Chapter 10

APPLICATION TECHNOLOGY

David B. Smith
Agricultural and Biological Engineering Department
Mississippi State University
Mississippi State, Mississippi
and
Randall G. Luttrell
Entomology and Plant Pathology Department
Mississippi State University
Mississippi State, Mississippi

INTRODUCTION

Pest control around the globe has been a problem for many years. The earliest references to the use of a pesticide date back some 3000 years to the writings of the Greeks, Romans and Chinese (Palm *et al.*, 1969). The modern use of pesticides in the United States began in 1867, when paris green was used to control outbreaks of the Colorado potato beetle, *Leptinotarsa decemlineata* (Say). By the 1920s, the use of pesticides was being accepted more widely in the United States. The development of pesticides expanded rapidly during the 40-year period since the early 1920s. The 1939 discovery in Europe of the insecticidal value of DDT was a revolutionary event for insect control. The use of insecticides on cotton was very instrumental in the establishment of large-scale pesticide applications. In 1986, there were an estimated 14.4 million pounds of insecticides used on cotton; associated chemical costs ranged from 3 to 51 dollars per pound (United States Department of Agriculture, Economic Research Service, 1986).

The application of chemicals with ground equipment began in the early 1900s. This equipment was designed primarily for one person to carry and use. The majority of the pesticide formulations were in the dust form; and accordingly, most of the equipment were dusters. Aerial application of pesticides came into being in 1921 when a load of powdered lead arsenate was dusted on a catalpa grove for control of the catalpa sphinx (Anderson, 1986). Brown (1951) noted that the first aircraft nozzles consisted of pipes extending from a boom and the degree of atomization obtained was not adequate. In 1947, the Mississippi Valley Aircraft Service designed and produced a modern Stearman spray unit (Anderson, 1986). Dusts were still widely used in 1948 but required very favorable atmospheric conditions for sufficient quantities to be effectively deposited. Also in 1948, dust supplies were exhausted by an unprecedented boll weevil, *Anthonomus grandis grandis* Boheman, infestation. Many aerial applicators switched to toxaphene sprays by 1949 (Anderson, 1986). In Texas, only about 5 percent of the treated cotton acreage was sprayed in 1949 (the rest was dusted) but by 1951, over 60 percent of the treated acreage was sprayed. Thus, the research history related to atomization, on-target deposits, drift, contamination and biological effectiveness of sprays is essentially less than 45 years old.

Today, there are many thousands of pest-crop-atomizer-formulation combinations available to producers and crop production personnel. Due to the large number of combinations of possible treatments coupled with a limited resource base, there are obviously many unanswered questions about pesticide applications. Smith (1978) estimated that there were 12.9 engineering scientific years being devoted to all pesticide application problems in the United States and 7.5 scientific years in the Southwest, South and Southeast sections. These estimates included all research on engineering principles as well as research involving all pesticide-pest-crop combinations. With this background and the understanding that the overall application database is incomplete, we will herein attempt to discuss the current state-of-the-art of pesticide application for cotton insect and mite control.

RELATIONSHIPS BETWEEN INSECT/MITE CONTROL AND APPLICATION, FORMULATION, AND/OR METEOROLOGICAL VARIABLES

A partial list of variables which can affect pest control (and yield) is illustrated in Figure 1. Some of these groups of variables such as operational, formulation, deposit on target and nutrients can be altered or controlled. Others, indicating meteorological variables, pest population density, and stage of development and crop foliage structure, must be accepted in their present state for a given temporal (relating to time) period. For purposes of this review, operational variables will include atomizer type, flow rate of the carrier-pesticide mixture, atomizer spacing, boom height, atomizer pressure, and ground speed. In order to further study the effects of "on-target" deposits on insect/mite control, let us attempt to define the target for a crop like cotton.

Some insecticides must be ingested in order to be effective (e.g., bacteria, viruses, protozoa, thiodicarb, [Larvin®], carbaryl [Sevin®]) whereas other insecticides or miticides (e.g., fungi and many chemical pesticides) can cause mortality by contacting an external part of the pest. The contact/consumption mode of pesticide entry can occur over a time period ranging from a few seconds after application until the deposits are washed off or degraded. In addition, any mobile pest may consume or otherwise contact residual deposits on multiple occasions whereas direct impingement on the pest must occur during the application-deposition process. A limited amount of research effort has been devoted to the impingement-residual contact question even though the effectiveness of the two deposition mechanisms is clearly an important issue from the atomization, deposition and safety perspectives.

Scott *et al.* (1974) studied boll weevil control with azinphos-methyl (Guthion®) by both the direct impingement and residual contact mechanisms for sprays applied with

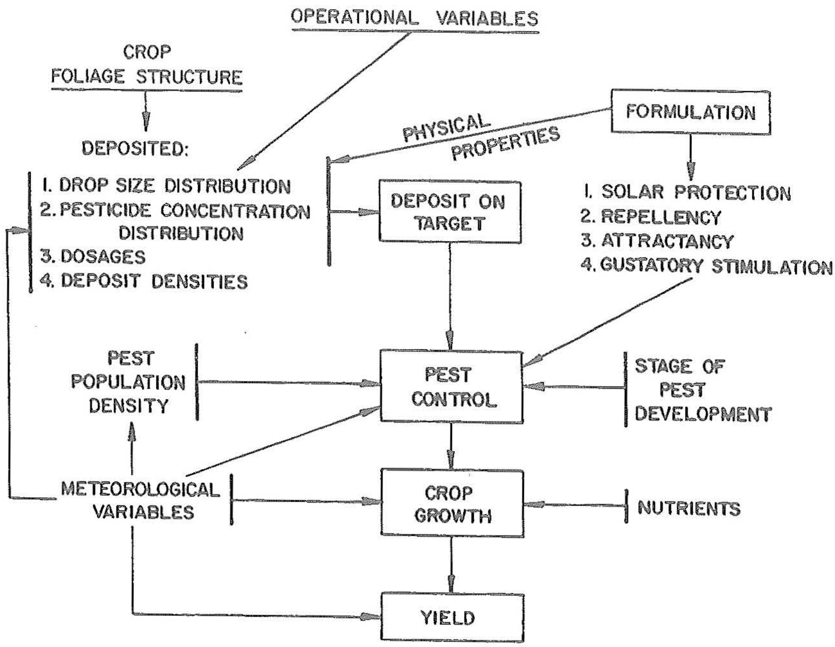

Figure 1. Relationship between application, operational, formulation and meteorological variables on pest control and crop yield.

rotary atomizers (mean droplet diameters between 100-200 micrometers[1]). They reported that the ratio of residual mortality to direct impingement mortality ranged from 1.9:1 to 7.5:1 and the ratio averaged 4.0:1 for all nine treatments. This average ratio indicated that 80 percent of the boll weevils were killed by contacting residual deposits and 20 percent were killed by spray droplets impinging directly on the insect.

Wofford (1985) used cotton terminals mounted in "water pics" to study 'impingement plus residual' versus 'residual' kill of five stages of tobacco budworm, *Heliothis virescens* (Fabricius) larvae sprayed with various droplet sizes and deposit densities (number droplets deposited on target area) for both oil and water carriers. Terminals with larvae on them were sprayed for "impingement plus residual" control and larvae were placed on sprayed terminals about five minutes after spraying for the "residual" control. He reported that the residual mortality accounted for 84 percent of the total mortality observed. Luttrell and Bell (Unpublished data, R. G. Luttrell and M. Bell, Entomology and Plant Pathology Department, Mississippi State University, Mississippi State, Mississippi) conducted a similar test except they released larvae 30 minutes prior to spraying on the upper canopy of whole cotton plants for their

[1]One micrometer (micron) is equivalent to: one millionth (1/1,000,000) of a meter; one thousanth (1/1,000) of a millimeter; and, one twenty five thousand and four hundredths (1/25,400) of an inch. The diameter of a human hair is about 90 microns.

"impingement plus residual" treatment. Their data indicated that for first instars, mortality due to the residual deposits was about 90 percent of the "impingement plus residual" mortality; the percentage progressively decreased to about 46 percent for fifth instars. Their data for first and second instars (i.e., about 90 and 78 percent respectively) are likely representative of field data because young larvae would primarily be located in the upper canopy. MacQuillan *et al.* (1976) directly sprayed native Australian budworm, *Helicoverpa punctigera* (Wallengren), larvae and sprayed tobacco leaf discs to which larvae were exposed. The ratios (LC_{50} data) for the residual to direct impingement mortality ranged from 1.98 to 5.86 and averaged 3.63. The ratio of 3.63 indicates that 78 percent of the larval kill was due to residual activity and 22 percent due to direct impingement.

The three studies with *Helicoverpa/Heliothis* and the one study with boll weevils discussed above indicate that about 80 percent of the control is due to residual deposits. If this trend holds true for other pest-pesticide combinations, then it would appear that the primary deposition target is the plant surface.

For each pest-pesticide-formulation-carrier-crop combination, there are four application related, on-target variables which potentially affect the degree of pest control obtained. These variables are: (a) droplet size, (b) deposit density, (c) dosage (weight of toxicant deposited/area), and (d) concentration of pesticide (weight of toxicant/volume) in the spray. Several studies have been reported relative to the effect of one, two, or three of the four application variables on insect control (Awad and Vinson, 1968; Polles, 1968; Himel, 1969; Burt *et al.*, 1970; Wolfenbarger and McGarr, 1971; Fisher *et al.*, 1974; Smith *et al.*, 1975; Fisher and Menzies, 1976; Jimenez *et al.*, 1976) for various crops-insecticide-insect combinations. These results have indicated that: (a) some larvae can avoid 700 micrometer diameter drops; (b) the predominant droplet size found <u>on</u> boll weevils and bollworm larvae was in the range of 20-40 micrometers; (c) droplets less than about 140 micrometers from ground sprayers will not deposit dependably in or near the treated area; and (d) droplet sizes between 140 and 200 micrometers are reasonable sizes for drift reduction and suppression of both bollworm and boll weevil populations with ground sprayers.

Collectively, these and other studies still leave the applicator in a quandary with respect to how to properly and adequately control insect or mite populations. Other studies have attempted to unify some of the prior data and answer other application questions.

Bioassay type studies have assessed the effect of each of the four application variables (singularly and in all combinations) on insect mortality for both ingestion- and contact-type insecticides (Table 1). The results from six separate experiments indicate that, in every case, dosage was the most important variable. Only in one case (Table 1, bollworm-permethrin-soybean oil) was another application variable nearly equal in relative importance to that of dosage. Collectively, these results indicate again, that the primary objective for an applicator is to get the pesticide onto the target foliage. Secondary considerations appear to be involved when considering the other three application variables (droplet size, deposit density and pesticide spray concentration). The above results (related to Table 1) are all based on bioassay-type tests. However, results from two years of field studies indicate that the predicted mortalities obtained in bioassays are significantly correlated with several measures of insect control (Luttrell and Smith, 1990).

Table 1. Correlation coefficients or standardized regression coefficients for the four application variables as related to insect mortality on soybean leaves.

Pest - pesticide combination	Application variable			
	Dosage	Droplet size	Deposit density	Concentration
Cabbage looper - *Bacillus thuringiensis* Berliner	0.65[1]	0.34	0.25	0.29
Bollworm - *Baculovirus heliothis*	0.66[1]	0.34	0.47	0.12
Bollworm - permethrin[2]/soybean oil	0.65[3]	0.61	0.20	NS[4]
Bollworm - permethrin[2]/water	0.68[3]	NS[4]	0.19	0.11
Bollworm - fluvalinate[5]/cottonseed oil	0.49[6]	NS[4]	0.07	0.27
Bollworm - fluvalinate[5]/water	0.94[6]	-0.07	-0.24	-0.15

[1]Correlation coefficients from Smith *et al.* (1977a).
[2]Permethrin products include Ambush® and Pounce®.
[3]Standardized regression coefficients from Wofford *et al.* (1987).
[4]Variable would not enter the regression equation due to its small tolerance value.
[5]Fluvalinate products include Mavrik®.
[6]Standardized regression coefficients from Smith and Luttrell (1987).

ADJUVANTS AND BEHAVIORAL MODIFIERS

Insecticides are often applied in conjunction with various materials designed to improve deposition efficiency and/or efficacy. Collectively these materials are referred to as adjuvants, implying that they are usually mixed with insecticides in the spray tank prior to application. However, most insecticide formulations include materials designed to enhance the performance of the active ingredient.

There are many adjuvants designed to perform a diversity of functions. This diversity of materials and functions is extremely complex and beyond the scope of this review on insecticide/miticide application. Popular press articles addressing the advantages and disadvantages of spray adjuvants are common and in some instances (Grondin, 1985) attempt to describe the functions of different adjuvants. This is extremely important since there are many commercial products available for production agriculture. The 1992 Farm Chemical Handbook (Meister, 1992) classifies adjuvants into 23 separate categories based on commercially described functions. Included in these 23 categories are about 225 products or product lines. Often a single adjuvant will be included in several categories (i.e., deposition agent, drift control agent and penetrant, etc.). While the effects of these materials on physical properties of spray mixtures are usually investigated in laboratory studies, effects on field efficacy are difficult to measure and are often unknown (Grondin, 1985). This lack of experimental data and the complexity of functions associated with adjuvants creates confusion for growers faced with insect control decisions. Recently, Chow *et al.* (1988) attempted to standardize terminology associated with adjuvants and compile available scientific information associated with the performance of adjuvants. Based on their review of the literature, there are more than 1100 scientific papers dealing with various aspects of adjuvants used with pesticide applications. Interested readers should refer to Chow *et al.* (1988) for information on the functions of various adjuvants. Discussion in this chapter is limited to studies associated with the effects of adjuvants on insecticide performance.

In a broad sense, adjuvants affect insecticide performance either by altering spray atomization and/or spray deposit or by altering insect behavior. Spray deposits may be altered before impingement on the target area by changing physical properties of the spray (e.g., changing droplet size distribution, retarding evaporation, and altering viscosity) or after impingement, by changing physical properties of the deposit (e.g., spreaders, wetting agents, and ultraviolet screens). Insect behavior can be altered to enhance the probability of insect contact with the active ingredient (e.g., attractants, feeding stimulants and arrestants). Much of the experimental data associated with the use of adjuvants in insecticide mixtures is associated with microbial insecticides. This is because microbials alone have historically lacked sufficient efficacy to control cotton insects and researchers have sought methods of improving their performance.

EFFECTS OF SPRAY DEPOSITS

A history of adjuvant use with insecticides can be found in Chow *et al.* (1988). During the 1970s, research efforts were made to develop improved formulations of microbial insecticides. Smith and Bouse (1981) reviewed the various factors affecting the application of entomopathogens (pathogens causing insect diseases). The physical effects described would be applicable to all insecticides and are essentially the same as those discussed previously in this chapter. Angus and Luthy (1971) compiled a list of additives used with microbial insecticides prior to 1970. This list includes materials that act as diluents, wetting agents, spreaders, emulsifiers and adhesives. In some cases, adding these materials to unformulated preparations of entomopathogens significantly increased activity. In others, there was no advantage. Angus and Luthy (1971) discussed the importance of using adjuvants with crude preparations of entomopathogens in regard to understanding the physical and environmental factors that limit activity. Most commercial insecticides include in the formulation various materials that alter spray deposits. Smith and Bouse (1981) and Angus and Luthy (1971) advocated more indepth studies on the functions of adjuvants as related to efficacy of entomopathogens. The literature is essentially void of sound scientific data that relate physical properties of spray deposits to insecticide efficacy. Some of the earlier discussion associated with spray deposit studies (Wofford *et al.*, 1987 and Smith and Luttrell, 1987) indicates the general lack of information on these relationships.

During the 1980s, interest in using vegetable oils as a carrier for insecticide applied at reduced volumes stimulated additional research. Several researchers (McDaniel, 1982; McDaniel and Dunbar, 1982; Clower *et al.*, 1982; Luttrell and Wofford, 1984; Luttrell, 1985; Hatfield *et al.*, 1984; Robinson *et al.*, 1986) reported that reduced volume applications in vegetable oil controlled *Helicoverpa/Heliothis* on cotton as well as higher volume applications in water. Similar findings in studies with the boll weevil were reported by Treacy *et al.* (1986) and Wolfenbarger and Guerra (1986). In some of these studies, a slight trend for increased insect control was observed with the reduced-volume, vegetable oil, application technique. However, the exact reasons for the trend were poorly defined and any increased control was not consistent enough to justify the additional cost for the carrier.

Reducing the volume and simultaneously changing the carrier affects the characteristics of the deposited spray (Smith and Bouse, 1981). Hatfield and McDaniel (1984) and Luttrell (1985) measured differences in deposit characteristics between the two application techniques. McDaniel *et al.* (1983) concluded that the trend in increased performance with the reduced-volume, vegetable oil treatments was associated with a more uniform deposition of spray across the spray swath. Slight differences in insect mortality observed in laboratory studies (Luttrell and Wofford, 1984) would suggest that other factors may also be involved. Wolfenbarger and Guerra (1986) suggest that the vegetable oil may enhance movement of pyrethroid insecticides through the insect's cuticle. Reduced-volume applications of insecticides in vegetable oil most certainly alter the physical properties of the spray deposit, but the relative importance of these changes in regard to overall performance of the insecticide is unknown. Most of the studies conducted with the reduced volume-vegetable oil techniques had many variables confounded in the experimental design. Also, most of the studies were direct comparisons between two application methods and were not specifically designed to describe the mechanisms involved. In most cases, dosage (actual amount of active ingredient deposited per unit of area) was not directly measured. Thus, it is difficult to separate treatment differences due to deposition efficiency and deposit characteristics following impingement. Furthermore, since vegetable oils may act as feeding stimulants (Daum *et al.*, 1967), it is difficult to separate effects of these application methods on deposit characteristics from effects on insect behavior.

Until research is conducted that will accurately relate the effects of spray deposits to insecticide performance, the confusion over the value of spray adjuvants will continue. Studies which include measurements of the physical properties of the spray deposit and quantitative indices of insect behavior, both relative to overall efficacy, are essential if we are to understand the role of adjuvants in the application process.

EFFECTS OF BEHAVIORAL MODIFIERS

The use of baits in insect control has a long history. In cotton insect control, the development of a bait which acted as an attractant and a feeding stimulant for boll weevils (Daum *et al.*, 1967) stimulated research with adjuvants as behavioral modifiers. Since most microbial insecticides must be consumed to be active, the bait principle had a logical appeal to researchers interested in improving the efficacy of microbial insecticides.

McLaughlin (1967) used a cottonseed based material as a feeding stimulant in studies conducted to evaluate the effectiveness of a protozoan for boll weevil control. This same bait was modified and included in numerous studies [Bell and Kanavel, 1978; Bell and Romine, 1980; Luttrell *et al.*, 1982a,b; Luttrell *et al.*, 1983; Smith and Hostetter, 1982; Smith *et al.*, 1982b; and prior research reviewed by Bull (1978)] to identify materials which would improve the efficacy of microbial insecticides for *Helicoverpa/Heliothis* spp. control. In general, the cottonseed based adjuvants and some soybean based adjuvants (Smith *et al.*, 1981) increased the efficacy of the microbial insecticides. The increase was generally not enough to make microbials perform as well as chemical insecticides. As with studies associated with adjuvant affects on spray deposits, the exact mechanisms involved in increased performance were difficult to measure. Ignoffo *et al.* (1976) reported that a spray adjuvant commonly described as a bait may actually function as a sunlight protectant and an evaporation retardant, as well as a gustatory (relating to the sense of taste) stimulant. Most of the literature associated with the use of baits in applications of microbial insecticides was reviewed by Bull (1978).

Semiochemicals, such as pheromones, have also been tested as possible components in insecticide sprays. These materials offer potential as control agents alone (Mitchell, 1981), but their appeal as an attractant for insecticides is of contemporary interest among entomologists. There has been some interest and success in using pheromones with insecticides targeted against adult insects such as the pink bollworm and the boll weevil. McKibben *et al.* (1990) recently developed an attract-and-kill device for boll weevils that has considerable promise in managing field populations. Although experimental data are lacking, increased research on the role of semiochemicals in insecticide formulations is likely. Some commercial products (Meister, 1992) that include behavioral modifying components in the formulation are appearing on the market.

Overall, the role of adjuvants in cotton insect control is poorly understood. Previous research has shown that adjuvants can alter spray deposits and alter insect behavior. With societal concern for reducing insecticide usage, increased research on the role of adjuvants for improving efficacy is needed. These studies should emphasize an understanding of the mechanisms involved, both from the perspective of the degree of spray atomization and the resulting spray deposit and from the perspective of altered insect behavior. Smith and Bouse (1981) suggested that researchers should consider innovative delivery systems for microbial insecticides. Transgenic plants that express the endotoxin of *Bacillus thuringiensis* is an example of an innovative insecticide delivery system.

APPLICATION OF MICROBIAL INSECTICIDES

In Europe, Aristotle was the first to mention that bees suffered from a disease and, in 1835, Agnostino Bassi discovered the fungus *Beauveria bassiana* as the causal agent (Burges and Hussey, 1971). They further stated that the first commercial microbial product in the United States (which contained *Bacillus thuringensis*) was produced before 1938. There have been several hundred bacteria, viruses, fungi and protozoa discovered and researched to some degree for possible use as an insecticide. The two groups which have received the most research emphasis for cotton insects are the bacteria and viruses.

The application of microbial insecticides for a wide range of crops, meteorological conditions, formulations and equipment (aerial and ground) has been reviewed by Smith and Bouse (1981). They concluded that on-target spray droplets in the range of 100-150 micrometers provided better insect control than larger drops when the on-target dosages were equal. They also emphasized that much of the "application" research in the literature involves a comparison of equipment types and/or formulations where insect control or yield was used as the independent variable, but typically there were few or no deposit measurements made. The absence of such data negates the possibility of answering the question, "Why was this piece of equipment or formulation better than another one?". Such answers are basic for the development of reliable, functional application systems. The above problem (related to the absence of adequate data) is not restricted to microbial applications but is also prevalent for chemical insecticide applications.

Many cotton insect control studies have involved evaluations of one or more microbial insecticides and/or formulations. In such tests, a chemical insecticide was often included as a reference treatment. Based on both field and field-plot tests, the current general recommendation and practice is to use a microbial insecticide (if one is used) in the early part of the cotton growing season (i.e., when pest populations are normally low) to minimize any detrimental effects on the predator and parasite populations present. The appropriate equipment and operating conditions for such applications currently have not been shown to be any different than those used to apply chemical insecticides. A list of some of the equipment and operating conditions for use with chemical insecticides or miticides are discussed in the next section of this chapter.

APPLICATION OF CHEMICAL INSECTICIDES AND MITICIDES

Several documents are available to assist applicators and others with the selection and proper use of spray equipment. These include multi-topic manuals such as those by Akesson and Yates (1974), Colvin and Turner (1976), Anonymous (1976), Shanklin and Tucker (1980), Hughes (1982) and O'Neal and Brazelton (1984). Other manuals deal with specific topics such as calibration (Rester, 1982) and spray drift (Ware *et al.*, 1983; Smith *et al.*, 1993). Also, many other brochures and manuals have been published by various divisions, departments or universities within each state. Due to the availability of this type of information, we will not attempt to include a synopsis of the same material here.

In a prior section of this chapter, the literature with respect to application variables—as they are presently understood to be related to insect, and possibly, mite control—is reviewed. This section summarizes some of the application equipment-operating conditions-carrier types which have provided effective insect or mite control or produced a droplet size distribution similar to treatments which have been effective.

Similar droplet size distributions should produce similar deposited dosages (for a given carrier) and the prior information in this chapter indicated that dosage was usually much more important than: (a) droplet size, deposit density and spray concentration (the three deposit related variables), and (b) the amount of insecticide impinged directly on larvae. The reader should be aware that the equipment-operating conditions-carrier type recommendations listed subsequently involve subjective decisions because every pesticide application will yield some degree of pest control. However, we have attempted to include only those combinations likely to cause a high degree of pest control under field conditions. These lists of "effective treatments" should not be considered as all-inclusive because there are an unwieldy number of combinations of atomizer types and sizes, aircraft speeds, atomizer orientations, carriers and liquid flow rates which will produce droplet size distributions within a given range. Also, many application related papers/reports have not included adequate information — information concerning one or more of the variables known to affect the degree of atomization — to be used herein. The omission of important application information is unfortunate because there are many good pest control data sets and excellent pest control is the primary objective for crop protection operations. For example, all of the suggested treatments in Table 2 for aerial applications are based on either atomization or deposition criteria, whereas most of the ground treatments are based on insect or mite control data. The lists (Table 2) should provide a selection of useful treatments per se and provide guidelines for selection of appropriate future treatments which are not listed. In addition, a computer spreadsheet has been developed to assist aerial application personnel with the selection of equipment and operating conditions which will produce a desired volume median diameter and a desired number of gallons applied per acre (Smith *et al.*, 1992).

Table 2. Equipment and operating conditions which have been judged to provide satisfactory insect or mite control under most application conditions when using oil[1], water or oil-water carriers.

Equipment and operating conditions						
Atomizer or Nozzle	Pressure (psi)	Nozzle[2] Orientation (degrees)	Speed (mph)	Size[3] (mm)	Pesticide criteria code[4]	Reference
			Aerial - Water			
D4	40	135	90	—	D	Nelson & Lincoln (1968)
D6	40	135	90	—	D	Nelson & Lincoln (1968)
D6	40	90	100	—	A	Yates *et al.* (1985)
D7	60	135	90	—	D	Nelson & Lincoln (1968)
D8	35-55	135	90	—	D	Nelson & Lincoln (1968)
D4-45	40	0	50	—	A	Yates *et al.* (1985)
D4-46	40	0	100	—	A	Yates *et al.* (1985)
D4-46	40	90	50	—	A	Yates *et al.* (1985)

D6-45	40	0	100	—	A	Yates *et al.* (1985)
D6-46	40	90	100	—	A	Yates *et al.* (1985)
D7-46	21	90	100	—	D	Ware *et al.* (1984)
D8-45	45	90	80	—	D	Brazzel *et al.* (1968)
D8-46	40	90	100	—	A	Yates *et al.* (1985)
B10-3	30	0	130	—	D	Southwick *et al.* (1986)
8004	40	0	100	—	A	Yates *et al.* (1982)
			Aerial - Oil			
8002	30	120	100	—	A	Bouse & Carlton (1983)
8002	30	120	120	—	A	Bouse & Carlton (1983)
8002E	35	90	130	—	D	Southwick *et al.* (1986)
8002E	30	120	120	—	A	Bouse & Carlton (1983)
Micronair				165	D	McDaniel *et al.* (1983)
Micronair		40 (blades)	80	—	D	Brazzel *et al.* (1968)
D2-23	18	90	115	—	A	Hatfield *et al.* (1984)
			Ground - Water			
Spinning disc				190	I	Robinson *et al.* (1986)
TX-6 cone	40			—	D	Ware *et al.* (1975)
TX-6 cone	60			—	I	Herzog *et al.* (1983)
TX-6 cone	65			—	I	Hopkins *et al.* (1979)
Raindrop/ D3-23	50			—	I	Hopkins *et al.* (1979)
8001LP fan	20			—	I	Hopkins *et al.* (1979)
Electrostatic				40 (-4 mA charge)	I	Herzog *et al.* (1983)
			Ground - Oil			
Spinning disc				100-140	I	Burt *et al.* (1970)
Spinning disc				100-120-150	I	Smith *et al.* (1973)
Spinning disc				80-190	I	Robinson *et al.* (1986)
Micromax (3500 rpm)				—	I	Treacy *et al.* (1986)
			Ground - Oil/Water			
Spinning disc				190	I	Robinson *et al.* (1986)
Mixcromax (3500 rpm)				—	I	Treacy *et al.* (1986)

[1]For research conducted between 1960-79, the oils were usually petroleum derivatives whereas in the 1980s, the oils were usually plant-derived products.

[2]For aerial sprays, a zero-degree orientation angle indicates that the liquid was sprayed straight back; 90 degrees indicates straight down; etc.

[3]Particle size is expressed as micrometers (*m*m) for volume median diameter (VMD). VMD is the size for which half of the particles is larger than the VMD and half from particles smaller than the VMD.

[4]Selections based primarily on deposit (D), insect or mite control (I), or atomization (A) considerations. Atomization guidelines for aerial sprays were volume median diameters of 275-350 micrometers for water sprays and 150-225 micrometers for oil diluants.

DEPOSITION EFFICIENCY

As indicated previously in this chapter, most of the early cotton insecticides were manufactured in the dust form and were applied with either ground or aerial dusting equipment. The change from dust to spray applications in either the suspension or solution form, was fortunate from an application perspective because sprays generally have a better deposition efficiency than dusts. The small size of dust particles causes them to decrease in velocity very rapidly and thus deposit very inefficiently on plant surfaces.

The terminal velocities for various sizes of droplets or particles and their corresponding predicted deposition efficiencies (Figure 2) are based on corresponding equations and data presented by Orr (1966) and Miles *et al.* (1975). The terminal velocity is the maximum speed which a given size particle or droplet will attain when freely falling. The deposition efficiencies were estimated for particles or droplets within a plant canopy (i.e., zone of low wind velocities due to the presence of a plant canopy). We used a droplet or particle velocity of 2 feet per second (0.61 meters per second) to calculate the deposition efficiencies. The characteristic target size was 0.25 inch (0.6 centimeter) which could represent parts of squares, small leaves, stems or small trajectory angles for droplets approaching larger leaves.

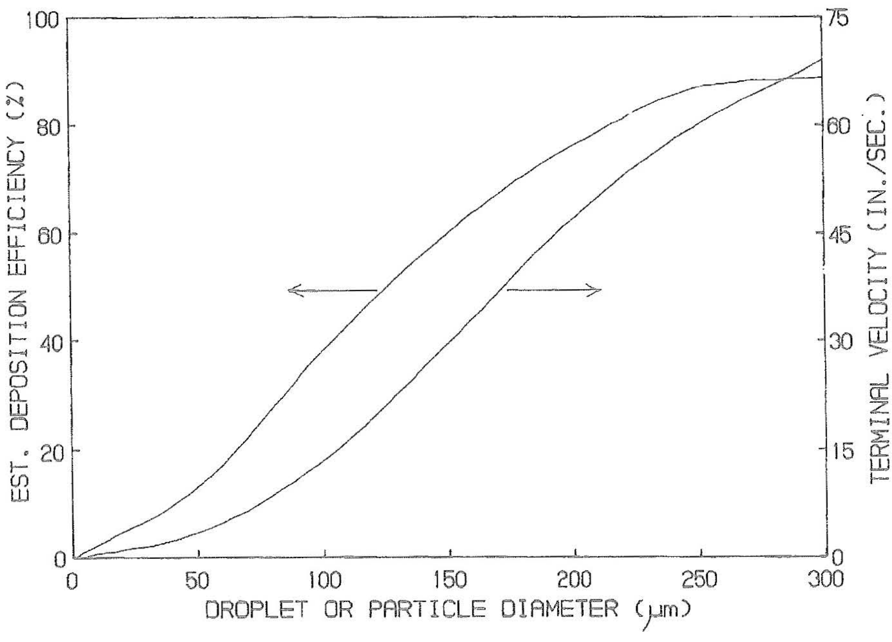

Figure 2. Estimated deposition efficiencies and the associated terminal velocities for spray droplet sizes normally used for insect and mite control.

The reason why small (i.e. less than 50 micrometers) droplets or particles do not typically deposit efficiently on cotton plants or other targets is illustrated in Figure 2. For example, the terminal velocities of 10, 50, 100 and 200 micrometer droplets or particles with specific gravities near 1.0 (i.e., specific gravity for water) are 0.24, 4.0, 13.5 and 47.0 inches per second, respectively. The corresponding estimates for deposition efficiencies are 1, 12, 34 and 76 percent. Thus the larger droplets possess the mass and velocity needed to effectively hit a plant surface. The results of Latta *et al.* (1947) and Miles *et al.* (1975) are in reasonable agreement for droplet or particle size of about 80 micrometers. Akesson and Yates (1974) listed particle size data for several clay dusts. Their data, as well as other sources, indicate that nearly all of the particles were less than 75 micrometers with the majority being less than 20 micrometers. The volume median diameter (VMD, size for half of the volume is from particles larger than the VMD and half from particles smaller than the VMD) for typical dusts would thus range between 15 and 50 micrometers. By comparison, typical spray droplet size distributions for cotton insect or mite control range from a few micrometers up to about 300-400 micrometers with volume median diameters between 100 and 200 micrometers for ground sprayers and 150 to 300 micrometers for oil and water sprays applied by air.

Bowen *et al.* (1952) ran several field tests and found that the deposition efficiencies on bean leaves for charged and uncharged lead arsenate dusts were 23 and 10 percent, respectively. Results reported by Bache and Uk (1975) indicated that the deposition of droplets greater than 40 micrometers in diameter on cotton was predominately by sedimentation rather than impaction. Both of these data sets are supportive of the wind tunnel and theoretical data reported by Miles *et al.* (1975) and the relationships illustrated in Figure 2.

Data from field tests with various sizes of droplets have indicated that droplets smaller than about 100 micrometers initially (larger for aerial sprays) will not be deposited dependably in the swath area unless forces other than gravitational forces are used (Smith *et al.*, 1975). Mist blowers or other types of high velocity air streams have been evaluated in an attempt to control the placement of the smaller droplets. Generally, such approaches have not been more effective than conventional ultra low volume (ULV) or low volume (LV) treatments for cotton insect or mite control (Wilkes, 1961; Burt *et al.*, 1966; Taft and Hopkins, 1967; Taft *et al.*, 1969). One exception to the above generalization was reported by Johnstone *et al.* (1977). They used droplets of about 60 micrometers entrained in an airstream and apparently released the droplets close to cotton plants. For their conditions, they accounted for 94 percent of the spray within 49 feet downwind. They estimated that the drift loss was about 5.5 percent. Small droplets (about 40 micrometers) have also been electrostatically charged to improve the magnitude of deposits on plant surfaces (Law and Bowen, 1966; Splinter, 1968; McCartney and Woodhead, 1983). Herzog *et al.* (1983) reported that cotton insect control for such a spray was superior to that obtained with a sprayer equipped with TX-6 cone nozzles if the charging system was functioning properly.

The knowledge base for the efficient deposition of the smaller, drift-prone droplets has improved substantially in the past ten to fifteen years but much engineering and safety work remains before such systems can be recommended for applicator use.

One would not realistically expect the deposits on the upper parts of a cotton canopy to be as large as the calibrated application rate for several reasons. The calibrated application rate (i.e., either the amount of pesticide or the volume of spray) is based on the land area involved whereas the deposited amount of spray is based on the surface area of a specific target on the plant. In the upper canopy, the wind often alters the orientation of leaves. The leaf may be inclined at some angle or even temporarily curled back over itself during applications. In such situations, the deposit area of the target can be substantially reduced relative to the surface area of the target. This means that the "spray cloud" was directed toward a smaller area than was used to calculate the magnitude of the deposits. Another reason why actual deposits are typically smaller than the calibrated amounts is that the spray droplets do not all approach a given target at the same angle. Miles *et al.* (1975) calculated the approach angles (referenced from the vertical plane) of various size droplets in a 2-feet-per-second air stream. Their approach angles for 20, 100 and 200 micrometers diameter droplets were 89, 67 and 49 degrees, respectively. The large approach angles (i.e., nearly horizontal trajectories for droplets less than 50 micrometers) reduce the effective deposit area of a horizontally oriented target and thus reduce the amount of pesticide deposited per unit of surface area. For example, interest in electrostatic charging of dusts and sprays was based on using electrostatic forces to draw the small droplets or particles toward a plant surface and thus increase the effective deposit area.

Another research area of particular importance is the proportion of spray material recovered at the target. We found only eight published papers/ reports on aerial-water sprays which were sufficiently complete with respect to the application equipment and operating conditions, so that a graph of percent recovery versus volume median diameter of the originating droplet size distribution could be developed. In some cases, we used the author's description of the atomizers and operating conditions to estimate the volume median diameter based on other published atomization data. Because some of the droplet size data were estimated by the present authors, the reader should be aware that the data are not likely to be totally accurate. However, our estimated volume median diameter data should be correct to within plus or minus 20 percent. The on-target recovery (Figure 3) on upper cotton leaves and inert targets increased from approximately 20 to 80 plus percent for volume median diameter droplet sizes of 150 to 1200 micrometers when using water as the carrier. Other than one high and one low set of data for volume median diameters between 300 and 400 micrometers, the rest of the data formed a reasonably well-defined relationship. For volume median diameters between about 90 and 800 micrometers, the variation in percent recovery for a given droplet size is on the order of ±10 percent. Because the recovery data ranged from about 20 to 60 percent of the amount applied for volume median diameters less than 800 micrometers, plus or minus 10 percent represents a substantial, but apparently real, amount of variation in pesticide deposits. The volume median diameters between 500 and 1300 micrometers (Boving and Winterfield, 1980) are larger than would typically be used for cotton insect control but are in general agreement with the recovery-volume median diameter data for volume median diameters less than 500 micrometers.

The data in Figure 3 raise some important questions related to aerial application of water-based sprays for insect or mite control. For example, if the volume median diameter is increased to, say, 500 or 600 micrometers, will the deposits on cotton plants increase? If the deposits do increase, will insect or mite control also be improved? Polles (1968) stated that tobacco budworm larvae could avoid deposited droplets as large as 700 micrometers. However, for a typical 500, 600, or 700 micrometer volume median diameter spray, one half of the spray volume would initially (prior to evaporation) be in droplets less than or equal to 500, 600, or 700 micrometers. Therefore, will the trade-off between possible increased deposits and reduced deposit densities or adverse insect behavior have a positive effect on insect or mite control?

The maximum size droplet which will adhere to a given target is a function of the physical properties of the target and liquid, the size and velocity of the droplet and the orientation of the target. It is not surprising that the magnitude of spray recoveries is quite variable because there are many uncontrolled variables which affect the deposi-

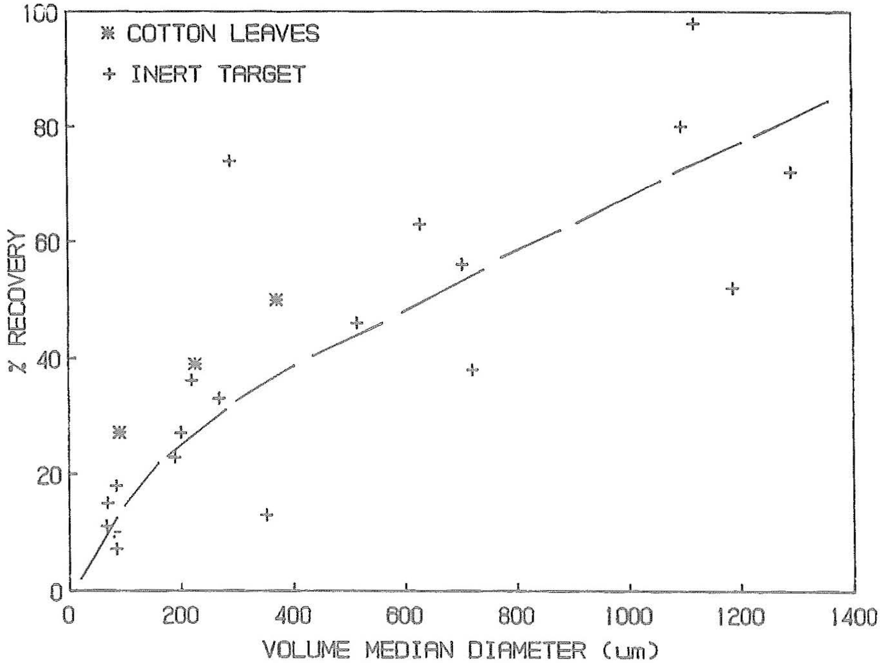

Figure 3. Percent swath recovery versus droplet volume median diameter for aerial sprays with a water carrier from results reported by Brazzel *et al.* (1968), Boving and Winterfield (1980), Uk and Courshee (1982), McDaniel *et al.* (1983), Potter (1983), Ware *et al.* (1984), Sanderson *et al.* (1986) and Southwick *et al.* (1986).

tion process. The largest volume median diameter sprays we found where deposits on cotton leaves were obtained was 350 micrometers (i.e., recovery on upper cotton leaves equaled 50 percent). In comparison, the recovery was less than 40 percent for sprays with volume median diameters of 250 micrometers or less. By deductive reasoning, the data in Figure 3 suggest that we are forcing recoveries to be generally 40 percent in an apparent attempt to maintain what is considered to be adequate deposit densities and thus pest control. In reality, this may be justified but we have not found research evidence which will either support or refute the supposition that larger volume median diameters than are typically used can be beneficial.

To our surprise, the deposits on upper cotton leaves (Figure 3) appear to be somewhat larger than corresponding deposits on inert targets for comparable volume median diameters. Due to the small amount of data for deposits on cotton and the fact that we had to estimate some volume median diameters, we do not consider this result to be irrefutable.

The data of Cadogan *et al.* (1986) for aerial deposits of oil and water sprays demonstrate the combined effect of small droplets and high (65 feet) flight heights on deposit recovery. They used a Micronair® unit to create small droplets (deposited volume median diameters ranged from 43 to 147 micrometers) for use in forest insect control. Their deposits across a 460 feet wide sampling area ranged from 1 to 15 percent and averaged 5 percent of the amount applied for 17 tests. Their recovery data seem to be reasonable, based on their droplet sizes and flight height, when compared with the data in Figure 3.

The corresponding literature for quantified spray deposits on cotton or similar plants for ground sprays is also very limited even though we found several papers where deposit-density or percent-area-covered data were used to evaluate spray deposits. Smith *et al.* (1977b) measured on-plant deposits for nozzle-pressure combinations of TX-1 at 80 pounds per square inch, TX-2 at 60 pounds per square inch and TX-4 at 54 pounds per square inch. The corresponding recoveries at the top of soybean plants were 72, 50 and 45 percent for estimated volume median diameters of 70, 87 and 110 micrometers, respectively. They used more than one nozzle over each row which may have altered the recoveries as compared with the usual one nozzle per row applications. As expected, these recoveries are considerably larger than corresponding aerial recoveries for similar volume median diameter sprays (Figure 3) because the spray was released about 15 inches above the plant canopy. Johnstone (1977) sampled leaves from entire cotton plants and reported leaf recoveries of 89, 67 and 74 percent of the amount applied for rotary atomizer sprays with volume median diameters of 90, 86 and 60 micrometers, respectively. Because the spray was released over six alternate middles, a given target may have received some spray from several or all of the passes. Thus, these data are representative of "field" deposits but does not address the lateral displacement of 60-90 micrometer droplets. Ware *et al.* (1975) also studied whole plant recoveries on cotton using TX-6 nozzles at 40 pounds per square inch on a ground, boom sprayer. They reported that 39 percent of the spray was deposited on plants and 34 percent on the soil for short (29 inches) plants for a total of 73 percent of the amount applied. For mature plants (49 inches tall), the recoveries were 83 percent on plants and 6 percent on the soil for a total of 89 percent. They concluded that their recovery rates for ground, boom sprayers were much larger than for aerial applications.

Most of the recovery data have been reported as means and the variation about the mean is not generally indicated. One may wonder how uniformly the spray needs to be applied in order to attain the best insect or mite control. Some work is in process to address this question but no prior data have been found in the literature. Some data on the variation in deposits on plant canopies are available. The raw data from the studies conducted by Smith *et al.* (1977b) were used to calculate the coefficients of variation (i.e., standard deviation of deposits on soybean leaves multiplied by 100 divided by the mean deposit) for the first replication of treatments 1 to 3 (cone nozzles) at the top, middle and bottom. At the top, middle and bottom (i.e., about 3 feet tall plants with bottom samples taken at one foot), the range of the coefficient of variation values for the three ground, boom sprays were 29 to 53, 50 to 95, and 104 to 117 percent, respectively. These data indicate that the spray deposits on leaves are considerably more variable at the middle and bottom locations than at the top. The increased variation for the lower positions on the plant is to be expected due to the variable screening effect of the leaves located above a given sampling location on a plant. Uk and Courshee (1982) reported that coefficient of variation values (for one aerial treatment along three sampling lines) ranged from 35 to 46 percent for deposits on upper cotton leaves. Cadogan *et al.* (1986) took samples from horizontal targets and reported both deposit means and standard deviations. The coefficients of variation for their data were found to range from 44 to 155 percent and averaged 93 percent for the small droplets and high flight heights they used. Yates (1962) reported coefficient of variation values for three aerial sprays (artificial targets on the ground) which ranged between 15 and 45 percent for swath widths of 40 feet. Smith (1983) reported that the coefficient of variation values are linearly related to the difference between the maximum and minimum deposits in a given data set. This means that a coefficient of variation of 30 percent indicates that the maximum deposit is about 2.7 times larger than the minimum deposit (Smith, 1983, 1992). If a 1.5x dosage represents effective insect or mite control, then larger deposits indicate wasted chemical and smaller deposits represent reduced pest control. Thus, our objectives should continue to focus on applying chemicals as uniformly as possible until we know whether or not less uniformly applied sprays are equally effective. A desirable level of uniformity is represented by a coefficient of variation no larger than 15 percent.

Because insects and mites are often not located on the upper part of the plants, one needs to know what magnitude of deposits are needed for the lower plant canopy locations. The penetration of sprays into plant canopies may be studied effectively by referencing all deposits to the amount deposited on the top of a canopy (Figure 4). The data shown in Figure 4 are from a variety of sources and include aerial, ground, water, and oil applications for a variety of canopy types including hardwoods, cotton, and soybeans. We did not include deposits from plants such as corn, milo, and tomatoes,

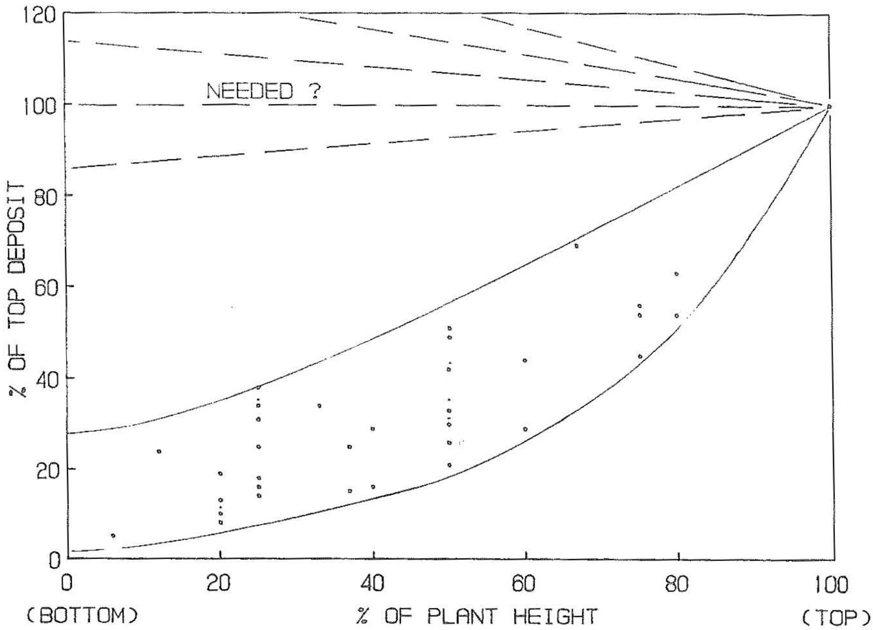

Figure 4. Penetration of sprays into cotton or cotton-like canopies for aerial and ground sprays based on results presented by Bouse (1969), Burt and Smith (1974), Smith *et al.* (1977b), Uk and Courshee (1982) and Ware *et al.* (1984).

because they are not structurally similar to cotton. The data in Figure 4 indicate that the penetration of several different types of spray applications are similar. For example, deposits half way up the plant for mature, overlapped canopies, ranged from 20 to 50 percent of the amount deposited on top of the plants and averaged about 35 percent. At the soil surface, or bottom of the plant, the deposits would be expected to be not greater than 25 percent of the top deposit and perhaps as small as 3 to 5 percent. The canopy penetration data illustrates why it is difficult to control older larvae which are located on the lower plant parts.

The upper part of Figure 4 indicates hypothetical deposit distributions which might be desirable, especially for larger larvae which have moved down to the middle or lower canopy locations. We have not found any data that indicates the most desirable vertical distribution of chemical for any plant type-pest combination. Even if the most desirable vertical distribution were known, the required application equipment and techniques may not be economically feasible. Thus, for the forseeable future, applicators are likely to be constrained to spray distributions within cotton canopies similar to those shown in the lower part of Figure 4. It seems apparent that fourth to fifth instar bollworm/tobacco budworm larvae will not be killed below some height in the plant canopy due to the severely reduced spray deposits at the lower levels and the fact that most of the larvae at the lower levels are located in bolls.

APPLICATION SAFETY

The safety aspects associated with the application of chemicals can be divided into two broad categories. These two groups involve situations where: (a) common sense and forethought are the primary considerations and (b) guidelines are not obvious and the applicator must rely on research data for assistance.

Handling, Flagging and Container Disposal — The first category involves the safety aspects where there is potential for exposure by direct contact during handling and application — manual transportation of pesticide containers, mixing and loading, flagging fields for aerial sprays and disposing of "empty" pesticide containers. With these types of operations, an individual will not normally encounter a serious safety problem if he: (a) exercises good judgement; (b) uses common sense; (c) thinks before he acts; (d) reads the pesticide container's label; and (e) is well informed about the relative toxicity of the various pesticides being applied. For example, good judgement indicates that one should not handle a pesticide container, especially one containing a highly toxic pesticide, without wearing adequate protective clothing. Unfortunately, this is not always done! Some research groups who have studied worker safety problems associated with the application of pesticides include Wolfe *et al.* (1967), Brazelton *et al.* (1981), and Lavy *et al.* (1982). In general the mixing and loading operation is more dangerous than operations associated with mechanical repairs/adjustments, piloting or operating a sprayer, flagging or working in the field after the reentry period as specified on the pesticide label. Because the mixing and loading operations normally cause the highest level of worker exposure, a wide variety of closed mixing systems have been developed in an attempt to reduce worker exposure levels. Those systems which open, empty and rinse the pesticide container while it is inside the closed system are more likely to reduce exposure levels than systems which require a person to insert a probe into the container. Brazelton *et al.* (1981) concluded that training workers on the proper use and maintenance of closed systems was essential for further reducing the exposure to mixers and loaders.

Spray Drift, Field Reentry and Worker Exposure — The second safety area relates to concerns such as drift, operator exposure, and the establishment of worker reentry periods. For these types of problems, the applicator typically needs some research information before a good decision can be reached. For example, it is not obvious whether the wind velocity, spray release height, atmospheric stability, relative humidity, temperature, or droplet size distribution is the most important variable for decreasing spray drift deposits (Smith *et al.,* 1993).

Spray drift has been, and is presently, of formost concern when herbicides are being applied. Herbicide damage to crops is visible and may be traceable to a given spray application. On the other hand, there has been less concern over drift when insecticides, miticides or fungicides are applied. The fact is, however, that the droplet size distribution used for applying these latter types of chemicals typically contains many more drift-prone, small droplets than are found in herbicide sprays applied with similar equipment (i.e., air or ground).

The increased concern about ground water contamination, human exposure and regulation of the "inert" ingredients in pesticide formulations has caused concern among regulatory agencies and the general public about spray drift from all pesticide applications.

The subject of spray drift has received much attention over the past 40 years. The current knowledge about the variables influencing spray drift from aerial applications has been summarized by Ware *et al.* (1983). Even though some of the more important variables are known, the relative importance of the relevant, independent variables was not known until recently (Smith *et al.*, 1993). Several computer simulation models have been developed to assist with aerial spray drift decisions (Teske, 1984; Akesson and Gibbs, 1988; Saputro *et al.*, 1991). However, most of the aerial drift studies have consisted of a few combinations of the independent variables and, as such, do not allow for the development of a comprehensive set of data. Such a statement is not intended to be a reflection on any of the researchers involved; rather it is a statement of where we are and what is needed. Additional comprehensive research in this area is warranted and needed.

Spray drift deposits associated with ground sprayers has received more research emphasis than aerial drift even though drift from aerial sprays typically is several times greater than that from functionally similar ground applications. On the other hand, ground applications using mist blowers may cause more drift than the corresponding aerial sprays.

Several large, ground sprayer studies have attempted to delineate the relative importance of several variables on spray drift (Threadgill and Smith, 1975; Bode *et al.*, 1976; Smith *et al.*, 1982a). Threadgill and Smith (1975) applied ultra low volume sprays over a cotton canopy in 74 tests with droplet sizes ranging from 27 to 200 micrometers. They reported that: (a) drift deposits were highest for stable atmospheric conditions; (b) increasing the mean droplet size decreased drift deposits; (c) increasing wind speed decreased drift deposits; and (d) drift deposits decreased as the vertical component of the wind speed decreased. Bode *et al.* (1976) studied drift deposits from hydraulic nozzles in 30 tests. Of the 15 variables and combinations of variables which they evaluated, the most important (i.e., highest ranked) variable was boom height. The interaction of boom height and wind speed was second; application volume was third; and wind speed was the fourth most important variable. They did not evaluate the effect of droplet size *per se* even though they varied atomization pressures and nozzle types and used a thickener in some tests. Smith *et al.* (1982a) ran 99 tests using hydraulic atomizers and evaluated 18 independent variables. They reported that the three most important drift related variables (in decreasing order of importance) were boom height, horizontal wind speed and vertical nozzle orientation. They did not find relative humidity, droplet size, volume applied, or atmospheric stability to be significantly related to the magnitude of spray drift deposits.

A word of caution is in order at this point. Some individuals have assumed that results from drift studies with ground equipment are directly applicable to aerial applications. Such extrapolations are discouraged. Aerial sprays are released much higher than ground boom sprays allowing more time for evaporation and cross winds to affect the spray droplets. Also, the air turbulence created by aircraft is much greater than the tubulence associated with ground sprayers. For example, atmospheric stability is frequently reported to be an important drift variable for aerial applications but it is seldom reported as such for ground boom sprays.

The exposure of operators and other workers to pesticides in either the concentrate or dilute form is another important safety area. Wolfe *et al.* (1967) reported that dermal exposure was much greater than respiratory exposure. However, they cautioned that equivalent doses are absorbed more readily and more completely through the respiratory tract than through the skin. In reviewing the relevant literature, no data related to the effect of sprayer speed, wind speed, wind direction and atmospheric stability on the dermal or respiratory exposure of a ground or aerial sprayer operator were found. Some data are available on exposure levels for various types of sprayers but, one would think that other test conditions may be more important than the type of sprayer used.

Most of the current guidelines for drift, exposure and reentry concerns involve subjective decisions. For example, ideally it would be desirable to have no drift, but in practice attempts are made to minimize it to an 'acceptable' level. The subjective decision process must continue until sufficient information is available to mathematically describe the crop, lake, river, and human exposure levels involved under a given set of application conditions. The time frame for the availability of such information will depend upon the support for such work. Drift and exposure studies are both expensive and time consuming.

CHEMIGATION

Chemigation may be defined as the application of crop production/protection chemical through an irrigation system. The types of chemigation referred to include fertigation (fertilizers), herbigation (herbicides), fungigation (fungicides), insectigation (insecticides), and nemagation (nematicides). The basic idea of applying a chemical through an irrigation system is over thirty five years old (Bryan and Thomas, 1958). Surface and trickle/drip type irrigation systems can be used for fertigation and herbigation in those cases where the chemical is needed on or within the soil. However, an overhead type of irrigation system can be used for any chemigation application if the pesticide will not cause damage to the crop and the formulation is appropriate.

The amount of water applied during each chemigation application varies from about 0.1 inches (2,715 gallons per acre) to 0.75 inches (20,634 gallons per acre). The chemical being applied must be metered accurately so that the correct amount is applied per unit area of land or crop. Many pumping systems are available to meter the chemicals.

A considerable amount of research has been conducted on the chemical formulations which are most suitable for chemigation applications. For soil applied chemicals, the type of formulation does not appear to be overly important. However, for foliar applied chemicals, the most consistently positive results have been obtained when the technical chemical was formulated in an oil without the addition of any emulsifier (Threadgill, 1985). Some work has been done on the method in which the chemical is injected (i.e., nozzle size or orientation and injection pressure) but these effects are not likely to be as important as formulation effects.

Safety is an important consideration when contemplating the use of chemigation systems. These safety considerations are discussed in the American Society of Agricultural Engineer's (ASAE) publication, Engineering Practice EP409 (ASAE, 1983). The primary safety considerations include a backflow prevention system and an interlocking injection system. The backflow system is designed to prevent any chemical from returning to the water supply when the water pump is not in operation. The interlocking injection system stops the chemical pump any time the water pump is inoperative so that chemical is not wasted. The Environmental Protection Agency's safety requirements for chemigation are the same as the requirements imposed by each state.

Several types of irrigation systems are capable of delivering relatively uniform amounts of chemical-water mixtures to a soil surface. The degree of uniformity has been favorably compared to that obtained with ground sprayers and is generally more uniform than that from typical aerial sprays (Threadgill, 1985). However, irrigation systems such as traveling guns, which depend on long spray trajectories usually will not provide a high degree of uniformity of the spray deposits (Shull and Dylla, 1976; Smith, 1989). Also, there is a void of information regarding chemical deposits on cotton plants resulting from chemigation applications. Additional research is warranted to assure that adequate on-target deposits are being attained and that ground level chemical deposits are reasonable.

Center pivot irrigation systems have been used extensively to study pest control resulting from chemigation applications on about 20 crops (Johnson *et al.*, 1986). Such application systems have been shown to be more economical than ground or aerial applications when: (a) more than one chemical application is needed per season and (b) the crop needs irrigation water. Other reported advantages for chemigation include reduced soil compaction and plant damage (as compared with ground sprayers), elimination of the need to incorporate some herbicides and reduced pesticide exposure. The most important disadvantages include: (a) greater management skills are required; (b) additional equipment must be purchased; (c) the possibility of contamination of the water supply if the safety equipment is not adequate and operating properly; (d) possible increased application time; and, (e) possible unnecessary water applications.

Chemigation is another proven chemical application system and can offer net advantages for some farmers.

RELEASE OF PARASITES AND PREDATORS

Some of the most promising alternative methods of cotton insect control involve the mass release of insects. Two of the most widely studied ones in the cotton production system are: (a) augmentative releases of entomophagous insects (insects that feed on other insects; Stinner, 1977); and (b) incorporation of sterile or sterile progeny-producing insects (Knipling, 1979) into natural populations. Although the biological and ecological factors influencing the efficacious use of these different control methods may be method-dependent, the application problems associated with mass releases of insects are similar. However, they are drastically different from those associated with the application of chemical insecticides. The distribution of competitive and healthy insects over target areas (often encompassing large acreages) will require application methods carefully developed to prevent damage to the insects, yet allow for efficient delivery of large numbers of insects to target areas in a rather short period of time. This requires a thorough knowledge of the release insect's biology and movement, as well as creative procedures and equipment specifically designed for the particular release insect-pest insect situation. Unfortunately, the efficacy of these control methods cannot usually be determined until efficient application methods are developed. Often, the required knowledge concerning insect biology and the effect of various environmental and physical stresses on the release insect's survival and competitiveness are unknown.

Most methods of insect control that include mass releases of insects require tremendous investments in research and development. Probably the two most researched examples in the cotton production system are augmentative releases of *Trichogramma* spp. for control of bollworm and tobacco budworm (Ridgway *et al.*, 1977) and mass releases of sterilized boll weevils in areawide suppression programs (Griffin, 1984; Villavaso *et al.*, 1986). Other notable examples in the cotton production system where release technology has received research attention are mass releases of *Chrysoperla* (=*Chrysopa)* spp. (lacewing predators; Ridgway and Jones, 1969; Kinzer, 1976) and *Trichogramma pretiosum* (egg parasites; Bouse and Morrison, 1985) for bollworm/tobacco budworm control and mass releases of sterile pink bollworms *Pectinophora gossypiella* Saunders (Ables *et al.*, 1979).

In a review of the methods used to release entomophagous insects, Ables *et al.* (1979) described three critical phases of the application process. First, the insects must be mass-produced in sufficient numbers and quality to allow field releases. Second, the quality of the insects must be preserved during transportation from the insectary to the release site. And third, the insects must be evenly and efficiently distributed over the target area. All three phases require technology and equipment specifically designed for the particular release-insect/pest-insect situation.

Most of the published scientific literature on mass releases of insects involve experiments where insects were released by various manual methods. For example, Stinner *et al.* (1974) manually released *Trichogramma pretiosum* Riley parasitized *Sitotroga* eggs for control of bollworm/tobacco budworm on cotton. Using insulated containers, they transported the parasitized eggs to cotton fields and emptied the containers onto plants. Villavaso *et al.* (1986) released sterilized boll weevils by attaching paper bags containing the weevils to cotton plants. Similar methods have long been used for various manual releases of entomophoagous insects.

Although release technology has evolved to the point that mechanical methods of release have been utilized for various programs, the technology associated with large scale releases of *Trichogramma* spp. is probably the most refined. These mechanical releases have involved both ground (Ables *et al.*, 1979; Jones *et al.*, 1977) and aerial (Ables *et al.*, 1979; Bouse *et al.*, 1981; Jones *et al.*, 1979; and Luttrell *et al.*, 1980) application methods. Since the specific procedures are described in several other references (Ables *et al.*, 1979; Bouse and Morrison, 1985; Bouse *et al.*, 1981; Jones *et al.*, 1979; Ridgway *et al.*, 1977; Bouse *et al.*, 1980 and King and Coleman, 1989), they will not be repeated here. It is important to emphasize the need to protect the release insect. This required considerable research in the development of effective production and transportation methods (Morrison *et al.*, 1978).

Ground releases have been made by automatically dropping containers from moving vehicles, by spraying liquid suspensions and broadcasting various granular mixes. The advantages and disadvantages of these techniques were discussed by Ables *et al.* (1979). Aerial releases have usually involved the dispensing of containers, the dispersal of granular mixes or the free release of entomophagous insects. Again, these methods are discussed by Ables *et al.* (1979). When granular mixes are used, the insects are usually mixed with some inert dispersal medium (e.g. wheat bran flakes). This sometimes requires that the insect be attached to the the inert carrier. Free releases usually involve the use of a venturi spreader similar to those used for application of insecticide dusts or granules.

The development of application methods for mass release of entomophagous insects is complicated because the equipment and methods may need to be specifically designed for each release-insect/pest-insect situation. As a result, the application technology associated with mass release of entomophagous insects is rather limited. The most elaborate application systems are those associated with mass releases of *Trichogramma* spp. (Bouse and Morrison, 1985).

SUMMARY

Most of the pesticide application research has been conducted during the last forty years. Those papers/reports related to application equipment, spray atomization and on-target deposition represent only one or two percent of all of the scientific publications related to insect/mite control on cotton. There are thousands of possible insect-crop-insecticide-formulation- application system combinations. Only a relative few of these combinations have been evaluated in a comprehensive manner. It is hoped that a recent increase in USDA-ARS funding for application research will have a positive impact on some of these problems.

Residual contact accounts for about 80 percent of the bollworm/tobacco budworm and boll weevil control with chemical insecticides. The remaining 20 percent is attributable to direct impingement on the insect's body. Such data have helped define the intended target for the crop-insect-insecticide combinations studied. Most of the questions regarding the optimal deposition of spray deposits on or within plant canopies currently remain unanswered. Much research remains to be completed toward the development of complete, quantified data sets from which the effects of application,

formulation and meteorological variables on spray deposits — and, in turn, the effect of such deposits on insect/mite control— can be determined.

There are about 22 categories, 225 products or product lines and 1100 scientific papers that relate to adjuvants (materials used with insecticides and miticides to improve their performance). Much of the prior work with adjuvants has been associated with the use of entomopathogens. The use of adjuvants in conjunction with entomopathogens has increased insect mortality in some studies while having no significant effect or a detrimental effect in other studies. Additional research is needed to delineate the effect of adjuvants on: (a) insect/mite mortality per se and (b) on the atomization-deposition-insect behavior process and the effect of these variables on insect/mite mortality.

One microbial insecticide (*Bacillus thuringiensis* Berliner) is commercially available and is used on a limited basis for cotton insect control. Much of the prior laboratory insect mortality-dosage data for microbial insecticides indicates that they are very effective. However, results from many field studies indicate that the level of insect control obtained is less than that which is often needed. The level of insect control obtained on cotton is usually lower than that obtained on soybeans and some horticultural crops. A considerable effort has been devoted to the use of feeding adjuvants, baits, and ultraviolet light protectants, in conjunction with microbial insecticides. Even so, there still appears to be a substantial need to increase the half-life of such insecticides for effective utilization in the field.

Many manuals are available on: the selection, use and care of spray equipment; calibration of sprayers; and spray drift. A list of atomizers and operating conditions which are likely to provide adequate insect/mite control is included in this chapter. Unfortunately, all of the recommendations for aerial sprays are based on atomization or deposition information without regard to the level of insect or mite control obtained.

Dust formulations are not used widely today due to their relatively poor deposition efficiency (i.e., generally less than 25 percent of the amount applied). Spray droplets greater than about 100 micrometers are needed for use with ground boom sprayers in order to minimize spray drift. The corresponding desired lower limit for aerial sprays is about 150 micrometers. The latter lower limit suggests that aerial sprays with volume median diameter equal to or greater than 300 micrometers are needed to minimize spray drift. Electrostatic charging of sprays has shown promise in some studies but additional research (i.e., engineering and entomological) is required before this technology is usable at the farm level.

The on-plant deposition efficiency for typical aerial and ground sprays are on the order of 40 and 85 percent, respectively. Future research in this area needs to focus on: (a) the upper limit for spray droplet size with respect to spray drift; (b) on-target deposition; and (c) insect/mite control. This type of research is needed because most researchers in the pesticide application - pest control area believe that the public's concern over environmental, safety and ecological issues will continue increase during the next ten or more years.

A clearer understanding about the effects of the physical properties of the spray liquid on the resulting droplet size distribution is needed. Results from several atomization studies indicate that the effect of a given physical property of a spray may be confounded with atomizer types. Progress in obtaining a comprehensive understanding of the spray atomization process for a variety of liquids would provide part of the foundation needed to improve future insecticide applications on cotton and other crops.

At the present time, it is essentially impossible to obtain uniform spray deposits under field conditions. Coefficients of variation for aerial and ground sprays often exceed 30 percent. A coefficient of variation of 30 percent indicates that the maximum deposit sampled is about 2.7 times larger than the minimum deposit. Such extremes in the deposits suggest that pesticides are not being used effectively either due to over- or under- dosage effects. Some limited simulation work has been done to estimate the effect of deposit nonuniformity on insect control. However, results from field evaluations of similar deposit variation work are not currently available.

Some of the safety aspects associated with the application of pesticides can be overcome by the use of good, common sense. However, sound research data is needed to provide safety guidelines for problems such as reentry intervals, contamination, drift and human or animal exposure. The operator exposure literature is woefully incomplete due to: (a) the limited number of studies which have been run; and (b) the omission of either the measurement- or reporting- of key variables which affect the magnitudes of deposits on sprayer operators. Closed-systems used for mixing and loading pesticides can substantially reduce exposure levels of workers associated with these operations. There remains a continuing need for a comprehensive, aerial spray drift data set in order for researchers and extension personnel to be able to provide more substantial advice for aerial applicators and the producers whom they serve.

Chemigation has been shown to be an effective method for applying certain formulations of insecticides and miticides. Such applications can be economical, especially if the crop also needs to be irrigated. The use of proper safety equipment on chemigation rigs is essential (or manditory in most cases) so that the water supply source is not inadvertently contaminated.

Aerial and ground methods have been developed for the release of some parasites and predators. Other equipment may be needed in the future. For future equipment development research, the primary design emphasis should be focused on protection of the released predator or parasite.