J. Econ. Entomol. 65(3): 884-6.

Potts, S. F. 1958. Concentrated Spray Equipment. Dorland Books, Caldwell, N. J., 598p.

Randall, A. P. 1974. ULV-changing concepts and technology for the control of the spruce budworm in canadian forests. Br. Crop Prot. Conc. Monogr.

Ranz, W. R. and J. B. Wong. 1952. Impaction of dust and smoke particles on surface and body collectors. Indust. Eng. Chem. 44: 1371-81.

Rathburn, C. B. 1970. Methods of assessing droplet size of insecticidal spray and fogs. Mosq. News 30(4): 501-13.

Rathburn, C. B. and A. F. Miserocchi. 1967. Direct photomicrography of airborne droplets. J. Econ. Entomol. 60(1): 247-54.

Roberts, R. B., R. L. Lyons, M. Page, and R. P. Miskus. 1970. The use of laser holography to study insecticide particles. Science 165: 1250-3.

Smith, D. B., W. P. Scott, and E. P. Lloyd. 1973. Selected spray droplet sizes and cotton varieties for bollworm control. J. Econ. Entomol. 66(1): 260-261.

Uk, S. 1975. The concept of biological optimum droplet sizes with particular reference to cotton in the Sudan Gezira. Workshop on ULV spraying for cotton pest control. Big Bend, Swaziland.

Yeomans, A. H. 1952. Influence of particle size on application of insecticide sprays. Advan. Chem. Ser. no. 7, Amer. Chem. Soc. Washington D. C.

Yeomans. A. H. 1960. A method of determining particle size of liquified-gas aerosols. USDA Agricultural REs. SEr. ARS-33-5.

Yeomans. A. H., E. E. Rogers, and W. H. Ball. 1949. Deposition of oil drops. Ann. Appl. Biol. 55: 267-74.

ACKNOWLEDGEMENT

We would like to thank Dr. H. R. Hermann Jr. and Dr. R. E. Bargmann for their help in portions of this work. In addition, I would like to thank Mr. R. E. Morton for his assistance in the design and construction of the equipment used in this research. Dr. Hermann developed the photographic method which was a major key in field use of droplet harps and droplet slides.