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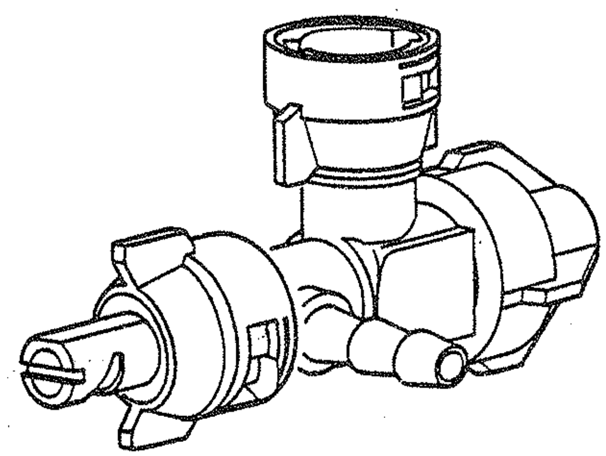
Performance characteristics of air-assist nozzles

Mats Andersson



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PREFACE

This work "Performance characteristics of air-assist nozzles" is my thesis for a Masters degree in Agricultural Engineering. The work contains both technical and biological performance of air-assist nozzles; that is the technological characteristics, the field performance with different herbicides and an evaluation of off-target spray-drift.

Most of the work was conducted at the University of Illinois in Urbana at the Department of Agricultural Engineering. Droplet size measurements were conducted at the University of Agricultural Sciences, Ultuna, in Sweden.

I want to thank my supervisor in the USA, Dr. Loren E. Bode, and also Dr. Robert E. Wolf for all their help and advice. I also would like to thank my head supervisor, Dr. Hans Hagenvall, Ultuna, for his help and encouragement which without I could not have gone abroad to do my thesis.

Finally I would like to thank the Department of Administration at Ultuna from which I received a stipend, which made it possible for me to travel to the University of Illinois and conduct this research.

Uppsala September 1991

Mats Andersson

ABSTRACT

Air-assist nozzles mix air with the spray liquid and help transport the spray to the target. These nozzles make it possible to reduce application rate and still be able to provide adequate coverage while minimizing spray drift. Air-assist nozzles are relatively new for agricultural spraying and evaluations to date are limited.

The performance of air-assist nozzles (Spraying Systems Airjet) were explored and the nozzles were evaluated in field tests using systemic and contact herbicides. Spray-drift assessments for the Airjet nozzles were also conducted. Application rate varied between 30 l/ha to 200 l/ha for the field tests and the spray-drift assessments. For most of the tests two different pressure settings were used.

The overall conclusion for the Airjet nozzles is that the choice of air pressure and liquid pressure are very important in determining an acceptable spray pattern, droplet size spectrum and in minimizing spray-drift. The field studies with systemic and contact herbicides did not result in significant differences among the application rates. A spray volume of 30 l/ha gave poor control in the field studies and in the spray-drift assessments. Control improved dramatically with spray volumes above 50 l/ha. Different size inserts and different air and liquid pressures determine the spray volume. It was observed that different size inserts to the air-assist nozzles should be choosen rather than changing pressures if an entirely different spray volume is desired. Changing pressures affect the droplet size distribution and spray pattern uniformity a great deal.

The characteristics of a ULV air-assist sprayer (AAN) were also explored. No field tests were conducted with this sprayer. The AAN-sprayer was not evaluated sufficiently to express extensive conclusions. A major observation was that the AAN-sprayer produces a non uniform droplet size distribution in the spray fan and has a high variation in the spray distribution.

These studies indicated that air-assist nozzles have potential for applying pesticides at low spray volumes, provided that the air pressure and liquid pressure are maintained sufficiently low.

BACKGROUND

Different techniques are used to protect crops from weeds, diseases and insects. Mechanical, thermal and chemical techniques are used. To apply pesticides, farmers most commonly use crop sprayers. The purpose of the crop sprayer is to apply pesticides as evenly as possible with small losses and at a low cost. Different kinds of nozzles are used depending upon the field conditions and the pest to be controlled.

Spray nozzles are designed to produce a spray pattern of some kind. A liquid sheet is created which breaks up into different size droplets. Specific spacings between the nozzles provide the proper overlap to obtain uniform coverage.

There is a movement to reducing the spray volume normally used. This is mostly due to farmers desire to reduce filling time and eliminate crop sprayers that must be equipped with large tanks that compact the soil. The problem is that conventional nozzles do not work very well at low volume rates; they produce too small droplets and the spray pattern becomes non-uniform. A solution may be air-assist nozzles which can vary the droplet size distribution and efficiently apply low spray volumes.

PROBLEMS CONNECTED WITH THE APPLICATION

Ever since the first crop sprayer was built, universities, the chemical industry and manufacturers of crop sprayers have been conducting research to improve the efficiency of applying pesticides. Even after more than 40 years of research, scientists do not know how all the parameters of the crop sprayer, chemical and the field interact. What we do know, however, is that there are still a lot of problems to solve. Some of the goals of research are (Hadar, 1991):

- To increase the penetration of the spray material into the crop.
- To increase the coverage of the leaf on both the top and bottom surfaces.
- To reduce the number of applications required and be able to reduce chemical rate.
- To reduce spray-drift.
- To increase the available time for spraying (i.e. to enable spraying even in adverse and windy conditions).
- To eliminate the necessity of spraying with the boom at a constant height above the crop.

Other areas where research needs to be done are increasing the capacity of the crop sprayer and in reducing the initial cost of the crop sprayer. In the literature review only the first six research goals are discussed and all of them are related with the transport of the droplets into the canopy where they finally deposit.

PHYSICAL FACTORS AFFECTING SPRAY DISPOSAL

There are several factors that affect the transport of the droplets and a great deal of research has been done in this area. I will only discuss this field briefly, in order to make it easier to understand which application problems must be dealt with.

Forces affecting droplet movement

On their way from the nozzle-tip to impaction the droplets are affected by three forces (Elliott & Wilson, 1983). These forces, which affect the movement of the droplets, determine whether the droplets are going to deposit within the target or drift out of the target area. The forces are due to gravity, to aerodynamic drag and to electrostatic effects for electrically charged droplets. I will here consider gravitational and aerodynamic forces only.

Gravitational force is due to gravity acting on the droplets and is proportional to the cube of the droplet diameter and to the density. The droplet density is near that of water, except for some insecticides specifically formulated for waterless spraying.

Aerodynamic force results from a combination of viscous and turbulent wake effects (Elliott & Wilson, 1983). This phenomena occurs when air moves relative to the droplet. For small droplets, less than 50 µm, the air flow past the droplets is stream- lined and therefore only effects due to the air viscosity have to be considered. For larger droplets the air flow begins to separate behind the droplets and vortices are developed leaving a turbulent wake. Part of this wake is carried along with the droplets which decreases the velocity of the droplets.

After a certain time the droplets reach an equilibrium when the gravitational force and the aerodynamic drag balance. The droplet speed at equilibrium is called sedimentation velocity. The time required by the droplets to reach 63 % of their sedimentation velocity is called the "relaxation" time. The stopping distance for a vertically projected droplet can be regarded as the distance through which the droplet has to fall before it effectively loses its excess velocity. All these factors for droplet sizes ranging from 10 to 500 µm are listed in Table 1 below.

Table 1. Relaxation time, sedimentation velocity and stopping distance* for water drops in still air at 1 atmosphere and 20°C. (Elliott & Wilson, 1983).

Diameter (μm)	Relaxation time (s)	Sedimentation velocity (ms^{-1})	Stopping distance (m)
10	0.00031	0.0030	0.004
20	0.0012	0.012	0.012
50	0.0073	0.0072	0.065
100	0.025	0.25	0.20
200	0.071	0.70	-
500	0.20	2.0	-

*Initial projection velocity = 20 ms^{-1}

Droplets larger than 200 μm are likely to be projected directly into the crop, but droplets smaller than 50 μm acquire the local air velocity very rapidly. Intermediate size droplets reach part of the distance to the crop before being significantly affected by wind and turbulence.

A further complication with hydraulic nozzles is that the initial liquid sheet produced by the nozzle entrains surrounding air, leading to an air flow circulation. The air flow can affect the initial trajectories of the smaller droplets, so that they take longer to be affected by wind than the stopping distances predict. (Elliott & Wilson, 1983).

Wind and turbulence

The frictional drag at the ground or plant surface slows air movement and results in a wind profile in which the mean speed increases with the height above the surface, see Figure 1. The increase in wind speed is approximately logarithmic and is determined by the roughness of the surface. Droplets released into such a wind profile will have a trajectory that makes an angle with the horizontal, so that the droplets fall at steeper angles closer to the surface. This is not valid though in low wind speeds and/or strong inversion conditions. The shearing stress associated with the logarithmic wind profile produces eddies in the air flow. The frictional turbulence is produced only by the wind action and is separated from the convective turbulence produced in unstable conditions.

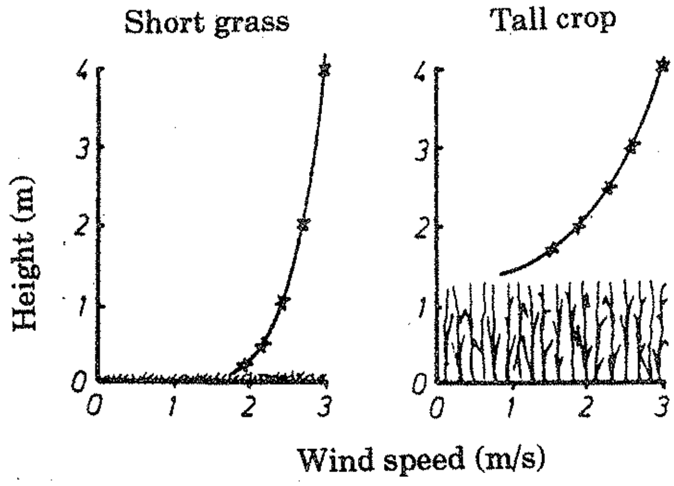


Figure 1. The wind profile over short grass and a tall crop at a wind speed of 3 m/s measured 4 m over the ground surface. (Zemp, 1984).

The effect of wind and turbulence on droplet movement

Wind influences spray movement in two ways. It carries the droplets away from the target area and, because of the action of turbulence, modifies their fall-speed relative to the ground. According to Elliott & Wilson (1983) the dispersal of "big" droplets is determined by sedimentation rather than turbulence. The relationship is reversed for "small" droplets. The dispersal of intermediate droplets is determined by both sedimentation and turbulence. It is important to know that the range of intermediate droplets increases with wind speed, see Figure 2.

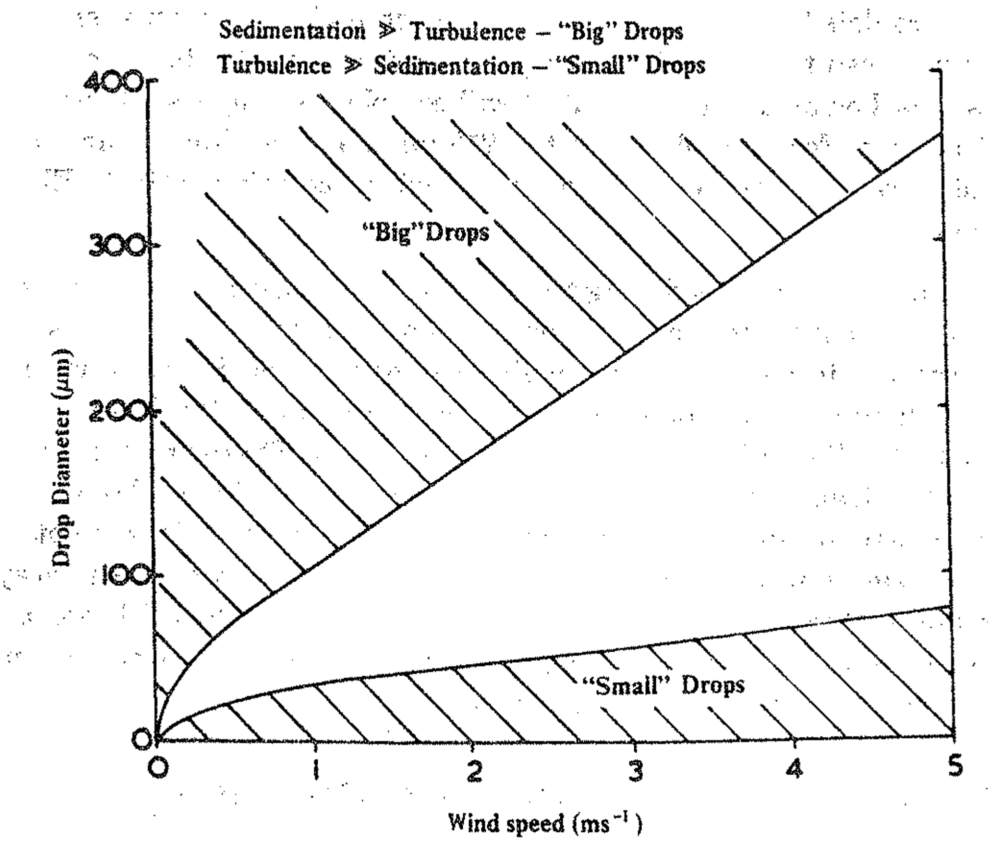


Figure 2. Areas of dominance of sedimentation on turbulent transport. (Elliott & Wilson, 1983).

The dispersal of small droplets can be regarded as a spreading cone. A simple assumption is that the distribution of droplets about the cone centre line is Gaussian, and the standard deviation of the distribution is determined by the turbulence conditions (Elliott & Wilson, 1983). The distribution of small droplets across the cone is approximately symmetrical, but the intersection of the cone with the ground leads to an assymmetrical distribution of the ground-deposit and the presence of a downwind "tail". This is one process of how spray droplets drift off target.

Evaporation and volatilisation

Evaporation affects the droplets during transport by reducing their diameter. Considerable theoretical and experimental studies have determined the diameter of a water droplet falling at its sedimentation velocity at various times and distances after release. The rate of evaporation of water droplets of a particle size is almost entirely dependent on temperature and humidity, and is not affected by sunlight.

Studies have shown that droplets evaporate relatively slowly down to about 150 µm in diameter. As the droplets become smaller the rapidly changing ratio between surface area to volume results in an accelerating evaporation rate. At the time when a droplet has reached 50 µm in diameter it will completely evaporate before it can fall another 10-20 cm. For example, an initial 217 µm diameter droplet (under 59 % humidity and no wind conditions) will fall 23 m before becoming extinct. (Elliott & Wilson, 1983).

Although evaporation of the droplets during transport to the target is a concern, volatilization of the pesticide from the crop is a more severe problem. Since for most conventional applications droplets are airborne for less than a second, evaporation of airborne droplets should not provide vapour-sources comparable with those formed by vaporization of liquid from the surface of the targets. There are numerous cases in which chemicals, after application, have volatilized and moved downwind in the vapour phase to cause significant damage to nearby crops. This is not confirmed in all countries, but in Austria, for example, as much as 75 % of the spray damage has been ascribed to volatilization rather than to off-target drift (Elliott & Wilson, 1983). The amount of volatilization depends on many factors, but mostly on the temperature and on the volatility of the chemical.

PENETRATION OF THE SPRAY-LIQUID INTO THE CROP

Penetration of the droplets into a plant canopy depends on the diameter of the droplets and the weather conditions. Droplets must have sufficient energy to penetrate the crop. Droplets produced by a regular flat-fan nozzle will not always have sufficient energy, unless the droplets are large. During dispersal of the droplets, evaporation and wind affect the trajectories and the time required for the droplets to reach the target. The longer the droplets stay in the air, the more they will be affected by the weather conditions.

SPRAY-COVERAGE

There are two ways to obtain good spray coverage of the crop canopy. The first is the addition of spray additives to the spray solution. The use of mineral oil or solvent blends in the spray-liquid has increased and with this kind of spray-liquid it is sometimes possible to apply low spray volumes (≤ 5 l/ha). The second method to obtain a good spray coverage is to apply very small droplets which will also increase the drift potential. Oil added to the spray-liquid allows the use of moderate size droplets. According to Elliott & Wilson (1983), there is a distinction between mass of droplets and number of droplets to provide good spray coverage. The droplet number deposition is more readily apparent than the mass number deposition. Spraying with small droplets as mentioned before increases the risk for spray-drift, insufficient penetration and evaporation.

REDUCTION OF CHEMICAL RATE

To reduce the chemical rate is very much connected with what I discussed earlier. Good canopy penetration, sufficient coverage and low drift losses of chemicals allow reduction of the chemical rate required to obtain pest control. Spraying at the right time also reduces the chemical rate necessary for control. Timely spraying requires high field capacity for the crop sprayer; this means wide spray-booms, high travel speed applications and applying low spray volumes. Wider spray-booms than in use today would be hard to maintain at a constant height. The boom-tip amplitude of 12 m booms is approximately 0.5 m and 24 m boom self-propelled spray rigs have boom-tip amplitudes of approximately 1.0 m (Elliott & Wilson, 1983).

Higher travel speeds than crop sprayers normally operate in will increase spray-drift. Using lower spray volumes is more probable for increasing the capacity of a crop sprayer. With a low spray volume the crop sprayer do not need to be refilled as frequently. Conventional nozzles on regular spray-booms often produce very small droplets when reducing spray volumes; sometimes to small. As discussed earlier small droplets give good coverage but have insufficient canopy penetration and increase spray-drift.

REDUCTION OF SPRAY-DRIFT

Hagenvall (1990) stated that spray-drift depends on weather conditions, properties of the spray-liquid, properties and use of the crop sprayer. He separated important weather parameters as:

- Relative humidity
- Temperature
- Horizontal air movement
- Vertical air movement

According to Zemp (1984) vertical air movement, wind speed and the droplet size spectra determine more than anything else the magnitude of spray-drift. Nordby (1979) has a different point of view and points out that the height of the boom, droplet size, liquid pressure and wind speed are the major factors affecting spray-drift.

When humidity is low droplets evaporate very quickly. Droplets greater than 150 μm in diameter are not greatly affected because they have sufficient energy to reach the surface before a significant amount of their volume is lost. Small droplets (less than 50 μm) either evaporate to pure chemical or to very small droplets of saturated solution of the chemical. It is clear that the significance of humidity depends on the droplet spectra and the chemical being applied.

An increase in temperature has the same effect as a decrease in humidity; that is the evaporation process increases. Normally during a typical day during the growing seasons the temperature rises during the day up to 14-15 o'clock and the humidity decreases.

Elliott & Wilson (1983) report that the major influence on the number and size spectra of droplets which become airborne is the wind speed. The primary cause of wind is the difference of barometric pressures in the horizontal plane. Greater pressure differences create stronger wind. Stronger winds are usually more predictable than light winds, which is a important factor to consider in crop spraying.

The height of the spray-boom is of great importance in determining spray-drift. Arvidsson (1985) found in his wind-tunnel experiments that the spray-drift increased 106 % when the spray-boom was raised from 0.4 m to 0.6 m. When he raised the spray-boom from 0.4 m to 0.8 m the spray-drift increased by 209 %.

TECHNIQUES FOR IMPROVING EFFICIENCY OF CROP SPRAYING

There have been many solutions during the years to the problems with crop spraying that have been described. The most well-known and successful solutions include:

- Electrostatic charging
- Controlled Droplet Application (CDA)
- Spray-curtain
- Crop-opener
- Air-foil
- Air-assistance

Some of these techniques have proven more successful than others. Hagenvall (1990) reported that in the late 1970s, electrostatic charging of the droplets was considered to have great potential in reducing spray-drift. Sharp (1984) found that it was possible to reduce spray-drift up to 40 % in windy conditions for charged droplets. Other researchers like Matsuo et al. (1986) and Miller (1989) did not find any significant difference between spraying with electrostatic charging and conventional crop spraying in terms of reducing the spray-drift. Electrostatic charging was also proposed for giving better deposition on the leaves. We know that the expectations for electrostatic charging were too high.

The CDA-boom crop sprayer utilizes spinning discs that are designed to deliver droplets with almost the same diameter. CDA allows spraying with the dropletsize that best suits the conditions. The spinning discs also accelerate the droplets to a high speed, which should increase canopy penetration. Bode (1991) points out that much of the spray-liquid is exiting the nozzle horizontally, so gravity is the only force affecting the droplets.

Spray curtains around the spray boom is another way of protecting the droplets from wind on their way from the nozzles to the target. According to Hagenvall (1990), curtains have to be very close to the ground (< 50 mm) to be effective in reducing spray-drift. A Canadian crop-sprayer, the Windproof Sprayer, utilizes curtains that prevents turbulence (Figure 3).

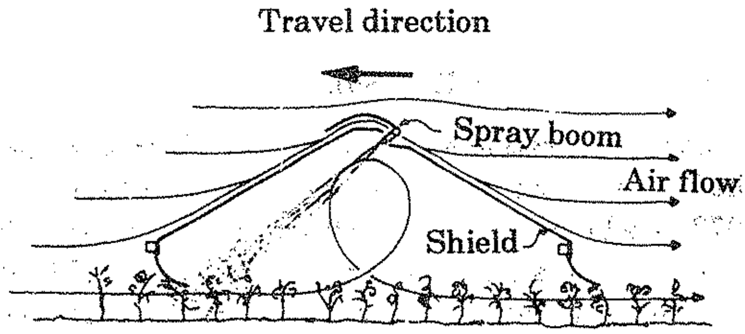


Figure 3. The principle of the Windproof sprayer. (Brandt, 1988).

The "crop-opener" separates the plants in canopy with a pipe that is mounted below and along the spray-boom (Figure 4). The crop-opener makes it possible to spray at a lower height than with a conventional spray-boom which reduces spray-drift (Brandt, 1989). With a crop-opener, it is also possible to obtain a better penetration and coverage in the lower part of the canopy (Brandt, 1987). The crop-opener will not work satisfactorily if the crop is in an early stage, which limits this system to fungicide applications.

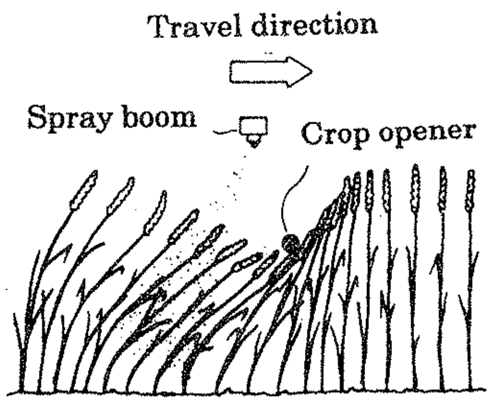


Figure 4. The crop-opener in action. (Brandt, 1989).

The most likely way to increase penetration and coverage and decrease the chemical rate and the spray-drift is to use air to carry the spray-liquid into the crop. Jegatheeswaran & Göhlich (1978) used two "wings" to redirect the horizontal wind down into the crop. This system is called an air-foil. Moser et al. (1981) found that spray-drift is reduced with the air-foil boom but that the boom was to complicated and cumbersome to use.

Air-assistance is a another method of transporting the droplets to the target. Air-assist systems has been used since the late 1800s in vines and orchards. Using air as a transport medium for spray-liquids in field crops is more novel and has not been well researched.

Air-assistance can be divided in two areas; air-assist systems and air-assist nozzles (Bode, 1988). The main difference is where the spray-liquid mixes with the air. This work is an investigation of the performance of air-assist nozzles, so a more thorough review have been done of air-assist nozzles compared to air-assist systems.

AIR-ASSIST SYSTEMS

Air-assist systems are designed similar to regular sprayers equipped with hydraulic nozzles except that a sleeve is mounted on the boom. The sleeve has openings along the bottom length of the sleeve. Air is discharged from the openings at high velocity and is accompanied with spray-liquid emitted from the hydraulic nozzles.

There are several companies manufacturing air-assist sprayers. The most common brands in Europe are Hardi Twin, Degania and Danfoil. Whether the Danfoil sprayer belongs to the group of air-assist systems or to air-assist nozzles is debatable. Nozzles on the Danfoil sprayer are mounted in openings on a tube that serves as the spray-boom. Spray-liquid is metered into the nozzles from the side of the openings. The nozzles are air foil shaped with the high speed air used to atomize the liquid into droplets (Figure 5).

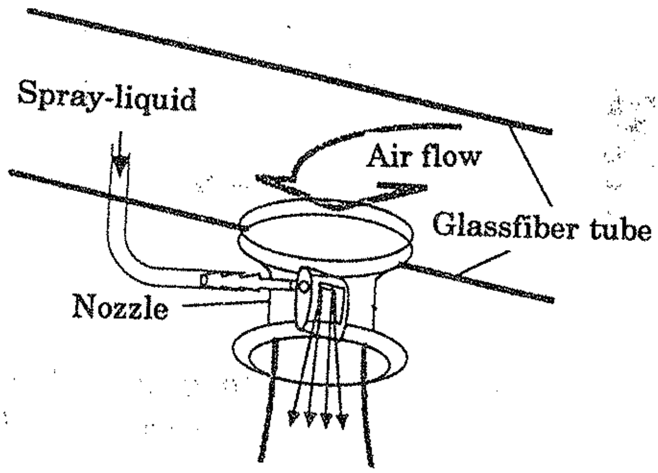


Figure 5. The principle of the Danfoil sprayer. (Wikström, 1989).

The Hardi-Twin and the Degania-sprayer are similar in design.The sleeve and the boom equipped with the nozzles on the Hardi-Twin can be tilted to accomodate different weather conditions, travel speed and plant canopies (Figure 6). The main difference between the Hardi-Twin and the Degania-sprayer is the choice of nozzles and spacings between the nozzles. Hardi (1991) recommend 110° flat fan nozzles spaced on 0.50 m centers, while Hadar (1991) says that the nozzles should be 80° cone jets on 0.25 m spacings, like on the Degania-sprayer. Another difference between the two sprayers is that the angle between the air flow and the spray-liquid flow is greater on the Degania-sprayer (Fig 6).

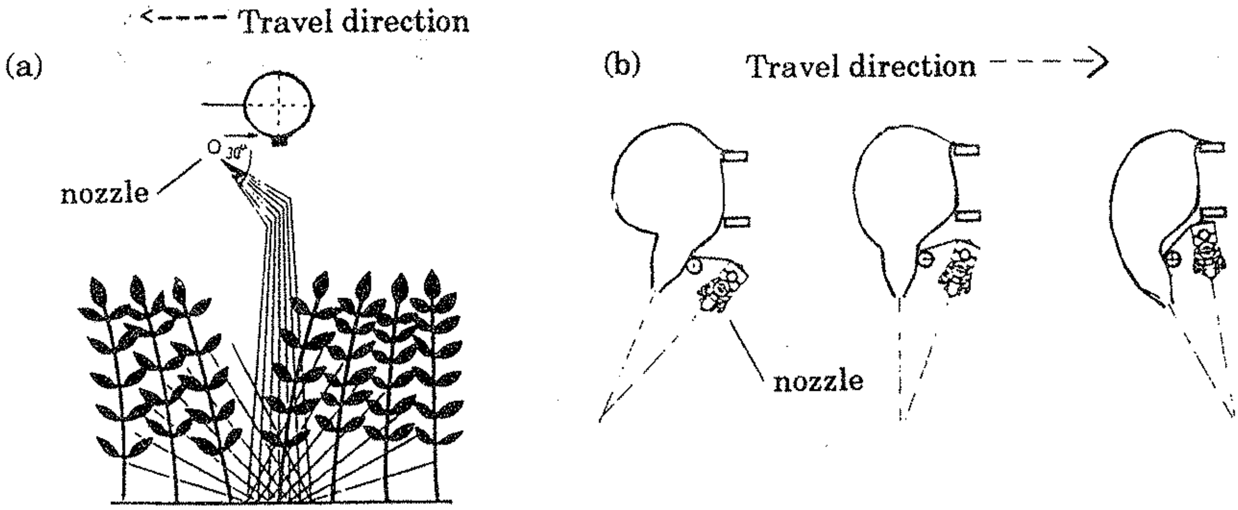


Figure 6. The principle of outlets for air flow and spray-liquid flow on; (a) the Degania-sprayer and (b) the Hardi-Twin. (Anonymous, 1989 b; Hardi, 1989)

AIR-ASSIST NOZZLES

Air-assist nozzles, also called twin-fluid nozzles, work entirely different from air-assist systems. The spray-liquid is atomized by the air inside these nozzles. A conventional sprayer with a regular spray-boom is used, but air lines and an air compressor is attached. Air-assist nozzles have limited history and presently there are only two nozzles commercially available; Cleanacres "Airtec" and Spraying Systems "Airjet". These two nozzles look very much alike and they work similarly.

The Airtec nozzle is fed with the spray-liquid on top of the nozzle (A), see Figure 7. The spray-liquid is then directed via the interchangeable restrictor (C) on to the baffle plate (D) where primary atomization occurs. The compressed air, which is included through the air line (E) mixes with the spray-liquid in the swirl chamber (F). The secondary atomization takes place in a flood jet, prior to the emerging in a flat fan pattern (I). A diapragm check valve (J) prevents dripping when the spray-liquid is turned off.

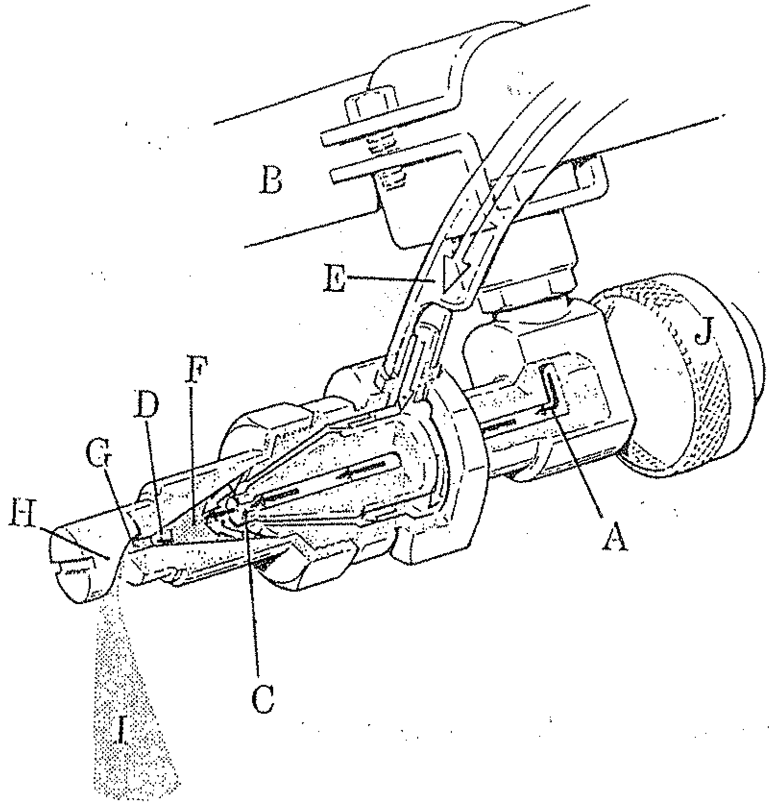


Figure 7. The Airtec nozzle. (Cleanacres Machinery Ltd, 1988).

The Airjet nozzle from Spraying Systems also atomizes the spray-liquid twice, but the first atomization occurs earlier than in the Airtec nozzle (Figure 8). The air atomizes the spray-liquid immediately when it arrives into the body. Both the Airtec and the Airjet have an insert on which a restrictor is mounted; but on the Airjet nozzle the restrictor is positioned in the middle of the body instead of in the front as on the Airtec nozzle. Both of the nozzles have diaphragm checkvalves and flood jet spray-tips. The Spraying Systems Airjet nozzles were used in these experiments.

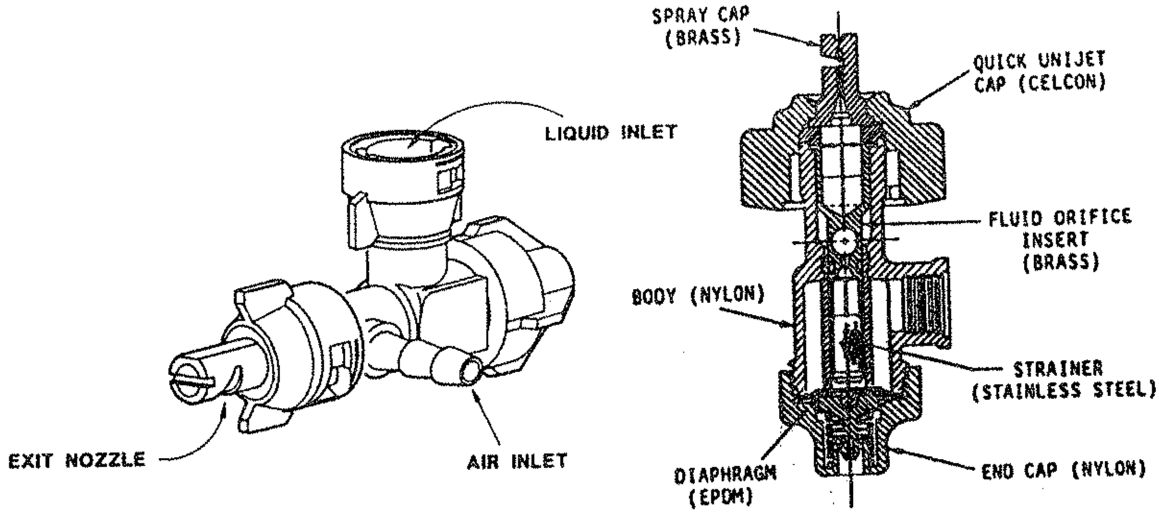


Figure 8. The Airjet nozzle. (Spraying Systems Co, 1991).

Previous investigations with air-assist nozzles

The purpose of this research study is to evaluate the characteristics of air-assist nozzles when the spray volume is used to make low volume applications of pesticides. Most of the reported investigations on the biological and technical performance of air-assist nozzles have been conducted with the Airtec nozzle.

Spray-drift measurements

Miller et al. (1991) conducted drift measurements with the Airtec nozzle. Spray-drift deposits were collected on 2 mm polythene tubing supported from masts 11 m tall at distances 8, 20 and 50 m downwind from the end of the boom. The experiments were conducted over a cereal or grass stubble on which re-growth had been stimulated to give a reasonable dense crop-canopy approximately 150 mm tall. For comparison, they used conventional hydraulic flat-fan nozzles (F 110/1.6/3.0 and F 110/0.8/3.0).

Millers (1991) results showed that spray-drift was lower with the Airtec nozzle than with the hydraulic flat fan nozzles, especially the spray-drift from fine spray quality nozzles. The difference in spray-drift between the Airtec nozzle and the hydraulic flat fan nozzles increased with wind speed (Figure 9). According to Young (1991) the spray-drift from air-assist nozzles can be controlled by altering the spray quality from very fine to coarse at a given flow rate.

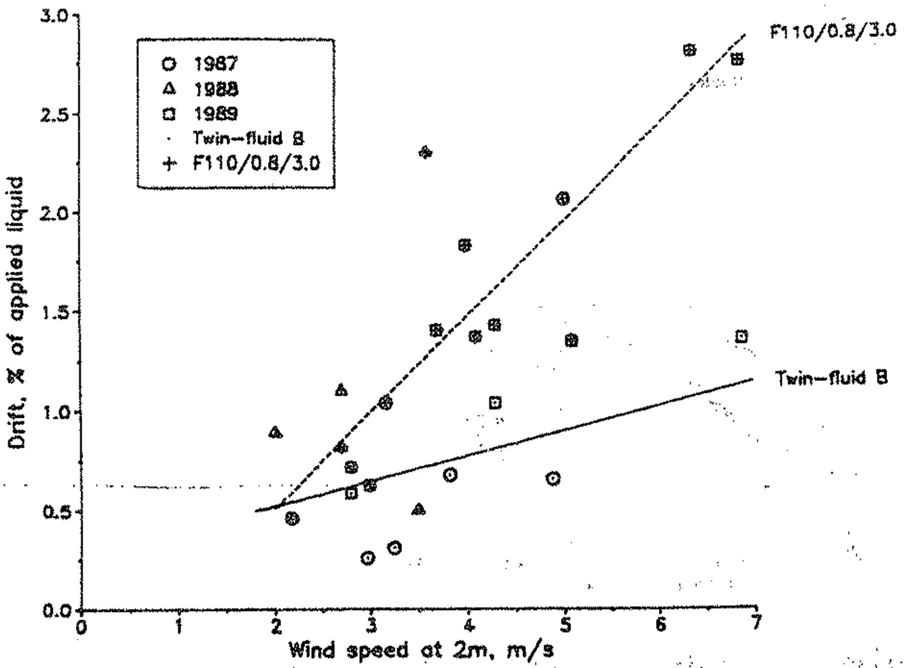


Figure 9. Measured spray drift from fine spray quality nozzles at 8 m downwind of the end of a 12 m spray boom. (Miller et al., 1991).

Droplet size / velocity

Miller et al. (1991) also conducted a thorough investigation of the performance characteristics of the Airtec nozzle. For droplet size and velocity measurements, they used a Particle Measuring System's analyser with a two dimensional probe (Type 2D-GA1) positioned at 450 and 700 mm below the nozzle. For comparison, they selected a hydraulic flat fan nozzle (F 110/1.6/3.0).

They found that the velocities of droplets above 400 μm diameter from the flat fan nozzle and above 500 μm diameter from the Airtec nozzle had relatively wide variations. This was due to the small numbers of droplets measured in these size ranges (Figures 10 and 11).

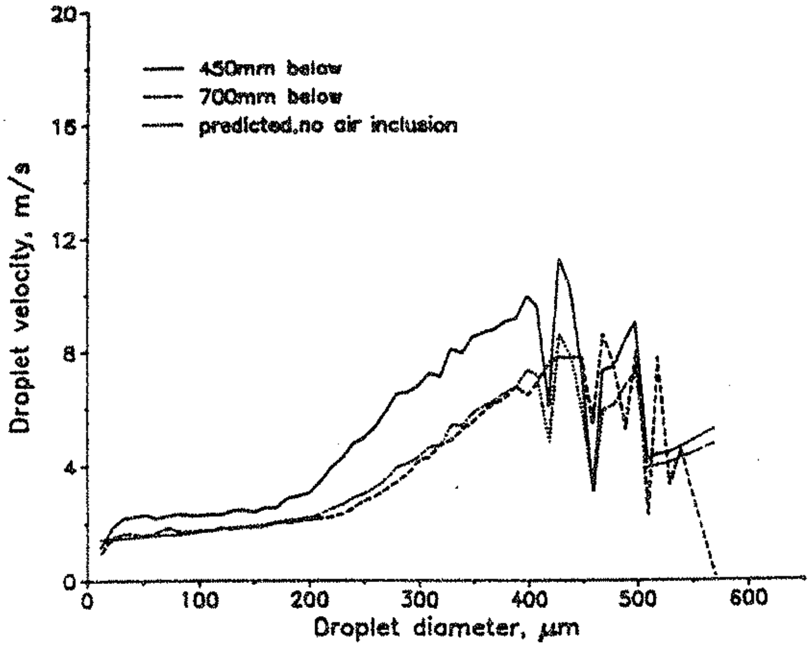


Figure 10. Comparison of velocity profiles for a F 110/1.6/3.0 nozzle at 2.5 bar at two heights. (Miller et al., 1991).

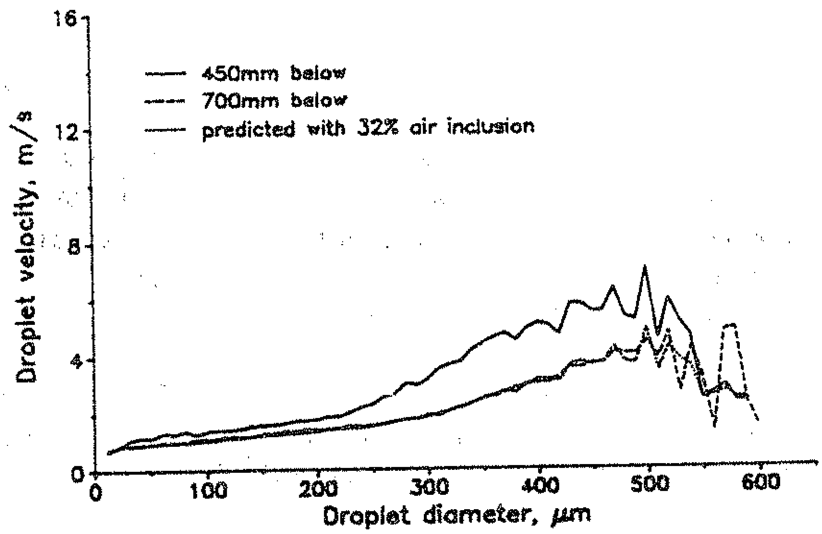


Figure 11. Comparison of velocity profiles for a air-assist nozzle at two heights. (Miller et al., 1991).

They also found that the mean droplet velocity from the Airtec nozzle was less than for the conventional nozzle. The velocities of the entrained air are higher for the conventional nozzle than for the Airtec nozzle at a distance of 450 mm below the nozzle. Miller et al. (1991) indicated that the reduction in spray-drift may be due to a reduced percentage of spray volume in droplets less than 100 µm in diameter (Figure 12) and/or higher velocities close to the nozzle with the Airtec nozzle because of the compressed air used to atomize the liquid.

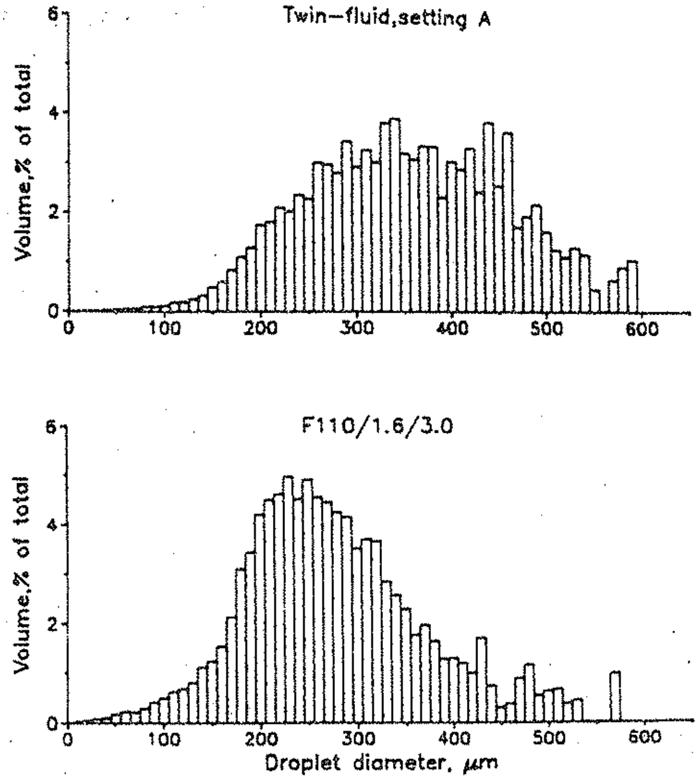


Figure 12. Distributions for medium spray quality nozzles 450 mm below nozzle. (Miller et al., 1991).

Field performance and experiences

Miller et al. (1991) showed in their studies that there were no significant differences in pest control between the Airtec nozzle and conventional flat-fan nozzles at comparable spray volume. Their measurements were made on weeds in cereal crops. Work by Cooke & Hislop (1987) shows that fungicide deposits on winter barley from the air-assist nozzle were somewhat higher than from conventional nozzles applying at 200 l/ha. The disease control from the two systems was not different.

Miller et al. (1991) reported results of other investigations concerning spray deposits and biological performance of sprays applied with air-assist nozzles and compared to conventional flat-fan nozzles. In these investigations, no significant differences were found between the systems when operating at comparable volumes.

Nettleton (1991) reviewed some experiences regarding agrochemical applications for air-assist sprayers on 2000 hectares of cereal crops since 1987. Most agrochemicals are currently applied by boom-mounted hydraulic nozzles applying water volumes of 100-200 l/ha. The air-assist nozzles applied pesticides in spray volumes as low as 50 l/ha (Nettleton, 1991). However, most of the agrochemicals had no label recommendations for application at such reduced volume rates. Some countries have guidelines for how low the volume rates can be without any toxic or corrosive hazards (Nettleton, 1991).

Nettleton (1991) found that most herbicides gave good results at low volume rates. Glyphosate, Difenzoquat and Flamprop-M-isopropyl formulations are suitable down to 80 l/ha and the substituted urea group of herbicides, Pendimethalin, Diclofop-methyl and Metsulfuron methyl have also given good results at low spray volumes.

Results from insecticide applications with air-assist nozzles have given mixed control. Pyrethroids have been successful at 85 % of recommended rate when sprayed at correct time using spray volumes as low as 70 l/ha. The Pyrethroids were used against barley yellow dwarf virus in cereals. The success rate has only been about 60 % with air-assist nozzles at low volume rates. For good results high spray volumes should be used. (Nettleton, 1991).

For fungicide applications, air-assist nozzles have proved to be ideal, as they conveniently allow the use of low dose and low spray volume applications at regular intervals. In some cases, like severe infections of brown or yellow rust, chemical dose rates should not be reduced and volume rates maintained at 90 l/ha and above. (Nettleton, 1991).

The opinions of some users of air-assist sprayers claim that they get less spray-drift, better penetration, more uniform crop coverage and faster application with their sprayers (Anonymous, 1989 a). These opinions agree with what Nettleton (1991) has found. Both authors also claim that air-assist nozzle users generally apply less agrochemicals than with conventional systems.

THE PURPOSE OF THESE INVESTIGATIONS

The purpose of these investigations was to determine the performance characteristics of air-assist nozzles and to determine from field studies if adequate weed control can be obtained from the nozzles when herbicides are applied at spray volumes ranging from 200 l/ha to 30 l/ha.

SPECIFIC OBJECTIVES

To be able to fullfill the purpose of these investigations the experiments were divided into two parts. The first part was conducted in laboratories to determine the technical performance of air-assist nozzles. The second part consisted of field studies to evaluate the biological performance of air-assist nozzles. Specific objectives of the experiments were:

- To determine the operational parameters that provide acceptable spray patterns. Parameters to be evaluated include liquid pressure, air pressure, boom height, spacing between nozzles and orientation. Visual drift assessments, experiments with drift control additives and other various experiments were also done.
- To measure the droplet size spectrum at various air pressures and liquid pressures.
- To evaluate weed control achieved from air-assist nozzles when spraying systemic herbicides and contact herbicides at spray volume from 200 l/ha down to 50 l/ha.
- To assess the spray-drift deposits from air-assist nozzles compared to conventional flat-fan nozzles at spray volumes from 200 l/ha down to 30 l/ha.

AIR-ASSIST NOZZLES USED IN THE STUDIES

For the experiments, Spraying Systems nozzle no 23258 (diaphragm check valve Airjet nozzle) with inserts no 35, 42 and 62 and Beta-T-Mizer nozzles were used. Beta-T-Mizers nozzles were part of a ULV-sprayer (Ultra Low Volume) that was built and used in the experiments for measurement of droplet sizes and spray pattern uniformity. This sprayer, also called AAN, was built the same as described by Hanks & McWhorter (1991), except only one compressor with an air-tank instead of two compressors without air-tanks were used (Figure 13).

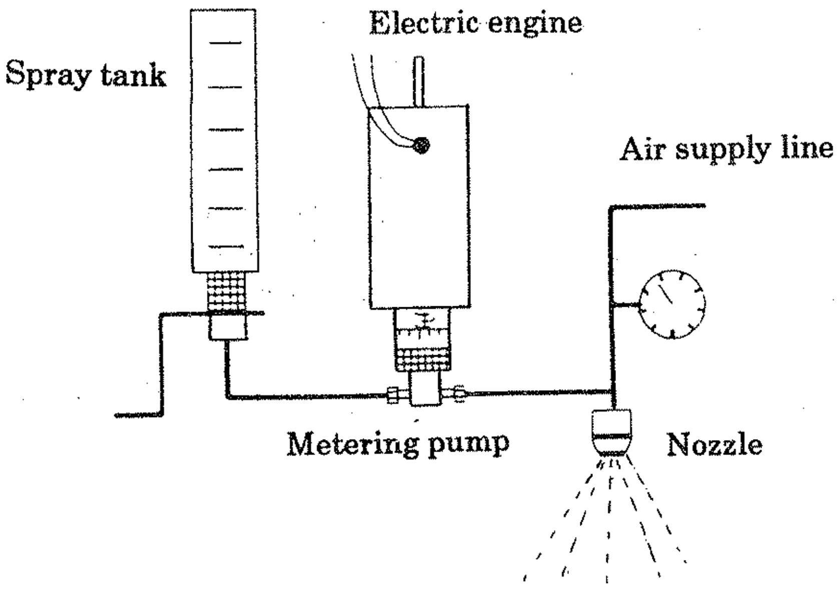


Figure 13. The principle of the AAN-sprayer. (Hanks & McWhorter, 1991).

The purpose of the AAN-sprayer is to apply ultra low spray volumes (5 l/ha and below). These low spray volume often cause problems with conventional ULV-sprayers because the rate of diluent applied is usually controlled by disc orifices in the liquid line (McWhorter, 1991). When making ULV applications the disc orifice required has an orifice so small that plugging easily occurs. The AAN-sprayer uses a positive displacement pump attached to each nozzle; which means that the flow rate is not determined by a small orifice.

At low spray volume of 5 l/ha or less, water does not provide sufficient spread on plant leaves to ensure adequate coverage. Water has a relative spread coefficient of 1, silicone surfactants increase the spread coefficient to 3 to 6, and droplets of oil have spread coefficients of 400-700 and thus provide vast increases in coverage (McWhorter, 1991). Instead of water, Orchex 796 F is recommended as a diluent for the AAN-sprayer. Orchex 796 F is a light-weight paraffinic petroleum-based oil and has provided better results than vegetable oils mostly because of the higher spread coefficient. Sta-Put is a drift control additive which also is recommended by McWhorter (1991) for the AAN-sprayer to be applied when using water as the carrier. The effect of the drift control additive is to increase droplet sizes as well as to increase the spread coefficient.

TECHNICAL PERFORMANCE CHARACTERISTICS

As discussed earlier the technical performance characteristics were determined in two parts; measurement of the spray pattern uniformity and measurement of droplet sizes.

Spray Pattern Uniformity

To see how sensitive the air-assist nozzles are in spraying even when different parameters are being changed the Coefficient of Variation was determined. By doing this it was also easy to see how the parameters should be set to give ideal results with the air-assist nozzles.

Method

The spray pattern uniformity was measured by using a spray table with 0.04 m dissolution. A spray-boom was placed over the table in which multiple nozzletips could be installed. The boom could be raised or lowered and the angle between spray-fan and the spray table could be changed. The pressure gauges were placed as close as possible to the nozzle to minimize errors in readings due to pressure losses. The spray-liquid was water or in some experiments water with a drift control additive (Sta-Put). Every 0.04 m along the edge of the spray-table a tube was attached for collecting the spray-liquid. The heights of spray-liquid in the tubes were measured.A computer program was then used which could calculate the coefficient of variation for the spray pattern when using one nozzle or for simulating several nozzles at different spacings.

Spray pattern uniformity is generally expressed by the coefficient of variation (C.V.) of the data collected in the tubes. Although no standard exists, it is generally accepted that a C.V. of less than 15 % is acceptable but C.V.:s less than 10 % are more desirable. Spraying Systems Co (1991) recommends a 0.50 m nozzle spacing for the Airjet nozzle and that was the nozzle spacing most frequently used in this study.

There are different ways of measuring the spray pattern uniformity and the results are not always comparable. Therefore, for a comparison check, several tests were conducted with a conventional flat-fan nozzle (Spraying Systems 11004-VS). The boom height was 0.45 m and the liquid pressures used were 2.0 bar, 2.5 bar and 3.0 bar. The respective C.V. got to be 6.2, 11.8 and 10.3.

Variation among nozzle tips

Initial experiment was performed to determine the consistency of the spray pattern between the Airjet nozzles when using the same size insert. The No. 35 and 42 inserts were used for these tests. Nozzle height was 0.5 m and the nozzle spacing was 0.5 m. The experiment was conducted at the air and liquid pressures shown in Table 2.

Table 2. Spray pattern uniformity of Airjet nozzles.

Spraytip	Insert No.	Air pressure (bar)	Liquid pressure (bar)	Flow rate (l/min)	Spray pattern uniformity, C.V. (%)
A	35	0.75	1.0	0.32	10.0
B	35	0.75	1.0	0.32	12.8
A	35	0.75	1.5	0.47	9.4
B	35	0.75	1.5	0.47	8.5
A	42	0.75	1.5	0.58	4.8
B	42	0.75	1.5	0.58	8.4
A	42	1.0	2.0	0.66	3.9
B	42	1.0	2.0	0.66	7.8

Two spray-tips designated as A and B were evaluated. The same nozzle body and quick connect cap was used in all trials. The difference in C.V. obtained between the two spray-tips was consistent except for No. 35 insert at 1.5 bar liquid pressure where tip A resulted in a poorer spray pattern than tip B. One reason for the difference among the tips was that the centreline of the spray fan, when looking at it from the back, is not pointing straight down for all of the spray-tips. This study shows that there are differences in the spray patterns among the Airjet tips.

Effect of liquid and air pressure

Experiments were executed to determine the effect of liquid pressure on spray pattern uniformity. Nozzle height was 0.50 m except for the four last trials where it was either 0.45 m or 0.55 m and the nozzle spacing was 0.50 m in all the trials. Metering inserts No. 35 and No. 42 were used (Table 3).

Conclusions from the data in Table 3 is that the liquid pressure greatly influences the spray pattern obtained. It is clear that the C.V. reduces considerably when increasing the liquid pressure. This tendency was true for both insert No. 35 and No. 42.

In order to determine the effect of air pressure on the spray pattern, the liquid pressure was held constant. In these tests only the No. 42 insert was used but two separate spray-tips were used (A and B). The nozzle spacing was 0.50 m and the height 0.50 m (Table 4).

Table 3. Effect of liquid pressure on the spray pattern uniformity of Airjet nozzles.

Insert No.	Air pressure (bar)	Liquid pressure (bar)	Nozzle height (m)	Flow rate (l/min)	Spray pattern uniformity, C.V. (%)
35	0.75	1.0	0.50	0.32	12.8
35	0.75	1.5	0.50	0.47	8.5
42	0.75	1.0	0.50	0.40	8.0
42	0.75	1.5	0.50	0.58	4.8
35	0.75	1.0	0.45	0.32	16.1
35	0.75	1.5	0.45	0.47	7.9
35	0.75	1.0	0.55	0.32	13.5
35	0.75	1.5	0.55	0.47	5.9

Table 4. Effect of air pressure on spray pattern uniformity of Airjet nozzles.

Spraytip	Insert No.	Air pressure (bar)	Liquid pressure (bar)	Flow rate (l/min)	Spray Pattern Uniformity, C.V. (%)
A	42	0.75	1.0	0.40	4.9
B	42	0.75	1.0	0.42	8.0
A	42	1.5	1.0	-	14.4
B	42	0.75	1.5	0.58	4.9
A	42	1.25	1.5	0.41	5.8

Air pressure affected the spray pattern almost the same as liquid pressure did. The C.V. decreases when air pressure is decreased. Even though two spray-tips were used in this experiment, it is clear that the air pressure should be lower than the liquid pressure to obtain an acceptable spray pattern.

Effect of boom height, nozzle spacing and orientation

To determine the optimum nozzle height insert No. 35 was used. The air pressure was held constant but the liquid pressure was varied. The nozzle spacing was 0.50 m. (Table 5).

Table 5. Effect of boom height on spray distribution patterns of Airjet nozzles.

Spraytip	Insert No.	Air pressure (bar)	Liquid pressure (bar)	Boom height (m)	Flow rate (l/min)	Spray Pattern Uniformity, C.V. (%)
A	35	0.75	1.0	0.45	0.32	18.0
A	35	0.75	1.0	0.50	0.32	10.0
B	35	0.75	1.0	0.50	0.32	12.8
A	35	0.75	1.0	0.55	0.32	13.5
A	35	0.75	1.5	0.45	0.47	7.9
A	35	0.75	1.5	0.55	0.47	5.9

All the tests in this experiment were conducted with the same spray-tip except one. From the data a height of 0.50 m provided the most consistently uniform spray pattern. A height of 0.55 m was adequate but the pattern at a height of 0.45 m was unacceptable. The spray angle of the Airjet nozzles is 100° and with this angle it appears from the data that an spray overlap of at least 60 % is required to obtain a uniform spray pattern with these nozzles.

Nozzle spacing can be used as well as height to obtain the overlap required to obtain a uniform spray pattern. Tests at various nozzle spacings using inserts No. 35 and No. 42 at various air and liquid pressures were conducted (Table 6). The boom height in the trials was 0.50 m.

Table 6. Effect of nozzle spacing on spray distribution pattern of Airjet nozzles.

Insert No.	Air pressure (bar)	Liquid pressure (bar)	Nozzle spacing (m)	Flow rate (l/min)	Spray Pattern Uniformity, C.V. (%)
35	0.75	1.0	0.40	0.32	4.4
35	0.75	1.0	0.50	0.32	12.8
35	0.75	1.0	0.60	0.32	13.2
35	0.75	1.5	0.40	0.47	4.7
35	0.75	1.5	0.50	0.47	8.5
35	0.75	1.5	0.60	0.47	5.7
42	0.75	1.5	0.40	0.58	5.7
42	0.75	1.5	0.50	0.58	8.4
42	0.75	1.5	0.60	0.58	6.3
42	1.0	2.0	0.40	0.66	4.3
42	1.0	2.0	0.50	0.66	7.9
42	1.0	2.0	0.60	0.66	7.0

The effect of changing nozzle spacings was very consistent. A 0.40 m nozzle spacing provided the best and a spacing of 0.50 m the worst spray pattern uniformity. The percent overlap that provided most uniform pattern was 75 %. Generally nozzle spacings less than 0.40 m are unrealistic when spraying with the 100° fan angles that Airjet nozzles provide.

It may be possible to obtain a non uniform spray pattern by tilting the spray-fans. Several tests were conducted with a 10° orientation from vertical. Inserts (no 35 and no 42), air pressures, liquid pressures, spacings and heights are given in Table 7.

Table 7. Effect of nozzle orientation on spray patterns of Airjet nozzles.

Orientation	Insert No.	Air pressure (bar	Liquid pressure (bar)	Height (m)	Spray Pattern Uniformity, C.V. (%)
Regular	35	0.75	1.5	0.45	7.9
10°backwards	35	0.75	1.5	0.45	15.7
Regular	42	1.0	2.0	0.50	3.9
10°backwards	42	1.0	2.0	0.50	7.5

The C.V. increased consistently at the different settings when the spray-fan was tilted 10° backwards. It did not matter if the height or the spacing was changed, the effects were the same.

From all the tests of spray pattern uniformity, it can be concluded that there are differences in spray patterns among the Airjet tips. Further, the C.V. reduces considerably when increasing the liquid pressure and decreasing the air pressure within limits. To obtain a uniform spray pattern the overlap should be 60-75 %. The spray pattern uniformity deterioated when the spray-fan was tilted 10° backwards.

Visual spray-drift assessments

Visual assessments were made of the spray-drift potential at various operating parameters. This experiment was conducted to see at which pressure ranges the nozzles would provide acceptable droplet sizes. The spray-drift assessment was conducted by visually watching the spray-fan from the side to see whether vortices and spray clouds were created (Table 8).

From these observations it was determined that the interaction between air pressure and liquid pressure determine when spray-drift occurs. When both air and liquid pressure was high, spray-drift occurred and it appeared as if the liquid pressure could be high as long as the air pressure did not exceed certain levels. Under no conditions should the air pressure be higher than the liquid pressure.

Table 8. Maximum air and liquid pressure to avoid excess spray drift from Airjet nozzles.

Insert No.	Air pressure (bar)	Liquid pressure (bar)	Height (m)	Spray Pattern Uniformity, C.V. (%)
35	1.0	1.0	0.50	14.0
35	1.0	3.0	0.45	16.0
35	1.2	1.5	0.50	18.4
42	1.2	2.5	0.50	14.1
42	1.5	1.0	0.50	14.4

Evaluations of a drift control additive (Sta-Put) with the Airjet nozzles

In the experiment with the AAN-sprayer a drift control additive (Sta-Put) in the spray-liquid was used, as was recommended by McWhorter (1991). How does Sta-Put affect the C.V. for the Airjet nozzles? To check this an experiment was conducted in which all parameters except height and nozzle spacing were varied (Table 9). The concentration of Sta-Put was 0.75 %.

Table 9. Spray pattern uniformity obtained with the Airjet nozzles (Inserts No. 35,42 and 62).

Sta-Put in the spray- liquid (%)	Insert No.	Air pressure (bar)	Liquid pressure (bar)	Flow rate (l/min)	Spray Pattern Uniformity, C.V. (%)
0	35	0.75	1.0	0.32	11.6
0.75	35	0.75	1.0	0.32	13.6
0	35	1.0	1.0	0.25	14.0
0.75	35	1.0	1.0	0.25	8.6
0	42	1.0	2.0	0.29	7.8
0.75	42	1.0	2.0	0.29	7.8
0	42	1.5	2.0	0.53	11.9
0.75	42	1.5	2.0	0.53	9.5
0	62	1.0	1.5	0.91	16.7
0.75	62	1.0	1.5	0.91	7.7
0	62	1.5	2.0	0.95	8.1
0.75	62	1.5	2.0	0.95	11.1

There was no consistency in the results from these tests. Sometimes a spray-liquid with Sta-Put gave a lower C.V.; sometimes it did not. Visual spray-drift was sometimes decreased with Sta-Put but the spray-drift never increased when Sta-Put was used.

Various experiments with the Airjet-nozzles

While conducting all these spray pattern uniformity experiments it was noticed that the air pressure and the liquid pressure greatly affected each other. For instance, if the liquid flow was switched on while the air flow was operating already the air pressure increased. To further investigate this and other effects a pressure gauge (A) was connected with the air line approximately 8 m away from the pressure gauge (B) which was connected close to the nozzle. The diameter of the air line was 5 mm.

When only the air flow was on, the pressure loss measured between the gauges was within a range of 20-50 % of the pressure 8 m away from the nozzle. The pressure loss increased when the air pressure was raised which follows the rules of fluid mechanics. When the liquid flow was turned on the pressure loss decreased tremendously. It decreased even more when the liquid pressure was raised and the air pressure (A) was held constant (Table 10). Insert No. 42 was used. The liquid flow is approximately redoubled when the liquid pressure is doubled at the same time as the air pressure goes down.

From this small experiment it was concluded that the liquid restricts the air, which will increase air pressure (B) and decrease air flow. Due to the high air flow, 10-90 l/min according to Spraying Systems Co (1991), the pressure loss will be perceptible even at high liquid pressures. This means that air pressure must be measured as close as possible to the nozzle, because air pressure influences the spray pattern uniformity as well as droplet size. These tests also showed that the relationship between air pressure and liquid flow is linear (Figure 14). The straight lines on the ground is a regression line to the data.

Table 10. Interaction of air and liquid pressure on flow rate.

Air pressure A (bar)	Air pressure B (bar)	Liquid pressure (bar)	Liquid flow rate (l/min)
0.76	0.69	1.0	0.47
0.90	0.80	1.0	0.42
1.00	0.90	1.0	0.38
1.00	0.97	2.0	0.79
1.17	1.10	2.0	0.75
1.31	1.24	2.0	0.66
1.45	1.36	2.0	0.62
1.59	1.45	2.0	0.62

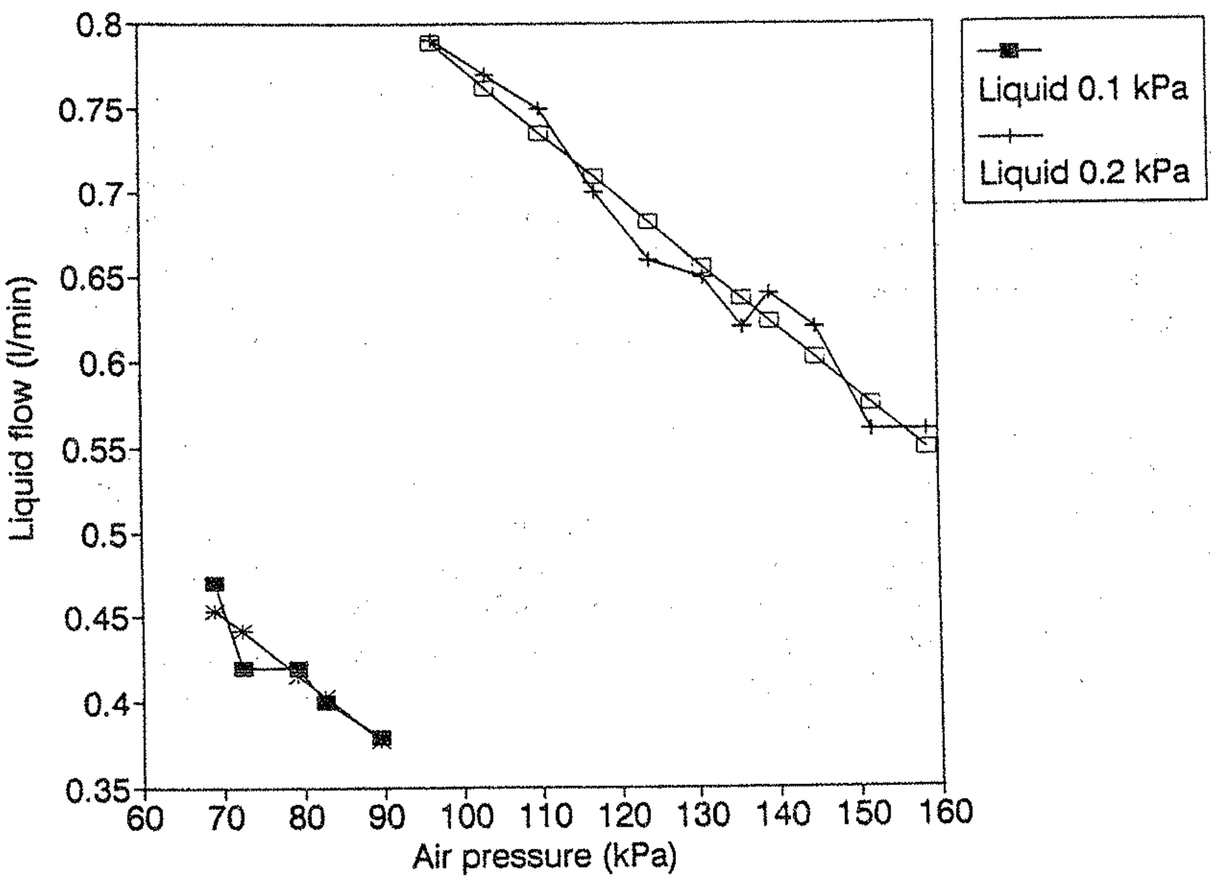


Figure 14. Linear relationship between air pressure and liquid flow for Airjet nozzle.

Experiments with the AAN-sprayer

Water and water with Sta-Put (conc 0.75 %) were used in several tests with the AAN-sprayer. The air pressure, volume rate and the spacing between the nozzles were varied. The height was set to 0.50 m (Table 11).

Table 11. Spray pattern uniformity obtained with the AAN-sprayer.

Sta-Put in the spray- liquid (%)	Air pressure (bar)	Liquid flow (ml/min)	Nozzle spacing (m)	Spray Pattern Uniformity, C.V. (%)
0	0.15	40	0.50	66.0
0	0.15	80	0.50	33.7
0	0.30	40	0.50	32.8
0.75	0.30	40	0.50	44.5
0	0.30	80	0.50	27.9
0	0.30	100	0.50	26.4
0	0.30	120	0.50	25.7
0	0.55	40	0.50	8.7
0.75	0.55	40	0.35	8.3
0.75	0.55	40	0.50	8.7
0.75	0.55	40	0.65	9.4
0	0.55	80	0.50	16.6
0	0.55	100	0.50	18.7
0	0.55	120	0.50	16.0

In no case was the C.V. acceptably low with air pressures below 0.55 bar. Visually the main reason why the C.V. values were high when air pressure was low was because of the nozzles producing extremely large droplets in the middle of the spray-fan. When the air pressure was 0.55 bar the C.V. tended to increase when liquid flow was increased. No dramatical changes in spray pattern uniformity were found when Sta-Put was added.

Droplet size measurement

To measure C.V.:s and to do field studies with spraying nozzles are no good unless the droplet sizes at the different pressure settings are known. In this work droplet size measurements were conducted with all the settings used in the field studies.

Method

Droplet size measurements were made with a Malvern 2600 C particle measuring instrument. By using lens No. 1000 the instrument could measure droplets up to

1800 µm in diameter. This lens was not used due to low accuracy when measuring small droplets. Instead lens No. 800 and No. 300 were used for the droplet size measurements in all the tests and covered the droplet size range produced by the Airjet nozzles. The droplet size range for lens No. 800 is 15 to 1504 µm and for lens No. 300 the droplet size range is 6 to 564 µm. In some cases, for example when spraying with large inserts at high liquid pressures, the droplets were so large that not even lens No. 1000 could be used to measure them. In those cases a volume median diameter ($D_{v0.5}$) could not be calculated because the largest size droplets were not measured and the data would be inaccurate.

Measurements were made 300 mm below the nozzle tip at five locations across the spray-fan; directly below the nozzle and 100 mm and 200 mm on each side of the centreline. Spray table tests at the same boom height and inserts and pressure settings as in the droplet size measurements were done to determine the spray volume at various locations in the spray fan (Figure 15).

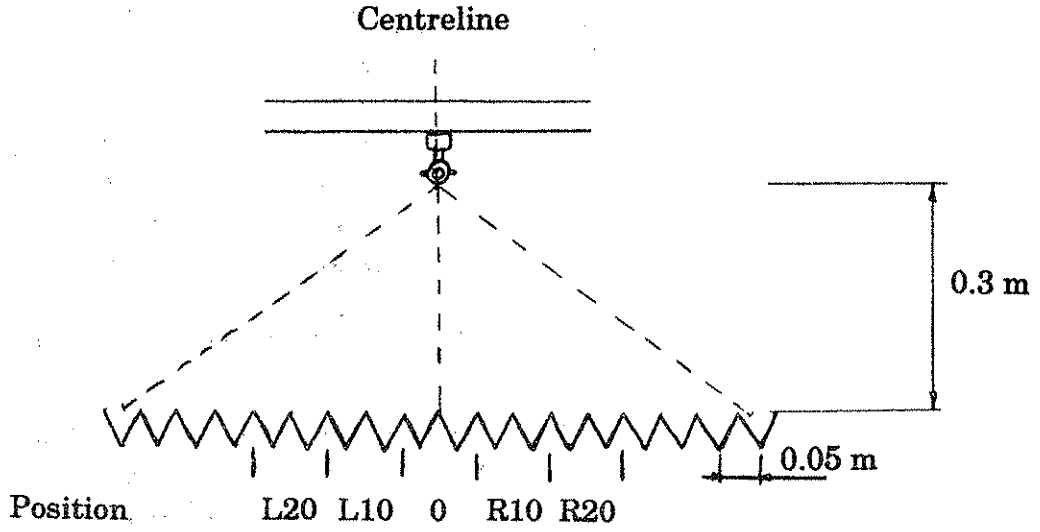


Figure 15. Schematic diagram for collection of spray-liquid at the different locations in the spray-fan.

By collecting the spray-liquid at the five locations in the spray-fan, a weighted $D_{v0.5}$ could be calculated. The formulas used were:

$$V_s = \sum_{i=1}^{5} V_i$$

$$Weighted\ D_{v0.5} = \sum_{i=1}^{5} \frac{(V_i * D_{v0.5_i})}{V_s}$$

where V_s=Total collected volume

V_i=Collected volume from one of the locations

$V_{v0.5i}$=Volume median diameter

The percent volume of spray contained in droplets less than 100 µm was calculated in accordance with the weighted $D_{v0.5}$. This method in recalculating the $D_{v0.5}$ and the volume percentage less than 100 µm has been described by Lagerfelt (1991).

Droplet size measurements were conducted with both the Airjet-nozzles and the AAN-sprayer. The spray-liquid included water as well as water with Sta-Put (conc 0.75 %) for the Airjet-nozzles and water with Sta-Put (conc 0.75 %) for the AAN-sprayer.

Droplet Sizes produced by Airjet nozzles

The weighted $D_{v0.5}$ and the volume percentage less than 100 µm at each setting are shown in Table 12. Data is missing for two settings with insert No. 62 because it was not possible to measure the largest droplets in those spectra.

Table 12. Droplet sizes produced by Airjet and 11004-VS flat-fan nozzles.

Insert No.	Air pressure (bar)	Liquid pressure (bar)	Sta-Put concentration (%)	$D_{v0.5}$ (μm)	Spray volume in droplets <100 μm (%)
35	0.75	1.0	0	116	39.2
35	0.75	1.0	0.75	119	37.6
35	1.0	1.0	0	93	53.7
35	1.0	1.0	0.75	87	57.6
35	0.75	1.5	0	107	26.5
35	0.75	1.5	0.75	150	28.5
42	0.75	1.0	0	147	29.2
42	0.75	1.0	0.75	144	30.9
42	0.75	1.5	0	216	16.9
42	0.75	1.5	0.75	188	21.7
42	1.0	2.0	0	212	18.8
42	1.0	2.0	0.75	201	20.2
62	1.0	1.5	0	354	7.8
62	1.0	1.5	0.75	345	8.5
62	1.0	2.0	0	-	-
62	1.0	2.0	0.75	-	-
62	1.0	2.5	0	-	-
62	1.0	2.5	0.75	-	-
11004-VS	-	2.0	0	202	14.1
11004-VS	-	2.5	0	193	16.9

As can be seen in the table, the drift control additive tends to slightly decrease the droplet size. The three inserts function as "gears" and give different droplet size ranges which do not significantly overlap each other. Insert No. 35 produces very small droplet sizes, especially when the air pressure is close to the liquid pressure. It appears as if insert No. 62 produces very large droplets even at fairly high air pressures. To decrease $D_{v0.5}$, the air pressure must be raised which also decreases the volume flow rate.

The "real" droplet size might be different from what was measured. Droplets produced by air-assist nozzles are believed to have air inclusions. Miller et al. (1991) estimated that air inclusions reduced the mean droplet density by an average of 32 % in their trials. Rutherford et al. (1989) suggested that the percentage of air inclusions increases with droplet size and at sizes of less than approximately 100 μm there are no air inclusions in the droplets. This may explain the huge droplets produced when using large size inserts and relatively high liquid pressures.

The droplet size distribution curves for the Airjet nozzles were usually uneven and most of them had two peaks, one higher than the other. There were no recurrent distinctions between the distribution curves at the five different locations in the spray-fan for each pressure setting. A typical distribution curve for the Airjet nozzles is shown in Figure 16. Additional curves are presented in Appendix 2-5.

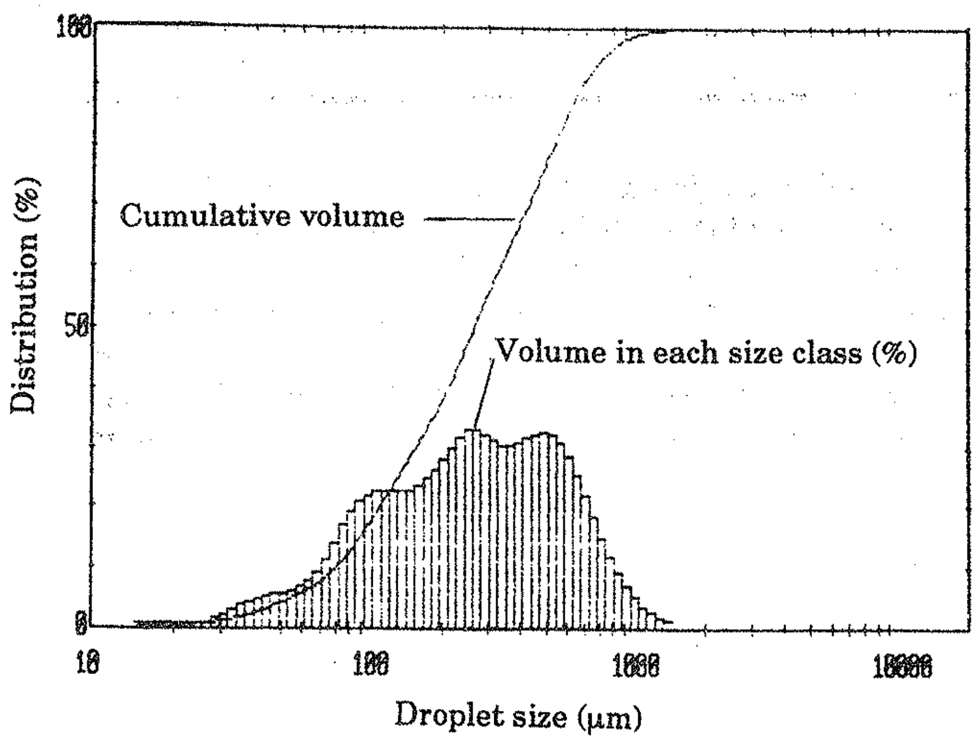


Figure 16. Spray volume distribution curve for Airjet nozzle with insert No. 42, air pressure 1.0 bar and liquid pressure 2.0 bar.

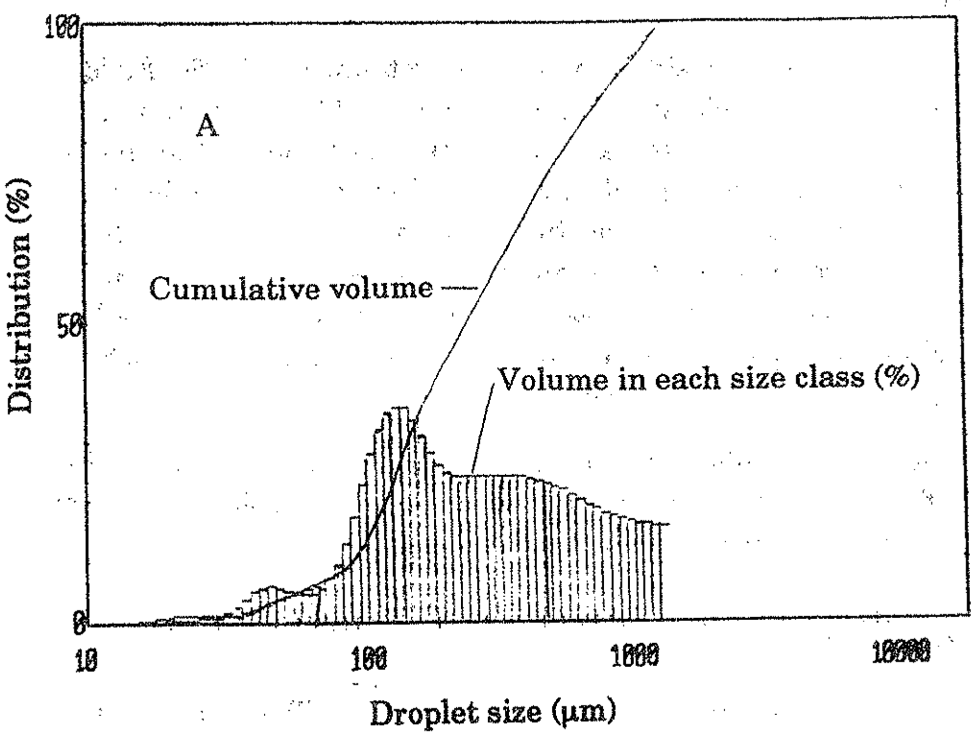
Droplet size produced by the AAN-sprayer

Results from the droplet size measurements with the AAN-sprayer are difficult to evaluate. This is because the AAN-sprayer produced a bi-modal distribution; one peak within the range of 100 to 200 μm and another peak at 1000 μm or higher. The second peak was extremely high for all the settings tests and contained large volumes. The sprayer produced droplet diameters above 1500 μm which made it impossible to measure the $D_{v0.5}$. Settings used in the AAN-sprayer tests are presented in Table 13.

Table 13. Settings used for the AAN-sprayer droplet size tests.

Air pressure (bar)	Liquid flow (ml/min)	Sta-Put (%)
0.55	80	0.75
0.55	40	0.75
0.30	80	0.75
0.30	40	0.75
0.15	80	0.75
0.15	40	0.75

All the settings produced similar distribution curves except for the 0.15 bar air pressure at a 40 ml/min flow rate. At this setting, most of the spray liquid was formed in very large droplets (Figure 17). These large droplets may have a large percentage of air inclusions, but this does not entirely explain the droplet size obtained. There was a significant difference in the droplet spectrums obtained at the five sampling locations. At all settings, the $D_{v0.5}$ was higher 0.20 m from the centreline than the $D_{v0.5}$ at the centre of the nozzles. Typical results are given in Appendix 6:1 through 6:5.



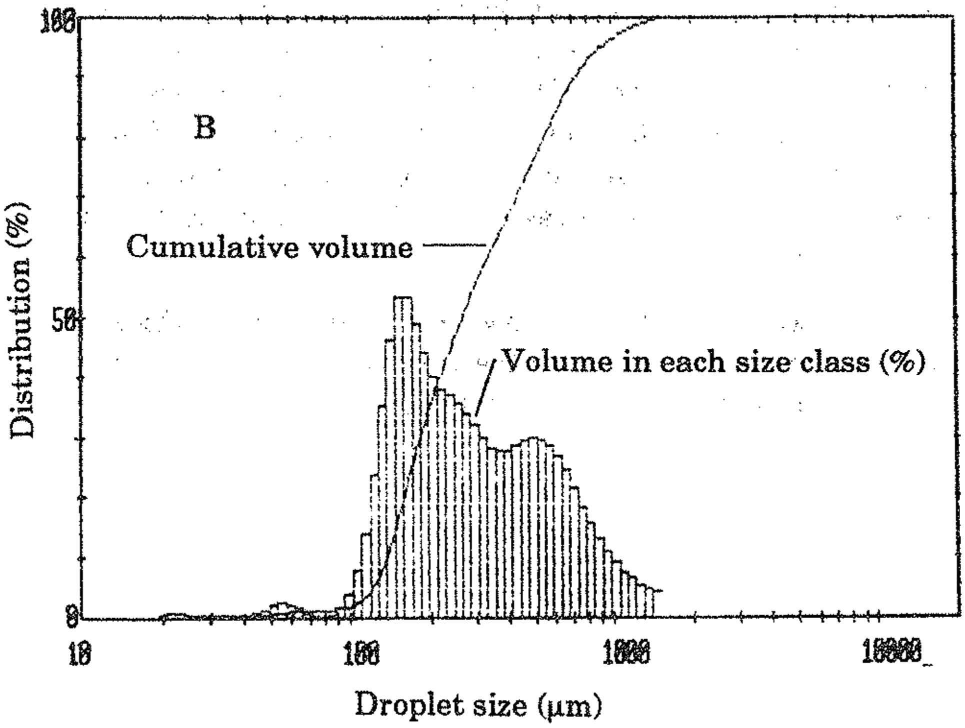


Figure 17. Droplet distribution curves for the AAN-sprayer with air pressure of 0.14 bar and liquid flow 40 ml/min (A) and air pressure 0.28 bar and liquid flow 80 ml/min (B).

FIELD PERFORMANCE

This section is divided in three parts; Field study with a systemic herbicide, Field study with a contact herbicide and Field study of drift deposits. The field studies with herbicides were conducted to evaluate penetration and spray deposit by evaluation of weed control experiments. These studies were conducted only with herbicides, mainly because of two reasons. At the location of the studies, Illinois in the USA, herbicides are the most common pesticide and as a matter of fact this is also true in most countries in Europe. The second reason is that herbicides are usually being sprayed before drilling and planting or in an early stage of the crop, which means there are great problems with spray-drift.

A field study with a systemic herbicide, a field study with a contact herbicide and a spray-drift study show fairly well the biological performance of air-assist nozzles, at least in weed control and in spray-drift reduction.

Equipment and methods

In all three field studies a test plot sprayer was used (Figure 18). The sprayer was equipped with two spray-booms, one in the front and one in the back of the sprayer. The the front boom was equipped with regular flat-fan nozzles (Spraying Systems 11004-VS) which were used for conventional spraying. The spray-boom in the rear of the sprayer was equipped with Airjet nozzles. Both booms had six nozzles at 0.50 m spacings between the nozzles and the pressure gauges were mounted in the center of the booms. The spray-liquid was supplied by using pressurized air coming from a pump via a 150 l air tank and through a regulator. The same air system was used to supply air to the air-assist nozzles.

The tread width of the sprayer was 3.0 m and the row width was 0.75 m, which means that the sprayer covered four rows between the wheels. The transmission on the sprayer was hydrostatic and maximum speed was 15 km/h.

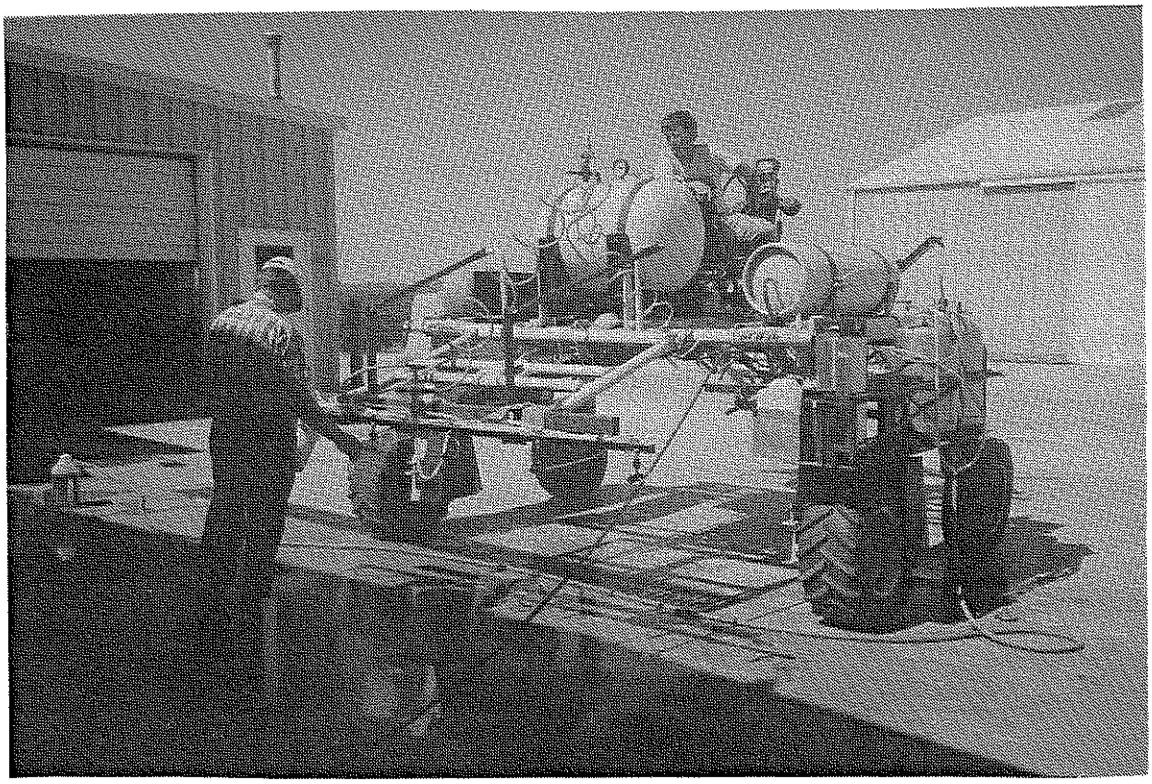


Figure 18. The test plot sprayer used to apply treatments in the field studies.

Calibration of the sprayer was difficult. Even though pressure gauges were mounted very close to the nozzles, there still was a significant pressure drop. The calibration was conducted in the following manner:

1. The liquid flow was turned on to approximately the desired pressure.
2. The air flow was turned on to the desired air pressure.
3. The liquid flow rate was checked from two nozzles at a time. All six nozzles on each spray-boom were checked.
4. The liquid pressure was adjusted to give the liquid rate required. The air pressure did not change most of the times, but if it did the calibration procedure had to be started all over again.

The liquid flow was not consistent between the nozzles. This was most likely due to pressure losses in the lines. The variation could be as large as 20 % of the mean flow. Variation was reduced by replacing some of the inserts.

Field study with a systemic herbicide

Method

In the field study using a systemic herbicide, a soybean crop was planted in 0.75 m rows. Each test-plot was four rows wide and 100 m long. Three replications were made for each treatment. Three levels of spray volume were applied and, for the air-assist nozzles, each level was applied in two nozzle settings. The conventional nozzles were only used at the 200 l/ha spray volume (Table 14). The first digits in the treatment numbers represent the spray volumes and the last digits represent the settings. Each replication contained all these treatments and a weed check were placed in a randomized order.

Table 14. Treatments used for the field study with a systemic herbicide applied with Airjet nozzles.

Treatment No.	Volume rate (l/ha)	Insert No. or nozzle type	Air pressure (bar)	Liquid pressure (bar)	Travel speed (km/h)
50-1	50	35	0.75	1.0	8
50-2	50	42	0.75	1.0	10
100-1	100	35	0.75	1.5	6
100-2	100	42	1.0	2.0	8
200-1	200	62	1.0	1.5	5.5
200-2	200	62	1.0	2.5	9.4
Conv	200	11004-VS	-	2.5	8.2

The major weed infestation in the plots was foxtail and the population of it was very dense. Both the soybeans and the foxtail were approximately 0.40 m tall at the time of application. The population of velvetleaf was also large but the herbicide was effective only for grass control. The herbicide used was Fusilade 2000 with a cropoil added. The chemical rates were 1.75 l/ha for the herbicide and 1.2 % (by volume) for the cropoil.

The spraying was done in the morning of July 3 and the weather conditions were good for spraying. The temperature was 29°C, 50 % humidity and wind speed between 1-1.5 m/s. Due to the lack of rain in the two weeks before the time of spraying the water transport in the soybeans and in the weeds was relatively low. The conventional spraying was conducted at 0.45 m height and the air-assist spraying at 0.50 m height. The heights were measured between spray-tip and the top of the soybeans.

Evaluation procedure

An evaluation of the field plots was done seven days after application. During that time there were some light showers. Evaluation was done by measuring the height of the foxtail plants. Because of the lack of rain fall following application the herbicide had a minimal effect on the foxtail. However, this turned out to be an advantage when evaluating this field study. The foxtail was not killed but differences in height could easily be seen.

At each measure-spot the foxtail height was measured five times and a approximate mean height was calculated. This procedure was continued five times at different places evenly spread over the field. By estimating the height using this method, unbiased data was collected.

Results

The statistical program SAS was used to compare differences among the different treatments. The procedure statement used in SAS was ANOVA. The statistical difference found between the treatments were highly significant. The confidence interval chosen was 95 %. The results are shown in table 15. Treatments with the same letter in the T grouping are not significantly different.

Table 15. Statistical results from the field study with a systemic herbicide.

Treatment No.	Replications	Foxtail height (m)	T grouping
Weed check	3	51.8	A
Conv	3	32.7	B
50-1	3	32.2	B
200-1	3	32.2	B, C
100-2	3	29.8	B, C, D
50-2	3	29.3	B, C, D
200-2	3	28.5	C, D
100-1	3	28.0	D

The table shows four groups in which the treatments were significantly different. The weed check was significantly differed from the rest of the treatments and the next group contains the conventional treatment, 50-1 and 200-1. The third group contains treatment 200-1, 100-2, 50-2 and 200-2 and finally the fourth group contains 100-2, 50-2, 200-2 and 100-1. Noteworthy are the small differences obtained between treatments with different spray volumes.

Field study with a contact herbicide

Method

The crop was soybeans in the field study with a contact herbicide. The row width was 0.75 m and each test-plot was four rows wide and 100 m long. In this field study the field was not divided, which means that the treatments were not replicated.

For the air-assist nozzles, four levels of spray volumes were chosen with two settings at each level, except for the lowest rate which only was sprayed with one setting. The conventional nozzles were used only at the 200 l/ha spray volume. (Table 16).

Table 16. Treatments used for the field study with a contact herbicide.

Treatment No.	Volume rate (l/ha)	Insert No. or nozzle type	Air pressure (bar)	Liquid pressure (bar)	Travel speed (km/h)
30-1	30	35	0.75	1.0	12
50-1	50	35	0.75	1.0	8
50-2	50	42	0.75	1.0	10
100-1	100	35	0.75	1.5	6
100-2	100	42	1.0	2.0	8
200-1	200	62	1.0	1.5	5.5
200-2	200	62	1.0	2.5	9.4
Conv	200	11004-VS	-	2.5	8.2

The major weed was foxtail and both the foxtail and the soybeans were 0.55-0.60 m tall. In this field study, the objective was to kill both weeds and soybeans. The soybean population was more even than for the foxtail. In this field study control of both soybeans and foxtail were evaluated.

The herbicide Gramoxone was used at the rate of 2.9 l/ha with 1.2 % (by volume) of cropoil added to the solution.

Evaluation procedure

The evaluation of this field study was done differently from the one in which a systemic herbicide was used. Because of lack of plot areas it was not possible to include replications. Instead evaluations were conducted three times; July 18, July 22 and

July 29. These dates were three days, seven days and fourteen days after the application. At all three dates two different kinds of evaluations were done; plant weight and plant height evaluation of control. At the last date a visual evaluation of control also was done.

Plant weight was done by cutting 1 m length of the soybeans three times in different places in each test-plot, and weighing the plant mass collected. Measurement of height of the soybeans was also done in three different places in each test-plot and then the mean height was calculated.

Visual evaluations were made by looking at the amount of dead leaves on the plants. The test-plots received ratings relative to weed check plots. The results from all three types of evaluations are shown in Table 17.

The results from the evaluations by weight and height were analysed with a variance procedure in SAS (ANOVA). This was done to see whether any differences in weight and height were present between the evaluation dates. A correlation analysis was also done to see if the results of these two evaluations were connected to each other.

Any statistical operations to find out differences between treatments were not possible as the treatments were not replicated. As the soybean population in the test field was visually quite even, rankings of the treatments were done anyway. These rankings were done manually by comparing the results from the different types of evaluation procedures. The rankings only indicate the performance of air-assist nozzles in spraying contact herbicides.

Table 17. The results from the visual evaluation and the evaluations by weight and heigth.

Treatment No.	Evaluation date 1. July 18 2. July 22 3. July 29	Evaluation by weight (g)	Evaluation by height (cm)	Visual evaluation
30-1	1	1 982	60.0	
	2	1 843	72.5	
	3	2 208	77.5	90
50-1	1	1 347	55.0	
	2	1 180	65.0	
	3	1 083	67.5	75
50-2	1	1 211	57.5	
	2	1 102	62.5	
	3	1 390	67.5	80
100-1	1	1 294	52.5	
	2	967	55.0	
	3	1 044	62.5	80
100-2	1	1 502	57.5	
	2	1 058	57.5	
	3	1 269	65.0	90
200-1	1	1 326	52.5	
	2	1 055	60.0	
	3	1 268	65.0	80
200-2	1	1 275	55.0	
	2	1 222	60.0	
	3	1 372	65.0	85
Conv	1	1 171	55.0	
	2	1 134	57.5	
	3	1 225	65.0	80
Weed check	1	2 100	62.5	
	2	2 477	80.0	
	3	1 960	85.0	100

Results

The analysis of variance of the results from the evaluations by weight and height showed that there were significant differences between the results from the evaluation dates (α=0.06). As there were no replications of the treatments, the cause of these differences could not be determined. The cause could be either due to differences between treatments or test-plots.

The correlation analysis showed that there was a connection between the results from the evaluations by weight and height. The Correlation Coefficient was 0.72 (***). After the statistical model that was used had explained the differences between treatments and evaluation dates, there was still a connection between the residuals of the results from the evaluations by weight and height. The Correlation Coefficient was 0.65 (***). The conclusion of the results obtained from the correlation analyses showed that a strong connection between the two evaluation procedures was present.

The rankings of the treatments which were conducted manually are shown in Table 18. Results from all the evaluation dates have been used in the rankings. These rankings must not be used as a proof of which treatment is the best one. They are only indications of how air-assist nozzles work with different volume rates when spraying contact herbicides.

Table 18. Rankings of treatments by weight and height together with the relative numbers from the visual evaluation.

Treatment No.	Ranking by weight	Ranking by height	Visual evaluation
30-1	8	8	90
50-1	7	3	75
50-2	6	5	80
100-1	1	1	80
100-2	4	6	90
200-1	2	4	80
200-2	5	7	85
Conv	3	2	80
Weed check	9	9	100

The ranking and the visual evaluation did not always show similiar results. The correlation analysis showed that there were strong connections between the evaluations by weight and height. This obviously means that these evaluations are more trustworthy than the visual one.

The low rank of treatment 30-1 indicates that air-assist nozzles do not work satisfactorily at very low spray volumes. Another observation is how little significance the spray volume had in the weed control. A third observation is the effect of different settings for the nozzles in each treatment. Apparently the settings have some significance in the weed control. As the field study did not consist of any replications, it is hard to draw further conclusions.

Spray-drift study

Method

Several different techniques of measuring spray-drift in the field have been used through the years. There are two main factors that differ between techniques and they are the choice of collector and where and how the collectors are placed. The type of collector used in this study was pipe cleaners, mostly due to the low variation in deposition within each run and the fact that the amount of deposits increase on pipe cleaners in higher wind speeds (Nordbo et al., 1991). Further, the deposit efficiency of pipe cleaners increase as the droplet size spectra gets smaller, which may not be the case for other type collectors.

Pipe cleaners are recommended to be placed vertically as the deposit increases with wind speed in this case but decreases with wind speed when the pipe cleaners are placed horizontally (Nordbo et al., 1991). Vertical placed collectors have been used intensively in spray-drift studies (Nordbo & Taylor, 1991; Miller et al., 1989; Brandt & Bengtsson, 1990).

The distances from the sprayer at which the collectors were placed were 1, 2, 3, 4, 5, 7.5, 10, 15, 20 and 30 m. At the 5 m distance a pole was placed with collectors every 1 m starting at the ground level and ending 2 m above. There were three similar rows in the field with 15 m distance between them. The pipe cleaner collectors were placed two together in a block of wood on the ground except for the 5 m distance where the poles stood. This system is almost the same as Eichhorn et al. (1990) describe in their paper.

In each run, four passes were made and each pass was 90 m long (i e 30 m pass the test field in each direction). Humidity, temperature, wind speed and wind direction were measured during each pass at a point about 10 m upwind from the spray swath. In an alignment with the German standard, the wind direction was not allowed to be off more than 30° from the intended direction.

The fluorescent dye Rhodamine B was used as a tracer in the study.

One half of the tests were conducted July 19 and the remainder on July 20. The weather conditions in the two days were quite similar, except for the evening on the first day when the wind was calm. Sometimes during the runs there were gusts of wind, but these conditions were avoided as much as possible.

The pipe cleaners never stayed in the wooden blocks more than five minutes before and five minutes after the trials. The pipe cleaners farthest away, with low deposits, were collected first. While there were three rows of sample points and two pipe cleaners at each point, six pipe cleaners could be collected at each distance. All these six were put in one tube. The pipe cleaners were sealed in darkness shortly after each run. The tracer was washed off the pipe cleaners with ethanol (99 %) and then the fluorescence in the solution was measured with a Turner model 112 fluorometer. Using standard curves for the fluorometer and dye, it was easy to determine the amount of tracer in the solution. A test was done to determine the efficiency of the washing procedure and it showed a 85-90 % recovery.

The different treatments used were similar to those in the field studies with a couple of additions (Table 18).

Table 18. Parameters for the spray-drift study.

Treatment No.	Volume rate (l/ha)	Insert No. or nozzle type	Air pressure (bar)	Liquid pressure (bar)	Flow rate (l/min)	Travel speed (km/h)
30-1	30	35	0.75	1.0	0.32	12
30-2	30	35	1.0	1.0	0.25	10
50-1	50	35	0.75	1.0	0.32	8
50-2	50	42	0.75	1.0	0.40	10
70-1	70	35	0.75	1.5	0.47	8
70-2	70	42	0.75	1.5	0.58	10
100-1	100	35	0.75	1.5	0.47	6
100-2	100	42	1.0	2.0	0.66	8
150-1	150	62	1.0	1.5	0.91	7.4
150-2	150	62	1.0	2.0	1.25	10
200-1	200	62	1.0	1.5	0.91	5.5
200-2	200	62	1.0	2.5	1.56	9.4
Conv(150)	150	11004-VS	-	2.0	1.29	10.3
Conv(200)	200	11004-VS	-	2.5	1.44	8.6

Evaluation procedure

Evaluation of spray-drift is difficult, because there are so many factors involved. The best way of handling the problem associated with unstable weather conditions is simply to avoid them and run the experiments in as similiar conditions as possible. Still, there are many difficult factors to handle such as how to analyse and present the data collected. One way is to graph the spray-drift deposits from the different treatments and compare them with the spray-drift deposits from the conventional trials. Another way is to calculate the deposits relative to the amount of tracer applied per hectare. This technique has been used by Young (1991), Miller et al. (1991) and Nordbo et al. (1991) in their spray-drift experiments. There is one problem as Miller et al. (1989) pointed out. If the results from the spray-drift experiment are expressed in terms of the spray emission of the nozzle, the total spray-drift from the collector deposits needs to be estimated.

In this study, the spray-drift deposits on the downwind collectors were supposed to be related to the ground deposits under the sprayer. However the pipe cleaners under the sprayer were completely saturated with tracer, which make made it impossible to compare with the other collectors. Instead the spray-drift deposits were related to the amount of tracer applied per hectare.

To be able to do this calculation, the collection area of the pipe cleaners had to be estimated. Miller et al. (1989) indicated that defining the collection area of a pipe cleaner is difficult, especially since the effective collecting area changes with wind speed. Nordbo et al. (1991) based the spray-drift deposits on the half of the circumference and this was the area used in this field study. It is important to know that this is only an estimation of the collection area of a pipe cleaner.

The data from the spray-drift study were divided in two parts; data from the ground sample points and data from the pole sample points. Curves were fitted to the data from the ground sample points for each treatment. When doing this collector deposits farther than 15 m from the spray swath were not used as they were very low. Errors in measuring these low deposits made them unreliable. The equations of the curves were individual for each treatment.

To be able to compare different treatments, the total deposits between distance 5 and 15 m from the spray swath were calculated for each treatment. This reasoning originates in that spray that drifts far away from the sprayer is usually more harmful to other crops, gardens etc than spray-drift close to the spray swath. Another reason is that spray-drift close to the spray swath (0-5 m) is easier to control than the spray that drifts far away. Just by avoiding to spray in the borders of the field adjacent crops can be spared.

The data from the pole sample points up to 2 m height were plotted on graphs and analysed by looking at them. The shape of the curve for each treatment may indicate susceptibility to spray-drift. High spray-drift deposits detected high up on the poles for a treatment may be an indication of a great risk for spray-drift.

Results

The data from the ground sample points were plotted on graphs to show the spray-drift deposits produced by each treatment. The data were logarithmised and then curves were fit to them (at the 5 % level). This procedure made it easier to fit proper curves to the data. By comparing the curves on the graphs it was easy to see differences in spray-drift between the treatments (Figure 19). The most remarkable conclusions just by looking at the curves are the high spray-drift deposits of treatment 30-2 and the low spray-drift deposits of treatments 200-1 and 200-2 (Appendix 7-10). Observe that the scales on the graphs differ from each other.

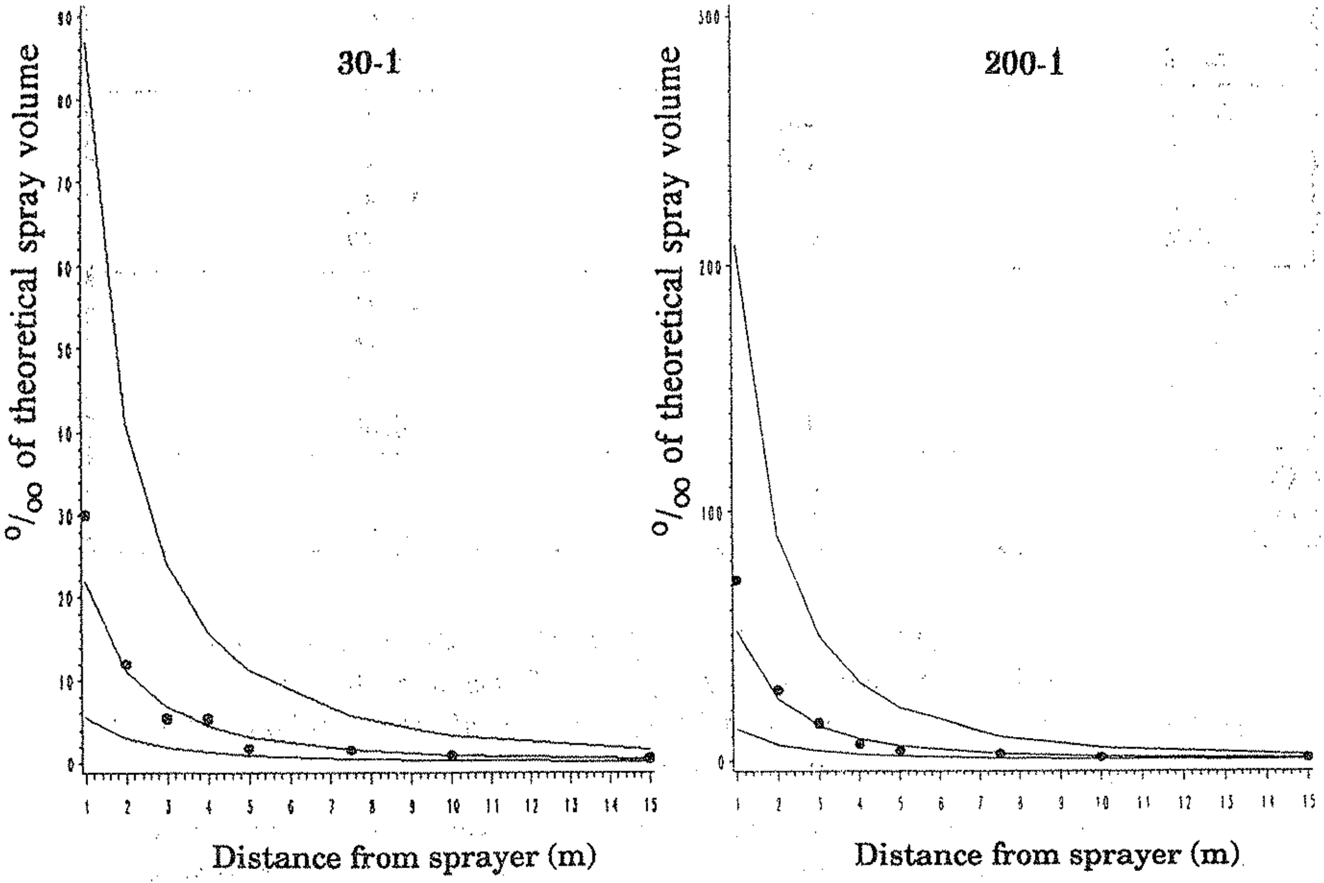


Figure 19. Collected spray-drift deposits on the ground sample collectors from treatment 30-1 and 200-1.

The statistical computer program SAS was used to integrate the total spray-drift deposits between 5 and 15 m from the spray swath for each treatment. These total deposits were then related to the amount of tracer applied per hectare and the results of this procedure are shown in Table 20.

The weather data measured at the time of each trial are shown in Appendix 13. The climate factor that changed the most during the spray-drift study was the wind speed. As wind speed determines the amount of spray-drift to large extent, it was interesting to compare wind speeds with spray-drift deposits in each treatment. Results from the analysis of the ground sample points are:

Table 20. Wind speed and total spray-drift deposits collected between 5 and 15 m from the spray swath expressed in ‰ of the theoretical spray volume.

Treatment No.	Wind speed (m/s)	‰ of theoretical spray volume (5-15 m)
30-1	1.80	12.90
30-2	2.30	42.06
50-1	1.50	10.64
50-2	2.00	4.09
70-1	2.30	5.16
70-2	1.90	5.45
100-1	3.00	11.81
100-2	2.40	5.79
150-1	3.30	10.48
150-2	2.50	10.45
200-1	2.60	2.76
200-2	3.50	0.96
Conv(150)	2.70	21.44
Conv(200)	1.80	3.21

- No clear tendency could be seen with the low volume treatments except for 30-1 and 30-2 that produced very high spray-drift. Some of the rest of the treatments resulted in high spray-drift deposits despite low wind speeds while others resulted in low spray-drift deposits.
- Treatments 150-1 and 150-2 resulted in almost the same spray-drift deposits but the wind speed for treatment 150-1 was 30 % higher than for treatment 150-2.
- The 200 l/ha treatments resulted overall in low spray-drift deposits.

The analysis of the data from the pole sample collectors (Appendix 11, 12; Figure 20) resulted in the following conclusions:

- The 30-2 treatment resulted in very high spray-drift deposits, especially at 1 m height.
- The differences between treatments in spray-drift deposits were relatively larger at the ground level than higher up on the poles. At the highest level the differences between the treatments were the smallest.
- The shape of the curves representing the conventional treatments did not differ significantly from the curves representing the rest of the treaments.

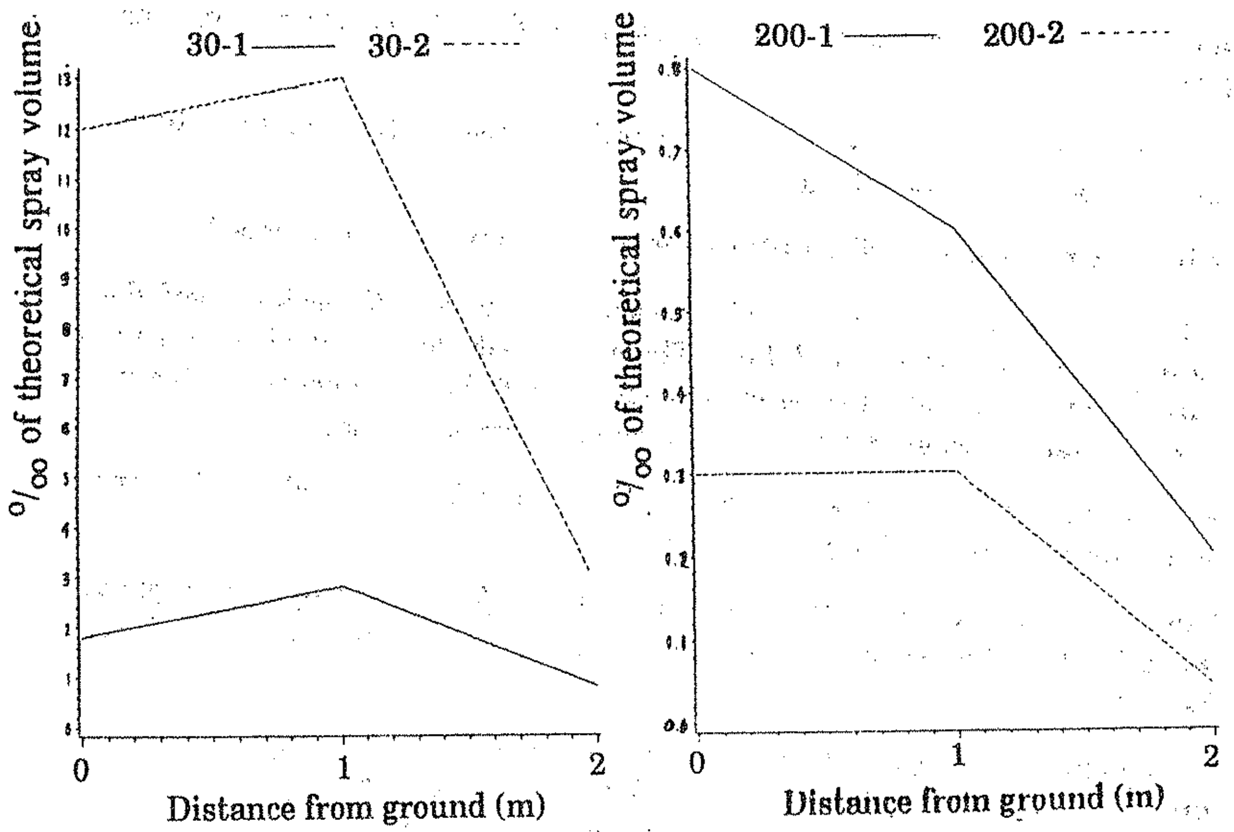


Figure 20. Deposits from the pole sample collectors from treatment 30-1, 30-2, 200-1 and 200-2.

As the treatments in the spray-drift study were not replicated it is hard to draw further conclusions.

CONCLUSIONS

The Airjet nozzles

The studies with the Airjet-nozzles showed:

- There were differences in spray patterns between the spray-tips which were mostly due to less uniform angles sideways for the spray-tips.
- The liquid pressure determines to a large degree the uniformity of the spray pattern. There was a clear tendency that an increasing liquid pressure decreases the C.V. when nozzle spacings are between 0.60 m and 0.50 m but increases it for a nozzle spacing of 0.40 m.

- The air pressure also determines the spray pattern uniformity and the air pressure should never be as high as the liquid pressure.
- A 0.50 m boom height appeared to be optimum when the nozzle spacing was 0.50 m.
- A 0.40 m nozzle spacing resulted in less uniform distribution patterns than spacings of 0.50 m and 0.60 m.
- When the nozzles were tilted 10° backwards the uniformity decreased.
- A drift control additive (Sta-Put) in the spray-liquid sometimes improved the spray pattern, sometimes it did not. The visual drift decreased with some pressure settings when using Sta-Put. The visual drift did not increase with any pressure setting when Sta-Put was added to the spray-liquid.
- Air pressure must be measured close to the nozzles because high air flow and small air lines cause high pressure drops.
- The relationship between air pressure and liquid flow is approximately linear when the liquid pressure is constant and the same insert and nozzle orifice are beeing used..
- By changing inserts, air pressure and liquid pressure a very wide range of droplet sizes can be achieved. The droplet size measurements clearly showed the importance of choosing the right air pressure and liquid pressure and measure the pressures at the correct location. It also showed that it is better to change inserts than pressures if an entirely different flow rate is desired. The droplet size ranges in which the inserts operated in the droplet size measurements were 87-150 μm for no 35, 144-216 μm for no 42 and 345- μm for no 62.
- Calibration of the test plot sprayer was very difficult because both the air pressure and the liquid pressure determine the flow rate. Changing inserts of the same sized may also change the flow rate.
- In the field study with a systemic herbicide differences between treatments with different spray volumes were very small. Most of the treatments with the air-assist nozzles gave significantly better control of the foxtail than the conventional treatment. Spray volumes were 50, 100 and 200 l/ha for the Airjet-nozzles and 200 l/ha for the conventional flat-fan nozzles.
- In the field study with a contact herbicide four spray volumes were applied; namely 30, 50, 100 and 200 l/ha. Treatment 30-1 provided poor weed control. Another observation is how little significance the spray volume in the rest of the treatments had in the weed control. A third observation is the effect of different settings within treatments with the same spray volumes. Apparently the settings have some significance in the weed control.

- Treatments 200-1 and 200-2 provided the lowest detected spray-drift of all the treatments. This was expected since the $D_{v0.5}$'s were so high that they could not be measured with the equipment used. The conventional treatment of 200 l/ha also gave low detected spray-drift deposits but this may be due to the low wind speed at the time of this spraying. It is interesting that most of the treatments from 50 l/ha to 100 l/ha are in the middle of the spray-drift range. Treatment 30-2 gave the greatest detected spray-drift which was expected because the $D_{v0.5}$ was 93 µm. The analysis of the data from the pole sample collectors showed higher deposits at 1 m height than at the ground level. This analysis also showed that the differences between the treatments were larger at the ground level than higher up on the poles.

While, as Miller et al. (1991) point out, passive collectors like pipe cleaners do not give reliable results at wind speeds below 2 m/s, the conclusion of this spray-drift study can not be stated as beeing absolute. However, it can be stated that for the Airjet-nozzles, low spray volumes (>50 l/ha) do not give higher spray-drift than high spray volumes, as long as the spraying is done with the same $D_{v0.5}$.

The AAN-sprayer

The studies with the AAN-sprayer showed:

- The results from the spray-table tests with the AAN-sprayer showed that the nozzles should be narrowly spaced to obtain a uniform spray pattern. The air pressure should be higher than 0.5 bar to get a low C.V. and higher liquid flows provide better spray patterns. No dramatical changes in spray pattern uniformity could be found when Sta-Put was added to the spray liquid.
- Even with this air-assist nozzle, the value of the air pressure is important. All the settings produced large droplets, so large they were impossible to measure with available instruments. The AAN-sprayer produced a bi-modal droplet distribution; one peak within the range of 100 to 200 µm and another peak at 1000 µm or higher. The second peak was extremely high for all the settings and contained large volumes.

Discussion

Air-assist nozzles, in this case Airjets, have the potential of replacing some of the spray-liquid with air which also partly atomize the spray-liquid to form droplets. By doing this, it is possible to reduce spray volumes and at the same time it is possible to choose which droplet size the nozzle should produce. This gives the air-assist nozzles a good potential for future spraying. In these studies, the air-assist nozzles worked very well on the spray-table, in the field studies with herbicides and in the spray-drift study. It is important to know that a testplot sprayer was used that allowed uniform and precise application. A commercial crop-sprayer of today has wide booms with long liquid lines with large pressure drops. If air-assist nozzles are going to be commonly used, the pressure loss has to be the same to all nozzles and the pressures have to be measured near the nozzles. This should be valid for both the air and the spray-liquid. With a crop-sprayer properly designed the air-assist nozzles have great potential.

The AAN-sprayer is also an interesting concept in air-assist spraying. In the studies with and without the drift control additive, Sta-Put, added the results showed that the characteristics change dramatically at low spray volumes (5 l/ha). The problems with the AAN-sprayer were a non uniform droplet size distribution sideways in the spray fan and a high C.V. in the spray pattern.

SUMMARY

Today a lot of research is concentrated on improving the efficiency of chemical applications. Some of the problems are how to increase penetration in the crop, how to increase coverage on the leaves in the canopy, how to reduce spray-drift and how to reduce spraying time. One solution to these problems is to use air-assist nozzles. Air-assist nozzles mix air with the spray liquid, which makes it possible to reduce the spray volume and to vary the droplet size distribution.

The objective of this work was to determine the characteristics of air-assist nozzles when the spray volume is reduced from 200 l/ha to 30 l/ha. Another purpose was to determine the technical characteristics of air-assist nozzles for ultra low volume spraying.

Several spray-table tests were done to determine how different parameters interact, such as air pressure, liquid pressure and boom height. The results from these investigations showed that the air pressure and liquid pressure determine the uniformity of the spray pattern. It appears that each size insert works only in a narrow pressure range, and that it is important to change the size of inserts if an entirely different spray volume is desired. The droplet size measurements confirmed this and also showed that the droplet size range is extremely wide with air-assist nozzles.

Field studies with a systemic and a contact herbicide were also conducted. Spray volumes were 50, 100 and 200 l/ha and 30, 50, 100 and 200 l/ha respectively. In both field studies conventional flat-fan nozzles were used at 200 l/ha for comparison. In the field study with a systemic herbicide, differences between the treatments were very small. Almost all of the treatments with air-assist nozzles gave better control of the weed than the conventional treatment. The field study with a

contact herbicide showed that 30 l/ha was to low of a spray volume for this herbicide. In this field study the weed control was almost as good with all spray volumes over 50 l/ha.

A spray-drift study was also conducted to determine the spray-drift deposits from different spray volumes applied with air-assist nozzles. The spray volumes were 30, 50, 70, 100, 150 and 200 l/ha for the air-assist nozzles and 150 and 200 l/ha for the conventional flat-fan nozzles. Application at a spray volume of 30 l/ha gave the highest drift. The overall conclusion of this spray-drift study is that air-assist nozzles give low spray-drift deposits even at low spray volume (down to 50 l/ha).

The ULV-sprayer (also called AAN) was only evaluated in the laboratory. This sprayer is designed to work at spray volumes around 5 l/ha. At this spray volume the sprayer did not give satisfactory results when spraying with pure water as spray liquid. The AAN-sprayer produced big droplets and the droplet size distribution sideways in the spray fan was not uniform.

Overall the air-assist nozzles seem to work well at low spray volumes, but while the interaction between the air pressure and the liquid pressure influences the droplet size, pressure losses must be kept low if satisfactory results are to be achieved.

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Appendix 1

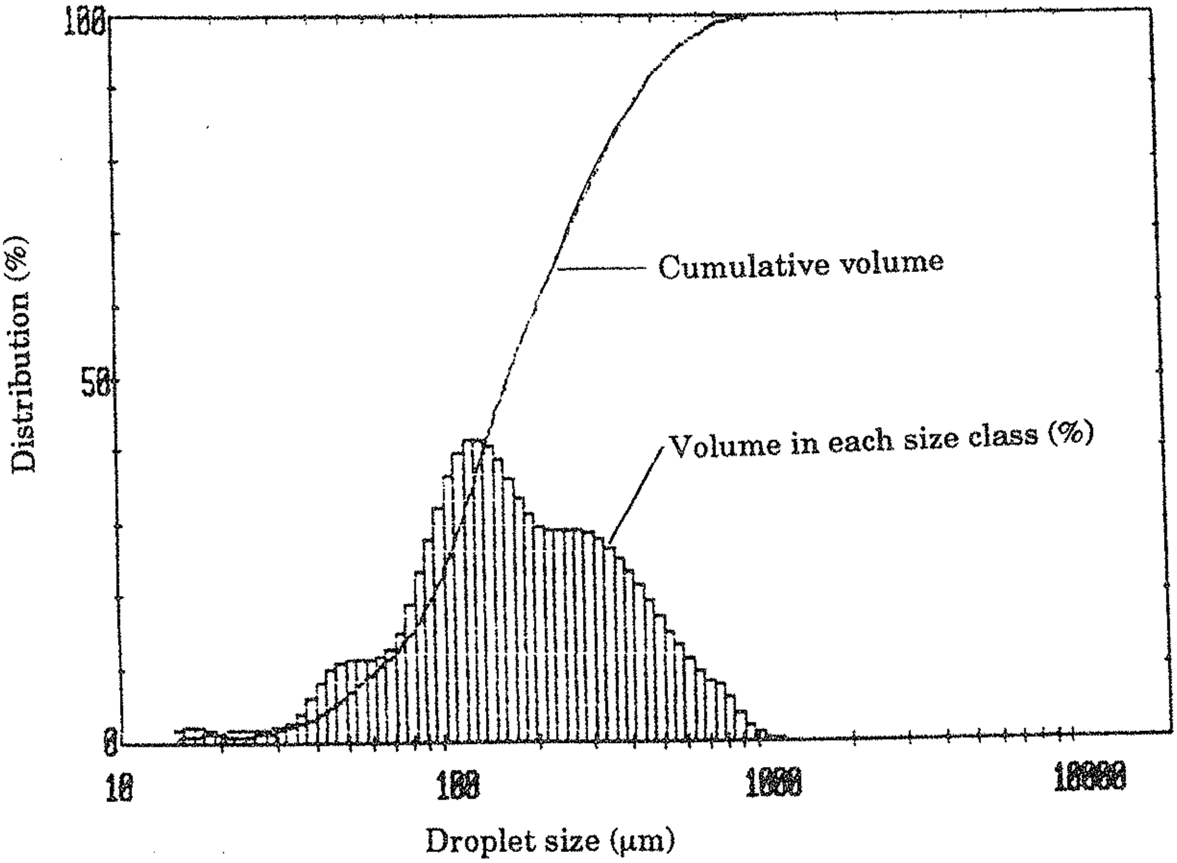
NOZZLE SETTINGS (SPRAYING SYSTEMS CO, 1991)

LIQUID ORIFICE NUMBER	EXIT NOZZLE NUMBER	AIR PRESSURE (bar)	LIQUID PRESSURE (bar)	APPROX. AIR FLOW (L/min)	LIQUID FLOW (L/min)	APPROXIMATE APPLICATION RATE L/ha USING 50 cm SPACING			
						6 km/h	8 km/h	10 km/h	12 km/h
31	TK-VS 10	0.75	1	56.2	0.21	42.0	31.5	25.2	21.0
			1.5	49.0	0.32	64.0	48.0	38.4	32.0
			2	44.0	0.40	80.0	60.0	48.0	40.0
			2.5	40.8	0.46	92.0	69.0	55.2	46.0
			3	32.7	0.55	110	82.5	66.0	55.0
		1	1	67.2	0.17	34.0	25.5	20.4	17.0
			1.5	59.3	0.28	56.0	42.0	33.6	28.0
			2	57.1	0.36	72.0	54.0	43.2	36.0
			2.5	52.8	0.42	84.0	63.0	50.4	42.0
			3	49.6	0.50	100	75.0	60.0	50.0
		1.25	1.5	81.3	0.15	30.0	22.5	18.0	15.0
			2	73.2	0.22	44.0	33.0	26.4	22.0
			2.5	68.5	0.41	82.0	61.5	49.2	41.0
			3	63.7	0.46	92.0	69.0	55.2	46.0
		1.5	1.5	91.4	0.21	42.0	31.5	25.2	21.0
			2	83.8	0.31	62.0	46.5	37.2	31.0
			2.5	76.8	0.38	76.0	57.0	45.6	38.0
			3	71.9	0.45	90.0	67.5	54.0	45.0
35	TK-VS 10	0.75	1	52.1	0.32	64.0	48.0	38.4	32.0
			1.5	39.6	0.47 •	94.0	70.5	56.4	47.0
			2	34.9	0.59	118	88.5	70.8	59.0
			2.5	30.8	0.69	138	104	82.8	69.0
			3	26.7	0.78	156	117	93.6	78.0
		1	1	65.0	0.25	50.0	37.5	30.0	25.0
			1.5	57.1	0.40	80.0	60.0	48.0	40.0
			2	50.6	0.53	106	79.5	63.6	53.0
			2.5	45.2	0.65	130	97.5	78.0	65.0
			3	41.8	0.75	150	113	90.0	75.0
		1.25	1.5	72.2	0.34	68.0	51.0	40.8	34.0
			2	64.7	0.49	98.0	73.5	58.8	49.0
			2.5	59.0	0.60	120	90.0	72.0	60.0
			3	51.8	0.69	138	104	82.8	69.0
		1.5	1.5	87.8	0.28	56.0	42.0	33.6	28.0
			2	76.6	0.42	84.0	63.0	50.4	42.0
			2.5	69.4	0.55	110	82.5	66.0	55.0
			3	63.4	0.66	132	99.0	79.2	66.0
42	TK-VS 10	0.75	1	41.4	0.40	80.0	60.0	48.0	40.0
			1.5	33.6	0.58	116	87.0	69.6	58.0
			2	25.4	0.74	148	111	88.8	74.0
			2.5	21.4	0.87	174	131	104	87.0
			3	18.5	0.97	194	146	116	97.0
		1	1	62.6	0.29	58.0	43.5	34.8	29.0
			1.5	49.6	0.51	102	76.5	61.2	51.0
			2	41.8	0.66	132	99.0	79.2	66.0
			2.5	35.2	0.81	162	122	97.2	81.0
			3	26.4	0.92	184	138	110	92.0
		1.25	1.5	67.2	0.41	82.0	61.5	49.2	41.0
			2	53.1	0.58	116	87.0	69.6	58.0
			2.5	45.8	0.73	146	110	87.6	73.0
			3	38.9	0.86	172	129	103	86.0
		1.5	1.5	80.4	0.36	72.0	54.0	43.2	36.0
			2	64.4	0.53	106	79.5	63.6	53.0
			2.5	54.5	0.69	138	104	82.8	69.0
			3	49.9	0.81	162	122	97.2	81.0

LIQUID ORIFICE NUMBER	EXIT NOZZLE NUMBER	AIR PRESSURE (bar)	LIQUID PRESSURE (bar)	APPROX. AIR FLOW (L/min)	LIQUID FLOW (L/min)	APPROXIMATE APPLICATION RATE L/ha USING 50 cm SPACING			
						6 km/h	8 km/h	10 km/h	12 km/h
62	TK-VS 10	0.75	1	30.8	0.72	144	108	86.4	72.0
			1.5	17.0	1.16	232	174	139	116
			2	11.3	1.47	294	221	176	147
			2.5	>7.5	1.75	350	263	210	175
			3	>7.5	2.03	406	306	244	203
		1	1	52.8	0.47	94.0	70.5	56.4	47.0
			1.5	37.4	0.91	182	137	109	91.0
			2	24.2	1.25	250	188	150	125
			2.5	19.8	1.56	312	234	187	156
			3	11.0	1.83	366	275	220	183
		1.25	1.5	51.8	0.7	140	105	84.0	70.0
			2	33.0	1.14	228	171	137	114
			2.5	28.1	1.46	292	219	175	146
			3	17.3	1.76	352	264	211	176
		1.5	1.5	70.7	0.49	98.0	74	58.8	49.0
			2	48.7	0.95	190	143	114	95.0
			2.5	36.4	1.29	258	194	155	129
			3	29.2	1.59	318	239	191	159

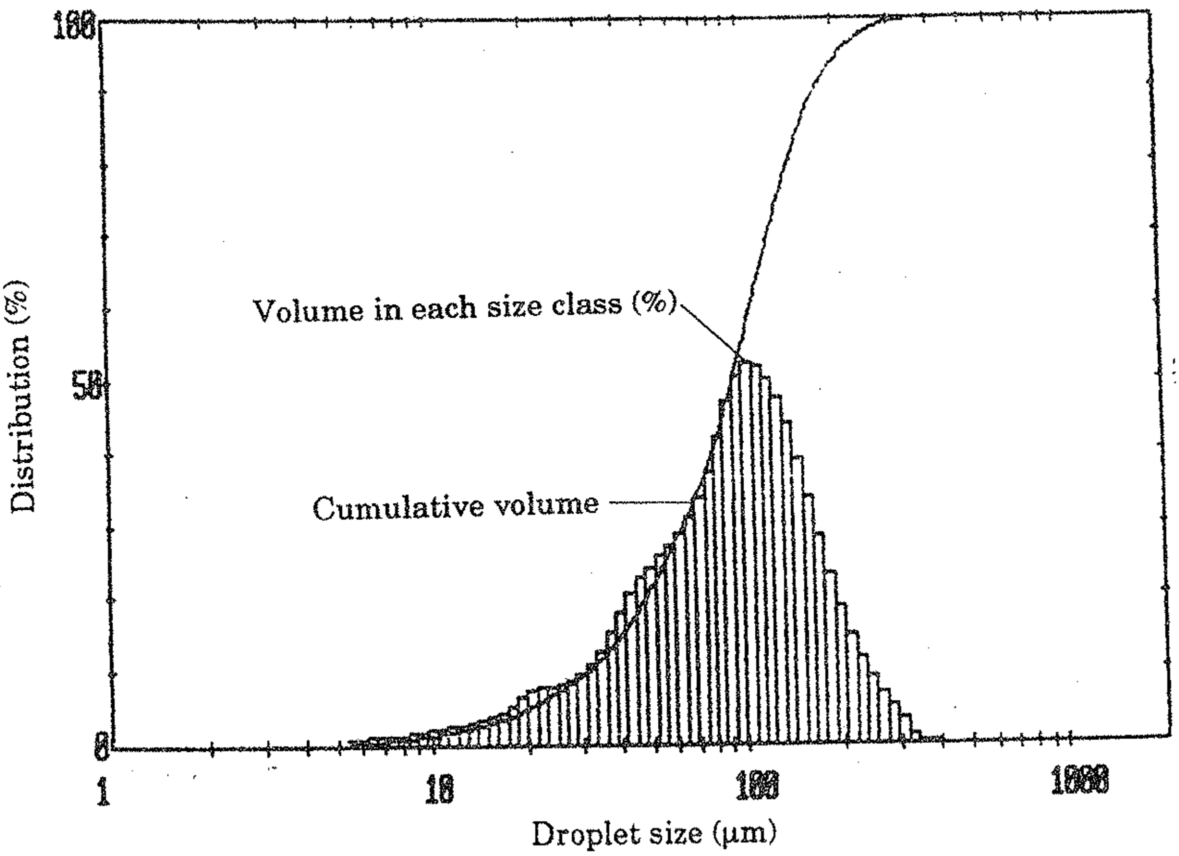
Appendix 2

DROPLET SIZE MEASUREMENT (INSERT NO 35, AIR PRESSURE 0.75 BAR, LIQUID PRESSURE 1.5 BAR, STRAIGHT UNDER NOZZLE)



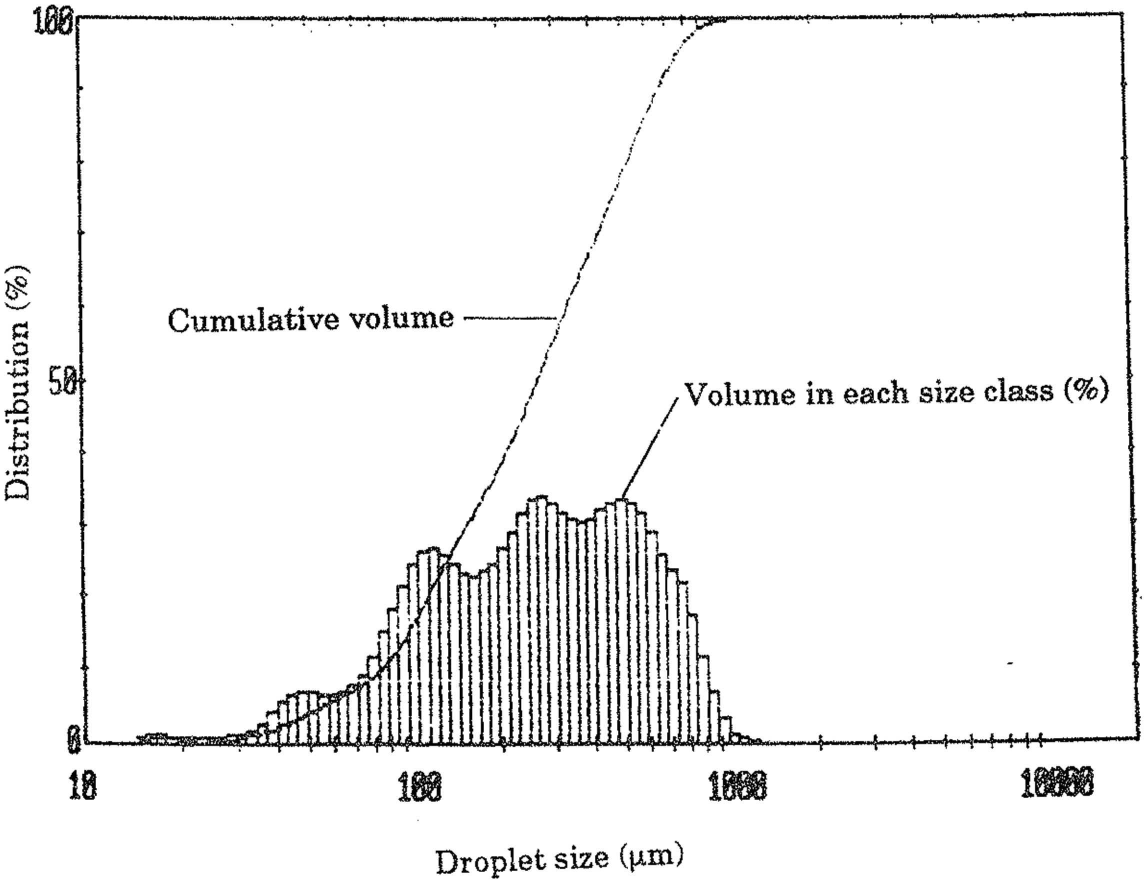
Appendix 3

DROPLET SIZE MEASUREMENT (INSERT NO 35, AIR PRESSURE 1.0 BAR, LIQUID PRESSURE 1.0 BAR, STRAIGHT UNDER NOZZLE)



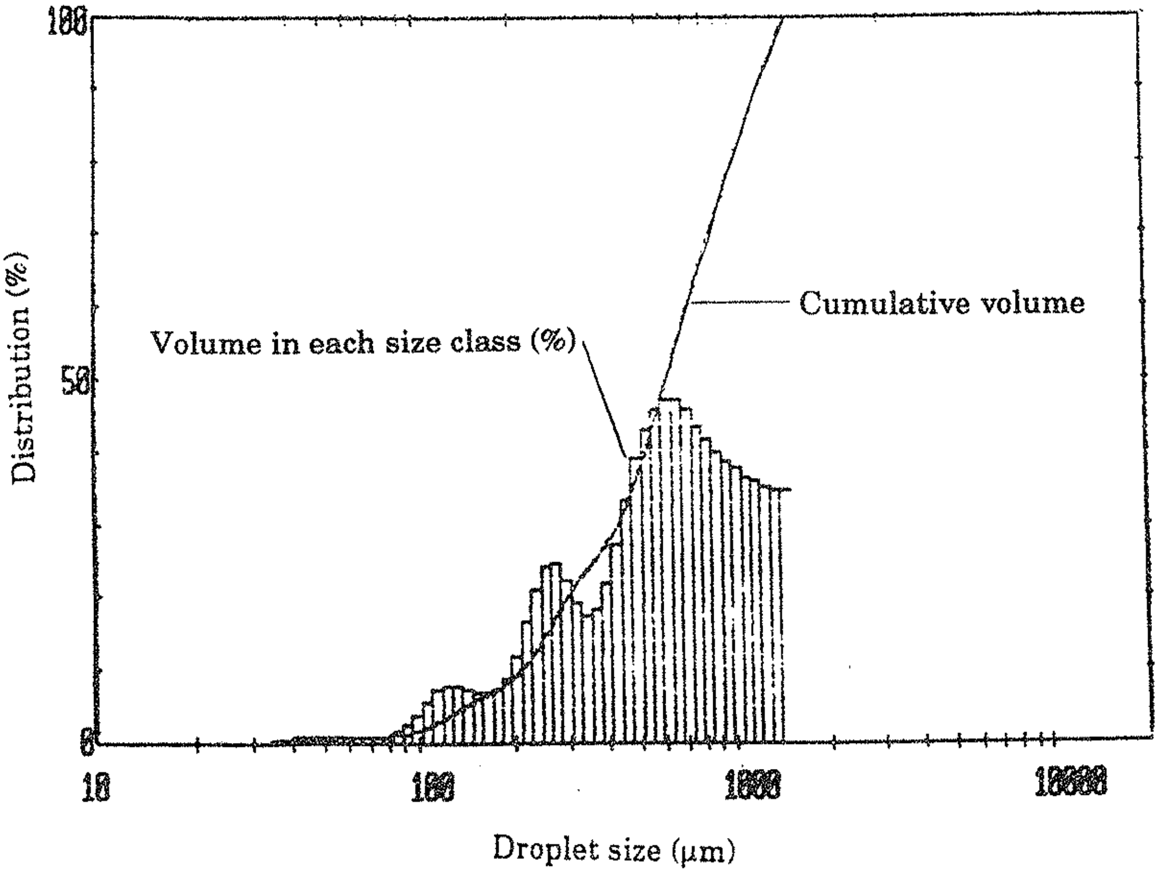
Appendix 4

DROPLET SIZE MEASUREMENT (INSERT NO 42, AIR PRESSURE 0.75 BAR, LIQUID PRESSURE 1.5 BAR, STRAIGHT UNDER NOZZLE)



Appendix 5

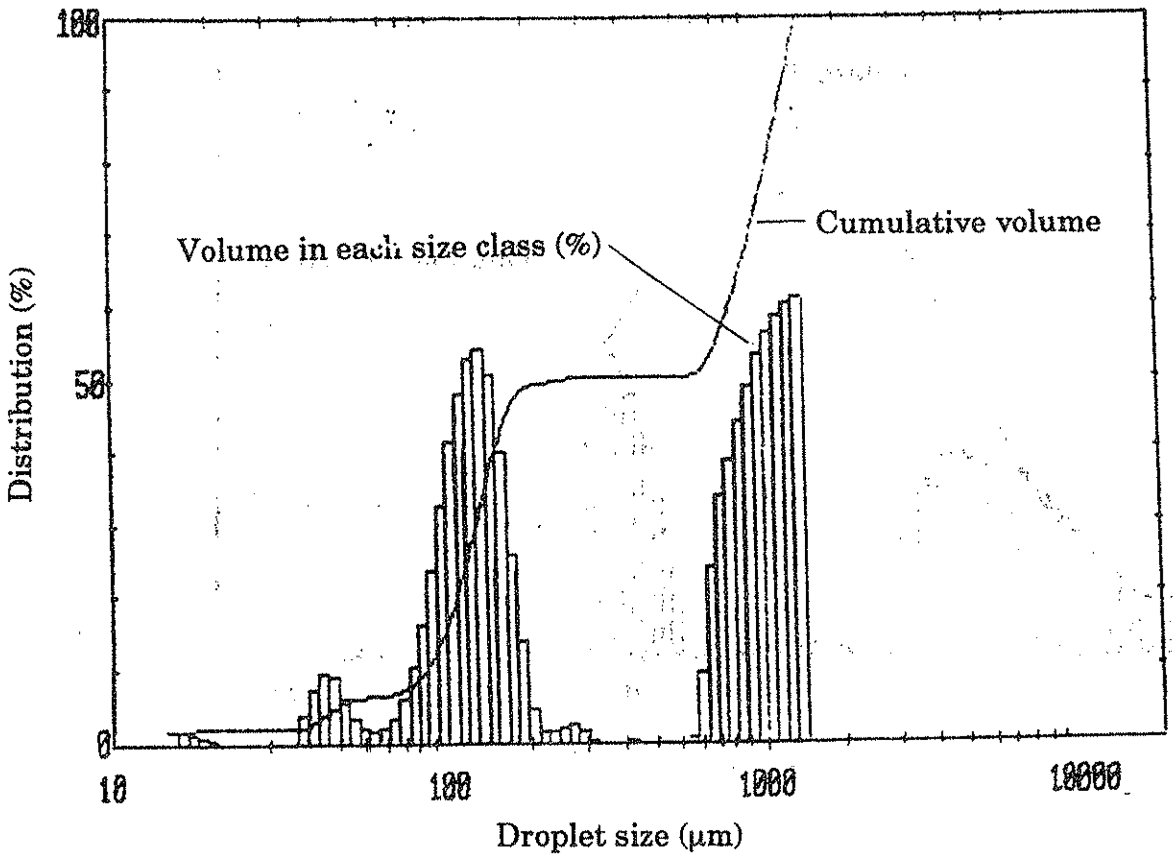
DROPLET SIZE MEASUREMENT (INSERT NO 62, AIR PRESSURE 1.0 BAR, LIQUID PRESSURE 2.5 BAR, STRAIGHT UNDER NOZZLE)



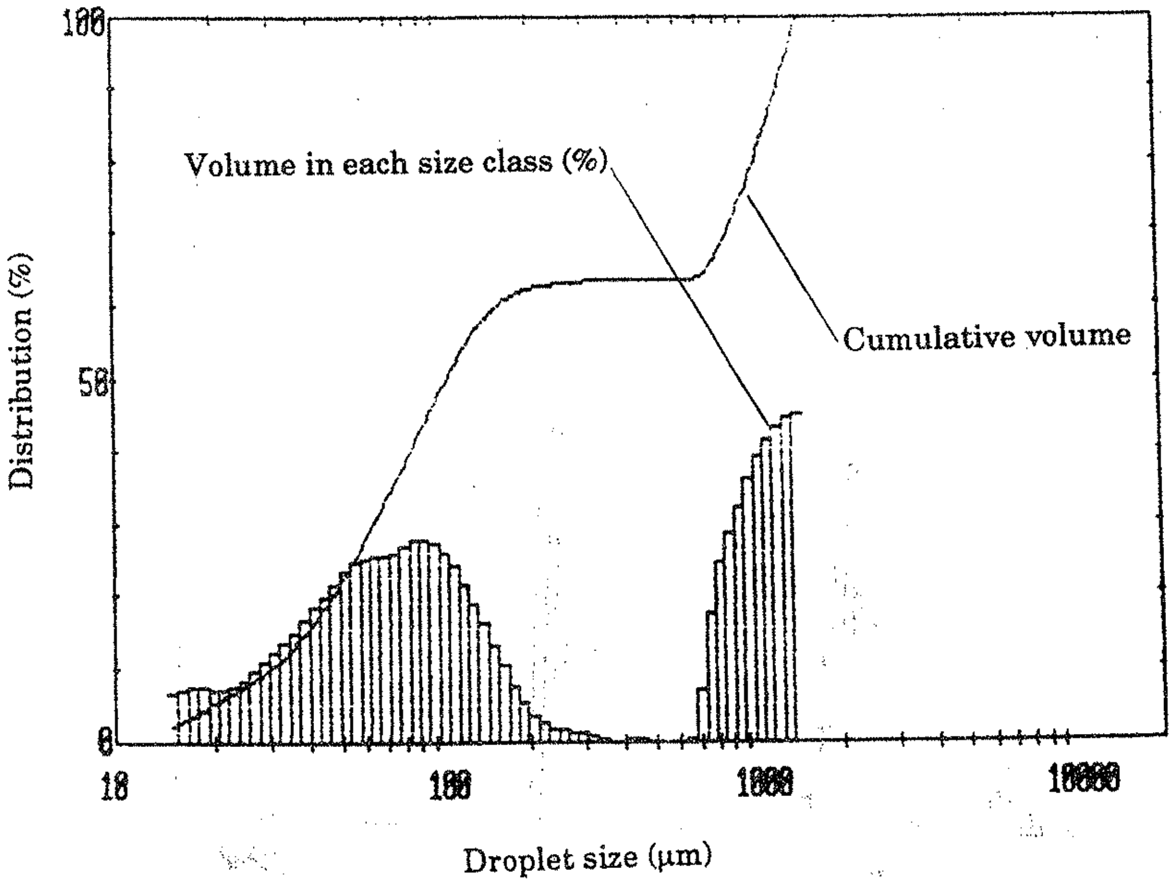
Appendix 6:1

DROPLET SIZE MEASUREMENT (AAN, AIR PRESSURE 0.55 BAR, VOLUME RATE 40 ML/MIN)

0.20 m to the left of the centreline

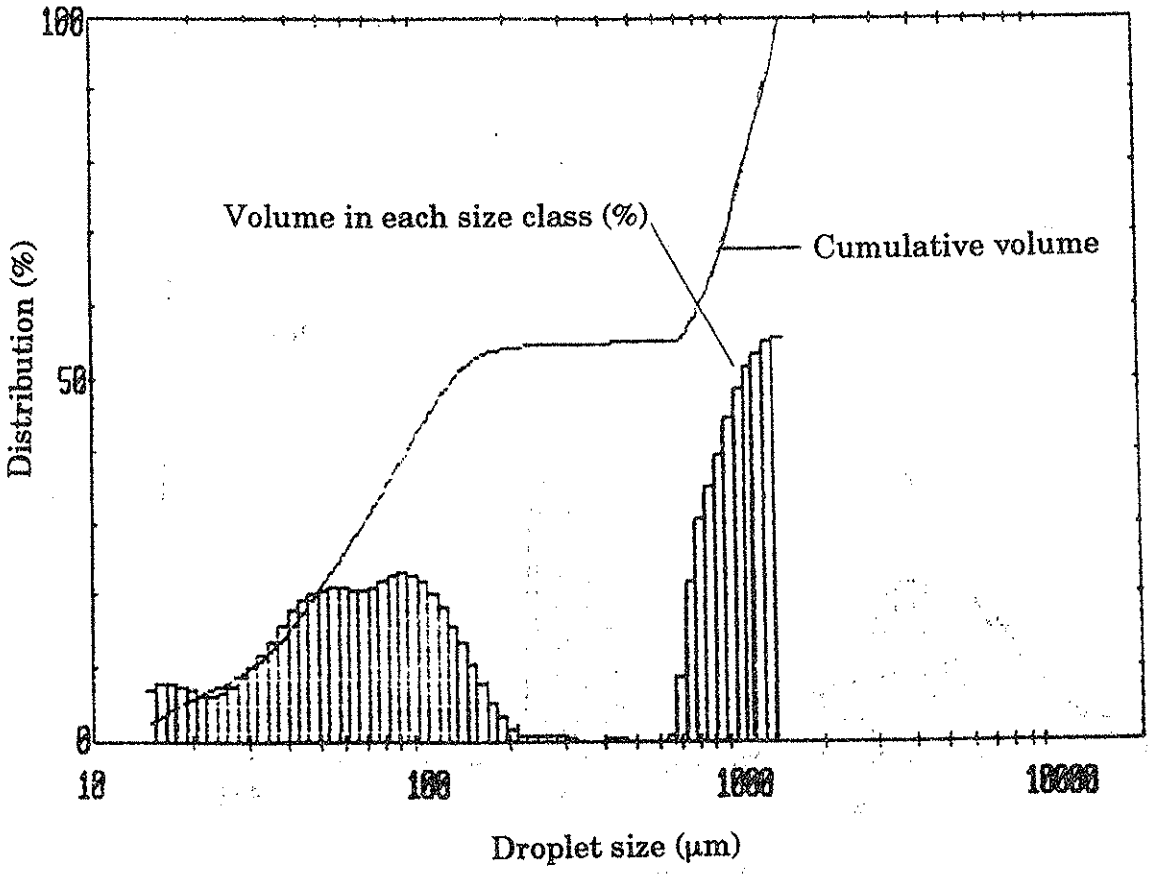


0.10 m to the left of the centreline

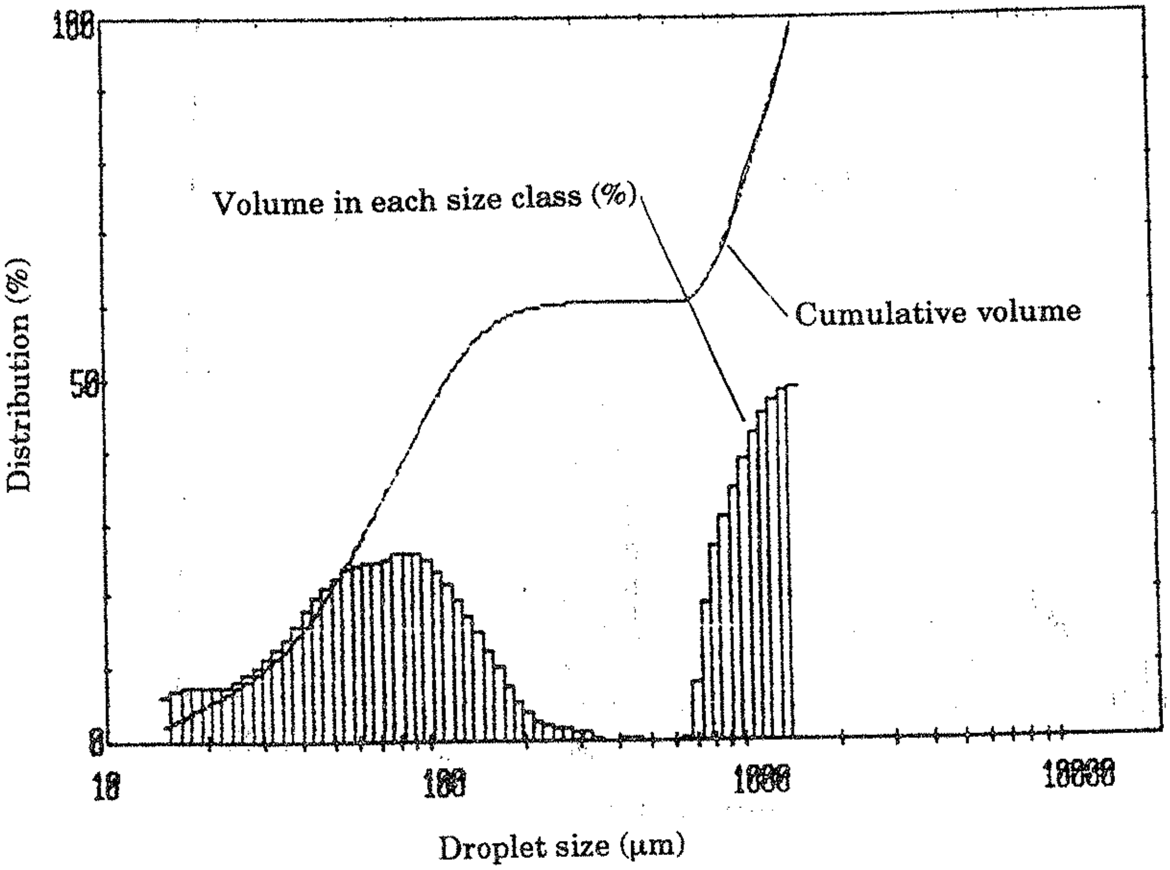


Appendix 6:3

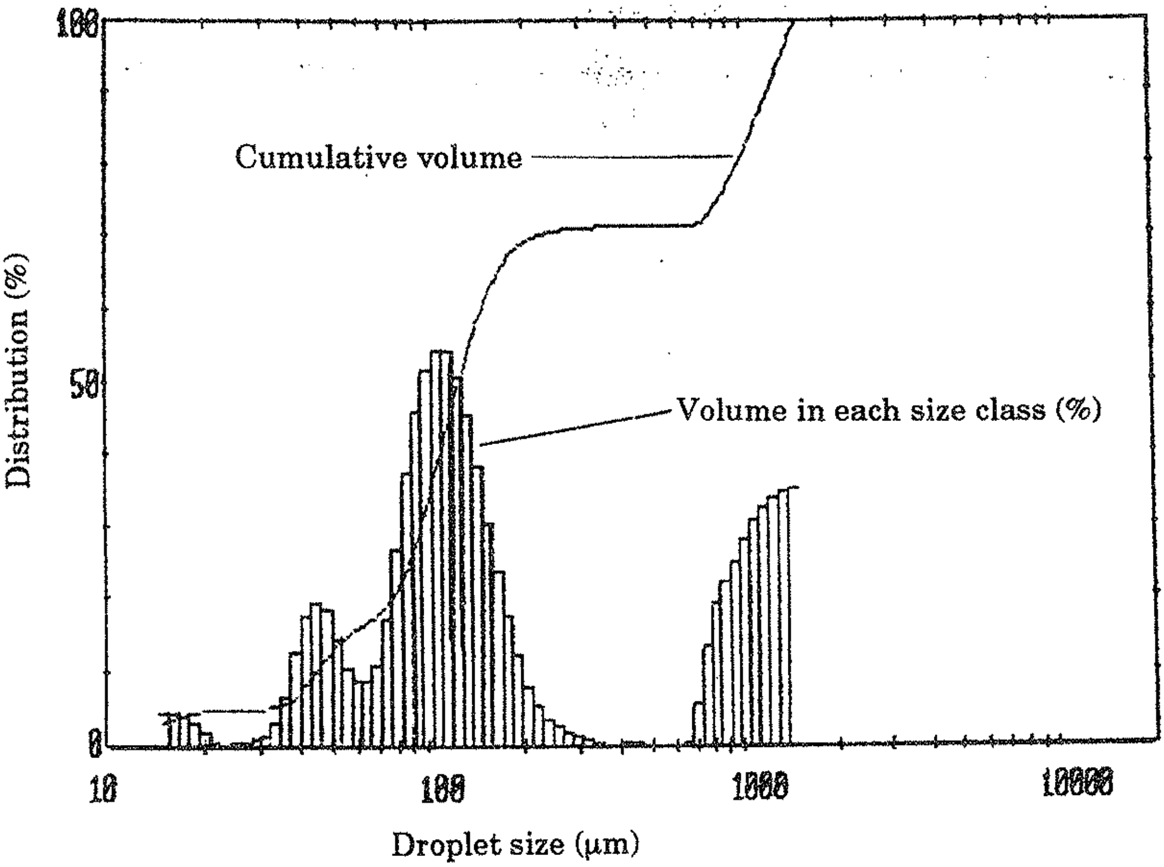
Straight under the nozzle (centreline)



0.10 m to the right of the centreline



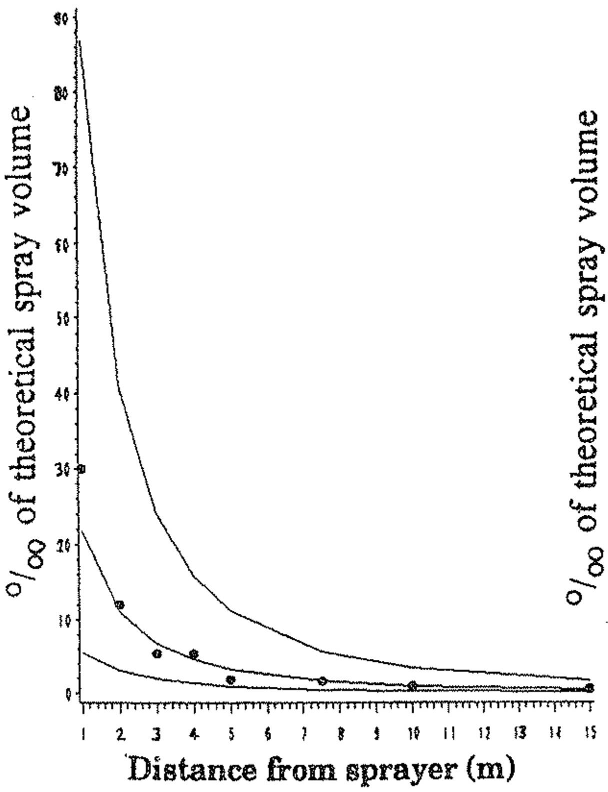
0.20 m to the right of the centreline



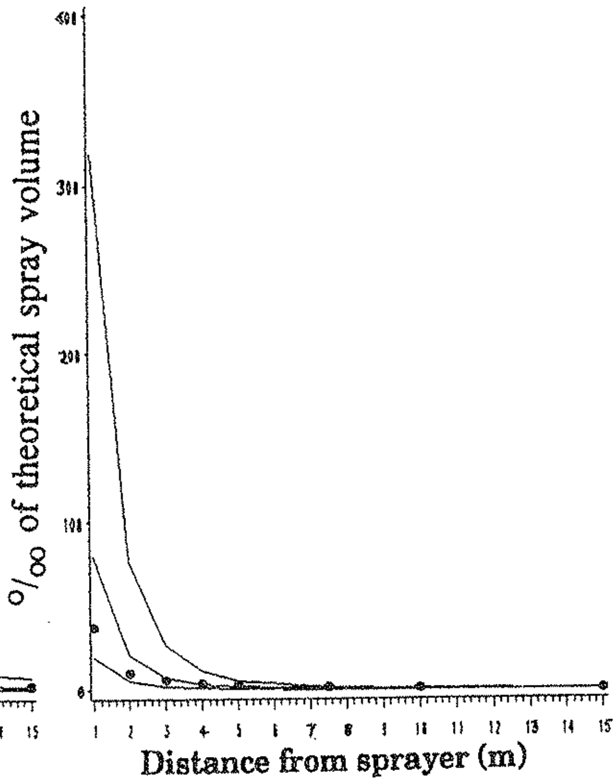
Appendix 7

DETECTED DEPOSITS IN THE SPRAY-DRIFT STUDY (GROUND SAMPLE POINTS)

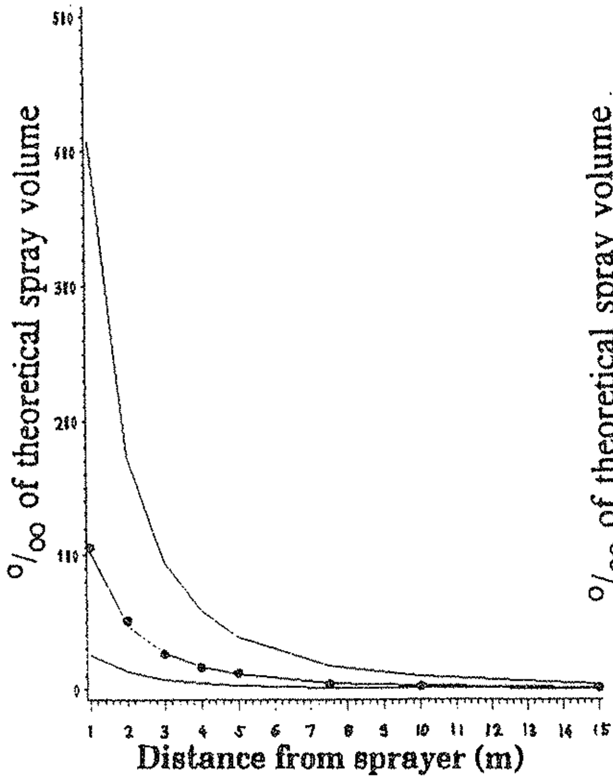
30-1



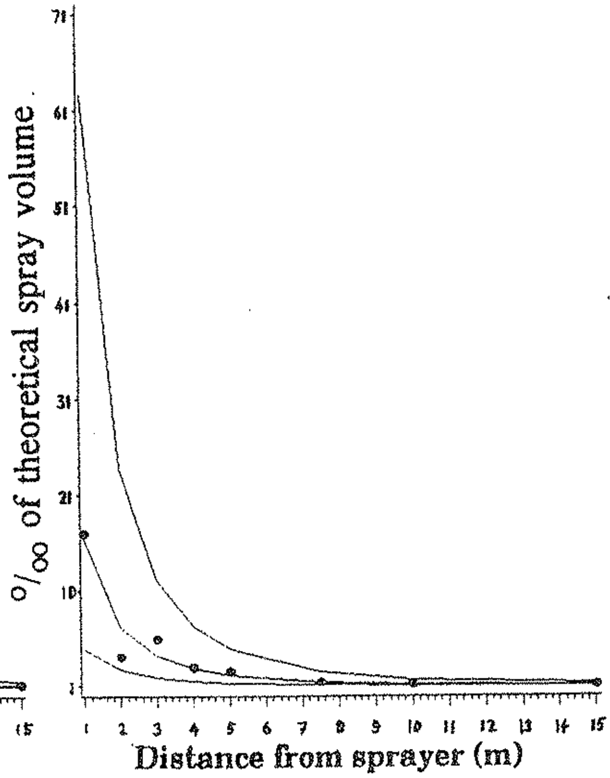
50-1



30-2

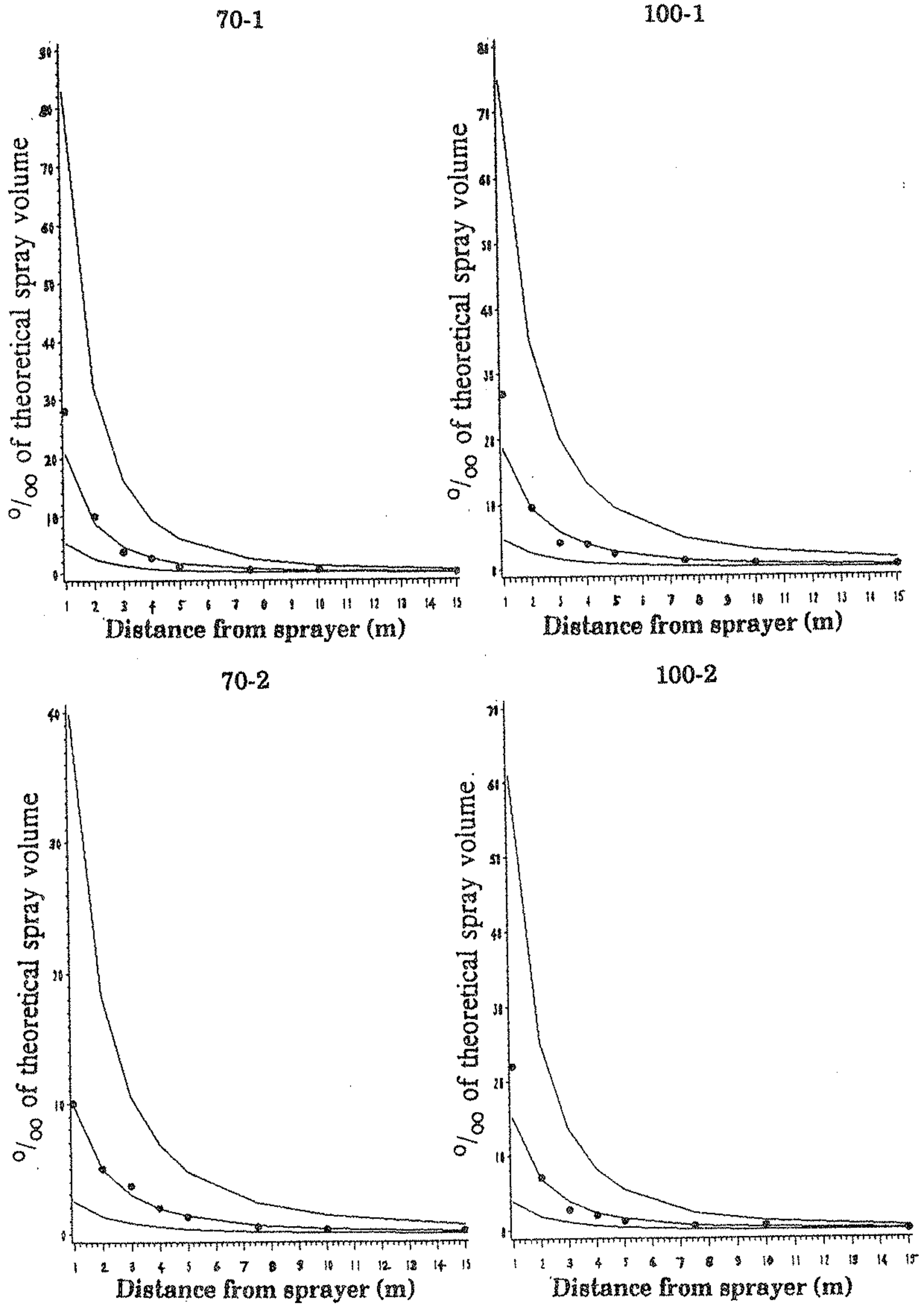


50-2



Appendix 8

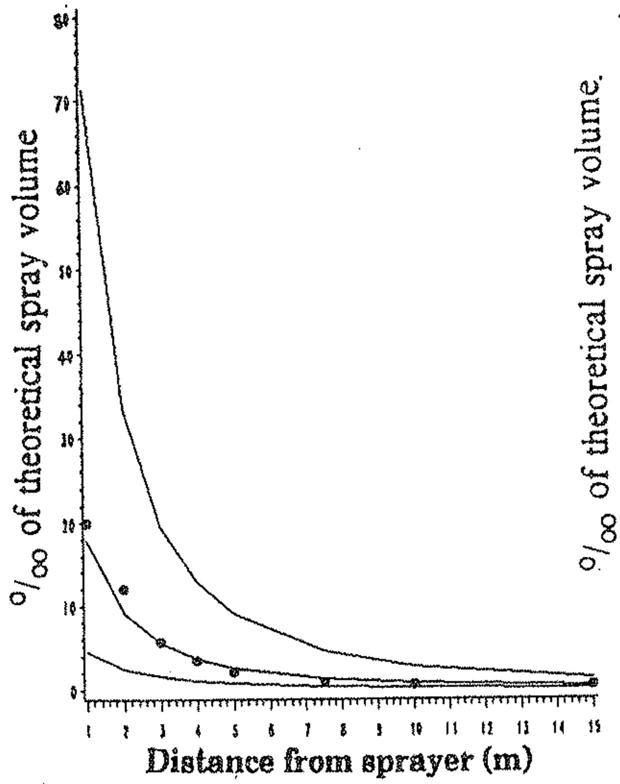
DETECTED DEPOSITS IN THE SPRAY-DRIFT STUDY (GROUND SAMPLE POINTS)



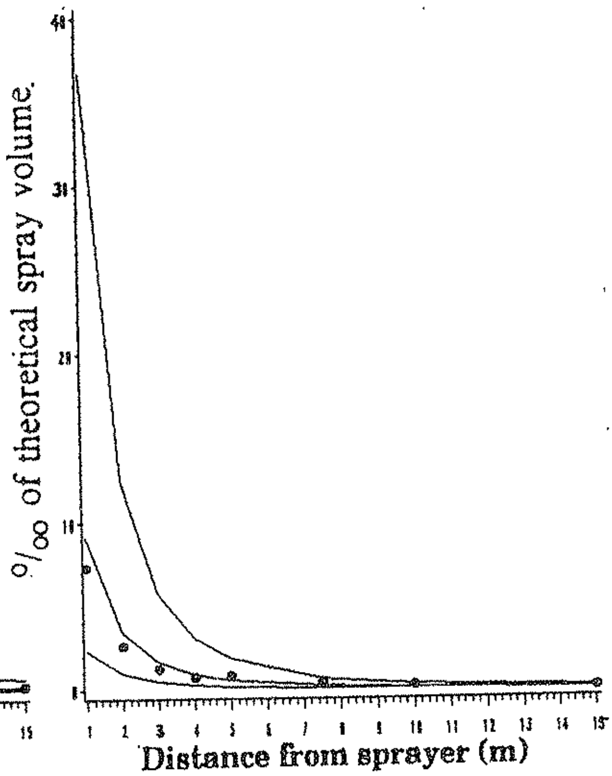
Appendix 9

DETECTED DEPOSITS IN THE SPRAY-DRIFT STUDY (GROUND SAMPLE POINTS)

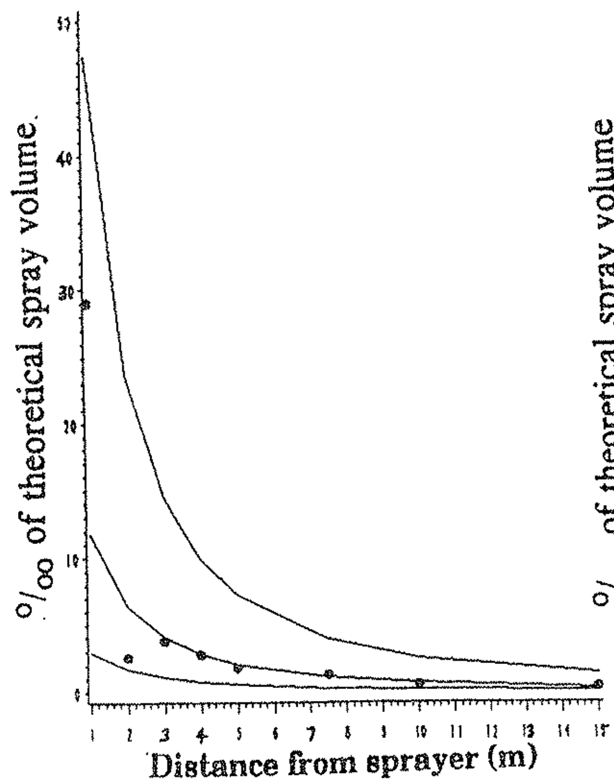
150-1



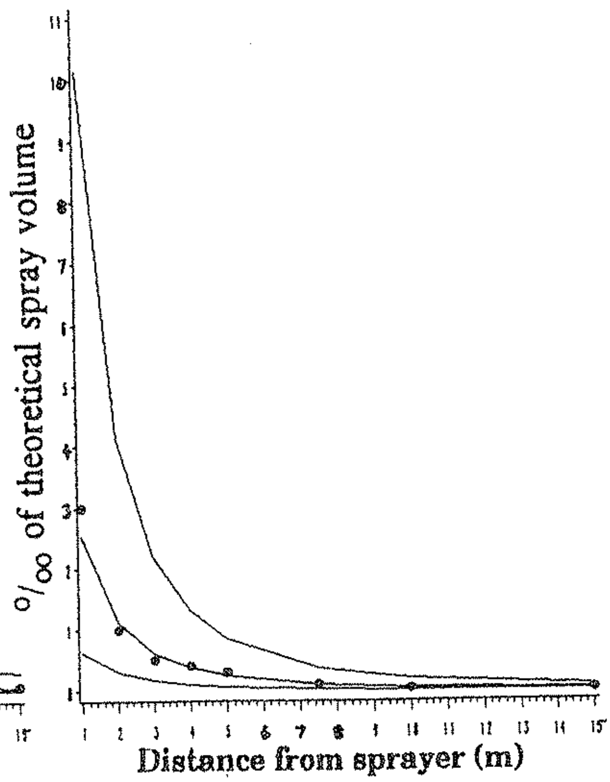
200-1



150-2



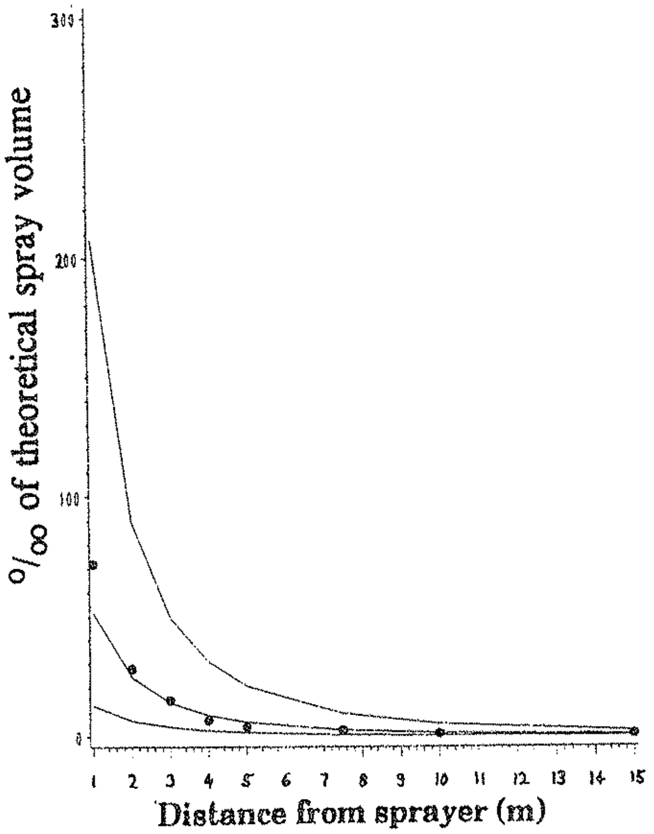
200-2



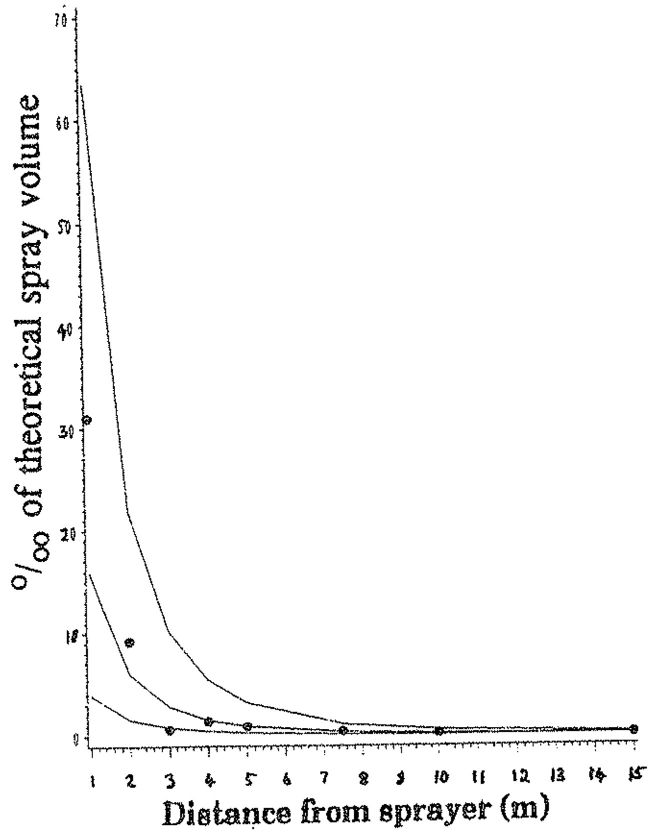
Appendix 10

DETECTED DEPOSITS IN THE SPRAY-DRIFT STUDY (GROUND SAMPLE POINTS)

Conv(150)

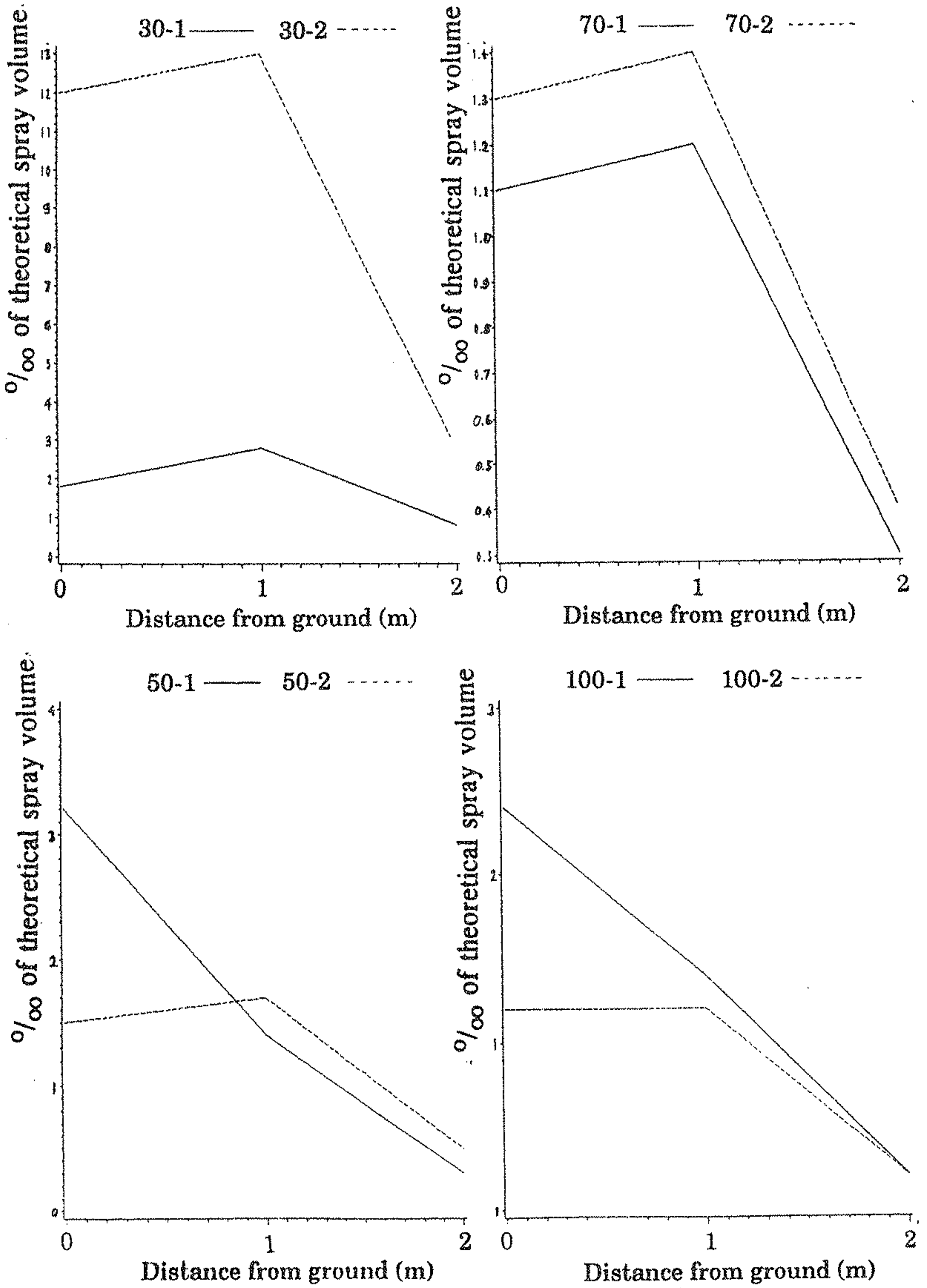


Conv(200)



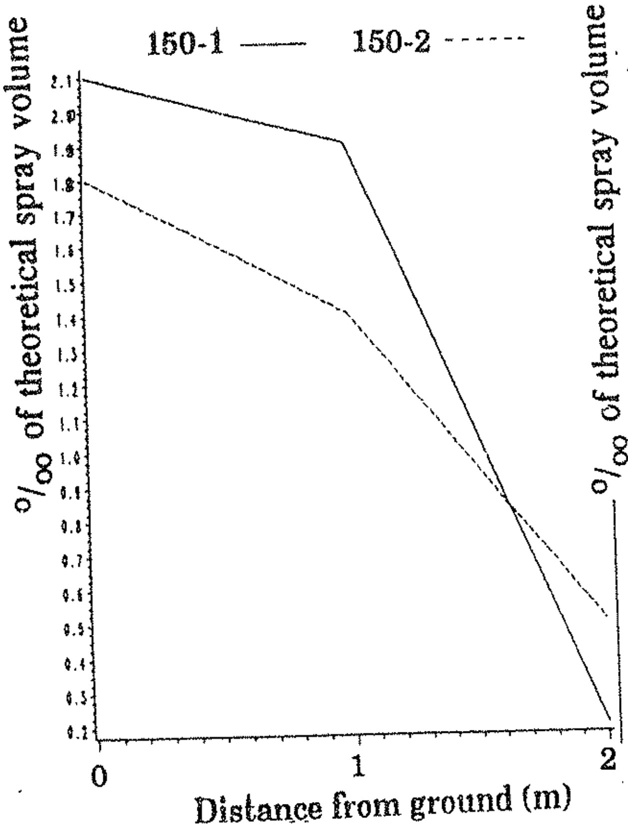
Appendix 11

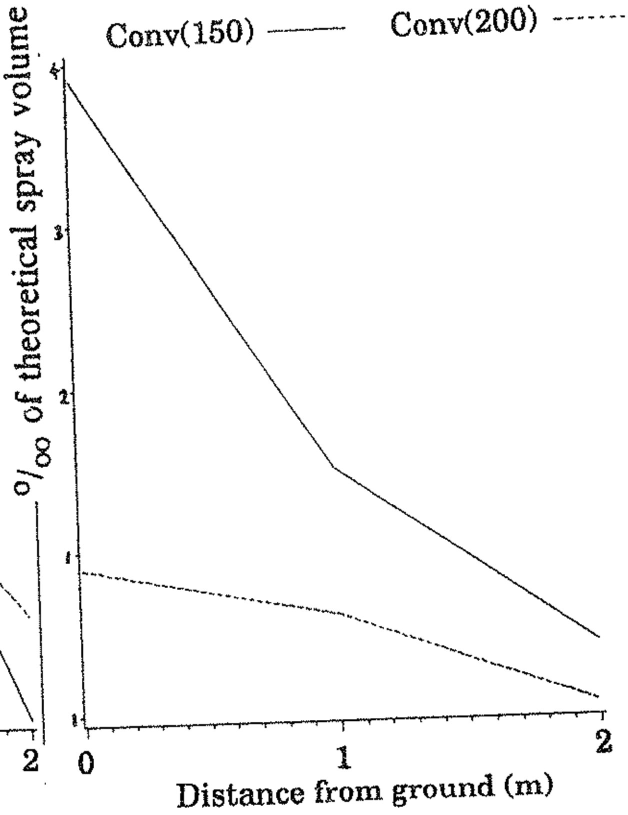
DETECTED DEPOSITS IN THE SPRAY-DRIFT STUDY (POLE SAMPLE POINTS)

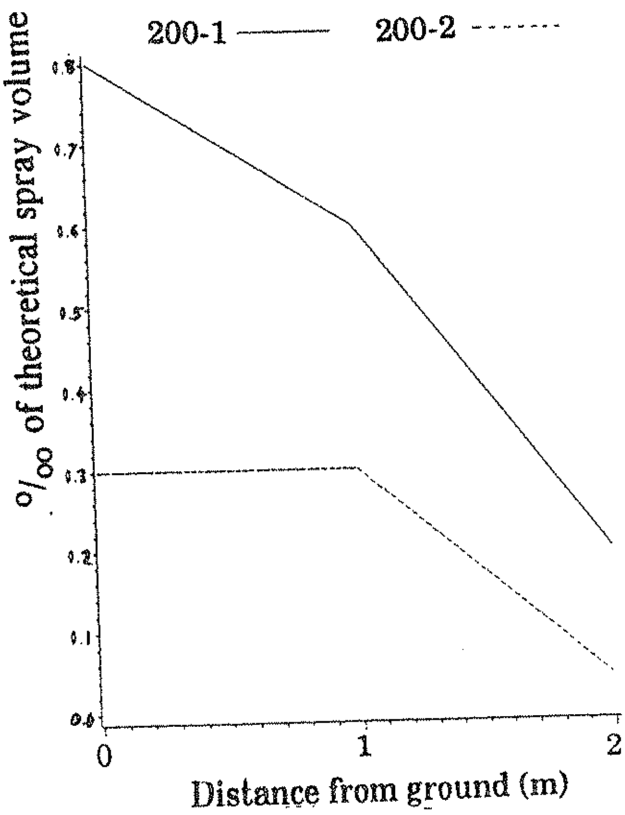


Appendix 12

DETECTED DEPOSITS IN THE SPRAY-DRIFT STUDY (POLE SAMPLE POINTS)







Appendix 13

WEATHER DATA FROM THE SPRAY-DRIFT STUDY

Treatment	Wind speed (m/s)	Wind direction, angle to the intended dir. (°)	Relative humidity (%)	Temperature (°C)
30-1	1.8	3	65	29
30-2	2.3	22	62	31
50-1	1.5	12	53	32
50-2	2.0	12	53	32
70-1	2.3	12	65	29
70-2	1.9	3	64	29
100-1	3.0	22	50	35
100-2	2.4	8	51	34
150-1	3.3	5	69	32
150-2	2.5	8	60	32
200-1	2.6	27	49	34
200-2	3.5	5	52	33
Conv(150)	2.7	25	50	32
Conv(200)	1.8	7	59	33