

**PESTICIDE SPRAY APPLICATION,
BEHAVIOR, AND ASSESSMENT:
WORKSHOP PROCEEDINGS**

**PACIFIC
SOUTHWEST
Forest and Range
Experiment Station**

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Experts from relevant disciplines exchanged information on three important problems of pesticide spray technology. The four papers presented are *Physical Parameters Relating to Pesticide Applications* by N. B. Akesson and W. E. Yates; *The Micrometeorology and Physics of Spray Particle Behavior* by H. E. Cramer and D. G. Boyle; *Impact of Zectran Particles on Spruce Budworm Larvae: A Field Experiment* by J. W. Barry and Others; and *Assessment of Insecticide Spray Processes* by C. M. Himel. Summaries of the three workshop sessions are also included.

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PATRICK J. SHEA, a research entomologist at the time of the workshop, is now supervisory research entomologist in charge of the Station's Field Evaluation of Chemical Insecticides. He joined the Station staff in 1967, and earned the M.S. degree in forest entomology in 1974 at the University of California, Berkeley. ROBERT L. DIMMICK, a research bacteriologist, is chairman of the Aerosol Sciences Department of the Naval Biosciences Laboratory, Oakland, California. He holds a doctorate in microbiology from Purdue University, Lafayette, Indiana. ALVIN M. TANABE was formerly an assistant research entomologist at the Naval Biosciences Laboratory. He holds a doctorate in entomology from the University of California, Berkeley.

PREFACE

The purpose of this workshop was to bring together experts from all scientific disciplines to exchange information and ideas on three of the most important problems of pesticide spray technology -- application, behavior and assessment. The broad range of scientific talent represented and the scope of the effort needed to keep abreast of this field are evident from the list of participants in the workshop.

There has been a growing tendency to emphasize the importance of controlling the spray cloud and the droplet (particle) size and the necessity of monitoring meteorological conditions. Increased concern over aerial application technology has developed for several reasons, including: (1) use of pesticides that biomagnify and adversely affect nontarget organisms, (2) increased use of transient insecticides and decreased use of residual insecticides, (3) increased awareness of the pollution problems resulting from drift and (4) increasing knowledge of the effective particle spectrum of contact insecticides.

It was our hope that this workshop would provide a common meeting ground for the free exchange of information and ideas among the workshop attendees. Judging by the contents of these proceedings, an excellent start was made toward accomplishing this goal. Certainly, the response to the call for committee members to aid in developing standards and guidelines was a good indication of the enthusiasm generated by the workshop.

The workshop was sponsored by two organizations. The Insecticide Evaluation Project, USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, was organized to develop safe, selective, nonpersistent, and effective materials and techniques to manage forest insect pest populations with minimal environmental effects. The program of research was divided into four problem areas: (1) screening and bioassay of candidate chemicals and formulations for selection of those most effective for control of specific insect pests; (2) chemistry and toxicology of selected chemicals, which includes synthesis and formulation of selected candidates, physiological and biochemical effects in insects, residue analysis, and spray particle behavior; (3) penetration, translocation, and metabolism of chemicals on and in forest trees to develop effective foliar systemic treatments; and (4) field evaluation of insecticide formulations to determine safety and efficacy.

The Naval Biosciences Laboratory, formerly the Naval Biomedical Research Laboratory, is a research unit funded in large part by the Office of Naval Research and the Bureau of Medicine and Surgery, United States Navy, and administered through the School of Public Health, University of California. Grants and contracts from other government agencies are also part of the funding structure. The Laboratory is located at the Naval Supply Center, Oakland, California. The primary specialty of the Laboratory is aerobiology and the study of respiratory disease and allied medical problems. Unique equipment and facilities have been constructed to permit the study of aerosols under highly controlled conditions, including the exposure of test animals to airborne particles.

The smooth functioning of the workshop would not have been possible without the aid of Patrick Shea of the Pacific Southwest Forest and Range Experiment Station, Berkeley, and Richard Dimmick and Alvin Tanabe of the Naval Biosciences Laboratory, Oakland. They provided assistance in planning the workshop and taking care of many details essential to its success. The help of Rose Marie Shea, Eileen Dimmick, Pat Tanabe, and Betty Roberts, together with staff members of the two organizations, who served as projectionists, chauffeurs, and secretarial assistants, was indispensable.

RICHARD B. ROBERTS



This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate State and/or Federal agencies before they can be recommended.

CAUTION: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife--if they are not handled or applied properly. Use all pesticides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and pesticide containers.

Trade names and commercial enterprises or products are mentioned solely for necessary information. No endorsement by the U.S. Department of Agriculture is implied.

WELCOME ADDRESS

Harry W. Camp¹

Welcome to this workshop concerned with pesticide spray technology. This meeting is particularly significant because of the use of chemicals in today's "atmosphere" of critical need for improving the production of food and fiber, in a situation where improvement of the quality of our environment and lowering of costs are every bit as critical. There are forces of men at work in both areas, and only through their cooperative efforts will we arrive at an acceptable solution to the problem of producing adequate supplies of food and fiber at acceptable costs in an environment suitable to all of us.

This workshop is a cooperative venture of the Naval Biomedical Research Laboratory,² Naval Supply Center, Oakland, California, and the Insecticide Evaluation Project, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. The general objectives of these two research units are outlined in your program so I shall not repeat them. Special credit is due to Mr. Allen Jewett, Head of the Microbiology Branch, Naval Biology Program, and Dr. William Waters, Head of Forest Insect Research, U.S. Forest Service.³ These two men from Washington D. C., are responsible for bringing together the two sponsoring units here in the Bay area. Locally, Dr. Richard Roberts and Mr. Patrick Shea of the Pacific Southwest Station, and Drs. Robert Dimmick and Alan Tanabe of the Naval Biomedical Research Laboratory are responsible for arranging the excellent program ahead of you.

I would be happy to dwell at length on the importance of the research being done in pesticide application, behavior, and assessment, but the fact you are here leads me to believe you are well aware of its importance.

It is with a great deal of pleasure I welcome you, on behalf of Dr. Neylan Vedros, Director of the Naval Biomedical Research Laboratory, and myself, to Berkeley and to this workshop on Pesticide Spray Technology. May you have a highly successful meeting.

¹At the time of the workshop, Mr. Camp, now retired, was Director, Pacific Southwest Forest and Range Experiment Station, Berkeley, California.

²The Naval Biomedical Research Laboratory is now the Naval Biosciences Laboratory.

³Dr. Waters is now Dean of the College of Natural Resources, University of California, Berkeley.

APPLICATION

Physical Parameters Relating to Pesticide Application

Norman B. Akesson¹ Wesley E. Yates¹

ABSTRACT--Integrated control of crop-damaging insects includes judicious application of pesticides. Dispensing equipment is available in wide variety to produce various drop sizes ranging from aerosols to coarse sprays. Size ranges and frequency distributions of drops produced by different types of equipment have been determined. Actual field deposit and insect contact rates are affected by chemical, physical, and biological factors. Ultra-low-volume spray techniques are being increasingly used, with varying success. Local meteorology, particularly temperature inversions, strongly affects spray dispersion and helps to determine suitable times for application.

A host of measures have been used in man's never-ending fight to protect his health and that of his domestic animals, and to protect and insure an abundant food supply in the face of an ever-increasing population and demands for a higher standard of living. In recent years, the widespread occurrence of pesticide chemicals in the environment, along with increasing pollution from industrial and agricultural sources has caused increasing concern for protection of the environment as well.

The folly of total dependence on any one of the many measures available for pest control, such as our recent overuse and reckless use of pesticide chemicals, has been clearly demonstrated by nature's reaction to such poorly designed measures. Examples are the development of insect resistance and the even more dangerous elimination of parasites and predators beneficial in controlling our economically important insects. Under these changed conditions, such insects can quickly destroy a crop despite frequent applications of larger and larger amounts of the most toxic chemicals.

This problem has led to a return to total crop management, or what is called integrated control. This is not a new concept, but one that was, of necessity, widely practiced before synthetic pesticides were available. The concept has been defined as the use of combinations of physical, biological, and chemical measures that have been found to

supplement and enhance one another, so that the coordinated efforts may achieve the highest degree of effective control. Thus, integrated control includes crop management, management of waste disposal and sanitation, and irrigation and drainage control, in addition to management and monitoring of crop pests, which includes consideration of seasonal and weather influences and biological means of control, and, most important, the judicious use and application of pesticide chemicals.

All these measures, normally directed toward maximizing crop production and reducing vector or forest insect population, must also be aimed at reducing the widespread indiscriminate use of pesticides, with their all-too-frequent injurious effect on the environment and the health of workers handling them.

New, more specific and biodegradable chemicals are needed, but there is also a need for greater use of biological control organisms, including predators, parasites, and microbial agents, as well as the more novel pheromones and juvenile hormones. These alone cannot overcome the pest problems today, or in the foreseeable future. But as part of an integrated control program, and especially in conjunction with chemical methods, they can achieve significant reduction in the need for chemical control, and substitute safer, less contaminating crop, forest, and vector control measures.

Important in careful pest control practices are (1) selection of chemicals best suited to the problems, but least damaging to the environment, (2) application of these at the proper time and place and in carefully metered dosages,

¹Department of Agricultural Engineering, University of California, Davis, California.

and (3) application in proper formulation and particle size, with consideration of weather and geographic influences, and other factors, such as safety to nontarget plants and animals.

EQUIPMENT

Suitable equipment, and effective and efficient techniques for its use, are as important as the chemical or biological agent itself. A wide selection of equipment for dispensing various formulations is available. The decisions governing the selection of equipment are momentous and all too frequently poorly evaluated. Whatever is immediately available, or the most popular machine of the day, may be the choice. The biologist tends to blame his failures on the machine, but all too frequently he is not sufficiently aware of how the basic machine functions, such as what particle sizes it produces; he is not familiar with techniques of volume metering or application placement, and the relation of these to weather and terrain.

Solid formulations, as dusts and granules, offer a fixed concentration of toxicant and fixed particle size, and thus also a limited application or use. A few materials control insect or disease pests through systemic transfer of chemicals from foliage or roots to all parts of the plant. There is a larger choice of systemic herbicides. Of existing systemic pesticides, probably the safest least-contaminating type of formulation is nondusting large granules, or the microgranule or coarse dust, in which all particles below about 50 μm in diameter have been eliminated. Ground-operated equipment for granules are of several types; the conventional swath-width hopper, the centrifugal slinger (broadcast), and the air carrier (broadcast). For helicopters, slinger spreaders and air carriers are popular, but for fixed-wing aircraft, the ram air spreaders are probably most widely used.

Spray formulations offer a wide choice in toxicant strength, particle size, and total applied volume per application. For depositing-type sprays, and for vertical penetration of foliage, large particle sizes are found desirable as applied by pressure nozzle, boom, and offset nozzle equipment, as well as air carrier application machines. For finer sprays and aerosols, special types of equipment capable of high atomization energy are found desirable. These may be high pressure hydraulic nozzles, producing drops down to about 125 μm volume diameter (vmd), two-fluid (air and liquid) nozzles, or volatile-type two-fluid nozzles, which can produce atomization as fine as 10 to 15 μm vmd. Similarly, aircraft have been set up for all ranges of drop sizes of sprays and aerosols, and for a wide variety of application volumes from several gallons to a few ounces per acre. Obviously the equipment must be matched to the formulation, either dry or liquid, but much more particularly so when liquids are to be used for distinct and specified operations, such as adulticiding as opposed to larviciding in mosquito control.

Atomizers for liquid sprays and aerosols may be categorized as follows, by the source of the atomizing energy:

Pressure	Centrifugal
Jet	Disk or cup
Cone (hollow & solid)	Brush
Fan	Screen or perforated cylinder
Deflector fan	
Offset	
	Gaseous
	Vortical: low pressure, high volume
	Shear
	High pressure, low volume

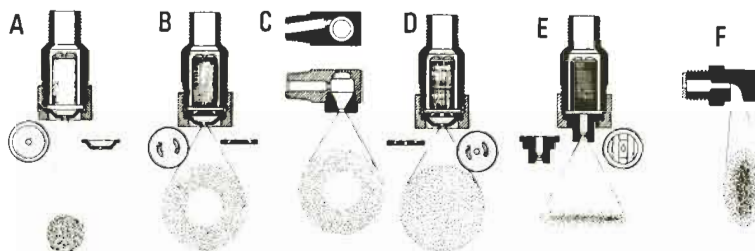


Figure 1. Pressure-type atomizers produce a wide range of drop sizes suitable for both aircraft and ground machine use. From left to right, (a) jet, (b) hollow cone showing whirl plate, (c) centrifugal-type hollow cone, (d) solid cone showing hole in whirl plate, (e) fan, and (f) deflector fan.

Pressure energy nozzles—The jet nozzle (fig. 1a) and the deflector fan nozzle (fig. 1f) produce sprays of large drop size. These two may be operated at pressures from a few pounds per square inch to a hundred or more, but to produce large drops with a minimum of small driftable drops, pressures should not exceed 5 to 10 lb/in². The use of these nozzles is confined to such applications as larviciding for mosquito control, or to low-drift-loss applications of herbicides by aircraft or ground equipment.

The fan and cone types are the most widely used pressure energy nozzles on aircraft or ground equipment. Drop size may range from 100 to 1000 μ m, varying primarily with liquid pressure. If liquid is discharged into an air stream, the air shear action increases the liquid break-up, increasingly so as the two streams approach 90 degrees or are directed toward one another. The fan types (fig. 1e, f) are most used with ground equipment where uniform cover is needed, whereas the cone types (fig. 1b, d), with stainless steel (hardened) orifices and whirl plates, are widely used with aircraft and air carrier ground equipment. Drop size ranges for cone types are from 125 μ m vmd to 500 μ m vmd.

Gaseous energy atomizers—The gaseous energy, two-fluid-type atomizers (fig. 2) are capable of sprays ranging from fine to aerosol-size particles. Pressures used may vary from a few pounds per square inch to several hundred, and because the energy required to produce an aerosol becomes rather significant in terms of the numbers of drops being produced, the aerosol-type atomizers are usually very sensitive to flow rates; drop size frequently increases rapidly as flow rate increases. Size range varies from 10 to 100 μ m vmd.

In the widely used cold fogger or vortical-type atomizer (fig. 3) air pressure seldom exceeds 5 lb/in², but air volume supplies energy at around 100 ft³/min for each nozzle.

Centrifugal energy atomizers—Rotary-type atomizers (fig. 4) include those with a perforated metal sleeve type driven by an electric motor; the widely used Micronair, which is air-propeller driven; and a smaller spinning screen device, powered by an electric motor. All of these produce fine sprays to aerosols, or a range of 300 to 50 μ m.

The centrifugal spinners have been used on both aircraft and ground equipment. However, they are susceptible to rapid wear and initial cost is high for good quality units.

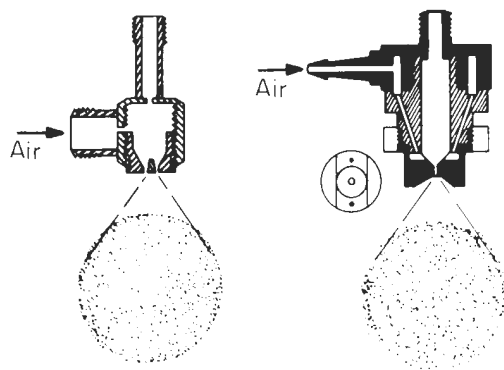


Figure 2. Two kinds of two-fluid atomizers are used: internal mixing (left), and external mixing (right). Both are designed for producing fine sprays and aerosols.

The spinners are very sensitive to flow rates, and increasing flow rate slows the air-driven types; the slower spinning, along with the increased flow of liquid, rapidly increases the drop size. Drop size range produced is similar to that of the two-fluid and hydraulic type atomizers; depending on the manner of operation.

In table 1, spray and drop size ranges and some of the atomizers that can be used to produce them are summarized. Pressures for liquid and air, and air speed for the rotary type nozzle, are also shown.

In table 2, for the various types of sprays and aerosols, and for the various drop sizes, the drop size distribution is shown, in cumulative percent. The 50 percent point corresponds to the volume median diameter² for the distribution of this type of spray, as produced by the nozzle specified in table 1.

The effectiveness of an aerosol is dependent upon the numbers of small drops, generally under 25 μ m, that are present. Thus it is easily seen why the aerosols are more effective for adulticiding; at least 97 percent of the drop volume is in drops below 20 μ m. In contrast, the very coarse spray,

²The volume median diameter is that size of drop which divides the total volume of drops found exactly in half; that is, 50 percent of the volume is in drops above that size and 50 percent below.

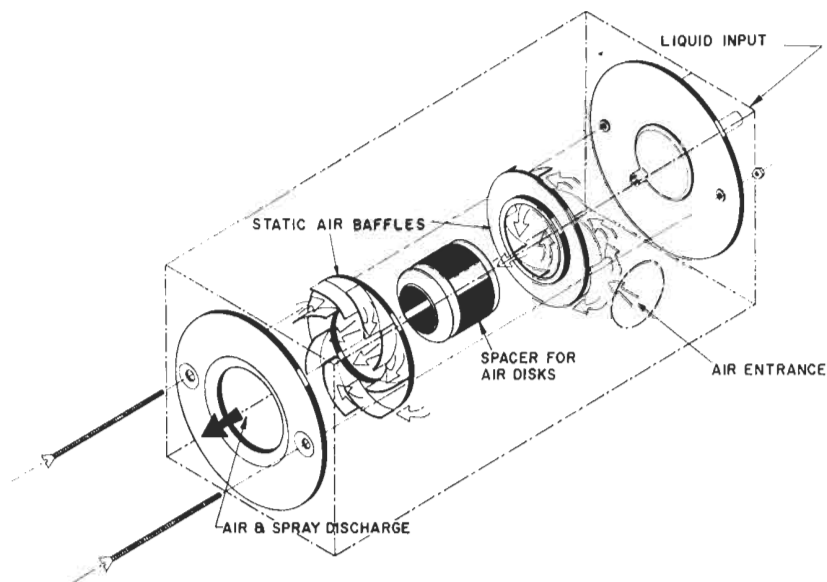


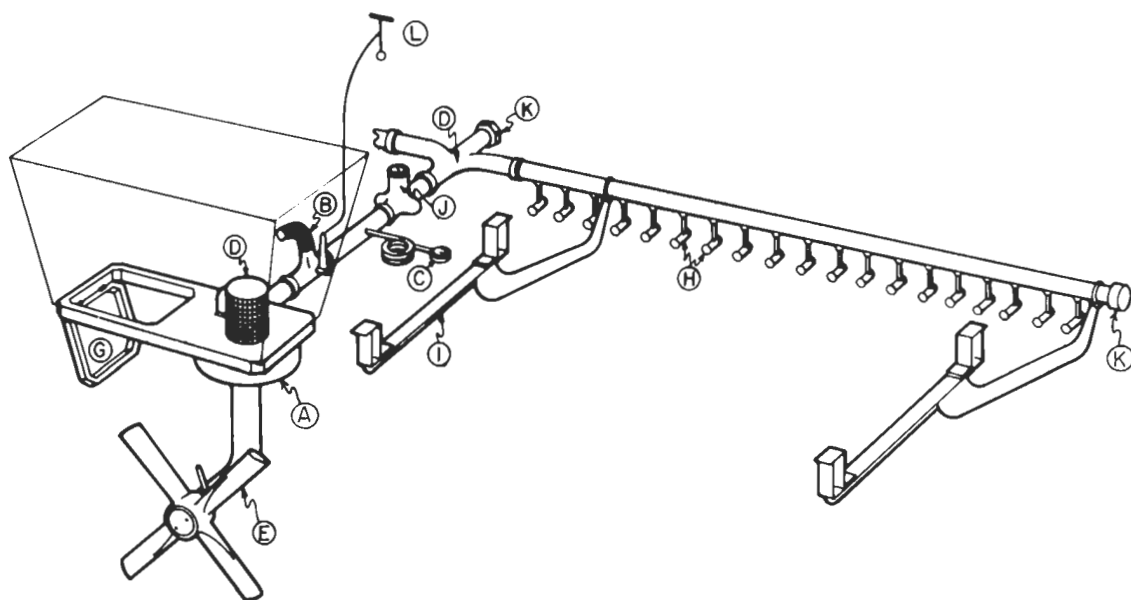
Figure 3. The vortical atomizer is shown here in an exploded view. Low pressure and high air volume produces aerosols as low as 10 microns volume median diameter.



Figure 4. Three kinds of centrifugal or rotary atomizers are shown here. The device at top has a perforated metal sleeve, and is electrically driven. In the center, the Micronair air-driven type has a spinning screen. At bottom another spinner has a stainless steel screen, and is electrically driven.

Table 1--Summary of approximate spray and drop sizes produced by the various atomizers

Spray size	Drop size range	Nozzle type	Operating constant
	<i>Microns</i>		
Fine aerosol	Less than 50	Cold fogger	5 lb/in ² air psi
Coarse aerosol	50 to 100	Two-fluid	30 lb/in ² air psi
Fine spray	100 to 250	Rotary	90 to 100 mph air velocity
Medium spray	250 to 400	65015 Fan, down	40 psi
Coarse spray	400 to 500	D6-46 Cone, back	40 psi
Very coarse spray	More than 500	D6 Jet, back	40 psi



- | | | |
|-------------------|------------------------------|-------------------|
| A - Pump | E - Propeller | J - Liquid |
| B - Control valve | G - Dump gate | K - Boom cleanout |
| C - Pressure gage | H - Nozzles and check valves | L - Valve lever |
| D - Screen | I - Boom mount | |

Figure 5. This schematic diagram shows a basic aircraft spray unit. Included are a tank (outline), spray pump and propeller drive, and the control valve, which directs liquid to the boom and nozzle during spraying or back to the tank for recirculation.

Table 2--Drop size distribution of
aerosols and sprays, cumulative percent by volume¹

Drop size (μm)	Fine aerosols	Coarse aerosols	Fine sprays	Medium sprays	Coarse sprays	Very coarse sprays
<i>Cumulative Percent</i>						
1-5	5	0.1				
5-10	45	0.4	0.1			
<u>11</u>	<u>50</u>					
10-15	77	2.0				
15-20	97		2.0			
20-40	100	12.0		0.1		
40-60		35.0	5.0	2.0	0.01	0.001
60-80						
<u>86</u>		<u>50.0</u>				
80-100		59.0	15.8	6.0	0.1	
100-120						
120-140					0.4	0.1
<u>130</u>			<u>50.0</u>			
140-180		100.0				
180-200			81.0	17.0	3.0	
200-220						
220-240					7.0	5.0
240-260						
260-280						
280-300			100.0	46.0	14.0	
<u>278</u>				<u>50.0</u>		
300-350					24.0	
350-400					36.0	
400-450					46.0	
<u>460</u>					<u>50.0</u>	
450-500				92.0	55.0	
500-600					74.0	25.0
600-700					88.0	
700-800					96.0	
<u>900</u>						<u>50.0</u>
800-1000				100.0	100.0	100.0

¹The volume median diameter (underscored) is that size of drop which divides the total volume of drops found exactly in half; that is, 50 percent of the volume is in drops above that size and 50 percent below.

such as that produced by the jet back nozzle, directed with the airstream, is for low-drift-loss applications, and shows less than 0.001 percent of drop volume in drops less than 60 μm (table 2).

Table 3, for aircraft use, summarizes drop size ranges and recovery rates. A complete aircraft spray unit is diagrammed in figure 5.

PARTICLE SIZE, DISTRIBUTION, AND COVERAGE

The success of pesticide applications depends largely on the particle size range of the spray or dry material, and on how this is affected by chemical, physical, and biological factors, some of which are described here:

1. The basic toxicity of the pesticide to the target pest. A small particle of a very toxic material may contain a lethal dose for the insect, whereas a larger drop or several small drops of a less toxic chemical may be required for lethal effect.

2. The physical characteristics of the chemical and its formulation, including density; flowability for dusts; and vapor pressure, viscosity, and surface tension for liquids. For liquids, these characteristics affect the initial atomization process, and the aerial transport, evaporation, and deposit of the drops.

3. The collection efficiency of target surfaces, such as insects, buildings, and vegetation. This follows Sell's law, whereby the collection efficiency (S) of an object is directly proportional to the drop diameter squared (d^2) and its relative velocity (V), but inversely proportional to the width or frontal area (D) of the object (figure 6). Thus, the collection efficiency of an object is increased rapidly by increased drop size and to a lesser degree by an increase in the relative velocity of the movement of the drop toward the object, but is decreased as the object size increases.

4. Location of the target insect, whether in the open or in a sheltered area, and in motion or at rest.

5. The local meteorological conditions. The presence and intensity of air turbulence, or the mixing and diffusion capacity of the air during application, greatly affect the dispersion of pesticides, particularly the small aerosol or airborne portions.

$$S(f) = \frac{d^2 V \rho}{D \mu}$$

$$S = \% \frac{d \text{ impacted}}{d \text{ available}}$$

d = drop diameter

V = drop to object velocity

ρ = drop density

D = object diameter

μ = fluid viscosity

(f) = object shape: plate > cylinder > sphere

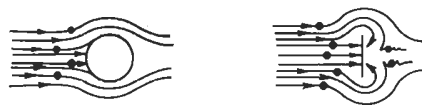


Figure 6. Sell's Law for deposit of liquid drops is illustrated here.

6. The type and characteristics of the ground cover. Grassy savannah or low-growing agricultural crops permit relatively unrestricted downwind transport of finely atomized sprays; increased bush and tree cover increasingly filters particles out of the air.

7. The characteristics of the application equipment, which determines the size range or frequency distribution of drops as well as the spatial distribution of all solid and liquid materials directed to the target area.

Generally, some optimum drop size range is recognized as most effective for each pesticide and for each formulation used for a specific vector control problem. Maximum effective control of the target organism with minimum use of toxic materials and minimum adverse impact on the ecosystem is the objective. This simple statement covers a highly complex physical and biological phenomenon that occurs during and following an area application of pesticides. Research toward the objective has been conducted over many years. The earliest work with Paris green and toxic botanicals progressed through petrochemical products, culminating in the extensive use of the synthetic pesticides, DDT and other organochlorines, as well as organophosphorous and carbamate materials.

Early observers found that although DDT and the other organochlorines are effective as direct contact applications, they are especially effective when used as residual applications. In contrast, many of the organophosphorus and carbamate compounds have a

Table 3--Spray drop size range, approximate recovery rate, and recommended use

Spray size or type and description of spray system	Typical nozzles and pressure ranges ¹	Drop size range ²	Estimated deposit in 1000 feet ³	Use
		<i>Microns $\mu\text{m vmd}$</i>	<i>Percent</i>	
<i>Coarse aerosols</i> Cone and fan nozzles, and rotary atomizers	80005 down D2-13 down (200 to 300 lb/in ²)	less than 125	less than 25	Aerosol applications, in vector control and control of forest insects and agricultural pathogens; used at low volume rates, primarily for adulticiding
<i>Fine sprays</i> Cone and fan nozzles, and rotary atomizers	80005 down D6-45 down (50 to 100 lb/in ²)	100 to 300	40 to 80	Forest pesticide chemicals, in large-area vector control, at low dosages of chemicals with low toxicity and rapid degradation; also useful for agricultural insect pathogens
<i>Medium sprays</i> Cone and fan nozzles, and rotary atomizers	D6-46 down (30 to 50 lb/in ²)	300 to 400	70 to 90	All low-toxicity agricultural chemicals where good coverage is necessary
<i>Coarse sprays</i> Cone and fan nozzles, spray additives	D6-46 back (30 to 50 lb/in ²)	400 to 600 with additives up to 2000	85 to 98	Toxic pesticides of restricted classification, when thorough plant coverage is not essential
<i>Sprays with minimum drift</i> Jet nozzles and spray additives	D4 to D8 down at less than 60 mph; Back at over 60 mph (30 to 50 lb/in)	800 to 1000 with additives up to 5000	95 to 98	All toxic, restricted--class herbicides such as phenoxy-acids and others, within limitations such as growing season and location near susceptible crops
<i>Sprays with maximum drift control</i> Low-turbulence nozzles	Microfoil (less than 60 mph airstream) ⁴	800 to 1000	99 or more	Restricted nonvolatile herbicides, phenoxy-acids and others in the area of susceptible crops, subject to limitations of growing season and type of crop

¹Spraying Systems Co. nozzles; position on aircraft boom is indicated as "down" or with the airstream.

²Determined with water base sprays; oils would give smaller drops.

³1000 feet downwind; wind velocity 3 to 5 mph, neutral temperature gradient; material released under 10 feet height.

⁴In drift tests, drift residue levels at 500 feet downwind for Microfoil were one-fourth those for D4 to D8 jets.

high contact and airborne toxicity to insects but degrade and lose effectiveness much more rapidly than the organochlorines, particularly in the presence of water.

Early researchers working on drop size presented data (verified in the laboratory and to some extent in the field) on the most efficient drop sizes to be used with given chemicals and on specified vectors. Latta and others (1974) calculated that the LD₅₀ for *Aedes aegypti* was obtained with minimum dosage when drops of 22.4 μm containing DDT were used with an air velocity of 2 mph past the mosquito. At 3 mph the drop size was found to be 18.3 μm , at 4 mph 15.8 μm , and at 5 mph 14.2 μm . Johnstone and others (1949) came to the conclusion that the most effective drop size of a 10 percent DDT oil solution for control of resting and flying mosquitos considering both impaction rate and lethal dose would be 33 μm . This, however, is still below the minimum drop size (83 μm) containing a lethal dose of DDT and, therefore, is a compromise size; impingement of several such drops is required to kill an individual mosquito.

Yeomans and others (1949) calculated from the Sell's law relationship (fig. 6) that a mosquito having a frontal width of 0.025 inch, at 2 mph air velocity, would collect 15.8 μm drops most efficiently. This size is somewhat smaller than Latta's 22.4 μm for 2 mph, because Latta used a smaller frontal width for his model mosquito. It has been shown in recent studies by Weidhass and others (1970) that with the newer highly toxic organophosphate materials, an LD₁₀₀ lethal dose for *Aedes taeniorhynchus* can be obtained from a 25- μm drop of malathion, a 17.5- μm drop of naled and a 20- μm drop of fenthion. These sizes are much closer to the size of drops earlier observers found to be most efficiently collected by small insects; such drops did not contain lethal doses of organochlorines, however. Sell's law shows that the minimum optimum drop size (the size of the drop most efficiently deposited) increases for larger insects. Thus houseflies showed increasing collection of drops up to 22.4 μm (David, 1946) and locusts up to 60 μm (McQuaig, 1962).

Drops carried by an airstream approaching a small object, such as a cylinder 1/8 inch in diameter (representing an insect body), are quite small in relation to the object (5 to 100 μm in relation to 0.318 cm, for

example). Such drops tend to be diverted in two streams around the object. Only those drops directly in line with the center of the object will be deposited (fig. 6). As the size of drops or their velocity increases, those drops approaching in the projected frontal area of the object are less likely to be drawn around it by the airstream and are also deposited. The collection efficiency (S), expressed as percent, is the number of drops caught by the object divided by the number of drops approaching the object in its projected width. The graph of the concept of Sell's law of drop collection efficiency (fig. 7) shows that a 0.318-cm object has about a 30 percent collection efficiency for 10- μm drops moving at 10 mph, but a 70 percent efficiency for 25- μm and a 95 percent efficiency for 100- μm drops. Because the larger 1.27-cm (1/2-inch) cylinder deflects larger drops, the 50- μm drops at 10 mph are collected with about 62 percent efficiency and the 100- μm with about 85 percent efficiency. When the drop velocity is decreased, as from 10 to 5 mph, the collection efficiency of objects decreases more rapidly for smaller than for larger drops.

These indications of the size of the smallest drops for near-maximum collection efficiency serve only as a guideline for actual spray application. In the field, not only is the aerosol or spray dispersed in a range of sizes, but also the chemical, physical, and biological factors discussed earlier affect the movement and deposit of the drops.

Earlier observers tried to evaluate application machines and techniques in relation to type of ground cover and weather in actual field trials. Johnstone and others (1949) developed theoretical data based on atmospheric diffusion equations which indicated that if 10- μm drops are released at ground level, cumulative recovery (deposit) out to 6 miles would never exceed 60 percent under conditions of a small temperature inversion with 2 mph velocity. At 5 mph velocity with no inversion, the recovery could be under 36 percent. Yeomans and others (1949) showed from field studies that an aerosol with a vmd of 50 μm deposits up to 60 percent in 2000 feet under temperature inversion conditions, but less than 23 percent with more turbulent or lapse weather. Tables 4 and 5 provide data on the deposit rates of various drop size ranges and swath widths attained by dispersal of pesticides from aircraft and from ground equipment.

Table 4--Calculated deposit rates and swath widths of various drop-size ranges of sprays applied by aircraft at various heights above the ground (neutral or small temperature gradient; wind velocity 3 to 5 mph)

Drop-size range (vmd, μ m)	Estimated deposit within 1000 ft	Estimated downwind swath width at release height (feet) of...					
		10	25	100	250	500	1000
	<i>Percent</i>	<i>Feet</i>					
400	80 to 90	50	70	125	400	750	1500
250 to 400	60 to 80	100	150	350	750	1500	2000
100 to 250	40 to 60	250	350	650	1500	2750	1 mi
50 to 100 ¹	15 to 40	1000	3000	5000	1 mi	2 mi	2 mi

¹Spray applications with vmd's under 100 μ m are not practical from aircraft because of extensive aerial drift.

Table 5--Calculated deposit rates and swath widths of various drop-size ranges of sprays applied by ground equipment (neutral or small temperature gradient; wind velocity 3 to 5 mph)

Drop-size range (vmd, μ m)	Deposit (cumulative) downwind ¹				
	49 ft	98 ft	327 ft	457 ft	984 ft
	<i>Percent</i>				
10	0	1	3	3.3	3.5
25	1.0	1.5	5	10	13
50	10	25	30	35	38
100	25	50	70	75	80

¹Dispersal of pesticide made at 3 feet above the ground.

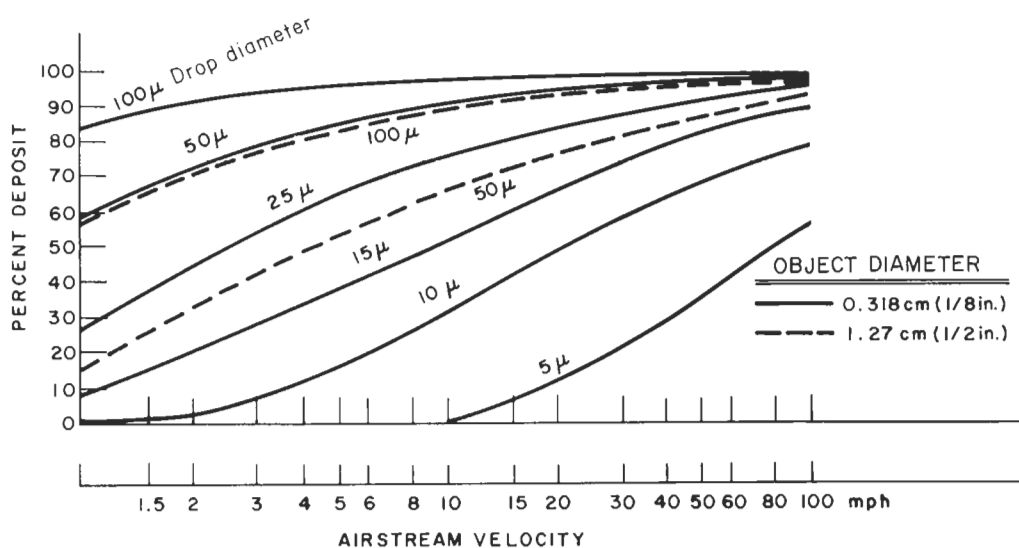


Figure 7. The calculated deposit rate (percent) of liquid drops of two different sizes traveling at different air velocities onto small objects is graphed here.

APPLICATION VOLUME

Liquids may be applied in dilute or concentrated form. Dilute sprays are most frequently used for large-volume applications as large drops and with a wetting coverage. Concentrated liquids, generally those with very little or no diluting carrier are applied as a fine spray, mist, or aerosol. Ultra low volume (ULV) is another name for the concentrate-type aerosol sprays; it covers a wide range of volumes and dilutions of applied sprays, from a fraction of an ounce to a pint or more per acre.

The ULV treatment is a technique for applying a minimum amount of liquid per unit area compatible with the requirements for achieving control of a specific organism with a specific chemical. Whenever small volumes are applied, the liquid is finely atomized in order to maintain a desirable number of drops per unit of area or per unit of space volume. The number of drops available from a given volume of liquid is inversely related to the cube of the drop diameter. That is, if the volume is held constant the following relation holds true, in which N_1 and d_1 are the initial number and drop size and N_2 and d_2 are the new number and size:

$$N_2 = N_1 \left(\frac{d_1}{d_2} \right)^3$$

This relation is more forcefully shown by the data in table 6. The values shown are for absolutely still air (virtually nonexistent outside of a closed laboratory). The table is based on the Stokes' law calculation frequently used by theoreticians to describe downwind transport of small drops. However, this is not a practical calculation for field operations, since in the outdoor air, even under a very calm temperature-inversion condition, the air is continuously in motion, and rising air currents will keep drops as large as 50 μ m suspended, not for the calculated 50 feet or so in a 1 mph wind when released at 10 feet height, but for several hundred feet before falling to the ground. As can be seen from table 6, a 150 μ m diameter water drop has a fall velocity of 1.5 ft per sec or about 1 mph. Thus, a 1-mph vertical air motion would keep such a drop supported indefinitely. Under field conditions, the wind will move up and down as well as travel horizontally and drops will be forced downward and deposited by these air movements as well as lofted by rising air.

From an application volume of 1 gal/acre, if all drops were spread uniformly, the number of drops per unit of surface area per square inch will vary as the diameter cubed (table 6). Thus, a 20- μ m diameter drop size would produce 140,000 drops/in² at 1 gal/acre, while a 50- μ m drop size would give only 9100. This points out the tremendous covering power of small particles, which permits thorough exposure of target organisms or other surfaces

Table 6--Terminal velocities of water drops¹ in still air and numbers per given volume in relation to unit area and air volume.

Drop diameter in microns	Terminal or steady- state velocity	Number of drops at applied rate of 1 gal/acre		
		At surface	In air to depth of 33 feet	
	<i>Ft/sec</i>	<i>Per in²</i>	<i>Per ft²</i>	<i>Per in³ air</i>
1	0.01×10^{-2}	1153.0×10^6		110.0×10^2
5	0.25×10^{-2}	91.8×10^6		85.0
10	1.0×10^{-2}	1.15×10^6		11.0
20	4.0×10^{-2}	0.14×10^6		1.3
50	0.25	91.0×10^2		0.08
70	0.4	34.0×10^2		0.033
100	0.9	11.5×10^2		0.011
150	1.5	3.5×10^2		---
200	2.5	1.4×10^2		---
300	3.8	43.0	6193.0	
500	7.0	9.0	1311.0	
1500	13.0	1.13	162.0	
2000	21.0	0.14	20.2	
5000	30.0	0.09	13.0	

¹Solid particles would have approximately same terminal velocity and numbers, but these would vary somewhat, depending on the density of the solid.

to the small volumes of applied aerosols. It is to be noted, however, that deposit of aerosols is limited by application conditions. Carrying this calculation one step further, the number of drops per cubic inch of air to a depth of 32.8 feet from a 1-gal/acre application is shown in the far right column, considering all the drops are of one size and uniformly dispersed. Again the cube relationship exists, and with 20- μ m diameter drops, 1.3 drops/in³ would be found, while at 50- μ m-diameter only 0.08 drops/in³ would exist; thus, space sprays, directed specifically at a small target organisms such as a mosquito, require the use of drops under 50 μ m diameter for adequate coverage. It should of course be pointed out that no atomizer system produces drops of one size, and for such calculations relating drop size to vector control, the normal or skewed Gaussian distribution of drops, covering a wide range of, for example, from less than 1 μ m up to 50 μ m for a 20 μ m vmd, usually exists.

Ultra-low-volume techniques are generally concerned with space spray as well as deposited spray, and so the drop size produced is in the range of aerosol and mist except in special cases where large drops can be used at a very low spatial distribution. A variety of machines using (1) high liquid pressures, (2) airshear such as that produced by high-speed aircraft or airstreams, and (3) various two-fluid and spinning devices are available for producing the fine drops required for ULV applications.

Large scale, low-cost mosquito control programs have been adapted to ULV techniques particularly for emergency treatment when entire cities or other large areas are treated. Increasing use is being made of ground aerosol equipment for ULV-type treatments. Utilizing the "drift spraying" techniques, aerosols of vmd below 50 μ m can be carried by prevailing winds for downwind distribution in open areas from 1000 feet to

a mile or more. However, the success of such applications is wholly dependent upon a temperature inversion condition that will restrain any vertical diffusion of the spray-laden cloud. It must also be appreciated that evaporation of the released aerosol must be kept to a minimum by use of low-volatility spray formulations. Applications of aerosols under 50 μm vmd by aircraft have shown erratic results; only under unique weather conditions will the pesticides under 50 μm settle toward the ground in sufficient numbers to produce either a detectable deposit or provide an adequate number of drops for space sprays. The use of thermal aerosols where a significant portion of the released aerosol is in particles below 5 μm as a smoke or fog is being replaced with aerosols mechanically produced for elimination of the wasteful and sometimes hazardous smoke of thermal machines.

A number of sources have been utilized to provide representative data in tables 4 and 5 concerning the fallout of various-size drops applied from the air and the ground. The estimated downwind recovery for aerosol size particles (under 50 μm vmd) is shown in table 5. Since aerosoling for adult insect control is largely by direct insect-drop contact, the most effective drop size would have to be small enough to impinge on the small surface presented and to remain airborne for a sufficient time for insect contact to take place.

Table 7 illustrates the size range and coverage capabilities of various grades of granular materials. Dust materials are generally made up of particles below 25 μm diameter (or longest dimension) and their characteristics would follow those of liquid drops of a similar density.

Table 4 presents data for aircraft distribution of various-size drops. The approximate downwind spread or swath width in feet of the released spray indicates where significant amounts of residue could still be found when spray is released at various heights. Thus, it is shown that for a coarse, rapidly falling spray at 400 to 500 μm vmd, the swath width is only 50 feet when spray is released at a 10-foot height, but increases to 1500 feet when spray is released at a 1000-foot height. For smaller drops of the mist category (50 to 100 μm vmd), the swath width at a 10-foot release height is 1000 feet, and at a 1000-foot release height may be 2 miles or more. Sprays or aerosols under 50 μm vmd, as noted earlier, are too unstable when applied by aircraft to be used anywhere except under highly controlled situations where supervisory personnel know the local weather conditions and can establish adequate vector control with such type of applications.

In summary, a very complex physical-chemical-biological system exists when chemicals are used for controlling insect vectors of human and animal disease. This system can be understood through using the knowledge and proficiency of the several scientific disciplines involved, including physics, meteorology, chemistry, engineering and entomology. It should be noted that the aerosol drop size which provides greatest coverage and potential adult insect contact is also the most susceptible to air transport, depending on local meteorological factors.

METEOROLOGY AND PESTICIDE APPLICATION

The local meteorology can be a significant factor controlling the success or failure of a vector control operation. The basic parameters are (1) temperature gradient or change with height, (2) wind velocity and wind velocity gradient with height, (3) wind direction during drift spraying or aerosoling, and (4) relative humidity as it relates to spray drop evaporation, particularly if water is the pesticide carrier.

These factors affect the rate of dispersion of pesticide materials release from either ground or aircraft equipment. The most significant of the factors listed is the temperature gradient. When the air overhead is warmer (which may occur at various levels) than that at the ground, any material released at the ground and transportable by air, such as aerosol particles smaller than 50 μm , will be carried by the moving air along at ground level and will not diffuse upward. The air velocity under the inversion layer will control the mixing process in the area and higher velocities will cause more rapid ground level dispersion. When temperature gradients are increasingly cooler overhead above a warm ground, the spray can easily be diffused upward and is rapidly dispersed and diluted by wind.

Temperature inversions (fig. 8) with low wind velocity and velocity gradient provide the greatest vertical confinement of released sprays, and thus the best application conditions, particularly for fine sprays, mists, and aerosols, when a large proportion of the released material is airborne size. This means that the time for application of aerosols, in particular, and for best success with fine sprays and mists, as well, should be early morning to mid-morning, and late afternoon and evening, when the inversion condition can be shown to commonly exist. Coarse sprays may be applied at any time during the day, the only limitation being the wind velocity, which will displace the aircraft swath significantly when

wind exceeds 12 to 15 mph. This high wind also makes ground applications difficult to manage. Downwind concentration (essential for aerosoling) is rapidly reduced by temperature lapse (temperature gradient decreasing with height) and windy conditions; hence this condition is favorable to least downwind contamination in combination with a coarse spray.

Temperature inversions are produced by several means and frequently more than one means may be causing this effect. The most common is radiation inversion caused by the heat loss or radiation by the ground to a cool sky (when the sun is low or below the horizon); this heat loss cools the ground and air close to it during the day. Another important inversion cause is the influx over the land of a late afternoon sea breeze along coastal areas. This cold air moving up valleys over the ground pushes under the warm air and causes a temperature inversion condition. A third cause of temperature inversion conditions is subsidence, the phenomenon by which air from a higher elevation is forced down into a lower level, such as a valley. This drop in elevation warms the air and places a warm layer over a valley to produce this temperature inversion condition.

Because of the dominant effect of insolation, the inversion and lapse conditions follow a diurnal pattern, with lapse and neutral (no change in gradient with height) conditions prevailing during the day while the sun's effect is strong, and the inversion condition taking place when the sun is low during early morning and evening hours or at night (fig. 8). During cloudy overcast weather, the temperature gradient will vary from neutral to inversion condition, depending on cloud density and the two other gradient-affecting conditions.

Turbulence of the air is a normal daytime phenomenon which lessens under late afternoon temperature inversion conditions, and generally also at night when the sun's heating of the ground is not contributing to vertical movement of the air. It is possible to have turbulence under a strong temperature inversion, but normally this tends to stabilize the air. Even more stabilizing is forest or overhead canopy. Here the temperature will frequently remain the same (neutral with height) to the top of the forest cover. The wind velocity will be but a fraction of that above the forest cover and applying an aerosol by ground under the cover offers a realistic approach to insect control. Normally, outside (or above) the forest cover,

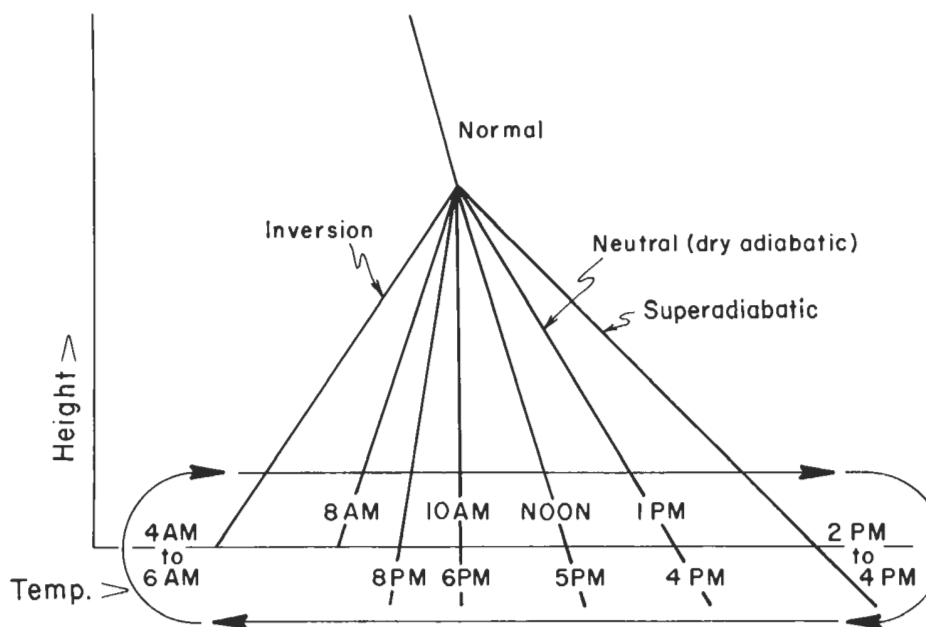


Figure 8. The diurnal variation in temperature gradient affects the dispersion of pesticide materials.

the usual daily changes in temperature and wind gradients will exist, with temperature inversions in early morning and late afternoon and daytime temperature lapse of turbulent mixing on most sunny days. During the night and under cloudy overcast, neutral conditions (neither strong lapse or inversion) would likely predominate.

Johnstone and others (1949) determined both horizontal and vertical (as discharged from an aircraft) forest penetration distances in terms of the percent of discharged aerosol that penetrated the forest to a stated distance, which he showed to vary with the density of the foliage cover. A very dense forest might have a vertical density of twice that of its horizontal density, owing to arrangement of leaves. He also shows that aerosols applied above the cover and having little downwind velocity do not penetrate but impinge on the foliage by horizontal wind motion. However, these aerosol drops do penetrate horizontally if dispersed under the cover, as with a ground aerosol machine. Penetration, however, would still vary with the density of the cover. For example, 15- μ m aerosols released near the ground under inversion weather conditions and 1- to 2-mph wind velocity gave deposits of DDT in the open (no cover) for a distance of 2000 feet. However, with light forest cover this distance was reduced to 600 feet, and in dense jungle growth the distance was further reduced to 200 feet of effective deposit. His data also shows that increasing the drop size to 200 to 300- μ m increases their vertical penetration through a forest canopy, but that most of those drops penetrating go to the ground. For mosquito larval control, sprays of 200 to 400 μ m vmd are quite effective by reducing losses to aerial drift and getting the highest deposit in the water. Filtration by rice foliage up to 3 feet tall had very little effect on the penetration of a 200 μ m vmd spray. Bioassay of chemicals in paper cups that were placed at the top of the rice and also in the water beneath plants showed little difference, although both the recoveries were unexpectedly low, varying from 10 to 45 percent of the applied spray (Akesson and others 1972).

Brescia (1945) was one of the first researchers to try to evaluate downwind transport and particle size in both adult and larval mosquito control. His tests involved thermal aerosols of 5 μ m and 16 μ m vmd. His results showed effective larva control of *Aedes taeniorhynchus*, also *A. sollicitans* and *Anopheles quadrimaculatus* at 0.001 to 0.002 lb/acre of DDT to distances of 2000 feet during strong inversion weather, and with grassy ground cover but no overhead canopy. Under a light forest canopy this

effective distance was reduced to 1100 feet, and for a dense forest, to 400 to 500 feet. For spray drops-to-adult or air-to insect contact, an aerosol under 10 μ m vmd, applied under strong inversion (but with a positive low wind drift), was effective to about 1 mile distance in the open areas, to around 1/2 mile under light forest, and 500 to 1000 feet under dense forest conditions. In any application downwind, the number of airborne drops and those deposited on the ground are increased by an increase in the applied dosage. Thus, the foliage obviously has a selective filtering capacity and permits a given percent of aerosol to pass no matter how dense the foliage may be.

Kruse and others (1949) used engine exhaust thermal aerosol generators on a Stearman type aircraft. With drop sizes of 35 to 40 μ m vmd, recovery on glass slides placed in the open in a 200-foot recovery swath, under near dead calm conditions, was 9 percent of the discharged spray, and the peak was only 12 percent at the center of the swath. Kruse's foliage penetration data is not available, but he indicates that the dose required for heavy, tall forest canopy would be 10 times that for the open field, while for moderate low foliage or grass cover he suggested five times the open area dosage for LD₉₀ control.

A wealth of information has been developed, mostly since 1960, on field use of the organophosphorus insecticides applied as technical concentrates or carried in nonvolatile petroleum and glycol solvents and diluents instead of volatile water base emulsifiable concentrates of solutions. With technical or near-technical concentrations of active ingredients of very high intrinsic toxicity, the phosphate and carbamate chemicals have made possible the reduction of liquid applied per unit of area to very low levels of 1 to 3 oz/acre, commonly referred to as LV (low volume) and ULV (ultra low volume) applications. However, it should also be pointed out that using these low application rates necessitates small drop size (under 100 μ m) to give an effective 8 to 16 drops per in² on flat surface, or under 25 μ m to give air volume (up to 33 feet height) dosage of 30 to 40 drops per in³ (table 6).

Recent literature suggests that the effective downwind range for a ground aerosol applicator using organophosphorus chemicals for adult mosquito control can be as far as 2 miles or more in open areas (Mount and others 1971) when drops of 10 to 15 μ m are released. Dosages of technical nonvolatile phosphate chemicals for caged and natural adult mosquito mortality of 75 to 100 percent vary from 0.1 to 0.001 lb/acre, depending on vector and chemical (Mount and others 1968). Recent data on the effect of dense and heavy forest or jungle growth on filtering of

Table 7--Deposit characteristics of various sizes of pesticide granules

Mesh size (Tyler sieve)	Size of mesh openings	Average number granules per pound	At dosage of 1 lb/acre, number granules deposited per ft ²
	<i>mm</i>		
8/16	2.36/0.99	145 × 10 ³	3
16/32	0.99/0.495	1,150 × 10 ³	26
20/35	0.833/0.417	2,708 × 10 ³	62
24/48	0.701/0.295	7,722 × 10 ³	177
32/60	0.5/0.246	12,300 × 10 ³	282

aerosols applied either by ground or aircraft indicate that for control of mosquitos in dense jungles an increase of 3 or more times the usual dosage per acre is required for effective control.

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Workshop Summary

Edward M. Fussell¹

The initial efforts of this workshop group on application were directed toward briefly describing the present technology related to application of pesticides. We discussed only those types of equipment and techniques that have been in use over the past few years. We considered two groups of equipment because two basic interest groups were represented: the forest entomology group and the mosquito control group.

For the forest insect work, we have fixed-wing aircraft ranging from single-engine equipment to DC7's, in addition to rotary-wing aircraft. All of these equipment systems are primarily based on liquid spray. The application rates for these systems in the United States are about 1 gallon of material per acre; this is total volume, not actual material. This figure varies somewhat in the other parts of the world: for example, in Canada the application rates are commonly 20 ounces per acre. In forest insect control, there is also a pretty wide variety of basic ground equipment, such as mist dust blowers, hydraulic sprayers, and backpacks. Obviously, use of ground equipment is limited to relatively small areas.

Equipment for mosquito control is a little more varied than that for forest insect control. It was necessary to categorize equipment, not only as aerial or ground types, but also as to suitability for adulticiding or larviciding. For mosquito larviciding, fixed-wing and rotary-wing aircraft are adapted for application of either liquid or dust formulations. Fixed-wing equipment for mosquito adulticiding is primarily limited to liquid dispersal systems. A few years ago, fogging with fixed-wing aircraft was a commonly used technique, especially in Florida. I believe it is not used as widely today. Larviciding with fixed-wing aircraft is principally the application of liquid or granular material. Ground equipment for larviciding--here again we use liquid or dry application--includes hydraulic sprayers, mist dust blowers, and backpacks. For adult mosquito control we have a variety of equipment. Mosquito abatement district in California are just coming around to adult control. The districts have concentrated principally on larval control in the past but now are looking to adult control through necessity.

Mosquito abatement districts in the Eastern and Southeastern United States have concentrated more heavily on adult control. Adult control equipment includes thermal foggers, cold foggers, mist dust blowers, and backpacks.

It was generally agreed that there is a real need for new equipment or for vast improvement in the presently available equipment. The development of insecticide dispersal equipment, for all practical purposes, started after World War II. Several different types of applicators were developed initially and not much change occurred for the next 20 or 25 years. Now we are beginning to realize that what was once considered adequate no longer meets our requirements. The relatively ineffective dispersal equipment used over the past years has resulted in a gross waste of insecticides and unnecessary contamination of the environment.

There is a need to determine median lethal doses for specific insects. We need additional information on the mode of action of insecticides. We need to know exactly how insecticides enter the insect. This is particularly true of aerosols. It is essential that we determine where the droplets impinge and how they gain entrance into the insect.

One of the most important things that could result from this conference is that we agree on the importance of the work on determining droplet size requirements and strongly support it. Although considerable work was done during the early forties on droplet size evaluation, only in recent years have we come to grips with the problem. Dr. Himel has been studying this problem for many years and I'm sure he will agree on the importance of droplet size. Achieving the proper droplet size could mean the difference between applying a quarter of an ounce of material per acre and applying a pound and a half per acre. There can be this much difference.

We feel that something should be done to determine the most efficient formulation for specific pesticides and pesticide delivery systems. It is time insecticide manufacturers and formulators started developing insecticides that fit a particular type of equipment or application. The old system of determining what is an ideal insecticide has been reversed. The emphasis on developing long-lasting insecticides has changed. Now, the point is not how long it lasts but how quickly it will

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break down. For the aerosols, the ideal insecticide could be one that would break down and become harmless a few hours after application. If you're depending on contact, as you would be with an aerosol, once the insecticide impinges on the target and performs its function, the insecticide is no longer of any use, and the sooner it breaks down the better. When put out in aerosol form many insecticides break down within a matter of hours, and this is a characteristic that can be used to great advantage. We don't wish to imply, however, that aerosols are the answer to all our problems, because there will always be a need for other types of insecticide application.

Something should be done to minimize loss of the insecticide to the target area. One of the most important things to keep in mind is that there is no way to control an aerosol so that it stops at a certain line. But, maybe there are ways to compensate for this, perhaps by manipulating concentrations and application rates. So that once the aerosol passes beyond that certain line the concentration of material, and the amount of material there, is no longer too significant. Also, when insecticides that break down rather rapidly are being used, loss beyond the target area is of less consequence. I believe we all agree that we're not on the verge of banning the use of pesticides. We're going to be dealing with these chemicals for decades.

There appears to be a need to clear up confusion in the use of terminology like "ultra low volume." Mr. Pierpont reported during the session that by EPA definition, ULV is the

application of less than half a gallon of total volume per acre without regard to insecticide concentration. Literally the definition is correct because the reference is only to volume. The problem here is that we were able to utilize ULV applications only because concentrations were increased, sometimes to near-technical-grade levels. For example, a few years ago we used malathion 6 percent as an adulticide for mosquito control. Now we use malathion 95 percent without dilution. Although the EPA definition may be useful to that agency it is likely to lead to further confusion for those engaged in the application of insecticides. It would be difficult indeed to refer to ULV without at least implying that the concentration of the insecticide had been increased, sometimes markedly, because as you decrease the volume you must compensate by increasing the concentration. It is obvious that we need more meaningful terminology. During his presentation yesterday Dr. Himel suggested the term Ultra Low Dosage. It certainly seems that ULD makes more sense than ULV. After all, we are primarily interested in the amount of insecticide that is applied to a given area and not so much in the application rate, except in special cases where specific dispersal rates would be required to achieve a desired effect or prevent undesirable effects.

It was brought to the attention of the group by Dr. Akesson that the World Health Organization has now substituted micrometer for micron and volume median diameter for mass median diameter.

Discussion

DR. TSCHIRLEY: You mentioned the need for new equipment or modification of existing equipment. What is the inference on this? Do you mean that new technology is needed for the development of the new equipment, or that the new technology is available, but it is simply economics that is holding it up?

COMMANDER FUSSELL: I am not sure that the technology is available. I think that what we are going to have to do, before we develop new equipment, is to determine what is needed. In the past, equipment was developed just to spray insecticides without regard to droplet size or anything of that nature. So I think that we first have to decide the optimum size for the target insect.

DR. TSCHIRLEY: When you are talking about this new equipment, are you talking about the spray distribution system or the vehicle that carries the distribution system as well?

COMMANDER FUSSELL: Well, I would be more concerned right now with the distribution system itself. The vehicle for that system is an entirely different thing, and I don't think it makes any difference whether it is ground equipment or aerial equipment.

MR. RANDALL: I noticed in the workshop that there seems to be a complete absence of reference to a standard. I think we should have a standard solution or a standard formulation for which all the work could be correlated.

So if you are talking of existing equipment or new equipment it should be carried out on a standard formulation.

COMMANDER FUSSELL: That was one of the comments made in the group yesterday, too. But I did not mention it because I knew it was going to come up in the assessment presentation. Everybody there agreed that there was a real need for some sort of a standardized assessment of spray droplets, because when you get into the field with your equipment you have no practical way to determine droplet size.

DR. LYON: Yesterday Dr. Akesson mentioned that he thought rotary atomizers were passé. Would he describe what he means by that? I wonder if that subject came up in the application workshop?

COMMANDER FUSSELL: It did come up, only briefly though. The comment that Dr. Akesson made was that on one particular model, where the specifications indicated that it produced droplets at a size of 10 microns, they actually observed droplets of 30 or 40 microns. They were not getting the droplet size that was advertised.

DR. ROBERTS: Dr. Akesson, do you have any comments to add to that?

DR. AKESSON: I don't believe that I said the rotary atomizers were passé. Rather, the point I was trying to make was that these devices, spinning at high speeds, are more subject to breakdown and are much more expensive than pressure nozzle systems. The drop-size spectra they produce is not significantly different from that obtained with the simpler pressure nozzles.

However, I would like to take this opportunity to take Commander Fussell to task. I got the impression yesterday that you felt the spray application equipment industry was not providing as much in the way of new equipment and application techniques as it should be. I would suggest that it isn't so much a matter of not having new equipment produced, as it is a lack of communication between many of our biologists who control our spray programs and the people who manufacture the equipment. In other words, the biologists request to equipment manufacturers may be mechanically illogical, while the machines that are being offered may appear to the biologists to be antiquated and impossible to use for the job to be done. Again, I would suggest that communication is the basic problem. As far as I can tell, there are no application machines on the market today that haven't been around, at least in basic design, for at least 25 years. However, in an

attempt to meet the sometimes nebulous demands of the biologist, the equipment manufacturer has produced some very fanciful devices, and all too frequently he also makes claims for these machines that strangely enough sound exactly like the requested performance.

Take, for example, the present enchantment with cold aerosols or cold foggers, particularly the ones that add ULV to the specifications. If you go into the literature and examine the work of Randall Latta, Alfred Yeomans and others of the early 1940's, you will find that the use of aerosols, both cold and thermal, was widely discussed, and extensive experimentation was carried out, the depth and quality of which has not been approached since then, with perhaps the exception of the biological-type research being done today at the USDA Gainesville Station.

However, I note that in a great deal of biological work, such as screening tests of various chemicals, and tests of the general results of each machine on adult or larvae control, basic parameters of weather, machine operation, and sometimes proper biological statistics are omitted or ignored. These are mighty poor examples of research, and to claim to report on population control without specifying or identifying the many variables involved—physical, chemical and biological—is too frequently only adding confusion and wasting good journal space.

Obviously this state of things is easily described, but much more difficult to do anything about. However, I would again suggest that the biological and physical science interface—the relationship between the insect population effects and the chemical, the mode of action, type of application, application machine, geographical terrain, and meteorological parameters—should be considered and carefully evaluated if sound research on such things as vector control, forest insect control, and of course agricultural economic insect control, is being attempted.

This total approach is being called systems control or integrated control, and of course cultural, sanitation, and biological control, including predator-parasite functions, must be included.

Another facet of our science research interface is the problem of communication in mathematical terminology. It is, I realize, very simplistic for me as a physical scientist, to point at the biologist and say that what he needs is more number-oriented data—statistics, computer analysis, modeling studies, and in general, a tightening up of data analysis. We must recognize that the computer, for example, is a very powerful tool and no amount of derogatory stories about its inhumanity

and stupidity, especially in relation to our charge accounts with a large department store, is going to detract from its tremendous capabilities in rationalizing the type of research and data analysis that we all need in our work.

I hope that I am not minimizing the tremendous efforts and very valuable work being done by many of the biological scientists involved in pest control work. Rather, I would hope that my speaking out here today will help to open a route of information exchange and research collaboration which will benefit us all, both as researchers and as citizens.

The work associated with particle size, whether of spray or dry particles, has always been significant in relation to pest control. Back in the DDT days, a lot of effort was devoted to determining the size of droplet that would do the best, most efficient job for specific insect control. Unfortunately, the researchers then got to the same place our people have reached today, the only difference being the chemicals used. Basically, the aerosol size drops that Drs. Himel, Weidhaas, Mount, and others have found to be most effective in controlled application studies, both laboratory and field, are not (1) easily produced, or (2) easily counted and sized, or (3) easily used under the conditions of practical application work. Is this not, in part at least, a lack of communication between physical and biological scientists? The physical scientist perhaps errs in his insistence on using easily managed, large-drop-size, rapidly falling sprays, but equally inconsiderate is the biological scientist's insistence that if his controlled tests prove certain facts, extrapolation to field applications should be automatically and easily accomplished if the equipment people would simply buckle down and do their end of the job.

I submit to the biologists that this situation is extremely unproductive and I would beg of you to give greater consideration to such means of approach as integrated or systems control, not after your decisions as to rates, drop size, and insect response work has all been done, but right from the time of the first chemical screening work which shows that a chemical formulation has promise for a particular job. I shouldn't expect that miracles are going to suddenly occur from such integration of research effort, but we certainly have little to lose and perhaps much to be gained by giving it a try.

COMMANDER FUSSELL: Thank you Dr. Akesson.

I don't think there was any intent to imply that the study of aerosols only started in the last decade. We would not want to discredit Yeomans or Latta or any others. Many assumptions have been made regarding aerosols, particle size, impingement and things of this sort, and I think that some of these assumptions are without basis. So the time has come to update this information and use that as a basis.

DR. KIETHLY: It seems to me we have studied the literature quite a lot on what people have done, but how do we put it to use?

COMMANDER FUSSELL: Something should be done. It might be something for government to consider or it might be something for industry or a combination of both to consider.

DR. TSCHIRLEY: I would like to return to my original question and ask Dr. Akesson, in light of this discussion, whether or not the technology is available now to do what we want with these spray systems, or do we need more research to define this, or is there a need to make the equipment that will produce what we want?

DR. AKESSON: I think that the technology is there, but I do believe that the key to this is the need to get the equipment and the biological requirements lined up and correlated. And again I would say, yes, the technology is there, it is a development process. I work in agricultural engineering, and where does our information come from? We get it from "space" people, mechanical engineers, civil engineers, sanitary engineers and others, and apply it to agriculture. There you have a tremendous background and source of technology. If we can find the information we need in these areas and bring it to bear, this is the general plan that we follow. I think that the technology is available but we do need that specific relationship.

DR. LILIJDahl: I do not see how you can say that we have the technology available. At least one important part of the technology required, if droplet size is important, is the ability to produce--in practical quantities and in practical situations--reasonably uniform spray droplets of a desired size. Now, as far as I know, there is only one process available for doing that in a practical situation in the field. That is the one that we have developed, that Dallas has worked on at College Station, and that I am working on again now. That has three important limitations. First, it will not go below 75 microns; secondly, it is not good if you have suspended materials in wettable powders; and third, nobody knows for

sure if it will work in high speed air streams. Chances are it will not. Consequently we do not have a method of producing spray droplets below 75 or maybe 50 microns of reasonable uniformity, that is, something that has a coefficient of variation of, say, less than 20 percent or even less than 50 percent. Most of the air atomizing nozzles that we use for fine sprays are terrible, when you consider their coefficients of variation. I do not see how we can consider those to be uniform sprays. When we are releasing these very fine sprays, who knows how many drops we are producing that are less than 2 microns --drops that we can not even measure. I do not think we have the technology available.

DR. AKESSON: The problem that Lou is bringing out, and again I agree with 100 percent, is that of trying to produce the tools that we need to do the research. We do not have those, let alone the practical type things that we could take into the field. Identification of small particles is greatly improved. We are doing quite a bit of work with a scanning electron microscope now, and we can identify sub-micron particles now, but it is not easy.

DR. LILIJDAHL: I thought that Fred Tschirley was referring to whether the information and technology was available to design and actually mass-produce such a machine. I do not think we have that technology.

DR. AKESSON: We have the first-step or first-generation equipment, as it were, to do the research work. Agreed, we can not go into the field with such a machine at this date.

MR. RANDALL: Can I ask a question at this point? Are you referring to droplet generators?

DR. AKESSON: Yes, both as laboratory types and field types.

DR. LILIJDAHL: Now I am not talking about laboratory generators. I was talking about practical field equipment.

MR. RANDALL: There is one point I would like to bring to the attention of the group here and I am sure, Ed, you are probably familiar with it. Laboratory droplet generators have been produced at Suffield for the Defense Research Board, and publications describing this equipment are available. As for droplet generators out in the field, the problem, I feel is that there are too many of them and there is no correlation between one machine and the next one, mainly because of the lack of a standard solution, which was a DDT-Velsicol-fuel oil combination. Of course the DDT was the standard insecticide and we

compared everything to that particular insecticide; the aromatic fuel oil formulation was our standard liquid, so that we could compare all new formulations against this standard. In this way we had some correlation between the various years that we did our work. But if we did one thing at this meeting, it would be to come up with a standard solution, so that everybody would use that one formulation or one liquid; then the next time we meet we would at least have that one thing in common. The data could be interpreted by everybody. Now even if the work was done with droplet generators, or done in the field, we would have some means of comparing our work or data.

DR. MAKSYMUK: I would like to add to Randall's comment on the need to develop standard formulations or solutions in order to compare our laboratory and field results. At the same time, we also need to standardize our methodology. Despite the fact that some existing methods for determining spray atomization and assessing spray deposit are comparable, additional standardization and common acceptance of methods are needed internationally.

I would like to comment on the three areas related to the aerial application spray equipment:

1. *Coverage: surface area of foliage vs. surface area of land* -- The amount of pesticide delivered by various kinds of spray equipment is currently expressed per acre of land area, disregarding the variable amount of the surface area of foliage per acre. For example: how many acres of surface area of foliage are there in an acre of land? We ought to consider horizontal and vertical variation in vegetation (cabbage field, Douglas-fir forest, oak forest, etc.). Therefore, it would be more realistic to express the coverage in terms of area of foliage (gpa, or amount of pesticide per unit surface area of foliage) instead of as traditionally expressed per unit surface area of land (gpa, pounds per acre, etc.). This concept, if used in the field, will provide more reliable determinations and comparisons of field dosages and will result in better reproducibility of insect operational control programs.

2. *Microbial insecticides* -- We underestimated in this workshop the importance and need of spray equipment for delivering microbial insecticides. These biological insecticides (bacteria, viruses) are applied as suspensions whereas most chemicals insecticides are applied as solutions. The major problem is that suspended insect pathogens settle out, in spray formulation mixing equipment, in aircraft tanks, and in spray

delivery systems. An acute problem in the storage of microbial suspensions is the sedimentation and agglomeration of particles. This leads to variable delivery of pathogen concentrations, with erratic foliage coverage, and in turn, variable and unreproducible results in insect mortality by place and time.

We eliminated this problem by working as a team with engineers in conceiving, designing, and fabricating special spray mixing and loading equipment and an aircraft spray system. This equipment provides for the continuous recirculation of spray formulation in the spray tanks and spray booms (on the ground or in flight) without injury to the pathogens either by mechanical sources or heat. Developed technology is being applied in the field research experiments. Hopefully, it will be transferred to the operational use as soon as microbial insecticides can be used operationally.

3. *Aerial application of pesticides* -- We have difficult problems in aerial application of pesticides in forestry mainly because we cannot control variable meteorological and topographic conditions. Therefore, the spray equipment must have versatility for obtaining the desired spray atomization (drop size spectra) and application rates (volumes of liquids) for achieving specific pest control objectives safely and effectively under a wide range of physical and biological field conditions.

DR. TSCHIRLEY: Formulations were mentioned as a need, too, in terms of further research. Two questions on this: What is the level of effort in developing new formulations now and was there any discussion of the group's feelings as to whether this was the responsibility of the public or the private sector?

COMMANDER FUSSELL: We really didn't delve deeply into that part of it. It is difficult to say at this point who will be responsible. The government probably does most of the research, but the people from Dow, MGK, Chemagro, etc., might argue about that since they do a tremendous amount of research themselves. This future research might not be assigned to any particular group, but it is work that should be done, to develop formulations, different concentrations, or different carriers. We have obtained some very interesting results with some of our work with emulsions. And this sort of thing should be explored more fully.

DR. ROBERTS: It seems to me that we have been talking about the need for standards of techniques and procedures but we have not pointed a finger at who is going to organize

this. We should organize some sort of governing body now so that we can assign committees and begin the task of defining standards and techniques. Otherwise, we will return to our laboratories, and next year will come back to this workshop and the same criticism and comments will be made about the lack of standards or means of comparing data. So let us organize ourselves here and now so we can start on this problem of standardizing our methods and techniques.

DR. MAKSYMCIUK: I understand EPA has a committee on standardization and nomenclature pertaining to pesticides. I talked to the head man just a few weeks ago. At a meeting somewhere in Philadelphia, several engineers walked in, and they were feeling uneasy because they couldn't participate. But the chairman asked the engineers to form a committee and assigned them the task of working on the standardization of methodology and nomenclature. I don't know whether a report transpired from that or not. Perhaps some of the engineers here now know what their colleagues are doing.

DR. ROBERTS: Are we talking about the same thing, Bohdan? I am talking about an internal organization composed of the people that are doing the work. I understand that there has to be some federal regulations established by EPA.

DR. MAKSYMCIUK: Once such procedures are accepted by EPA, then they are mandatory to use. It is very important that we participate on that committee so that the nomenclature and standardization are the kind that we would like. I urge that we pursue this matter and get in touch with them, then if the need arises we provide sizeable input. It would be a good idea also to solicit such input, maybe in an advisory capacity, from the Canadians and anybody else who would like to contribute.

DR. ROBERTS: Dr. Tschirley, I would like to hear your comments on that. Do you have any help or information on this matter?

DR. TSCHIRLEY: What the gentleman refers to I think is a current effort by ASTM, The American Society for Testing Materials. They have had several meetings now, with some difference of opinion as to just what the stimulus of this was. But, presumably, what they are to come up with at some point in the future is a standardization methodology for information that EPA needs in the pesticide registration process. Now the nomenclature I think is a part of this, and this is something that would come fairly easy. But

other than that, it is the methodology of the test that is required for the registration of the materials that they are looking at, insofar as I know anyway, rather than any methodology that is involved in the development of the equipment for delivering pesticides. According to the new pesticide legislation, this does not cover the registration of the application equipment itself. Of devices for pest control, yes, and of the pesticides themselves, yes, but not the equipment for delivering it. So what you suggest, Richard, that a group get together to standardize some of the parameters that you have to deal with day after day, is an excellent suggestion.

MR. PIERPONT: What Dr. Tschirley just said is correct, and I think that Dr. Roberts' suggestion is a good one. At the present time we are putting together guidelines for

the registration of pesticides in the United States. One part of that is the Appendix which will include all of the test methods acceptable for the development of these pesticides. This is where your input would be very greatly appreciated.

DR. ROBERTS: We have a golden opportunity here to "write our own book" so to speak. But who is going to take the initiative and will organize this group? This is really not my field, so I am going to pass the buck.

MR. RANDALL: I would like to take this golden opportunity to pass the buck a little further. I think the group that works in forestry should handle the requirements for their area and the group that does the mosquito work should handle that particular type of work, so at least the experts would be in their own field.

BEHAVIOR

The Micrometeorology and Physics of Spray Particle Behavior

Harrison E. Cramer¹ Douglas G. Boyle²

Abstract--During 30 years of experimental programs at Dugway Proving Ground, techniques were developed for computer modeling of spray cloud behavior. Atmospheric transport and diffusion processes within forest canopies are generally quite different from those in open terrain, as illustrated by normalized vertical profiles of windspeed and temperature. Deposition of aerial sprays on vegetation or insects is apparently the result of many different processes that are not well understood. Some data on canopy penetration has been gathered in tests using Zectran.

This discussion summarizes the techniques used to support experimental spray programs at Dugway Proving Ground. The time span is 30 years. The spray programs themselves were designed primarily to evaluate specific military systems or items of developmental hardware. For that reason, viewed historically, they show no continuity of objectives. Continuity is provided, however, by the recurrence of the same unknowns. It is reflected also in the evolution of improved sensors, assay and analysis techniques and, since the late 1950's, increased reliance on computer modeling of spray cloud behavior. The current approach to modeling is the central theme of this paper. In the development of the computational schemes presented, the objective has been and continues to be a more useful alignment between theory and field experiment in the physical description of aerosol and droplet behavior. Atmospheric transport and diffusion processes within a forest canopy are discussed in a later section. The concluding section presents the scant data generated (through 1972) under the cooperative agreement between Army and Forest Service investigators.

GENERALIZED MODEL CONCEPT

The employment of mathematical prediction models has proved mandatory in quantifying the atmospheric behavior of military systems, since many such systems cannot be tested. Use of prediction models is also essential in the design of field trials and in the interpretation of field measurements. The concept of generalized concentration-dosage prediction models was first stated by Milly (1958) who pointed out the necessity for separating the effect of source factors, meteorological factors, and site factors in the analysis and generalization of chemical and biological field test data. This concept has been broadened and implemented in work at Deseret Test Center (Cramer and others, 1964; 1972) and is the keystone of the model formulas for aerial spray releases given below. The generalized models are intended to be universally applicable, by suitable selection of source and meteorological input parameter values, to all dissemination systems, to all environmental regimes, and to all requirements. These requirements typically include the design of field tests, assessment of the results of field measurements, extrapolation of these results to field operations, development of dissemination systems, and hazard-safety analyses, among others.

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The basic generalized model format is a mass continuity equation that in principle provides a complete description of the trajectory and properties of an aerosol or heavy particulate

cloud, from the time of cloud stabilization (approximate equilibrium with ambient conditions immediately following dissemination), until the cloud has passed beyond the maximum downwind travel distance of interest. The terms included in the generalized model must therefore specify the direction and rate of downwind cloud travel; the alongwind, crosswind and vertical cloud dimensions as functions of travel time and distance; the distribution of material within the cloud as a function of time and distance; and losses of material through decay or removal by such agencies as hydrometeors, gravitational settling, and other surfaces. The generalized model must also provide for the effects of variations in the chemical and physical properties of the material contained in the stabilized cloud; in the mode of release and source emission time; and in the meteorological, terrain, and vegetative factors.

The Deseret Test Center model equations are similar in form to the Gaussian diffusion model formulas first developed by A. G. Sutton (1953) and later extended by Pasquill (1962) and others. A Cartesian coordinate system is employed, with the origin placed at ground level directly below the source. The x axis is along the direction of downwind cloud travel, the y axis is normal to the alongwind axis in the plane of the horizon, and the z axis is directed along the vertical. The auxiliary equations for the lateral, vertical and alongwind cloud dimensions are expressed as simple power laws and contain direct meteorological predictors. Other distribution functions, coordinate systems, cloud expansion laws and meteorological predictors can be substituted in the models. In addition to using direct meteorological predictors, the Deseret Test Center models also provide for the inclusion of mesoscale meteorological factors which control atmospheric diffusion, transport, and depletion processes for cloud travel distances in excess of 1 or 2 kilometers. The mesoscale factors most important in determining the dimensions or aerosol clouds at distances greater than a few kilometers downwind from the point of release are the depth of the surface mixing layer and the vertical shear of windspeed and azimuth wind direction in

this layer. It follows that a choice of expressions used in the model to account for the effects of microscale processes, particularly small-scale turbulent mixing, is frequently not of critical importance. Other important innovations in the Deseret Test Center models include specific provisions for the effects of initial cloud size and source emission time on downwind concentration-dosage patterns.

It should be recognized that the generalized model formulas are inherently interim or state of the art expressions reflecting the best available knowledge. Provision has been made for their refinement and improvement as new information becomes available. In many instances, the appropriate source and meteorological information is fragmentary or almost completely lacking. Because of inadequacies in existing measurements, the amount of rigorous model validation that has been possible to date is disappointingly small. However, the experience in model validation has demonstrated that the overall conceptual framework is sound and that the accuracy of model predictions is limited principally by the accuracy and adequacy of the source and meteorological inputs.

Generalized Model Formulas for Aerial Spray Releases

In aerial spray releases, the release of material to the atmosphere is completed almost instantly as the spray cloud generally reaches an approximate equilibrium with the ambient air flow within seconds. This approximate equilibrium is referred to as cloud stabilization and the source inputs used in the model refer to the properties of the spray cloud immediately after it has stabilized. These properties include the dimensions of the stabilized cloud, chemical species contained in the cloud, total amount of each species, size distributions and densities of particulates or droplets, and spatial distribution of each species within the stabilized cloud.

In the generalized concentration model for aerial spray releases, the concentration of airborne spray material downwind from the point of cloud stabilization is given by the product of five terms:

$$\chi(x,y,z,t) = (\text{Peak Concentration Term})(\text{Alongwind Term})(\text{Edge Effects Term}) \\ (\text{Vertical Term})(\text{Depletion Term})$$

The Peak Concentration Term refers to the concentration at the center of the cloud ($x = \bar{u}t$, $y = 0$, $z = H$) and is defined by the expression

$$\frac{Q_L}{2\pi \sigma_x \sigma_z}$$

where

$\bar{u}$ = mean windspeed

H = height of the center of the stabilized cloud or effective release height

Q_L = total quantity of spray material released per unit length of the release line

σ_x = standard deviation of the alongwind concentration distribution

σ_z = standard deviation of the vertical concentration distribution

The remaining four terms, which are all dimensionless, are defined as follows:

$$\text{Alongwind Term} = \exp \left[-\frac{1}{2} \left(\frac{x - \bar{u}t}{\sigma_x} \right)^2 \right]$$

$$\text{Edge Effects Term} = \left\{ \frac{1}{2} \left[\operatorname{erf} \left(\frac{L/2+y}{\sqrt{2} \sigma_y} \right) + \operatorname{erf} \left(\frac{L/2-y}{\sqrt{2} \sigma_y} \right) \right] \right\}$$

$$\text{Vertical Term} = \left\{ \exp \left[-\frac{1}{2} \left(\frac{H - (V_s x / \bar{u})}{\sigma_z} \right)^2 \right] + \exp \left[-\frac{1}{2} \left(\frac{2H_m - H + (V_s x / \bar{u})}{\sigma_z} \right)^2 \right] \right\}$$

where

V_s = gravitational settling velocity

H_m = depth of the surface mixing layer

Depletion Term (Precipitation Scavenging)

$$= \exp \left[-\Lambda \left(\frac{x}{\bar{u}} - t' \right) \right]$$

where

Λ = fraction of material by weight removed by scavenging per unit time

t' = time after cloud stabilization that precipitation begins

$$\text{Depletion Term (Decay)} = \exp (-kt)$$

$$= \exp \left(-k \frac{x}{\bar{u}} \right)$$

where

k = decay coefficient

The total weight of heavy particulate or droplets deposited per unit surface area (contamination density) is defined by the expression

$$\omega_L = \frac{f_i Q_L}{\sqrt{2\pi}} \left\{ \frac{1}{2} \left[\operatorname{erf} \left(\frac{L/2+y}{\sqrt{2} \sigma_y} \right) + \operatorname{erf} \left(\frac{L/2-y}{\sqrt{2} \sigma_y} \right) \right] \right\} \left\{ \exp \left[-k \frac{x}{\bar{u}} \right] \right\} \{ M + N \}$$

where

$$M = \left\{ \frac{\beta H + [V_s (x + x_z) / \bar{u}] [1 - (\beta x / (x + x_z))]}{\sigma_z (x + x_z)} \right\} \left\{ \exp \left[-\frac{1}{2} \left(\frac{H - (V_s x / \bar{u})}{\sigma_z} \right)^2 \right] \right\}$$

$$N = \left\{ \frac{\beta \left(\frac{2H_m}{u} - H \right) - \left[\frac{V_s (x + x_z)}{u} \right] \left[1 - \left(\frac{\beta x}{x + x_z} \right) \right]}{\sigma_z (x + x_z)} \right\} \left\{ \exp \left[- \frac{1}{2} \left(\frac{2H_m}{u} - H + \frac{V_s x}{u} \right)^2 \right] \right\}$$

In the above expressions for contamination density,

f_i = fraction by weight of heavy particulates or droplets with gravitational settling velocity V_s

β = vertical diffusion coefficient of the order of unity

x_y = vertical virtual distance

The auxiliary model formulas used to define the standard deviations of the concentration distribution (σ_x , σ_y , σ_z)—which contain the turbulent intensities, diffusion coefficients, wind velocity, and other meteorological parameters—will not be presented here. A complete description of these formulas may be found in the report prepared for Deseret Test Center by Cramer and others (1972).

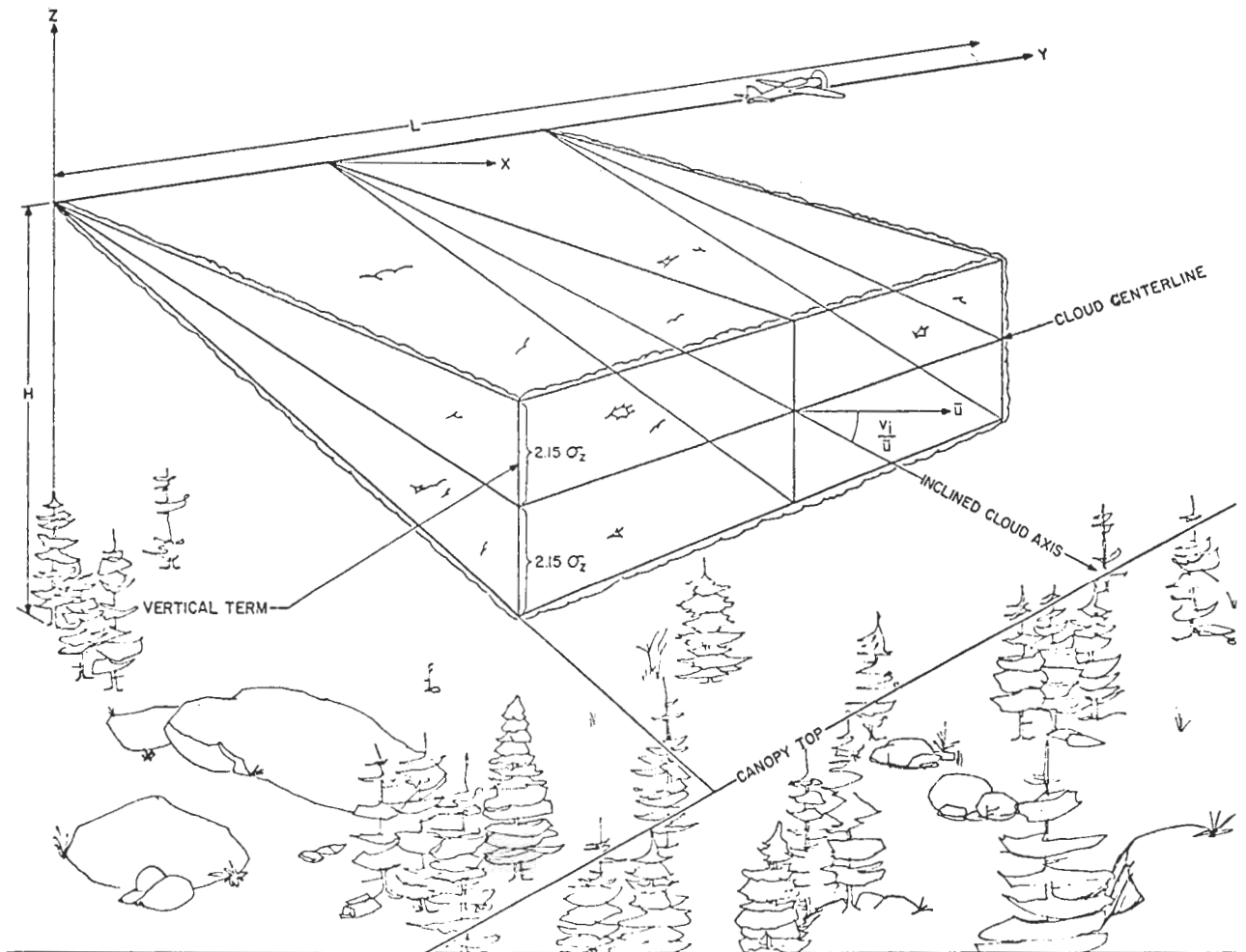


FIGURE 1. Schematic diagram of above-canopy line release model.

The aerial spray model just outlined was developed principally for use in open terrain and must be modified before it can be used to predict concentrations or contamination densities within forest canopies. As the model stands, it can very likely be employed to calculate spray concentrations and contamination densities at the top of a forest canopy resulting from aerial line source releases. The schematic diagram (fig. 1) shows the spread of a heavy particulate or droplet cloud from a line source release above a forest canopy. The features in the diagram refer to some of the more important model parameters. The inclination of the alongwind axis of the cloud centerline at an angle $v_i/\bar{u}$ to the horizontal (where v_i is the gravitational settling velocity of a class or heavy particles or droplets and $\bar{u}$ is the mean windspeed) shows the ballistic treatment of gravitational settling in the model. The growth of the cloud by turbulent mixing takes place about this inclined axis rather than about a horizontal axis, as in the case of a vapor or gas cloud.

The vertical term indicates the relationship between the vertical dimensions of the cloud and the standard deviation of the vertical concentration distribution. Although it is not shown in figure 1, the edge effects term accounts for the dilution of the cloud that occurs at the crosswind extremities (end points of the release line) produced by the entrainment and mixing of ambient air.

Examples are given (figs. 2, 3) of calculations of the total deposition of spray material, for selected drop sizes (density = 1.0), per unit surface area, at a height of 50 meters below the effective release height. This surface can be assumed to represent the top of a continuous forest canopy. When the mean windspeed is 5 m sec⁻¹, as shown in figure 2, the total deposition is approximately the same for all drops less than 100 microns in diameter. At low mean windspeeds, as shown in figure 3, the total deposition is approximately the same for all drops less than 40 microns in diameter.

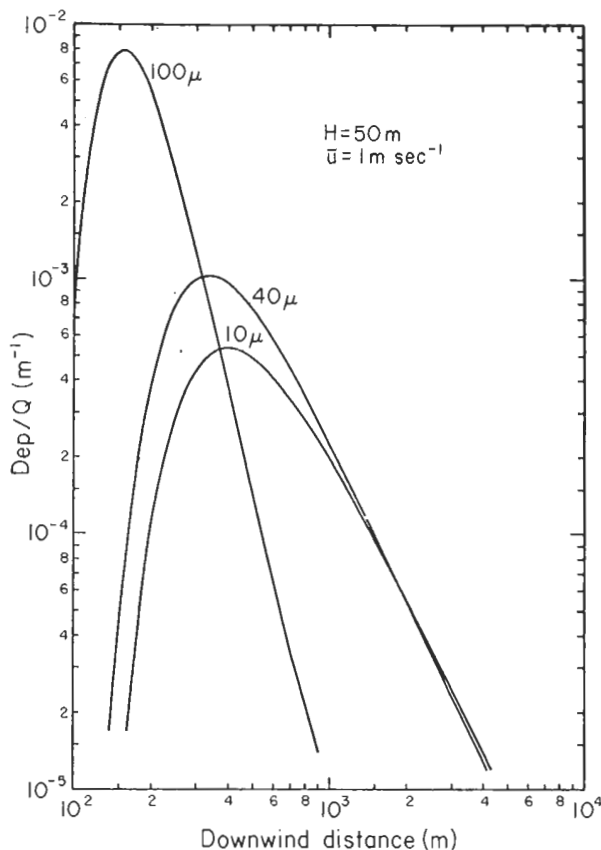


FIGURE 2. Total surface deposition from elevated crosswind line releases, at a height of 50 meters, for a mean windspeed of 5 meters per second for selected drop sizes.

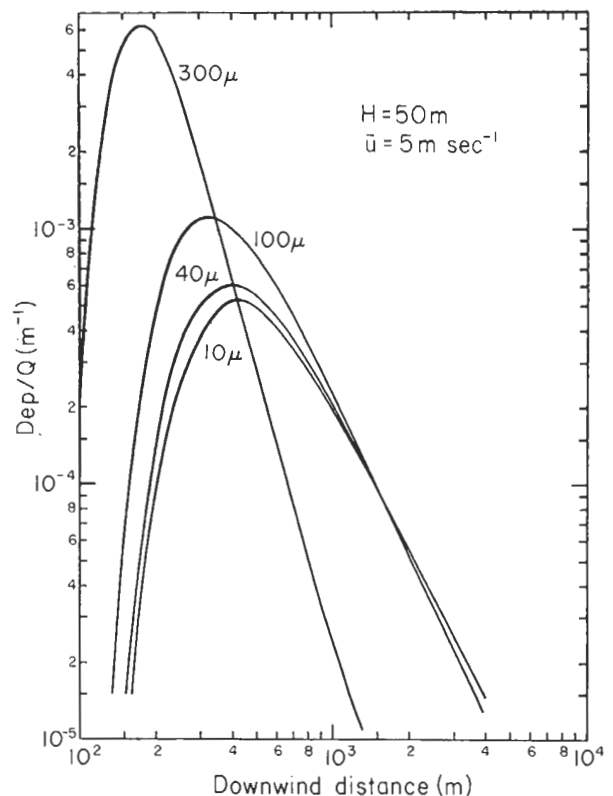


FIGURE 3. Total surface deposition from elevated crosswind line release, at a height of 50 meters, for a mean windspeed of 1 meter per second for selected drop sizes.

ATMOSPHERIC TRANSPORT AND DIFFUSION PROCESSES WITHIN FOREST CANOPIES

Atmospheric transport and diffusion processes within forest canopies are generally quite different from those in open terrain. In dense canopies, the meteorological structure is only very weakly coupled with the above-canopy meteorological structure. The wind and temperature fields that control below-canopy transport and diffusion consequently differ significantly from those that apply above open terrain in the absence of a canopy. The vertical profiles of mean wind-speed and air temperature below the top of a forest canopy are of special interest. Normalized profiles of windspeed between ground level and the top of selected canopies (fig. 4) were reported by Fritschen and others (1970). We are interested primarily in the normalized profiles in figure 4 for the Douglas-fir forest, dense conifer stand, and moderately dense conifer stand. The relevant features of these profiles are:

- In the upper third of the canopy, there is a sharp decrease in windspeed from the above-canopy speed
- In the lower two-thirds of the canopy, the windspeed is almost constant with height, and is approximately one-quarter to one-third the value of the windspeed at the top of the canopy

An additional fact to be kept in mind is that the windspeed in the undisturbed air flow above the canopy is approximately twice the windspeed at the top of the canopy. This level of undisturbed flow is found at an equivalent canopy height above the top of the canopy. It follows that windspeeds in the lowest two-thirds of dense forest canopies will range from about 5 to 10 percent of the windspeed in the undisturbed flow above the top of the canopy. Below-canopy transport speeds in dense forest canopies therefore are generally of the order of 0.5 meters per second (1 mile per hour).

Typical profiles of the height variations in temperature that occur between the air layer above the top of the canopy and the ground surface below the canopy are shown in figure 5. The shape of these profiles is principally determined by the radiational cooling or heating of the top of the canopy. In fair weather, the top of the canopy is warmed by solar insolation during daylight hours. At night, the top of the canopy cools down because of radiational heat losses to the air layers above the canopy. The temperature in the lower part of the canopy tends to remain unchanged. The result is the production of thermally-stable layers (temperature is constant or increases

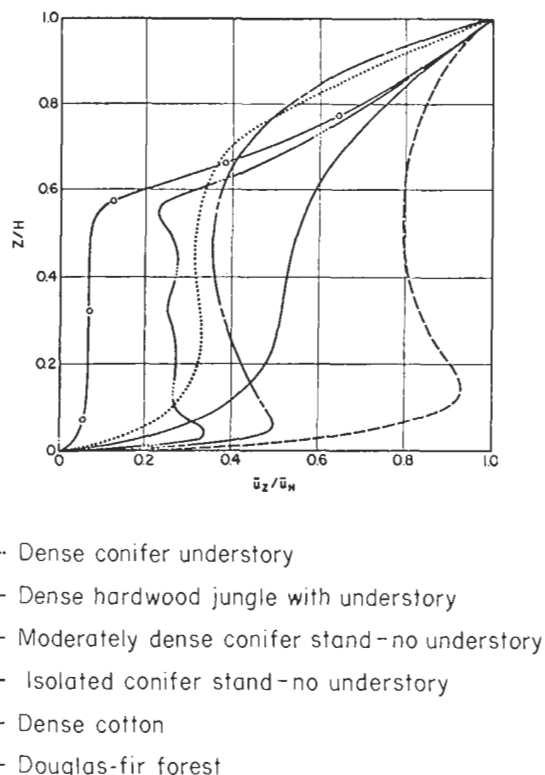


FIGURE 4. Comparison of normalized wind profiles of various vegetative canopies where Z is height above the ground, H is the height of the top of the canopy, and $\bar{u}$ is the windspeed. (From Fritschen and others, 1970)

with height) above and just below the top of the canopy at night and just below the top of the canopy during the day. As shown in figure 5, the air layer above the top of the canopy is thermally unstable (temperature decreases with height) during the day. On overcast days and nights, the temperature tends to decrease with height throughout the canopy and in the air layers above the canopy. A similar condition of thermal instability also occurs in fair weather during the early morning, late afternoon, or early evening. This condition is transient, and typically lasts for an hour or so during the changeover from day to day. The presence of thermally-stable layers is unfavorable for the diffusion of light particulates or aerosols containing small droplets. These materials are not able to penetrate thermally-stable layers, except as a consequence of gravitational settling which is generally insignificant for particles or droplets with diameters of from 10 to 20 microns or less. The practical significance of this phenomenon is that small

droplet aerial sprays released above dense forest canopies will have difficulty in penetrating and diffusing within the canopies except during the brief fair-weather change-over periods in the early morning or late afternoon, or during overcast conditions. If the spraying is performed with a helicopter that hovers at a low altitude above the top of a dense canopy, the downwash from the rotors may drive the spray material into the below-canopy region.

Another feature of below-canopy meteorological structure of interest is that the turbulent intensities tend to be quite large compared to typical values above open terrain. Turbulent intensity is defined as the ratio of the root-mean-square of the fluctuations of wind velocity about the mean velocity to the mean velocity. Typical values of this ratio above open terrain approximate 0.10. Beneath forest canopies, the ratio is approximately 1.0. The explanation is that the presence of the low wind velocities typical of below-canopy regimes and large fluctuations in wind velocity produced by air flow around obstacles lead to high values of the ratio defining the intensity of turbulence. Because the intensity

of turbulence is a good index of turbulent mixing or diffusion, this means that the diffusion processes below forest canopies are very effective in spreading light particulates or small droplets throughout the below-canopy region. It must be pointed out, however, that horizontal wind transport of airborne material is severely restricted by the low transport speeds. Also, because almost all canopies are open to the sky in selected location, entry and exit of airborne material is most likely to occur through these openings which act as natural chimneys. Much of this type of vertical transport of material occurs as the result of dynamic forces produced by the flow of air above the undulating surface presented by the top of the canopy. When the above-canopy windspeeds are of the order of 10 miles per hour, the below-canopy residence time of light particulates or small droplets is less than 1 hour, unless they are deposited firmly on vegetative or other surfaces prior to that time. This short residence time is principally caused by the rapid exit of material from the canopy in vertical air currents that form in the natural chimneys afforded by clearings or openings in the top of the canopy.

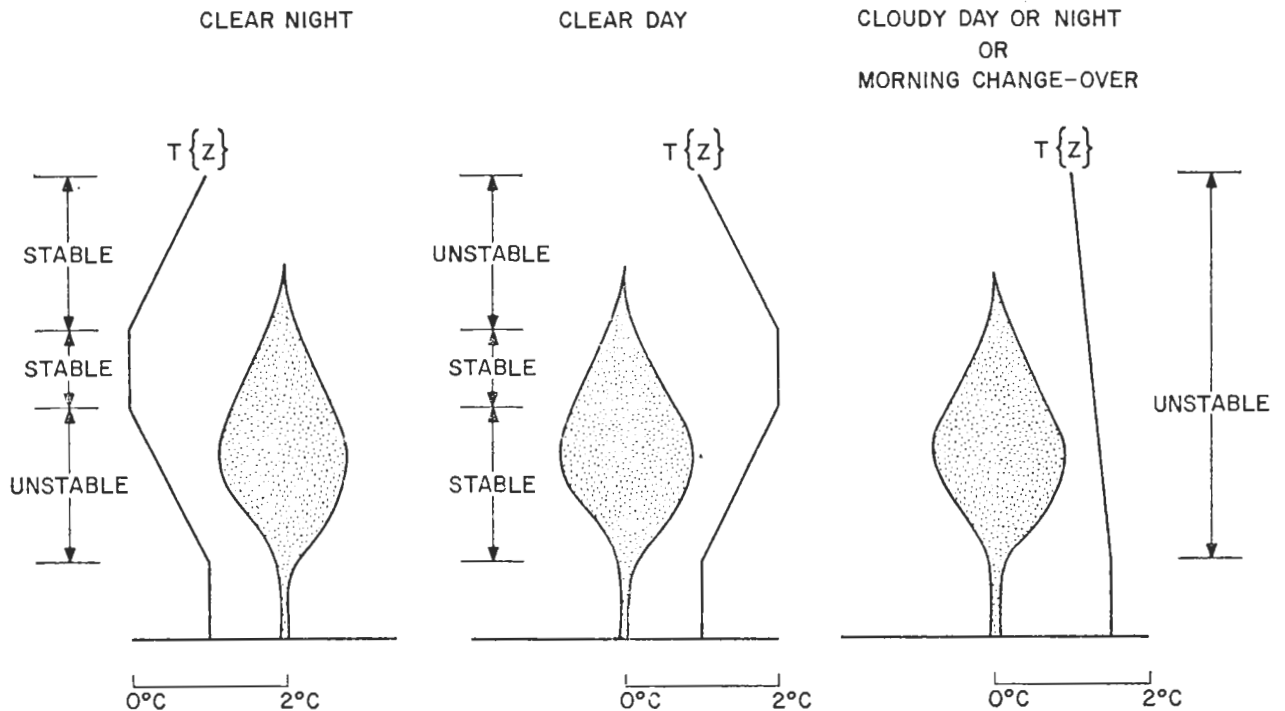


FIGURE 5. Vertical temperature profiles ($T\{Z\}$) above and below a forest canopy. Thermally stable layers prevent turbulent mixing.

DEPOSITION OF AERIAL SPRAYS ON FOREST CANOPIES

Deposition of aerial sprays on vegetation or insects appears to occur as the result of a number of different processes. Current understanding of the physics of some of these processes is severely limited. Also, the efficiency of the processes appears to vary with a number of meteorological, vegetative, and other factors. Four basic categories of deposition processes may be identified:

- Gravitational settling
- Inertial impaction
- Turbulent deposition or impaction
- Other processes such as electrostatic attraction, adhesion, and absorption

Gravitational settling would appear to be the dominant process leading to the deposition of heavy aerosols and possibly, under calm air conditions, may apply to light aerosols as well. The time required for spherical particles or droplets of unit density to fall through vertical distances of 10 meters

and 50 meters is shown (fig. 6) as a function of droplet diameter. Note that the fall times for 20-micron droplets are of the order of 10^3 seconds, whereas the fall times for 100-micron droplets are of the order of 10^2 seconds.

The inertial impaction efficiency E is shown (fig. 7) as a function of the inertial impaction parameter K for various target shapes. The theoretical basis of inertial impaction contains a number of listing assumptions, one of which is the existence of laminar flow. Within forest canopies, this assumption may be satisfied only under very special conditions, if at all. Figure 8, a simplified version of figure 7, shows an envelope of the values of the inertial impaction efficiency versus the parameter K for circular cylinders as the index ϕ for the Reynolds number of the cylinders varies over a wide range. Cylindrical shapes are assumed to be representative of small branches, pine needles, the spruce budworm and other insects that are targets for some aerial spray application. The graphs (figs. 9, 10) show the range of minimum droplet diameters (assuming unit density of the droplets) required to achieve inertial impaction efficiencies of 0.5 and 0.8 on cylindrical targets when the

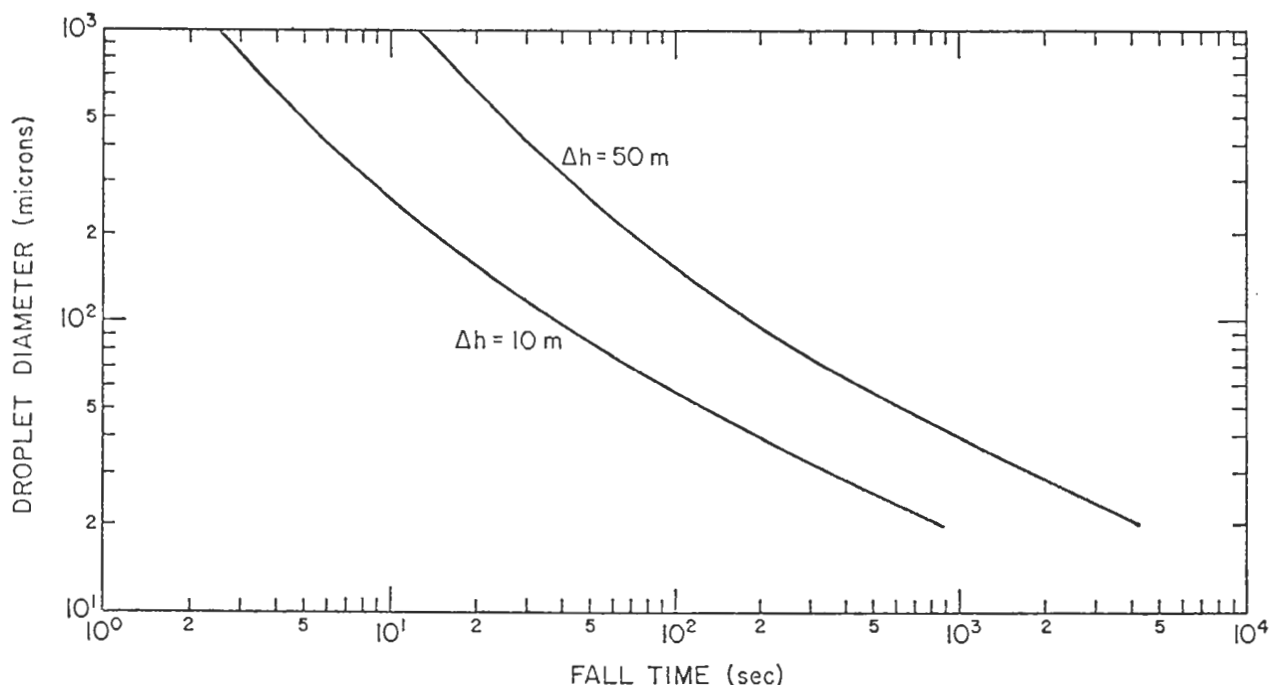


FIGURE 6. Time in seconds required for various-size drops of unit density to fall 50 meters and 10 meters.

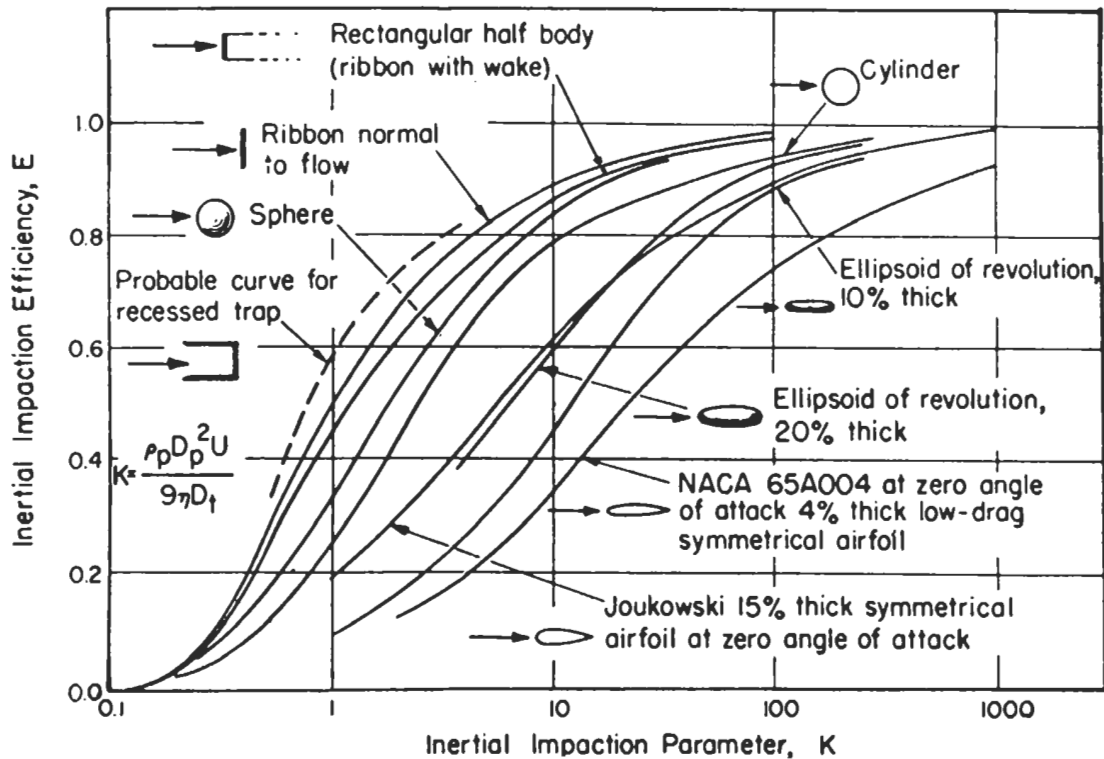


FIGURE 7. Inertial impact efficiency E as a function of inertial impact parameter K for a number of different target shapes. (From Golovin and Putnam 1962)

target diameter varies from 0.1 to 0.5 centimeters. The graphs have been constructed by solving the formula for the inertial impact parameter K shown at the lower left of figure 7 and marking off the regions in which the inertial impact efficiency E is equal to 0.5 and 0.8 by reference to the envelope of figure 8. In figure 9, the velocity U in the formula for the inertial impact parameter K has been assigned values from 0.1 to 0.5 meters per second. In figure 10, the value assigned to U is the gravitational settling velocity of unit-density spheres with diameters shown on the ordinate scale. According to figures 9 and 10, in order to achieve inertial impact efficiencies of 80 percent with aerial spray droplets, the droplet diameter must be of the order of 100 microns.

Turbulent deposition or impaction has been defined in two ways, both of which depend on the existence of large velocity fluctuations. Turbulent impaction is generally interpreted to mean that an aerosol particle or

droplet is physically transported to the surface of an object by a turbulent eddy and impacts on the surface. Turbulent deposition, on the other hand, refers to the fact that particles or droplets caught in vortex circulation or wakes in the lee of obstacles are brought to stagnation points or dead zones near the surface of foliage or other objects where the vortex circulation vanishes and the droplets or particles are thus deposited on the surface. This phenomenon has been offered as an explanation for the observed presence of small spray droplets on the undersides of leaves in canopies and other objects which cannot be explained as the result of either gravitational settling or inertial impaction.

Other processes such as electrostatic attraction, adhesion, and absorption are probably also effective under certain conditions. For example, there is evidence that some insects capture small droplets or particles by the action of cilia or by excreting a sticky substance.

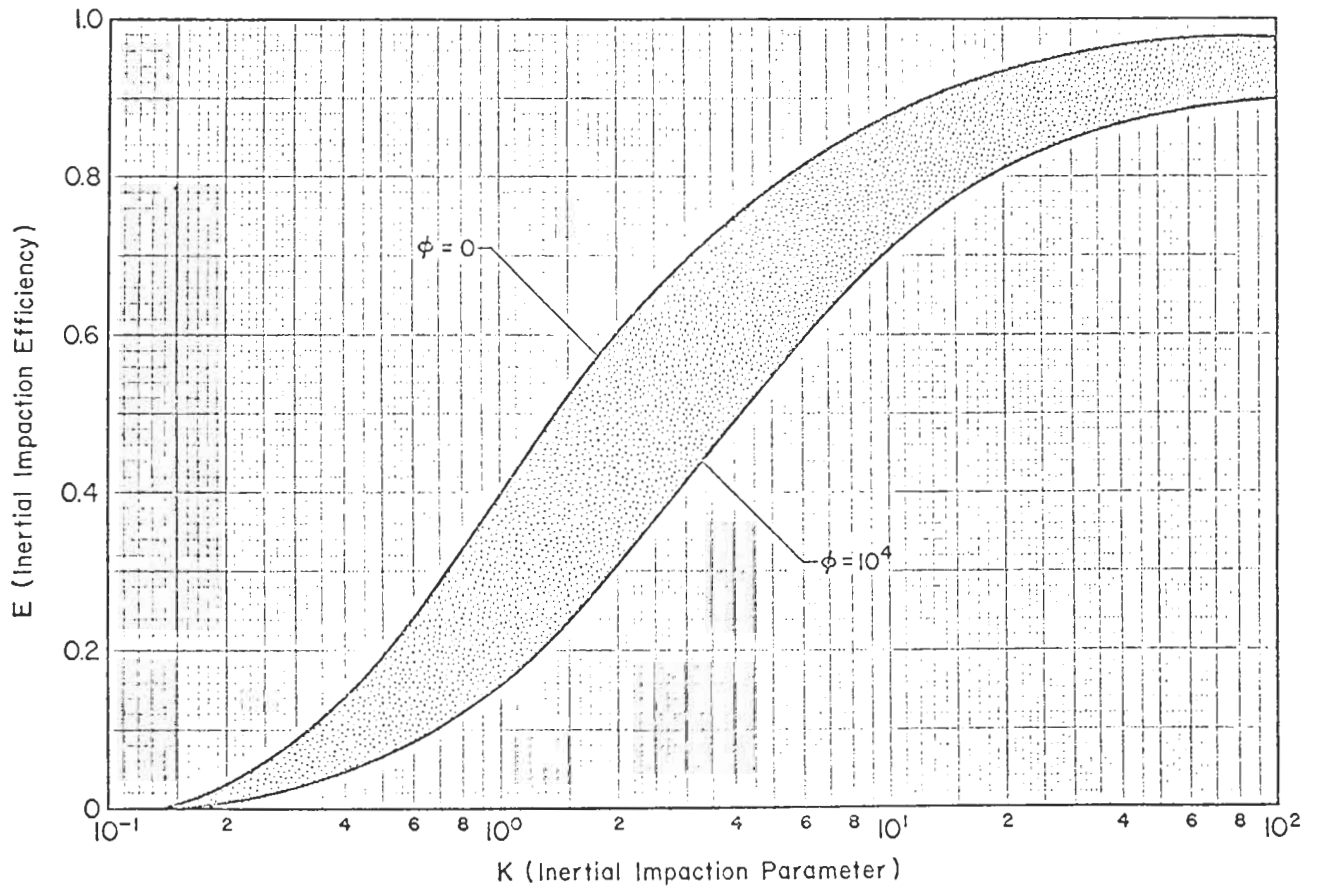


FIGURE 8. Inertial impaction efficiencies for circular cylinders;
 $\phi = \left(\frac{Re_p}{K}\right)^2$. (From Golovin and Putnam 1962)

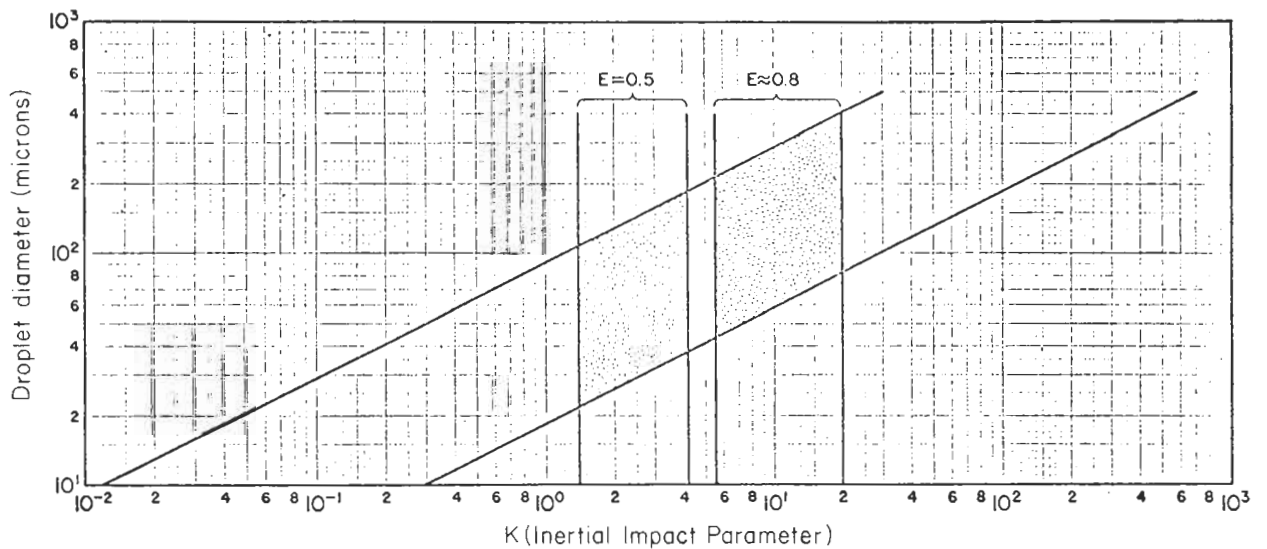


FIGURE 9. Minimum droplet diameters required for inertial
 impaction efficiencies of 0.5 and 0.8 when u varies
 from 10 to 50 cm sec^{-1} and D_t varies from 0.1 to 0.5 cm.

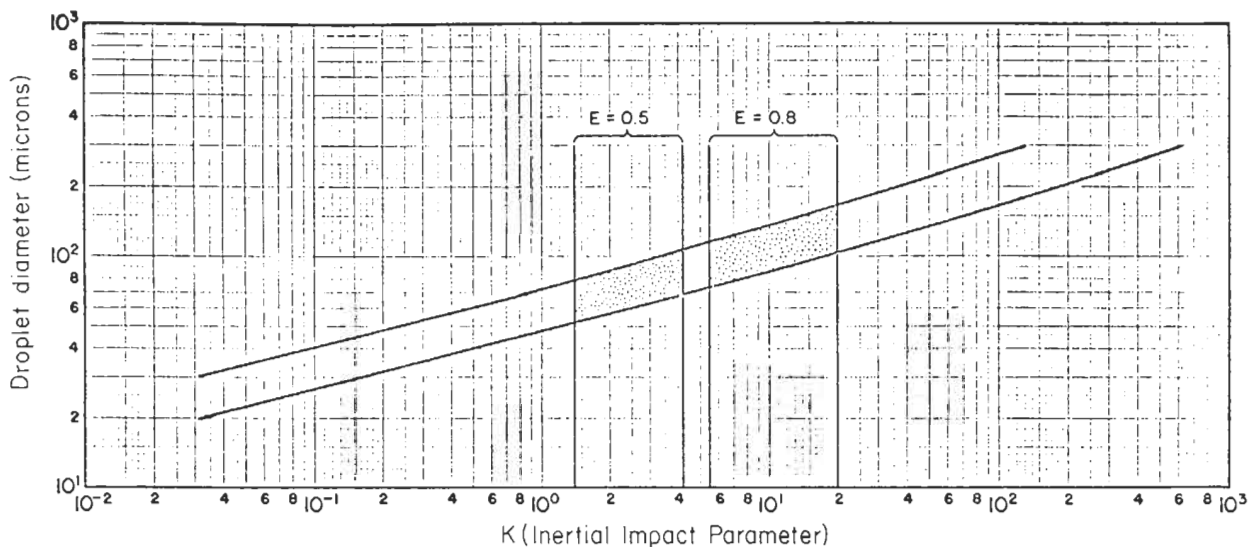


FIGURE 10. Minimum droplet diameters required for impaction efficiencies of 0.5 and 0.8 when $u = v_i$ and D_t varies from 0.1 to 0.5 cm.

A very simplistic view of the over-all problem of the optimum droplet size for aerial sprays intended for controlling insects in forest canopies--in the absence of such special phenomena as the capture of small droplets by cilia or adherence to sticky surfaces--is that the presence of small droplet sizes (drop diameters less than 20 microns) appears to be generally undesirable for the following reasons:

- Gravitational settling and inertial impaction are not very effective in depositing droplets of this size on the targets
- The efficiency of other processes is not sufficiently well established at present to justify dependence on these processes
- Retention of small spray droplets within the canopy is difficult and the problems associated with spray drift to nontargeted areas are maximized

COOPERATIVE PROGRAM REVIEW

To date, Deseret Test Center has provided limited meteorological support as well as droplet and aerosol sizing in support of four programs sponsored by Region One and the Missoula Equipment Development Center, U.S. Forest Service. On all four, Zectran was the insecticide used. Two of the programs involved a special dry formulation of Zectran. These tests have been reported by Barry and others (1972, 1973). In the other two programs, Zectran was diluted in fuel oil and released from both fixed wing and rotary wing aircraft as a coarse droplet spray. The first test involved the operational evaluation of a prototype military spray system. Testing was carried out both at Dugway, Utah, and the Lolo National Forest, Montana. Test results have been reported by Taylor and others (1972). Although the report cited is primarily an evaluation of military hardware, droplet spectra data derived from calibration runs conducted at Dugway are presented. The second operation, under the sponsorship of the U.S. Forest Service Pacific Southwest Forest and Range Experiment Station, was carried out near LaGrande, Oregon. The insecticide used was the Zectran-fuel oil mixture remaining after the Montana program.

Canopy penetration data obtained are shown in figures 11 and 12. The graphs generally follow the format developed by Hurlig and others (1953) to evaluate the screening effect of balsam fir foliage on coarse aerosols of DDT. In the figures, total mass beneath the canopy has been divided by the mass recovered in adjacent open areas. The mass ratio has then been plotted for each droplet size interval. Ordinate values can thus be read directly as percent penetration for a given droplet size interval (interval mid-points are plotted). Figure 11 shows both the first Oregon trial and the single Montana trial. Penetration factors are remarkably similar. The tree stand in Oregon was a dense clump of Douglas-fir surrounded by open meadow. Sampling (printflex) cards were placed 10 to 12 inches apart beneath the trees and in the open meadow. In Montana, fir was placed at 50 yard intervals over an area of several square miles. In Oregon, a helicopter was used, flying 75 to 100 feet above the canopy. In Montana, release heights of 200 feet were reached, with a fixed wing C-47 aircraft. Both operations, however, were daybreak operations

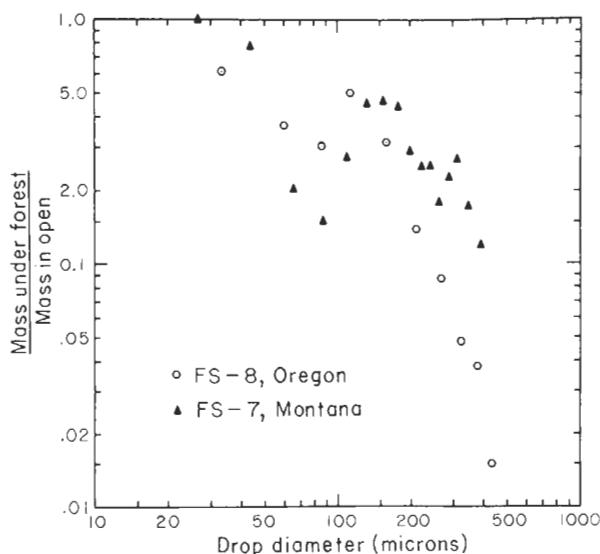


FIGURE 11. Percent penetration of a coniferous canopy for coarse Zectran fuel oil aerosols released under similar conditions of atmospheric stability.

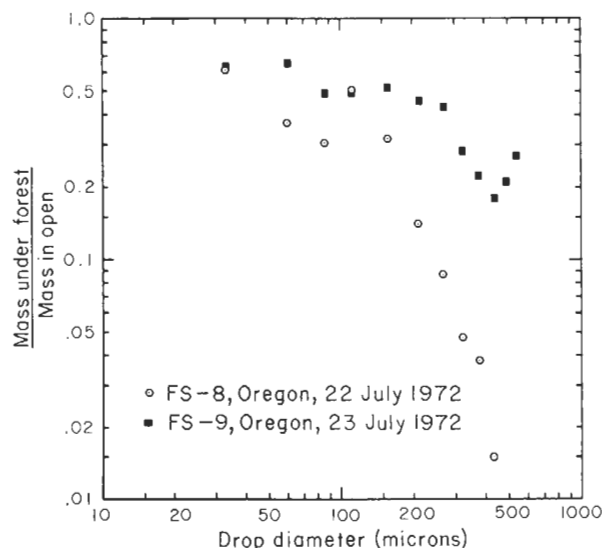


FIGURE 12. Percent penetration of a coniferous canopy for coarse Zectran fuel oil aerosols released under differing conditions of atmospheric stability.

(neutral atmospheric stability) and winds aloft were calm. That is to say, with similar stability regimes, there is a marked similarity of penetration ratios for quite different operating conditions. Figure 12 shows the two Oregon trials. On the second, fir trees more sparsely spaced dominated the sampled tree stand. Also, there was some understory broadleaf growth. No change was made in spray system parameters for the two Oregon trials; however on the second trial, the sample cards were arrayed on a steep slope and there was a light but detectable up-draft at the time of spraying. To the observer, the visible cloud had a slight but noticeable up-slope displacement. The 30-micron droplets coincide. With that exception noted, the slopes of the two lines are quite different. Such a small sample size cannot be conclusive. The data do stress, however, the importance of normalizing spray trial results in terms of the meteorological structure at the time of spray release as an essential prerequisite to any evaluation designed to compare biological effectiveness of pesticide application on coniferous forests.

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Impaction of Zectran Particles on Spruce Budworm Larvae

A Field Experiment

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Robert B. Ekblad⁴ Richard L. Marsalis⁵ William M. Ciesla⁶

Abstract--The U.S. Forest Service, supported by Deseret Test Center, conducted a field test during June 1972 in the Lolo National Forest, Montana. The objective was to investigate the impaction of dry-liquid Zectran particles on the western spruce budworm larvae as a function of particle size. A helicopter was used as the dissemination vehicle because of the downwash effect, which assists aerosol penetration of the forest canopy and enhances particle impaction. Rotorod samplers and glass impaction slides were used to obtain aerosol and particle-size data. Budworms and fir needles were examined, and impacting particles were counted and measured. Eighty-seven percent of the particles observed on the fir needles were 10 microns or less in diameter, and 87 percent of the particles observed on the budworms were 15 microns or less in diameter. The results and conclusions through based upon relatively limited data, provide baselines for planning future experiments.

Research work conducted by the U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station (Himel and others 1965, Himel and Moore 1967, Ekblad 1971), with the insecticide Zectran has disclosed that the highest rate of mortality of western spruce budworm (*Choristoneura occidentalis* Freeman) was achieved by contact with drops less than 50 microns in diameter. In an effort to produce small drops with standard dissemination equipment, a technique for developing a dry-liquid particle has been investigated. Dry-liquid insecticides are composed of a liquid formulation which is coated on a solid particle by a special blending process. The resultant

material may be up to 75 percent liquid by weight and still retain the free flowing properties of a granular solid.

Spandav (1944) reported that scientists in Germany were the first to use the dry-liquid concept (originally called carrier-dust) as a means for employing chemical agents which could not be dispensed by the usual methods. These scientists thoroughly investigated the use of alumina gel and fuller's earth as carrier-dusts. In general, they concluded that any substance could be dispensed on a carrier and that the use of carriers offered a new method for dispersal of viscous or gum-like materials and of those materials which could not be prepared in a finely divided form by grinding, such as naturally occurring poisons and bacterial toxins.

In 1948, the research begun in Germany was investigated by the U.S. Army Chemical Corps at Edgewood Arsenal, Maryland (Wilcox and Goldenson 1951, 1960). Physical characteristics of carriers were defined, and feasibility of the carrier-dust technique as a means for disseminating chemical agents was demonstrated.

In 1947, oil solutions of DDT were mixed with micronized dust (Brooks 1947) and dispersed from an aircraft by means of a dust-feed disseminator. This method was used to increase the particle size of the dusts.

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Insecticide dusts were commonly used during the 1940's and 1950's. However, the dust particles were generally less than 10 microns in diameter. Low impaction efficiencies, lack of retention on leaf surfaces, and drift problems associated with these small dust particles resulted in a shift of the use of liquid sprays consisting of larger droplets. The origin of the term, dry-liquid, is unknown although the term has been in use at the Edgewood Arsenal for some time.

The number of casualties from malaria and other insect borne diseases in the Pacific theater in World War II was equal to or greater than those from enemy action. This fact led the U.S. Government to sponsor extensive studies to understand the insecticide modes of action involved in reaching, impacting upon, and killing the target insects.

The timely availability of DDT and its apparent effectiveness in very low concentrations compared to other insecticides provided the military with a new chemical for possible control of disease vectors.

In order to design equipment for dispersing DDT efficiently, however, information was first needed on the optimum particle size. Without such information it would be impossible to take full advantage of the toxic properties of DDT, material would be wasted, and control would frequently be impractical. The particle size required to obtain the maximum effect would depend not only on factors peculiar to the insecticide, such as susceptibility of the insect to the insecticide, its mode of action, and its chemical and physical properties, but also on such external conditions as meteorological factors, terrain, and method of treatment.

The problem of optimum particle size of insecticides has been the subject of investigation by a number of workers for many years before the discovery of DDT. Smith and Goodhue of the U.S. Department of Agriculture (National Defense Research Committee 1946) summarized some of the earlier work on the relationship of particle size to insecticide efficiency, and concluded that the toxicity of solid-type insecticides increased with decrease in particle size.

Dry-liquid mixtures consisting of desired particle sizes offer several distinct advantages over liquid mixtures, such as: (1) ease of handling and storing, (2) ease of dissemination, (3) simplicity in laboratory assessment, and (4) minimum evaporation. Because of these advantages, the U.S. Forest Service investigated the dry-liquid concept and determined that the registered Zectran FS-14

formula⁷ could be coated onto a dry particle of selected size.

In 1971, a field experiment to investigate the feasibility of using dry liquid, was conducted in the Nezperce National Forest, Idaho (Barry and Blake 1972). The material disseminated was Zectran FS-15 coated on Micro-Cel E with a fluorescent tracer, Tinopal. The formulation of this mixture was a joint effort by the U.S. Forest Service's Pacific Southwest Forest and Range Experiment Station and the Missoula Equipment Development Center. The formulation consisted of 60 percent FS-15 and 40 percent Micro-Cel E. A single aerial line release was made using a Cessna Agwagon aircraft with a Swathmaster dispenser. Drainage winds were utilized to transport the dry-liquid aerosol throughout the designated test area. Surface samplers, placed throughout the test area, indicated that most of the area was covered by the aerosol. However, very little reduction in budworm population was noted and very little particle impaction was observed on the foliage. It was postulated that lack of impingement was the result of a very low impaction efficiency associated with the small particles which made up the aerosol. Over 80 percent of the particles, as measured in the laboratory, were 4 microns or less in diameter and further, approximately one-tenth of the recommended rate of Zectran was sprayed over the designated sampling area, i.e., 0.018 pounds of Zectran per acre instead of the required 0.15 pounds. The Tinopal tracer was unstable in light, which made microscopic assessment difficult. Also, Tinopal fluoresced blue, which complicated efforts to differentiate it from naturally occurring background material. This experiment, however, clearly demonstrated: (1) the feasibility of using dry-liquid as a means of employing insecticides; (2) that standard Swathmaster type dusters can be used to disseminate dry-liquid mixtures; and (3) that drainage winds in mountainous terrain can be employed to transport dry-liquid aerosols.

There is little information in the literature on the optimum particle size for impaction on spruce budworm larvae feeding on coniferous needles (except for the Himel and Moore study). There are, however, several studies which deal with impaction of particles on mosquitoes and with theoretical calculations of impaction of various size particles as a function of wind-speed, and of the size and shape of the impaction target.

⁷The Zectran FS-15 formula is made of 24 ounces of Zectran (4-dimethylanimo-3, 5-xylyl methyl carbanate) in solution with one gallon of tripropylene-monomethyl glycol ether (TPM).

Considerable empirical data are available (U.S. Department of Agriculture 1969) based upon U.S. Forest Service field experience on budworm kill as a function of mass median diameter⁸ of the disseminated spray. Recent pilot and control operations conducted by the U.S. Forest Service (U.S. Department of Agriculture 1971), under similar conditions in Eastern and Western United States, have shown both success and failure in achieving the desired degree of budworm control. The mass median diameter produced by the spray systems used on these tests was estimated to be between 113 and 160 microns. The U.S. Forest Service/C-47 spray system used in the western states was characterized by Deseret Test Center (Taylor and others 1972). This system produced a mass median diameter of 120 microns.

METHODS

The objective of this test was to investigate the impact of dry-liquid particles on the western spruce budworm larvae as a function of particle size.

The test was a cooperative effort between U.S. Forest Service and Deseret Test Center and was conducted in the Kennedy Creek area of the Ninemile Ranger District, Lolo National Forest, Montana, on June 28, 1972 (Barry and others 1973). A helicopter was employed to disseminate a dry-liquid formulation of the insecticide Zectran over two test plots in a Douglas-fir forest. The trees in the test plots were highly infested with western spruce budworm larvae.

The original scope of the test included several duplicate releases to compare liquid sprays to different formulations of dry-liquid sprays, in addition to comparing different types of disseminating aircraft. For economic reasons, however, the test scope was reduced.

Site and Test Plot

Plot 1 consisted of 217 stems per acre and Plot 2 consisted of 97 stems. Each test plot was approximately 200 feet wide and 300 feet long (fig. 1). The sampling array was identical on both plots consisting of 63 rotorod sampler stations. A glass impaction slide measuring 1 inch by 3 inches was positioned at each rotorod station.

⁸The mass median diameter is obtained by dividing the total volume of the spray into two equal parts; one half of the mass of the spray is contained in droplets of smaller diameter than the mass median diameter and the other half is contained in droplets of larger diameter.

Insecticide Mixture

The dry-liquid insecticide formulation consisted of a blend of the following, by weight:

Hi Sil 233	47.5 percent
Zectran FS-15	50.0 percent
Chartreuse Pigment 720	2.5 percent

Aircraft and Disseminator

A Bell G-3 helicopter equipped with a duster was used for spraying the dry-liquid mixture over the two test plots. The aircraft speed was 30 miles per hour, and the release height was approximately 50 feet above the canopy.

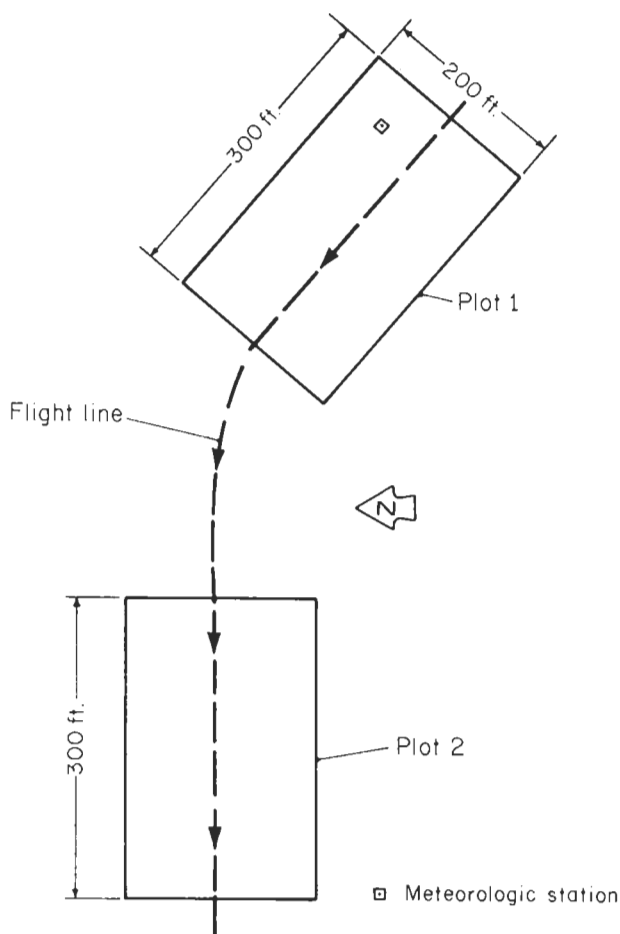


Figure 1. Orientation of Plot 1 to Plot 2 and Helicopter Dissemination Line.

Biological Sampling

A prespray insect survey was conducted in the test area approximately 24 hours before the spray release for the purpose of establishing prespray level of spruce budworm population. Branch samples were obtained to study particle impaction of foliage.

Four trees in each plot were selected as sample trees to investigate particle impaction on the budworm larvae. A plastic drop cloth was placed beneath each of the four trees to collect falling larvae. On the morning following the test, approximately 100 budworm larvae were collected at random from each drop cloth and placed in 35-mm film cans for transportation to the laboratory.

The fir needles and budworm larvae were examined under a dissecting microscope equipped with ultraviolet light for the presence of fluorescing dry-liquid particles. The particles were counted and measured.

Meteorological Instrumentation

Instruments to record windspeed and direction at the 2-meter level were positioned near the center of Test Plot 1. Wet and dry bulb temperature readings were taken at the same location during the test.

RESULTS

a. Eighty-seven (87) percent of the particles observed on the spruce budworm larvae were equal to or less than 15 microns in diameter; 87 percent of the particles on the fir needles were equal to or less than 10 microns in diameter; and, the majority of the particles on the fir needles were on the underside of the needle. Forty (40) percent of the particles on the glass plates were greater than 33 microns (table 1-5).

b. The number median diameter of the dry-liquid formulation was 1.3 microns and the mass median diameter was 37.0 microns.

c. Under the conditions of the test, the swath width exceeded 200 feet.

d. Budworm mortality was approximately 33 percent.

Table 1--Distribution, by size, of 150 fluorescent dry-liquid particles found on 108 spruce budworm larvae

Particle size (μ)	Number of particles	Percent	Cumulative percent by number
3-5	16	10.7	10.7
6-10	76	50.7	61.4
11-15	38	25.3	86.7
16-20	13	8.7	95.4
21-25	5	3.3	98.7
26-30	2	1.3	100.0

Table 2--Distribution, by size, of 191 fluorescent dry-liquid particles found on 4941 fir needles from Plots 1 and 2

Particle size (μ)	Number of particles	Percent	Cumulative percent by number
2-5	118	60.8	60.8
6-10	50	25.8	86.6
11-15	18	9.3	95.9
16-20	5	2.6	98.5
21-25	1	0.5	99.0
26-33	2	1.0	100.0

Table 3--Distribution, by size, of 355 fluorescent dry-liquid particles measured on impaction plates

Particle size (μ)	Number of particles	Percent	Cumulative percent by number
<2	28	7.9	7.9
2-5	26	7.3	15.2
6-10	23	6.5	21.7
11-15	34	9.6	31.3
16-20	48	13.5	44.8
21-25	24	6.8	51.6
26-33	31	8.7	60.3
>33	141	39.7	100.0

Table 4--Summary of percent of particle sizes observed on spruce budworm as a function of particle size distribution, by number, of particles disseminated

Particle size (μ)	Percent on budworm	Percent dissemination	Ratio:Percent disseminated/percent on needles
2-5	10.7	37.0	3.46
6-10	50.7	4.0	0.08
11-15	25.3	0.42	0.02
16-20	8.7	0.28	0.03
21-25	3.3	0.14	0.042
25-35	1.3	0.70	0.54

Table 5--Summary of percent of particle sizes observed on fir needles as a function of particle size distribution, by number, of particles disseminated

Particle size (μ)	Percent on budworm	Percent dissemination	Ratio:Percent disseminated/percent on needles
2-5	60.8	37.0	0.61
6-10	25.8	4.0	0.16
11-15	9.3	0.42	0.05
16-20	2.6	0.28	0.11
21-25	0.5	0.14	0.28
25-35	1.0	0.70	0.70

CONCLUSIONS

a. If the budworm is considered a cylinder 1/8-inch in diameter, the majority of the particles disseminated were too small for efficient impaction by inertial forces on the spruce budworm larvae, as illustrated by calculated impaction efficiencies in figures 2 and 3. The fact that small particles were observed on the larvae suggests that another mechanism or combination of mechanisms are causing impaction or deposition of particles on the budworms and fir needles.

b. Sell's theory (Sell 1931) can be used to estimate the particle/droplet size which has the greatest impaction efficiency for various objects, if the particle/droplet velocity and size of the impaction surface is known (table 6, fig. 4).

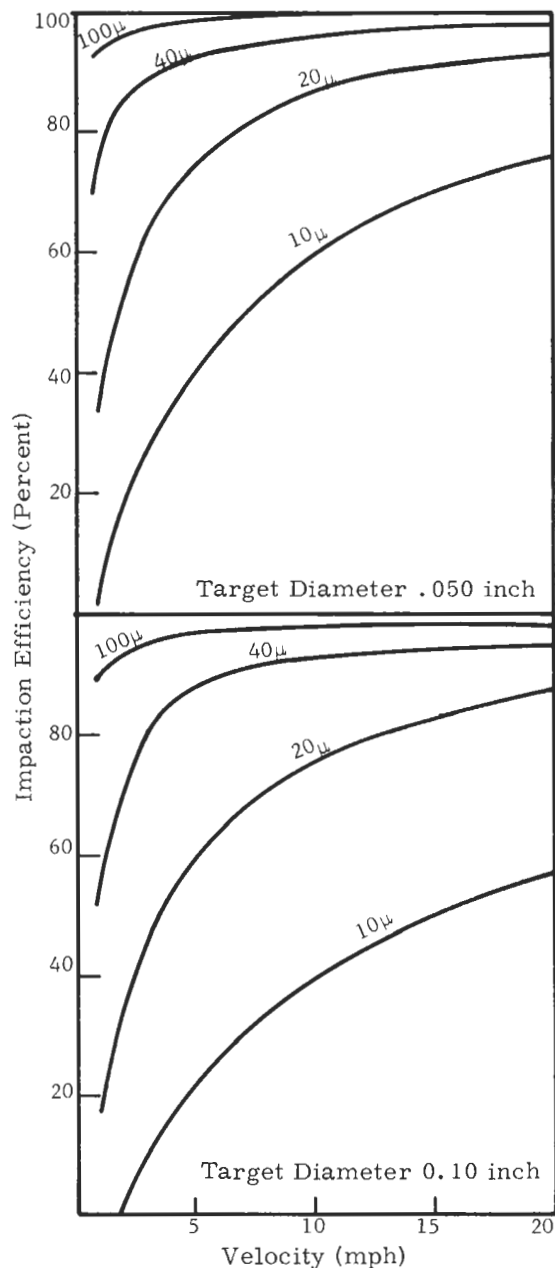


Figure 2. Inertial Impaction Efficiency of Various Size Particles on Cylinders of Various Sizes as a Function of Wind Speed Calculated from Golovin and Putnam (1962).

c. The particle size spectrum of the aerosol or particulate cloud and the horizontal and vertical wind velocity should be measured above and below the canopy in experiments designed to evaluate dissemination methods and the effects of various size particles.

d. The use of insect mortality data to judge the effectiveness of a new dissemination technique or system, without measuring the meteorological influences, should be avoided.

e. Helicopters provide a means of disseminating insecticides in complex mountain terrain with certain advantages over fixed-wing aircraft. Harnessing the downwash provides a means of overcoming or reducing unfavorable meteorological conditions. However, to be more effective than fixed-wing aircraft, the helicopter must be flown at speeds < 40 mph and close to the canopy (fig. 5). It is recognized that this may not be practical under many conditions.

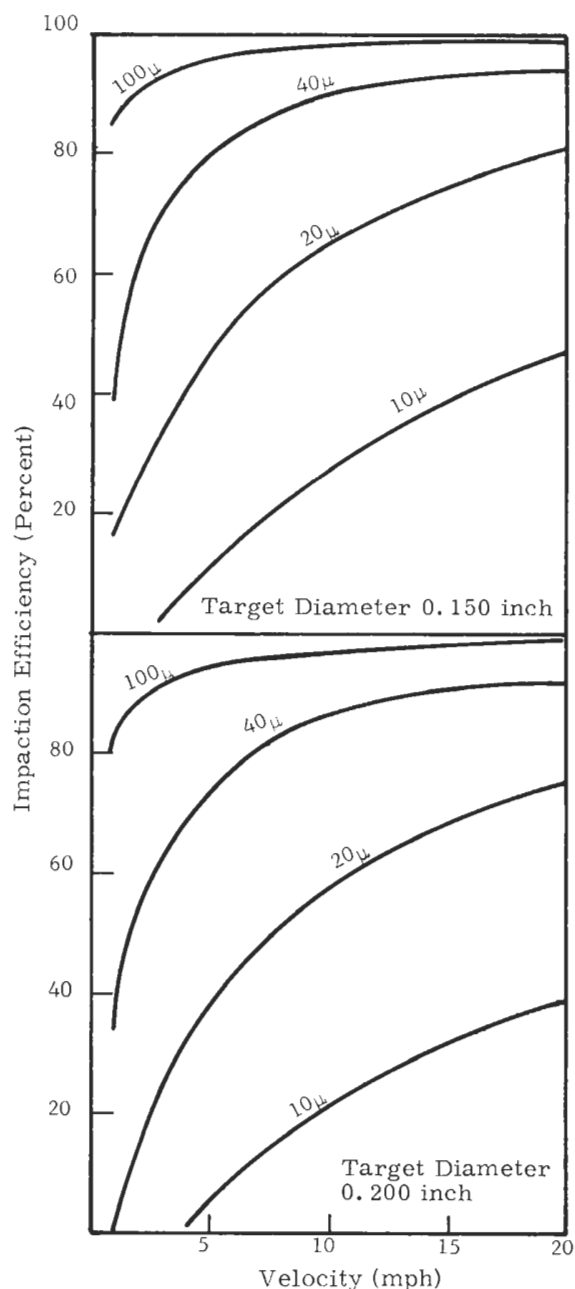


Figure 3. Inertial Impaction Efficiency of Various Size Particles on Cylinders of Various Sizes as a Function of Wind Speed Calculated from Golovin and Putnam (1962).

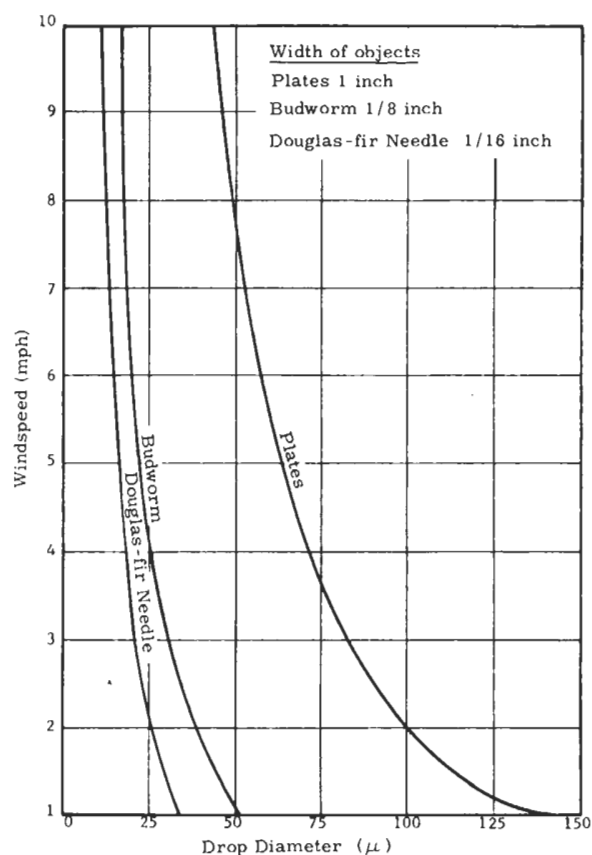


Figure 4. Relative Maximum Efficiency of Three Collectors as a Function of Wind Speed and Particle Size (According to Sell's Law).

Table 6--Particle size associated with maximum impaction efficiency (as a function of windspeed) on Douglas-fir, budworm, and glass plates, according to Sell's Law

Object (width)	Windspeed (mph)	Particle size (μ)
Douglas-fir Needle (1/16 in.)	1	35
	2	25
	3	20
	4	18
	6	14
	8	13
Budworm (1/8 in.)	10	11
	1	50
	2	35
	3	29
	4	25
	6	20
Plates (1 in.)	8	18
	10	16
	1	141
	2	100
	3	82
	4	71
	6	58
	8	50
	10	45

f. It was beyond the scope of this test to study the advantages and disadvantages of dry-liquids over those of liquid sprays. However, dry-liquids, aerosols or particulates, applied in the proper range of particle sizes may have certain advantages to control forest insects for specific applications, such as tree plantations, complex mountain terrain, seed trees, and specimen trees near recreation and summer home sites.

g. A simple and reliable method is needed for marking swath lines for aerial spray operations in forests.

h. The Hercules Chartreuse 720 fluorescent pigment is a satisfactory material for aiding in the microscopic examination of the dry-liquid particles.

i. Future research should be directed at answering such questions as how many droplets (of the size which has a relatively high impaction efficiency on the specific target) are necessary to give a high probability of contact with the target, and how many droplets of this size are necessary to produce a lethal dose of insect knockdown in the field.

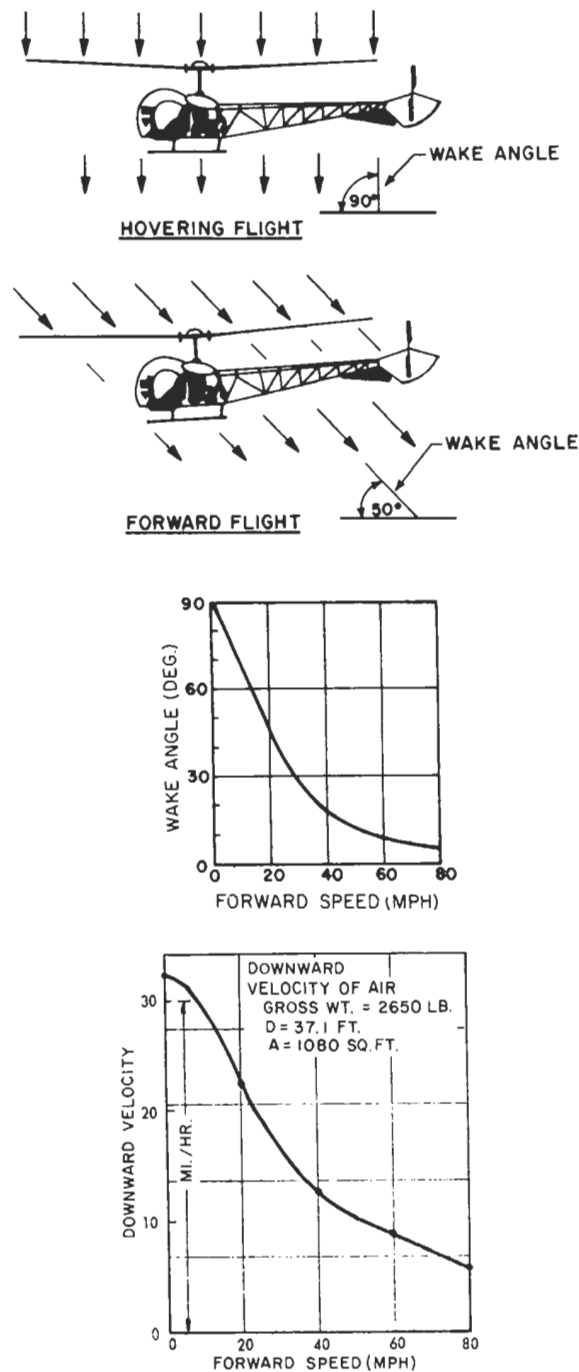


Figure 5. Helicopter Wake Angle as a Function of Forward Speed. (Source: Obtained from Bell Helicopter Publication "Helicopter Techniques for Aerial Application," Fort Worth, Texas, January 1966).

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Workshop Summary

Robert L. Dimmick¹

I shall present this as a chronology, because I think that a sequence of events can yield information not always visible in a categorized, historical recounting. Actually, our group just got started into the meat of the argument. We found (collectively) that we had a lot of knowledge, but it was difficult to combine and express it in a simple way because, surprisingly enough, semantics became a major problem.

We started by attempting to define behavior in its totality. We said, there is a source, there is the air, there is a target, there is the fate of a particle (it lands someplace), and there is the end result (it does something). Very quickly we decided this viewpoint was too large to consider, so we selected three parts. One part is the source, one is transport, and one is target.

Source must have several properties. We decided that devices used to produce aerosols were not part of our discussion and that the production of the aerosol was not part of the concept of behavior. We wanted to start with what we finally called a "stabilized aerosol." This immediately created semantic problems--an aerosol cannot be stabilized--what do you mean by that? When the argument was finally threshed out, we said a particle is emitted from a source, some evaporation (equilibration) occurs, and finally its initial production energy is dissipated and it "hangs" in the air--an aerosol particle. We even discovered that we were not sure what we meant by aerosols because people talked about aerosol "clouds." We decided that an aerosol is just a collection of airborne particles, and left it at that.

We then tried to define what we mean by "source." We started talking about the strength of a source. Then we said that "strength" is not exactly what we mean by "source strength" because that has connotations of how much active ingredient is in a particle. So we decided to call it emission rate: A source is defined by the emission rate of particles (material) going into the air times the time of spray.

Now we had the collection of particles hanging in the air. The first parameter we thought of was size, then size distribution. We agreed that size distribution is approximately log normal; the smaller the particle becomes the greater the number you expect to find. And the apparent size depends on the technique used to measure the particles. If you look into literature on measurements of size distribution, you get the idea that the absolute laboratory standard is to count and size them under the microscope; but even that has problems.

I was involved, for example, with some work with a pharmaceutical company that was making an aerosol product. They were having particle analysis (microscopy) done by an institute in the East. The company was not happy, since they were trying to use the data for quality control, and it varied unaccountably. So they sent the institute identical samples, but did not let them know that the samples were identical. The samples were returned with several different size estimates. So I finally convinced the company that what they were really interested in was the aerodynamic diameters; i.e., they should consider their product in terms of its behavior and not worry about the actual diameter of their odd-shaped particles. It was how well the particles penetrated into the lung that was the important parameter.

The panel kicked that idea around for a while and found we were again talking about a "stabilized aerosol"; you have material and you produce it as an aerosol and then it reacts with the air and comes to some sort of initial equilibrium. We said, what else besides size affects the aerosol? Well, the concentration does--and immediately the question arose, what do you mean by concentration? Someone said, "The number of particles per unit volume of air, that is the concentration." Someone else said, "No, that is not what we mean, we mean, how much active material is within the droplet."

How should we express concentration? Probably, one has to express it in some way that involves both of these properties: We decided to refer to the formulation as "composition" and the amount dispersed (the source strength) as concentration. We can all go home with dictionaries and look up some of these. What has all this to do with behavior? Certainly the chemical and physical properties, and the composition of the particle, affect the eventual behavior.

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We then turned our minds to the subject of transport of aerosols. We decided not to refer to air as a vector but rather as a process of transportation. There are a number of factors involved in transportation, but it was evident that a most profound factor with respect to transport of aerosols, as you might guess, was meteorological effects. As several speakers discussed meteorological properties, it became evident that some were talking about micrometeorological events, whereas others were talking about macrometeorological events, and the two were interlinked. For example, terrain is a factor that certainly affects the transport of aerosols (as it affects air) and is considered to be, I take it, a part of the meteorological picture--that is the macrometeorological part of it. On the other hand, some meteorological events include impaction of particles on the bottoms of twigs. We spent a considerable amount of time arguing about turbulent impaction, and I think if I may make a pun, we left that question up in the air. Perhaps we really did not understand how the particles got there and perhaps this is an area where somebody should do some work.

Under "transport" is included the idea of trajectory. Now, what do you mean by trajectory? We finally said as I recall it, "Well, depending upon the terrain and a lot of luck and everything else, the aerosol either goes in a straight line or it diffuses, or maybe it makes a bend; this phenomenon is extremely difficult to predict."

That statement is typical of committees, encompasses all knowledge and cannot be refuted; it is a reflection of the state of the art. However, there are a number of factors involved in the final trajectory, and in attempts to predict meteorological events, one thing that evolved from the discussion was that every parameter we talked about seemed to be interconnected with every other parameter. We tried but were unable to make a rational list of headings, subheadings, subsubheadings and so forth--something here belonged over there. Regardless, I will list some of the factors we thought might influence "transport": the effect of light on the particle, temperature, humidity, washout (washout, I believe, refers to fog in the atmosphere or rain or any action that reduces effectiveness), coagulation, photolysis, hydrolysis, evaporation, turbulence, diffusion, and time. Finally someone pointed out that, in the long run, the real problem involved accounting for 100 percent of the mass in making these measurements. If one can conduct experiments in such a way that he can account for 100 percent of the mass, then he is in a position to make meaningful statements.

During the course of the conversation we moved from trajectory and transport into "target." For a while we were not sure whether we were talking about transport itself or only about target. So we defined target as a two-valued word, target and nontarget. Here again semantics came up. What do you mean by the target? Take mosquitos. Is surface water (that you put insecticide on) the target, or is the mosquito larvae the target? One person talked about the target and I was confused until I realized that his idea of nontarget was something (e.g. cover) that kept the aerosol from getting to the target. There were at least two people talking about the same word and coming up with a different meaning. We wondered whether it is impingement or impaction when the insecticide gets on the target? Well, in my vocabulary impingement implies "going into" and impaction implies "going onto." That was not really brought out in the discussion, but it is again expressive of an attitude; we felt we had to begin defining our terms and explaining ourselves in simple language. Because we are in different fields, it is almost like speaking different languages.

We then moved to a discussion of the question what are the important factors making up a target. Well, the size of the target, the shape of the target, the location, the orientation of the target, and certainly the problems of the canopy effect (which was defined as shadow effects or as shelter effects) and the idea of "bounce-off," which implies that liquid particles larger than 50 microns might behave as elastic material and, as balls in a game of pool, rebound to a new trajectory. Mechanisms of gravity impaction and turbulent impaction and of ventilation within a canopy all have to do with the "target."

In summary, I feel that the group in general agreed that we need more research into micrometeorology. One of the earlier papers in this symposium referred to how the standard deviation of small vectors in a given body of air will give one a pretty good idea of what the whole cloud is doing. This certainly involved micrometeorological measurements. Some laboratory studies on turbulent impaction should be conducted under controlled conditions. I think it does not make too much difference what type of material you use to study turbulent impaction as a phenomenon. Using whatever type of material is easiest to look at and easiest to measure could be a starting point.

We need more effective measurements of size distribution. In our laboratory we do routine size analysis and we use whatever

technique seems to be most effective. But it depends upon the size you are talking about. If you are going to look at big particles and you are not concerned with how many of the little ones there are, then maybe the card method is fine. But if you want to know what is there, total and complete, you may have to apply more than one particle-sizing method--a card method for the large ones, and perhaps an optical-electronic counting method for middle size range. For the very tiny ones you will probably have to go to electrostatic precipitators or centrifuges.

Finally, we said that it would be nice if we had some concept of how to make aerosols go where we wanted them to go. If you could just define the target and define the nontarget, and then if you could come up with some kind of a magic box which would cause particles of just the right size to go exactly where the target is and nowhere else, then we would be doing the job. I know that sounds rather dreamlike, but the idea probably ought to be kicked around before we claim to be experts on behavior.

Discussion

DR. DRUMMOND: My question probably should be directed to Mr. Boyle. I was wondering if his turbulent diffusion models have been proven experimentally or are they just a set of equations we saw on the board yesterday.

DR. CRAMER: Doug Boyle is not here, so I will field this question. Model evaluation is a terribly difficult area and has been part of my interests for the past 15 years or so. The problem is that we hardly ever get our hands on enough data of the right kind to do model validation. The number of degrees of freedom required for statistical significance is probably around one per field trial. So because of the pressing problems that were discussed here, where we need answers we are proceeding in an evolutionary way. We are developing the best concepts that we have. We check them as we can and the model itself is really very simple. It is a mass continuity model to try and keep track of everything. To date, the experience is that where we are able to obtain good measurements, there are very few surprises in comparing the measurements and the predictions. Actually the model predictions give us a reasonably high quality of input information and are much better than the measurements by and large. So I think the answer is that we are now proceeding on the assumption that we have provided in the model for the processes that do occur. There is a judgment to be made as to how well the model will actually fit any data. When we get a chance to do that we might have considerable confidence in the modeling techniques that Mr. Boyle was describing. But it is going to be a very long time before we are sure that they are absolutely correct.

DR. DRUMMOND: If I may make a second comment about macrometeorology and micrometeorology. It seems to me that they are characterized by

just two parameters, the scale and the intensity of the turbulence. If the model works, why not use the same model under the canopy, because the same physics are applying, only the size of the parameters are different.

DR. CRAMER: Not quite right, I would say, but there is great merit in what you are saying. There is a limit, below the canopy problem, if the canopy is presumed to be a formidable barrier. There is a different kind of meteorology involved in some of the important details--very low wind speeds, for example, or transport speeds and some of the bulk concepts that work terribly well, in the open, we will say, have to be modified. It was our hope, in terms of this over-all problem of release into the tree air and going into the canopy, that there has got to be an amalgamation here, but we are not quite sure yet what you have to do under some conditions--under some canopies--to tie these two types of processes together. But in the end, I am sure we will work it out.

DR. MOORE: I would like to direct this question to Dr. Roberts. A few years ago you were doing some work with ruby laser holography, which if I can recall your work, will define the size distribution, and the behavior of the particle. Is this process impractical for any of these research purposes?

DR. ROBERTS: At this time the laser holographic process is still a lab tool. We had hopes of taking it into the field, but you have to set up fairly artificial conditions to obtain results. It is true that you can get drop spectra, however, 1 micron is the lower limit of the instrumentation. You can estimate drop size down to about 0.5 microns. You have to keep in mind also that the depth of field for focus on a hologram is the square of the diameter of the particle. So, if you have a

1-micron particle, you have one micron for the depth of field of focus, or with a 5-micron particle you have a 25-micron depth of field of focus. The other point to remember is that the field of view is limited to the diameter of the laser light, which is 1 cm. So that anything that passes through that field is going to be photographed. With the ruby laser, which has stop-action capabilities of up to 10,000 ft/sec, none of your spray particles are traveling at those speeds, so any particle that is passing through this 1-cm light path will be photographed and/or recorded on a hologram.

DR. HIMEL: In Doug Boyle's absence I want to reiterate some things that we discussed this morning and that he mentioned in passing yesterday and that I think are extremely important. I refer to his statement that "on a mass delivery basis you deliver the same mass with 100-micron droplets as you do with 20-micron droplets downwind of the spray area." Now to me this is extremely important, because in this process of looking at spray delivery, you have two major philosophies. One is gravity fall and that is an oversimplification, and the other is atmospheric transport and diffusion and that is an oversimplification. Now I do not want to take liberties with what Doug has said, and I am not quite sure I understand all he said anyway, but these two processes are in fact interrelated. But gravity fall has been the great philosophy and 100-micron droplets are at least reasonably large, and 20-micron droplets are reasonably small. To have this information--that on a mass basis you are delivering, by these transport processes, the same mass of insecticide downwind at any sampling station with either size droplets--is very important. The corollary then is that if you are in this aerosol range you are going to deliver downwind the same mass independent of drop size below 100 microns.

MR. PILLMORE: I was in the behavior workshop yesterday and in addition to the problem we were having in semantics we also had some other problems; different objectives, which I thought accounted for quite a bit of variation when we were trying to define target and nontarget. There were many different viewpoints. With respect to wildlife as nontarget organisms, I would like to give one illustration, and that involves droplet size as an exposure mechanism which can help to explain a lot of differences we may see in the field appraisal of insecticide effects. One of the most illuminating experiences that I have had was (in association with Dr. Himel) examining various insects for fluorescent particles following the 1965 Zectran applica-

tion in Montana. Earlier he said that the droplet sizes of over 100 microns were not important on the spruce budworm. Certainly they were not the ones killing most of the spruce budworm, but from the standpoint of avian exposure, droplets over 100 microns did occur and could be very important because these were the very first insects affected immediately following the application. Contamination levels of those first affected are the type of sample that is important in explaining exposure. At the other end of the droplet spectrum the aerosols probably reduce the contamination of the food substrate, but at the same time raise the question of whether or not there might be increased respiratory exposure, particularly of birds in flight.

DR. ROBERTS: With respect to the problem of respiratory inhalation, Dr. Dimmick, can you give us information on the inhalation studies you have conducted?

DR. DIMMICK: I am not sure that this is important in respect to behavior, simply because in our workshop we were not able to adequately define the target. However, I will briefly relate some of our findings. For example, if we exposed mice continuously to an aerosol of Dibrom of around 2 micron mass-median-diameter, it took 45 minutes before we could detect something wrong with the mice. We found their cholinesterase level was depressed to the point where these mice were not feeling very well. Under these same conditions we exposed Japanese quail for 2½ minutes and we observed 100 percent mortality. The respiratory toxicity of Dibrom in birds was increased about 100-fold by inhalation compared to that of ingestion. I think the point that Mr. Pillmore wanted to make was that of effective ingestion. Now, the effect of respiratory exposure to birds, especially in flight, which has never been looked at as yet, is so much greater than the ingestion problem that it probably needs to be studied much more than ingestion.

DR. CRAMER: At the risk of perhaps not adding anything to the discussion, I will say that it seems to me that diverse interests are represented here. From the point of view of the systems engineering, what we have to do is something like this. Describe a dispensing system if you will, a product, an aerosol cloud, and take it until we have accounted for all the mass for as long a time and distance as required, and this will vary with the written objectives. But after we have described the system and what happens in a very

general sense, then there is another loop that you have to go through, and then you can define what your requirements are, and what you must know about this. You can define the target at that point in a very particular way; then you go back through again and determine and perhaps eliminate some of the features of the operation which are of no interest to you. But I think it is that second loop that you have to go through in the requirements phase of it that is important, and if our approach is generalized enough, we will be able to meet all these requirements. But they do make a difference in the set of parameters that you have to consider.

DR. MAKSYMIAK: Dr. Dimmick, did you have the opportunity to observe coalescence of droplets in your aerosol sprays?

DR. DIMMICK: I have, in a way, to disqualify myself because it became evident yesterday in our workshop that when I referred to an aerosol I was talking about particles less than 10 microns whereas others were considering particles larger than that. What little work we have done simply corroborates that reported in many publications on the theory of small-particle coagulation. In general, if there

are less than 10^6 particles per cm^3 , then coagulation is negligible; if the number is greater than that, coalescence occurs as a second-order phenomenon. I have little knowledge of what happens with larger particles.

DR. MAKSYMIAK: It might interest you that in the Beltsville lab it was found that we could not demonstrate any coalescence of spray drops in the air in the range of a medium spray atomization. We used two spray booms systems on the aircraft. One system contained a blue dye and the other one contained a yellow dye, and we never found green drops on our deposit sample surfaces. But this does not apply to you, since your drop size was probably beyond the range that we investigated.

DR. HIMEL: On this question of multiple-converging impingements, we do not have really quantitative data on it, but I think that our data from the large spray room that I referred to yesterday indicated that this is a very real factor, but obviously a function of concentration. I cannot quantify the concentration, but under the conditions used in pest control, the coalescence and converging impingement of droplets I think is a very real problem.

ASSESSMENT

Assessment of Insecticide Spray Processes

Chester M. Himel^{1, 2}

Abstract--A critical need exists for field methods by which actual delivery efficiency of insecticide spray methods can be assessed. When that is accomplished, we will be able to determine the relationship between efficiency of sprays and their droplet deposition on cards, slides and other impingement devices. We will have a new basis for monitoring field spray applications.

New analytical instruments and new tracer molecules offer a reasonable potential for new assessment methods. Quantitative study of the interrelationship of meteorological effects, mass transport, and spray droplet size can be the basis for great improvement in our methods for spray delivery. Such an increase in efficiency is a logical approach to the solution of the insecticide problem.

In the application of insecticides to target insects we are in the spray delivery business, yet, tragically, we have had no means of measuring our delivery efficiency. Our delivery systems have all the subtlety of a dump truck. We worry greatly about small amounts of pesticides that are air-borne and may drift downwind. At the same time, we virtually ignore the massive ecosystem contamination that results from an unmeasured dump of pesticides into the target area. After decades of use of insecticides, there are still no unequivocal data on area-related mass transport. That ecological, scientific, and economic tragedy stems directly from the virtual absence of fundamental assessment methods and research.

Insecticides are delivered to target insects and enter the environment by complicated processes whose mechanisms are poorly

understood. In spite of the economic and ecological significance of insecticides, and their widespread use, all application methods are empirical. They are empirical because adequate, quantitative, analytical assessment methods have not been available. Application methodology was developed at a time when efficiency in the use of insecticides, and insecticide residue problems, were not recognized as important. Now, we face the absolute necessity of making the use of insecticides compatible with the protection of the environment.

The entire insecticide controversy is based on the empirical nature of spray delivery processes. In the absence of quantitative data, controversy started and continues unabated. Today, all agricultural, legal, economic, and ecological decisions are based on the results of processes whose mechanisms are poorly understood.

The transport of insecticides to target insects involves a complex mixture of meteorological and physical parameters. We need a basis for measurement of those parameters. They include, in part, the physics of atmospheric transport, diffusion, and impingement, plus meteorological and micrometeorological effects. In this complex world, we have been in a scientifically untenable position. We have had no quantitative facts on which to base a rational analysis of our problems.

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²Acknowledgment: I am indebted to my colleagues at the Pacific Southwest Station and at the University of Georgia for their many contributions to the research discussed here. At the University of Georgia, I have had the able assistance of Dr. Richard Mayer, Dr. Solang Uk, and Dr. J. Philip Keathley.

It was a scientific, economic, and ecological tragedy that quantitative assessment methods were not available in the 1950's and 1960's when the present ecological problems started. Millions of man-hours of research, government, industrial, and legal time have been and are being expended on the postapplication problems of insecticides and their ecosystem effects. The delivery system which causes these problems, and hence is responsible for all the time and cost, is largely ignored. Its efficiency may be less than 1 percent, yet it has not been measured! A substantial increase in efficiency to even 50 percent would virtually solve the "insecticide problem." To do that, we need new, highly sensitive quantitative assessment to measure target-area mass transport. It is true that a few years ago, such research was virtually impossible. Today, however, the requisite analytical instrumentation exists or can be developed, and today the many complex meteorological problems can be successful. These new instruments and methods can give us new facts to replace empiricism. We can attack our problems from an accumulation of new knowledge. The seeds of the present management crisis were sown when this was not impossible.

It is my purpose to review briefly just where new assessment methods will allow us to go in the future. It is also my purpose to show that the basis for effective solution of the "insecticide problem" is within our reach. We will be able to do all of those things which will ultimately be known as the concept of ultra-low dosage (ULD)—the concept of maximum efficiency in the use of insecticides. It is insect control with minimum use of insecticides. When we are able to put efficient control systems together, our results will be orders of magnitude better than those we have today.

OLDER METHODS

In the less complex and more relaxed era of the 1950's, assessment of insect control methods were limited to (1) analysis of target insect mortality and (2) spray droplet impingement devices, such as silicone slides and impingement cards. These are crude, imperfect, and nonquantitative assessment methods. For example, the simple physics of impingement of spray droplets on silicone slides has never been studied seriously, yet they are important field assessment tools. Dr. Keathley has shown that the forces of attraction of a liquid droplet-to-silicone surface are greater than

the surface tension forces of the impacted liquid.³ Thus, apparent droplet size on a silicone slide is a function not only of the droplet's actual size but also its velocity of impact. Finally, critical impingement velocity considerations prevent measurement of spray spectra of airborne sprays with silicone slides or impingement cards. The correlation with insecticide delivery to target insects is unknown. In the meantime, spray cards continue to be our most popular field assessment method.

One of the major problems inherent in the use of impingement slides and cards is their bias against impingement of droplets smaller than the range of 40 microns. In addition, spray droplets coalesce or evaporate in the air prior to impaction, or two or more may impinge on identical areas. The problem of multiple converging impingement (droplet-droplet coalescence and multiple droplet impingement) is important. It can make impingement data equivocal and artifactual. The biological evaluation of mortality and impaction measurement of spray spectra are inadequate as assessment methods. One of the critical deficiencies of the past was the absence of any method by which spray droplets could be traced by size to target insects in their natural environment.

The first breakthrough came in 1965 when Himel and coworkers at the Pacific Southwest Forest and Range Experiment Station and the University of Georgia developed the fluorescent particle spray droplet trace method (FP method) (Himel and others 1965; Himel and Moore 1967, 1969; Himel 1969a, 1969b, 1969c, 1969d). That method was the first assessment method for evaluating spray droplets by size and number on target insects in the field and showed the critical importance of airborne-size spray droplets in the delivery of insecticides to insects. It did not give data on how they were delivered, only the fact that they were delivered. The effect of the number of fluorescent particles, and their relation to droplet size, is shown in table 1.

The FP method makes possible experimental detection of the size of the droplets transported to target insects in their natural environments. If the droplets found on target insects are 200 microns and larger, then gravitational delivery systems are operational. If, however, only airborne-size droplets are found, atmospheric transport systems are the

³Keathley, J. Phillip. 1972. Unpublished data.

Table 1--Number of fluorescent particles (FP) in droplets of various sizes at three particle concentration levels

Concentration of FP in spray (particles per milliliter)	Droplet size at ...				
	1FP	5FP	10FP	100FP	800FP
	<i>Microns</i>				
1 X 10 ⁸	27	46	60	130	260
2 X 10 ⁸	21	36	46	100	200
2 X 9 ⁸	10	17	21	46	92

critical factors in delivery. If the delivery of insecticide to target insects is based on atmospheric transport, then the efficiency of our delivery systems can be improved by orders of magnitude. That improvement can eliminate the "ecological problem of insecticides."

The FP method allows absolute differentiation between 20- and 200-micron droplets. Therefore it allows absolute differentiation between the two possible transport mechanisms. Because of its probability basis, differentiation between narrow ranges of droplet sizes is virtually impossible with the FP method. Suspension of FP in spray liquids is difficult; therefore the lower limit of detectability of droplet sizes by the FP method is in the range of 10 to 15 microns.

In spite of FP method data (and the widespread use of particulate meteorological tracers in meteorological research), the great entomological cliché that "small droplets never get down" is still with us. It is scientific and experimental nonsense, yet it persists and continues to cloud experimental facts. Airborne spray droplets are the predominant sizes delivered to target insects. They are affected by meteorological factors and by physical delivery systems. When all systems operate effectively, target insect control is good, and when they operate ineffectively, target insect control is low, yet we know very little about *how* those physical and meteorological processes operate. That is the challenge of today: to develop quantitative methods by which we can assess insecticide delivery systems and mass transport. Data on delivery of insecticide spray droplets to target insects are given in table 2.

The data in table 2 were determined by identification and counting of over 100,000 spray droplets on the target insects. There

is no evidence that large droplets (greater than 200 microns diameter) have any significant contribution to target insect control under these conditions. Because of their disproportionate mass they are the major factor in the environmental contamination problem. In the above experiments, spray droplets smaller than 20 microns contained zero FP and were invisible.

The next major breakthrough came 5 years later when Roberts and others (1971) showed that laser holography could be used to determine the mechanism of impaction of 1 to 5-micron-diameter spray droplets on insect setae. The data are extremely important and represent an elegant contribution to insecticide assessment research. They show experimentally that 1-micron-diameter droplets can deliver insecticide to target insects, and they place the optimum size for spray droplets in the range of 5 microns.

As indicated previously, there are two major theories as to the mechanism of delivery of insecticides to target insects. The first and most widely accepted is that spray droplets fall by gravity and impinge on the target insect, or on foliage which the insect traverses or eats. In spite of decades of research, no unequivocal experimental data support this theory. The reason is very simple--all sprays from commercial spray devices contain significant numbers and volumes of the airborne spray droplets. They are ubiquitous, usually measured, and often assumed to be absent. In their presence, no unequivocal data on the mechanism of insect control by gravitational fall is possible. A typical spray spectrum is shown in figure 1.

Table 2--Size of droplets found on insects

Target insect	Proportion of droplets in diameter class (microns)			
	20-50	50-100	100	200
	<i>Percent</i>			
Spruce budworm	97	3	0	0
Boll weevil (adult)	99	1	0	0
Bollworm (larvae)	99	1	0	0
Cabbage looper (larvae)	99	1	0	0

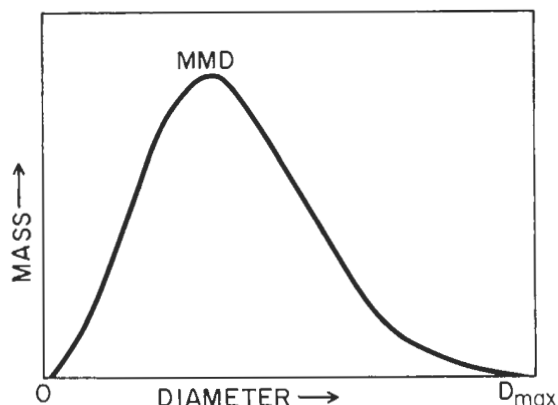


Figure 1. Typical spray spectrum;
mmd = mass median diameter.

The second and most controversial theory of spray delivery involves the physical concepts of atmospheric transport and the impingement of airborne-size droplets. Such droplets are limited to less than 100 microns and are generally less than 50 microns. Their delivery to target insects in a foliage environment depends on physical and meteorological parameters that are complex and difficult to measure. Finally, the efficiency of airborne spray droplets in very small sizes is limited by critical impingement velocity considerations and by volatility. In our laboratory we have shown the existence of a foliage-air interfacial barrier which is an important factor in the delivery of airborne spray droplets to insects within a foliage environment. It means that droplets of this size must be driven into a foliage environment. In the field, this is accomplished by the meteorological effects of a flying airplane, or by the hydraulic-pneumatic spray from ground equipment. If we are to understand spray processes, we must be able to study the processes by which they breach the foliage-air interfacial barrier. Some new concepts in analytical methodology are available for this purpose and will be outlined below.

NEW METHODS

In the past, spray assessment methods have been largely concerned with measurement of spray droplet size. A weight or mass balance in the target area has been beyond the sampling techniques and analytical methods available. Most attempts at mass analysis have required incorporation of dyes into sprays. Most dye molecules are not

designed for purposes of pesticide analysis. For this reason we have studied the design of special tracer molecules. They must have known stability, known metabolism rate (in the biosystem), and known spectroscopic responses. Our greatest experimental success, however, has been with designed molecules that can be used with gas-liquid chromatography (GLC). The requirements for such molecules are that they be (1) nontoxic, (2) unique to the environment, and (3) adapted to GLC or mass spectrometric analysis at very high (nanogram) or picogram) sensitivity. Two typical examples of new insecticide tracer molecules are given in figure 2. In our laboratory, we have studied a whole range of analogs and homologs of such tracer molecules as new tools for the study of mass transport of sprays and insecticide movement in the ecosystem.

New methods for mass analysis of spray distribution are of little value unless clean, readily available, impingement devices of known characteristics are available. We have, therefore, designed a series of quite small glass devices which we are testing for impingement efficiency. Glass devices are of particular significance because they are clean and contribute no biological contaminants to mitigate GLC or mass spectrometric analysis. The physics and meteorology of spray impingement are well known and efficient mass sampling devices for research are well within the current state of the art. A simple and efficient capillary impingement device (CID) is illustrated in figure 3.

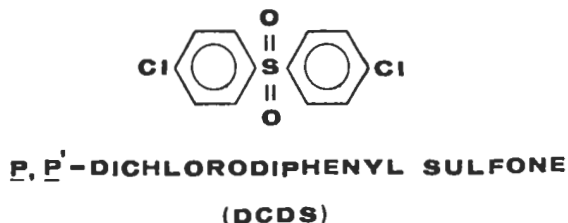
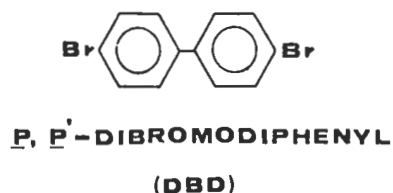


Figure 2. Insecticide tracer molecules.

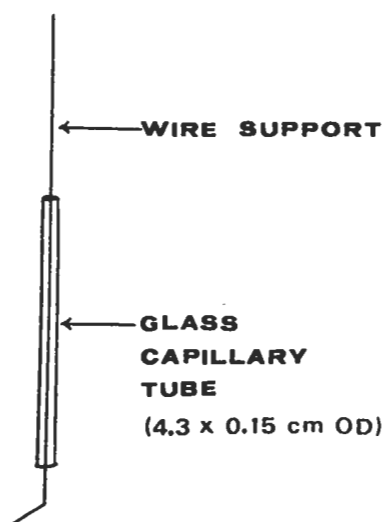


Figure 3. Capillary impingement device (CID) used in assessing airborne concentration of spray toxicant.

For several years, we have investigated the feasibility of actual analysis of the insecticide content of target insects. Unfortunately, this is very difficult because of biological contaminants and because of the rapid metabolism of most insecticides in insects. Field and laboratory research with Dursban and Thiodan have, however, been carried out. The laboratory research showed that the toxicity of an insecticide appears to be independent of the physical state of the insecticide prior to delivery to the target insect. Thus, the LD₅₀ of these insecticides is substantially independent of whether they are delivered to target insects by (1) airborne-size droplets, (2) single lambda-size droplets, or (3) vapor. In effect, then, insect control can only be achieved when a lethal dose is actually delivered to the target insect. Our insect control failures are caused by our delivery system failures (Himel and Uk 1972a, 1972b).

In the field, the more concentrated the spray cloud, the farther downwind it will retain biological effectiveness. Typical data (table 3) were obtained when spray clouds of various concentrations of Dursban were tested against caged houseflies. The mortality of the flies is directly related to their Dursban content (up to 100 percent mortality) and the distance downwind for 100 percent mortality is directly related to Dursban concentration in the initial spray.

We believe that these data are an explanation of why the typical, inefficient sprays used with ULV sprays and undiluted insecticides are successful in the control of insects. We also believe that these data show one method for minimizing the biological effects of downwind drift, by limiting the concentration of insecticides in the initial spray.

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Table 3. The effects of spray concentration of Dursban¹ on the delivery of insecticide to caged houseflies² placed downwind; maximum droplet diameter 15 microns.

Distance (ft)	Effects of Dursban spray concentrations of ...					
	1 lb/gal		2 lb/gal		4 lb/gal	
	Mortality	Mean Dursban content ³	Mortality	Mean Dursban content	Mortality	Mean Dursban content
	<i>Percent</i>	<i>ng/fly</i>	<i>Percent</i>	<i>ng/fly</i>	<i>Percent</i>	<i>ng/fly</i>
100	-	-	100	364	100	214
250	42	17	100	270	100	339
500	52	20	14	25	100	115
750	0	10	63	27	100	51
1000	0	6	0	11	100	59
Controls	0		0		0	

¹Flow rate: 32 oz/min, 5 mph transport, 2 min; spray formulated with DOP and benzene.

²Two replications of 25 flies per cage were used; one replication was preserved for gas chromatographic analysis, the other was transferred to clean containers within 15 min following dispersal.

³In the laboratory the LD₅₀ for Dursban was determined to be 40 ng/fly.

Workshop Summary

John A. Neissess¹

The participants in the workshop were concerned with a wide range of spray deposit assessment problems that vary according to type of pesticide application. The objectives of an assessment method for a researcher are necessarily different from those for an operational program. Similarly, the requirements of application for forest or agricultural purposes, or mosquito control, etc., vary widely. Therefore, it would be very difficult to come up with a nice, neat standardized method suitable for all.

Very generally stated the goal of an assessment method for research is to provide the identification and maximization of the variables needed to obtain an effective control program. This method should be simple and ecologically safe. The assessment technique is therefore a research tool for obtaining basic knowledge which will eventually lead to increased target mortality resulting from more efficient application.

The specific assessment parameters that interest researchers relate to the bioassay, that is, correlating deposit with mortality. They are interested in how much toxic material is in the environment and to what degree this material is reaching the target. There was much discussion in our workshop on droplet size and size variation. The researchers want and need to know the droplet sizes that most effectively impact on the target, and what part of the spray-drop-size spectrum this effective droplet represents. The ultimate assessment method would provide the researcher with information on factors that produce droplets of the desired size. The assessment method may not disclose the mechanism by which impaction occurs, but it can reveal the effects of such things as meteorological conditions, site, and application technique on the deposition of the spray droplets.

The principles behind operational programs dictate different assessment requirements. People dealing with operational programs must

be able to assess the adequacy of the spray coverage resulting from the aerial application of the insecticide, for the enforcement of the application contracts. The assessment method has to be fast and simple so that the field man can request respraying in areas of uneffective coverage. The people in research should have predetermined what parameters will determine effective coverage.

People in the field want an assessment method that evaluates how much material reaches a sampling surface, such as a white card. The actual evaluation may be in terms of drop sizes, density of drops, volume of toxic material, or combinations thereof. It is imperative that the method be simple and inexpensive because the field people do not have the time or facilities to perform precise analysis.

Operational personnel are also interested in residues, and the possible contamination of forage crops and waterways from toxic chemicals applied to nearby areas. Work on this problem is usually conducted in conjunction with fisheries and wildlife departments. Therefore, it is desirable to have an assessment method that evaluates the spray drift.

Various assessment methods currently being used by participants in the workshop were discussed with respect to measurement of spray coverage. A. P. Randall, of the Chemical Control Research Institute, Ottawa, Canada, gave a short report on the type of assessment methods used in Canada for the last 20 years. They dye their formulations with soluble dyes and collect the spray deposit on glass plates and white Kromekote cards. The spray deposit is sampled in the open, for they have found that the deposit sampled in the open correlated very well with the deposit found in the trees. They have also found that the drop counts on the white cards gave a better correlation with insect mortality than the volume of spray removed from the glass plates.

The limitations of such an assessment method are the inability to count accurately the very small droplets in the 0-25 micron range, and the fact that a card or glass slide does not very well approximate the geometry of an insect. That is, this method

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does not allow for assessing the amount of toxic material or size of droplet actually delivered to the insect or its natural environment. The inability to assess the small droplets may be very important in view of the discussion of small droplets in this workshop. If the small droplet is the most effective size of drop for impacting on the insect, as reported by Dr. Himel, then the ultimate assessment method should evaluate this droplet size. Otherwise, we are not analyzing the part of the drop-size-spectrum that is of most interest to the researcher.

Soluble fluorescent tracers have been used as a tracer system to evaluate spray deposits. The deposit can be sampled with various artificial surfaces--white cards, aluminum plates, Mylar etc. Also, the fluorescent tracer can be removed from the foliage to give an estimate of the amount of toxic material reaching the insect's environment. Although the method is fast, inexpensive and sensitive, there are some problems. The fluorescent dyes fade when exposed to sunlight, and there are natural fluorescing contaminants which might complicate the assessment for the foliage samples. Because the drops on the white cards are manually sized and counted, the very small droplets cannot be accurately counted. The soluble tracer also does not provide a method for determining the amount of toxic material reaching the insect.

Automatic counting devices are available which count the spray drops collected on white cards. One such method is used at the Desert Test Center. Photographs are made of the white cards, and the negatives are automatically scanned, and the drops sized and counted. The spread factor of the spray formulation is included in the calculation of the drop sizes. It was reported to the workshop that limitations in the photographic step restrict this method to the measurement of drops greater than 40 microns in diameter.

Dr. Himel described the use of gas-liquid chromatography (GLC) and mass spectroscopy as research methods for deposit assessment. Both of these instrumental methods have been used in the past for the direct chemical analysis of the actual pesticide. Dr. Himel described the use of tracer systems for evaluating the spray. These chemical tracers have the advantage of being fade resistant, and there are little or no contamination problems. However, this method can only evaluate the total volume of the spray deposited on some sampling surface. There is no provision for determining the number of droplets or droplet sizes.

The use of Rotor Rod Samplers was mentioned by Jack Barry in his paper dealing with the

Zectran dry liquid test. These samplers, again, sample only the total spray. This method does not give the delineation of the drop-size spectrum.

Anderson Sieve Samplers are another device used to sample the content of spray in volumes of air. By changing the size of sieves and the volume of air sucked into the sampling devices, specific drop-size ranges can be sampled by using a number of samplers together. It is possible to evaluate the entire spectrum of drops in a spray cloud with respect to particle size and cumulative percent of the spray in specific drop-size ranges. The only shortcomings of such a device are its expense and the need for a power supply--both of which would seem to limit the usefulness of the sampler in the field.

The only assessment method discussed in our session that provided a measure of the amount of pesticides and the size of spray droplets that was delivered to a target in its natural environment was the fluorescent-particle tracer method discussed by Dr. Himel. However, this method is a research tool only. The difficulty in handling the FP's and their cost make this method impractical for large-scale field use.

As for assessment methods currently used for operational programs, the most familiar is probably the oil-sensitive card used for years on the DDT programs. This method was adequate for enforcing contracts, but such methods have been shown to be unreliable for obtaining satisfactory correlation between the deposit and insect mortality.

Another assessment method, reportedly used with mosquito control, is the use of caged insects as an indicator of the amount of deposit. If the insects in the cages are dead, the overall coverage has presumably been adequate to obtain mortality.

A few new methods of assessment were discussed for use in research. A new sampling surface that better depicts the geometry of the insect was discussed. Ultimately this surface could be part of an analytical assessment method instead of a manual counting method. Such a surface could be washed, which would at least reveal the volume of spray impacting on a pseudo-insect, if not the actual drop size. Atomic absorption could be used to detect metallic salt tracers such as magnesium sulfate. These tracers would have the advantage that they do not fade. However, there might be contamination problems from naturally occurring salts. Electron spin resonance (ESR) was also suggested as an analytic tool for consideration. Nitroxides were reported as good tracers to be used with ESR.

A new method that might be applicable for operational use is the flying spot scanner, such as that used at the Deseret Test Center. The method provides for a visual estimate of the deposit on the card for enforcement of applicator contracts, but it is also sensitive enough to determine the specific parameters of drop size and the relative numbers of each size drop within the complete drop-

size spectrum, thus providing concise information about the extent of spray coverage.

In conclusion, if the workshop did not result in anything else, it made the participants aware of each other's problems. Alternate assessment methods, new professional contacts, or whole new concepts may have been initiated as a result of the workshop.

Discussion

DR. AKESSON: Just a quick comment, John. I feel that you are mixing the research instrumentation and the field instrumentation; you brought out both at various times, and you never separated them. May I suggest that we had better make a distinct separation, because if we do not we are going to confuse, confound, and frustrate the field people, especially when we refer to such things as scanning electron microscopes, atomic absorption spectrophotometers, and radiance trim, etc. So, if we are to continue in the future, the researchers should attempt to separate these two areas because of the differences. The field personnel frequently use indices, and tracers, where in research we attempt to deal with absolute values.

DR. NEISESS: Right, Norm, I tried to make that clear.

MR. BOYLE: I would like to clear up one point of possible confusion on automated droplet counting equipment. The Dugway machine can be set to count droplets as small as those falling between zero and 20 microns. The problem is that the process is photographic; what shows on the photograph is counted as a drop, and dust can pose problems in that size range. In practice, with droplets below 40 microns, the operator has to use optical magnification and count by eye to insure it is droplet stains that are being counted.

One other comment seems in order. Last year when the Missoula group brought their equipment to Dugway, we asked for only two changes in their standard operational procedures. The first concerned large drops, not small; overlapping droplet stains cannot be counted, and so we flew the aircraft high enough above the ground to minimize overlap of the large drops. The second was to fly crosswind instead of into the wind, and this too was intended to

provide an estimate of the decrease in average droplet separation and additionally to provide an estimate of the decrease in average droplet size as the downwind distance increased. Neither change complicates the analysis. If the droplet cloud is thought of as a stretched-out cone with the ground as its base and the aircraft at the vertex, you can easily pass a new plane closer to the aircraft, in effect, put the ground where you want it, and the process is interpolative, not extrapolative.

We tested the C-47 system over a sampling array covering several square miles, and with complete meteorological instrumentation. The Dugway droplet spectrum data, contamination density estimates, and swath widths matched what Missoula had already determined on a much less expensive program. We increased the sample size tremendously but I do not think we added much new information to the spray system characterization.

DR. PIEPER: I was in the assessment workshop also and I thought there was an interesting suggestion offered that was not mentioned here. That was the addition of spores of *Bacillus globigii* to the spray formulation. I thought this suggestion could be used by a great many people and it does not require expensive equipment.

DR. MAKSYMUK: I believe, John, that you mentioned that there was a minimum sensitivity on Kromekote cards using fluorescent tracers of a spherical drop size of 20 microns. Our published research shows that we can go down to 7 microns as far as spherical drop size is concerned. But the spot size on the card is around 20 microns. Now we do have simplified and accepted field methods for rapid determination of atomization based on the D-max method that I published in an article that is being, or was being used routinely over a number of years. As far as estimating gallons

per acre in a forest using oil-sensitive red cards and no dye in the sprays, or oil sprays, Isler and Davis at the Beltsville Laboratories developed this method, following some Canadian input by Elliot, and it was used operationally for years. It is very rapid and insensitive but it gives you go or no-go information and this is probably enough for the control operations and it takes minimum time to compare the standards to the cards in the forest and to estimate the coverage.

MR. FURLOW: I would like to ask your group a question with respect to the determination of aerosol droplet sizes of ULV sprays, and the evaluation of the equipment and the use of these sprays on a day-to-day basis in the field. What is the current problem on using any convenient technique that gives consistent comparable results from one nonthermal fogger to another, to get results that are known to be significantly different from the true volume mean diameter, and do not truly reflect the size of the particles that are actually more effective in reaching and killing the insect?

DR. AKESSON: May I suggest, John, that this is precisely what I was referring to. You are using an index because you are not obtaining an add-value for the drop size. The part that hurts is when someone uses a field technique and does not describe what he did or the relation between this as an index and the add-value. Then this gets into the literature as add-values, and it can really confuse things.

But if you do this, and acknowledge what you are doing, I see nothing wrong at all, because these are field techniques which are highly essential.

MR. FURLOW: Is that the consensus of your committee or group?

MR. RANDALL: There is one point I would like to bring out in regard to this method of using cards. That is, no one has mentioned standardizing the cards in terms of the spread factor. Now the solution you use will depend on the size of the drops in the cards, and you have a variation of a spread factor of 2 to 6. So that one material will have spread factor of 2 and others may have one of 6. The drop size may be identical with the same kinds of materials; therefore, you cannot compare these two together because they will not have the same spread factor at all.

MR. CHATIGNY: Responding to the particle size question, I think that the size you measure is directly dependent on the instrument you use to measure. There are a variety of instruments. However, there are obviously some methods that are standardized and some of these not found in the literature or connected with the disciplines of the scientists present here. Dr. Dimmick informs me that this came up in their session, and he will amplify this in his summary presentation.

Rapporteur Summary

Mark A. Chatigny

This workshop has covered a very broad spectrum of problems. Solutions for some are well in hand, others are emergent in new areas; all appear to have some intereffect. We have considered meteorological physics, water surface dispersion, leaf coverage, and the chemistry, toxicity and degradation of pesticides. The need for close control of aerosol output, formulation, and particle size to control hazards to the target and nontarget populations (if you will define as "nontarget" those organisms we do not wish to affect) has been discussed. Certainly the human and animal population and the environment have been endangered to some degree by some of the early pesticide applications. We have pointed out that there is a need for improved dose-response data from our insecticide applications, and these, of course, are going to vary as widely as the number of insecticides being used and the range of target species. There is also need for additional work on dispersal techniques.

All things considered, we have a need for a coordinated, multidisciplinary program. We have entomologists, physicists, biologists, engineers and meteorologists, each group with its own idiom. Basically they work in "English" (though I am not always sure of that) but it is apparent that some of the working groups spent a great deal of their time just getting their words to mean the same things or to arrive at some common usage during the course of their sessions. This is a problem, because if you belong to an entomological society, you are not usually going to be talking to microbiologists. If you attend engineering or civil engineering society meetings, you are probably not going to be talking to many agricultural engineers. Dr. Akesson pointed out that he obtains information from the mechanical engineers and the civil engineers "rather laboriously." There is a strong need for interdisciplinary communication. We find, for example, that some of the early characterization of spray-nozzle work was done by Japanese workers who were interested in spraying coal slurries for efficient burning. The spray parameters are the same, and the particle-size distribution from single and double fluid nozzles prevailed for them just as it does for us. What this amounts to--and I think Dr. Cramer pointed this out quite clearly--is that we are in need of a systems approach to our composite problems. It is essential for us to get together as often as we can, to share language, share approaches, and make a systematic coordination of our efforts in both the field and laboratory.

In this meeting we have also seen quite a gap in communications between researchers and the people in the field. Practical considerations limit the field people (in determining particle size) to such practices as putting out settling cards and saying, "That tells me right now what was put on, where it went and that the contract I had with a pest control operator to put out materials has been fulfilled." As researchers we might say, "Well, that does not tell you what is the effective fraction of the material applied." He might like to know the particle size, the concentration of pesticide in each particle, and the micro- and macro-meteorological conditions that affected these things. The control operator, although interested, must respond "I can't find out all that stuff; I just want to know, did it get there and did the contract get fulfilled." It is apparent that a systems approach, with measurement of many parameters, may be necessary.

We in research are going to ask the man in the field to get some information for us. We are going to have to get that information fed back into research and higher technology areas and use it in our system model, and in turn, give the operator some direct answers that will help him then and there. We are a long way from that, but we have some of the tools at hand.

Surprisingly enough we have more tools at hand than many of us are aware of. For example, Dr. Mort Rothenberg (Deseret Test Center) has some 30 years of experience in aerosol travel, chemical particle deposition rates, and micro- and macrometeorological effects under just about every conceivable condition. Much of it is tabulated and computerized and there is a veritable mountain of information available. We are not making adequate use of it; I can tell that from the conversations here. Some of the problems of particle physics described in this meeting were described some 25 years ago, when a great deal of that data such as that compiled by Dr. Rothenberg's group was being assembled. There have been offhand references to the work of Latta, Hochberg, LaMer, and others; many of these people who worked in the Office of Scientific Research and Development in the 1940's formulated many of the basic equations and principles on which a lot of dispersion models were built. The work needs updating, but more than that, it needs to be made available to this community--that is, to the people doing research, and (in usable form) to pest control operators.

I venture to say that our problems in application are going to get worse before they get any better. We are going to have increased pressure by the ecologists for minimal contamination of the biosphere. We are going to have decreased interest in development of new formulations by the chemical companies. It costs a great deal to develop a new chemical to be dispensed in small fractions of a pound instead of hundreds of pounds per acre and to meet stringent standards for nontoxicity and degradability. The manufacturers' incentives are certainly being decreased. Some of the manufacturers may want to take issue with me on that, but for our purposes it is not too far from the mark. We are probably moving toward more small-particle sprays. Much of the discussion centered around approximately 20 microns as the optimal particle size. Well, let us use that for the moment, with the reservation that we may, as Dr. Himel has suggested, want to put out a larger particle size with an equivalent amount of toxic material in order to control coverage on the target. We can formulate that way, but the trend may be toward the small particle size.

As Dr. Dimmick has pointed out, when we do that, we are getting into the respirable particle size range. Further, when we get into small-particle generation, we have the inevitable generation of a lot of very small particles. Now the very small particle (this may mean 0.5 to 0.8 microns and smaller) gets very deep into the respiratory system of the human or animal and is retained and adsorbed rapidly. When you produce an aerosol of a few million per cubic meter of 20-micron particles, you also produce 100 million or so per cubic meter in the 0.5 to 8 micron range. We have not had simple systems for measuring these particle sizes. If these are persistent pesticides, or in a carrier that is persistent, they are going to stay in the respiratory system or some other part of the human body, where they may, in fact, be concentrated. Many people are going to be asking, "What kind of hazard are these pest control operators giving us now?" And you will have to bear with them because they have a valid concern. While all this is going on, our legislators will be responding to public pressures and (although I do not want to criticize the legislators, who are "vox populi") they will sometimes respond in a manner that does not reflect the state of the art in control technology. They will simply say, "Do it!"--that is, "eliminate this hazard"--and we may not be prepared to "do it" at that time without undue loss or cost. There are no simple answers to these

complex problems that I can see defined in these meetings. I think we have given it a very good try and have made good progress in defining our problem areas.

Some directions are indicated. Certainly the voluntary communications, like this workshop, work very well. I think you will all agree that this has been a good and successful meeting. Also, I think we could establish research programs that are more closely tied to applications. On the other hand, the applications people need to come back to the researcher with some data and some indication of practical limitations. We may sit in the ivory tower and cook up a lovely particle-size analyzer that will work in the laboratory (and we need that), but it may be a harder task to get a simple piece of machinery to the man in the field so that he can give us back one or two parameters that can be fitted into our model at a given quantity and particle size, and what is the effective dose in the target area. I think we are not too far from this capability if we use the resources available to us.

Another suggested aim is perhaps more immediately attainable--that is to establish an ad hoc or *pro tem* standardization of working group. It certainly must be intersociety, interagency, interdisciplinary--or whatever the desired term--to cross the many disciplines represented here. We may need entry to several government agencies for this, and it has been suggested to Dr. Schirley that we go to the Federal Working Group on Pest Management for sanction and assistance. He has agreed that this is a reasonable thing. Perhaps he can speak on this working group to Environmental Protection Agency and Food and Drug Administration and other cognizant organizations. This is fine. He has suggested that he would be willing to go to the National Science Foundation and help us get some funding for a maintained working group. Dr. Rothenberg, who is on the committee of the National Science Foundation and the Research Applied to National Needs committee, said that he would support such a request. We should not underestimate the need for such a group or the complexity of their work.

I have had some personal experience in standardization of aerosol procedures. Our laboratory participated in a tripartite working group (The United Kingdom, Canada, and the United States) on aerosols; it functioned for about 8 years. A great part of that time was spent in standardizing aerosols, equipment, procedures, samplers, etc., so that we could

all so (simultaneously) at least one kind of experiment, or field test, in which the data would be directly comparable among all participants. One of the more elementary things that became a real problem was that the temperature of one of the aerosol chambers varied by about half a degree Centigrade from those in other installations. The data received from this unit differed considerably from that received from the others. Attention to exact details of every aspect of the equipment and work was essential for good control of the experiments.

Synopsis of Comments from Evening Dinner Session

At the dinner meeting following the first day of the workshop, participants were requested to submit comments and questions. These were summarized by the Coordinating Committee.

Several people indicated interest in holding the workshop annually; one person felt that it did not have the scope or "punch" for

an annual affair. At least two persons said (1) the workshop should be extended another day, (2) the individual workshops were too short, and (3) the workshop should not be so large, as the number of people and lack of time limited the discussion. One person felt that the chairman of the assessment group was too constrictive. Another thought that one single theme, rather than three, would be more productive.

Some general comments and suggestions were made. It was felt that (1) a definition of target and nontarget populations is needed; (2) too much time was devoted to drop spectrum and deposition analysis when there was no standard or basic formulation as a means of comparison; (3) a technique is needed to disseminate monodispersed aerosols; (4) the impaction efficiency of setae on spruce budworm should be investigated and environmental contamination from an assessment standpoint should be considered; and (5) a good reliable method for analyzing droplets or particles below 20 microns is needed.

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