8-1985

Evaluation of a prototype air-assist agricultural sprayer nozzle

Steven P. Manos

Recommended Citation

Manos, Steven P., "Evaluation of a prototype air-assist agricultural sprayer nozzle. " Master's Thesis, University of Tennessee, 1985.
https://trace.tennessee.edu/utk_gradthes/7456

To the Graduate Council:

I am submitting herewith a thesis written by Steven P. Manos entitled "Evaluation of a prototype air-assist agricultural sprayer nozzle." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering Technology.

Fred D. Tompkins, Major Professor

We have read this thesis and recommend its acceptance:

Luther R. Wilhelm, Bobby L. Bledsoe

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by Steven P. Manos entitled "Evaluation of a Prototype Air-assist Agricultural Sprayer Nozzle." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Mechanization.

Fred D. Tompkins, Major Professor

We have read this thesis
and recommend its acceptance:

Luther R Wilhelm

B. L. Bledsoe

Accepted for the Council:

C W Minkel
Vice Provost
and Dean of The Graduate School

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Master's degree at The University of Tennessee, Knoxville, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of the source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his absence, by the Head of Interlibrary Services when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature Steven P. Manos

Date June 25, 1985

EVALUATION OF A PROTOTYPE AIR-ASSIST AGRICULTURAL SPRAYER NOZZLE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Steven P. Manos
August 1985

DEDICATION

In honor of Mr. and Mrs. Perry Floyd Lewis
and
In memory of Mr. and Mrs. John Steven Manos,
my Grandparents

ACKNOWLEDGMENTS

The author wishes to express his gratitude and appreciation to the following:

The Department of Agricultural Engineering and its head, Dr. Houston Luttrell, for providing the opportunity to participate in the graduate program in Agricultural Mechanization.

Dr. Fred D. Tompkins for his instruction, guidance, and support while serving as major professor.

Dr. Luther R. Wilhelm and Dr. Bobby L. Bledsoe, committee members, for their advice and support throughout the graduate program.

Mr. William E. Hart and Mr. John B. Wilkerson, instructors and committee members, for their support and friendship throughout the graduate program.

Mr. Thomas F. Reed, agricultural specialist with Spraying Systems Company, for providing the air-assist nozzles used and technical support requested during the evaluation.

Mr. Henry Retzer, engineering specialist with the USDA, for his assistance during the evaluation of the nozzle at the USDA-ARS in Beltsville, Maryland.

Dr. William L. Sanders, Agricultural Experiment Station Statistician, for his assistance during the statistical analysis of the data.

Fellow Graduate Students of the Department of Agricultural Engineering for their support and assistance.

Mr. and Mrs. John J. Manos, the author's parents, for their support, both moral and financial, and continual love during this endeavor.

ABSTRACT

Droplet spectra and lateral spray distributions from a prototype air-assist agricultural sprayer nozzle were observed and evaluated at the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) in Beltsville, Maryland and at The University of Tennessee Department of Agricultural Engineering in Knoxville, Tennessee. Evaluations considered the effects of various air and liquid pressure combinations, different liquid physical properties, and other operational variables on the spray emitted by the nozzle unit. Evaluations of droplet spectra from six nozzle tips and at various positions within a given distribution were also performed.

Data describing the droplet spectra were collected using a helium-neon laser spectrometer. Air pressures of 34, 52, and 69 kPa in combination with liquid pressures of 207, 276, 345, and 414 kPa were used during the evaluation. Tapwater, a hard well water, distilled water, and an oil-in-water solution were used to analyze the effects of various liquid properties on droplet spectra emitted from the nozzle. Changes in the volume-surface (Sauter) mean diameter (SMD), the volume median diameter (VMD), and the 10 and 90 percent intercepts on the cumulative volume curve (DV1 and DV9, respectively) were analyzed for all test conditions.

Data characterizing the lateral spray distributions from the air-assist nozzle were collected using a patternator. The air and liquid pressures noted above were used during the evaluation.

Only tapwater and the oil-in-water solution were tested for their effects on the spray pattern emitted by the nozzle. Boom heights were 43, 48, and 53 cm above the patternator surface. Coefficients of variation for the lateral spray distributions produced were used to determine the appropriate nozzle spacing along the boom.

Results from the droplet spectra analyses suggest that droplet size decreases as air pressure is increased for a given liquid pressure; however, droplet size increases as liquid pressure increases for a given air pressure. The latter trend is opposite that which occurs in conventional hydraulic atomizers. These phenomena occurred for all liquids tested. Further, the evaluation indicated that little variation existed among the droplet diameters analyzed for liquid pressures of 276 kPa and 345 kPa in combination with the 52 kPa air pressure setting for the oil-in-water solution. The same trend was observed for tapwater at the same liquid pressures, but in combination with all air pressures.

Lateral spray distributions emitted from 48 cm above the patternator surface were analyzed using the coefficient of variation. The results suggest the nozzle should be spaced between 40 cm and 60 cm along the boom for most uniform lateral distribution.

TABLE OF CONTENTS

CHAPTER PAGE

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

FIGURE PAGE

FIGURE PAGE

FIGURE PAGE

CHAPTER I

INTRODUCTION

Background and Statement of Problem

Foliar applied pesticides should be evenly distributed across the topsides and undersides of the leaves both on the plant periphery and within the plant canopy. Uneven distribution of a foliar applied pesticide can result in poor control of the pest or disease which may lead to decreased yields and diminished quality at harvest. Increased awareness of the inefficiencies of conventional hydraulic spraying systems in providing adequate canopy penetration and thorough foliage coverage in crops has resulted in the development of new spray applicators. These applicators have been designed to improve atomization of the liquid and produce a narrower droplet spectrum to aid in achieving uniform distribution of chemical on leaf surfaces.

Knowledge of the droplet spectrum is of great importance in the application of pesticides. Spraying efficiency and, consequently, spraying cost can be affected by the range of droplet sizes produced as this range has great influence on effectiveness, mode of action, collection efficiency, and drift (Elbanna et al., 1984). Skoog et al. (1976) concluded that the optimum droplet size for efficient pest control and minimum contamination of the surrounding ecosystem is dependent upon a variety of conditions, many beyond the control of the operator. Elbanna et al. (1984) suggest that factors influencing droplet formation and size include atomizer parameters and design, ambient conditions, liquid properties, and transient effects along the path to the target.

Drift and evaporation are major problems when applying agricultural pesticides. When droplets that are too small enter the atmosphere they are often carried some distance away from the target area or evaporate before striking any surface. Further, production of small droplets leads to distortion of the application pattern under windy conditions (Kohl, 1974).

There is a need to develop new application technology. Concerns about adequate coverage, effects on the environment, evaporation, and drift have led to various studies of applicators and application techniques. Despite efforts to identify optimum operating parameters, few scientists agree on the adequate droplet size and distribution which provides optimum foliage coverage while minimizing economic losses and reducing damage to the ecosystem.

Research Proposal

An air-assist agricultural sprayer nozzle has been developed by Spraying Systems Company and may improve both foliage coverage and canopy penetration. The nozzle design utilizes liquid pressure plus a stream of compressed air to disintegrate a liquid. The unit is constructed of stainless steel and uses a flooding tip for dispersing the fluid. The nozzle is placed in a position such that the axis of the tip is oriented horizontally and a flat fan pattern is produced.

This study was designed to ascertain the influence of liquid pressure, air pressure, and other operational variables on mean droplet size and the distribution of droplet sizes produced by the nozzle. In addition, the effect of liquid pressure, air pressure, nozzle spacing, and boom height on lateral spray distribution was observed using a patternator.

Objectives

A study of a prototype air-assist agricultural sprayer nozzle was designed to evaluate its performance under various operating conditions. Specific objectives were:

1. To evaluate the droplet spectra over the range of liquid and air pressures recommended by the manufacturer using the volume-surface (Sauter) mean diameter, and the 10, 50, and 90 percent intercepts on the cumulative volume curve.

2. To evaluate the uniformity of lateral spray distribution using the coefficient of variation across the distribution on the patternator.

3. To determine appropriate liquid and air pressure settings for operation with water and an oil-in-water solution.

4. To evaluate nozzle performance with four liquids at a single air pressure setting in combination with several liquid pressure settings.

Considerable amounts of research have been conducted with regard to sprayer nozzles and application techniques. This evaluation may add to the continued effort to be able to spray crops more effectively and efficiently.

CHAPTER II

REVIEW OF LITERATURE

Analyzing Droplet Spectra

Introduction

Analysis of the droplet spectrum dispersed through an agricultural sprayer nozzle can be performed by various techniques. Simmons (1984) classifies these into intrusive and non-intrusive methods. Despite the level of sophistication of test equipment, particle sizing is not yet an exact science (Tate et al., 1980). A study of the droplet spectrum of a bypass nozzle shows wide variations among equipment and techniques used for droplet size analysis (Tate et al., 1980). Further, since available measuring devices utilize different qualities of the droplet to determine its size, information obtained from these various techniques may not agree except when extraordinarily ideal conditions exist (Bachalo, 1984).

Intrusive Methods

Intrusive methods include analysis by collection, solidification, and heat transfer (Simmons, 1984). Measurements obtained through these methods use certain physical properties of the droplet such as its ability to cool a surface or its aerodynamic qualities (Bachalo, 1984).

Collection. Tate (1977) used a collection method for evaluating droplet size distributions for drift reduction nozzles. Dyed water was sprayed into cells containing Stoddard solvent. The samples were then photographed at high magnification and scanned with the aid of an electronic analyzer. The processed data included the entire droplet size distribution, mean and median diameters, and the uniformity indexes.

This method lacks the ability to adequately collect droplets at high flow rates; and shattering results when large, high velocity drops are collected (Tate, 1977). In addition, small droplets may fail to impact on the collection cells (Tate, 1961). However, the method does give the temporal droplet size distribution.

Bode et al. (1968) used a photographic scanning technique to determine particle size frequency distribution. Photographic negatives of cards covered by dyed, atomized spray liquid were prepared with a plate camera. A flying-spot particle analyzer owned by the United States Department of Agriculture (USDA) was used to scan these negatives. The droplet frequency for 24 size classes was determined and recorded along with other information related to the droplet spectrum.

Heat transfer. Bachalo (1984) describes the hot-wire probe technique which has been developed to obtain the size and concentration of liquid droplets present in a gas stream. Based on heat transfer to the droplet, this method measures the cooling effect caused by a droplet attached to a hot wire. Without a droplet present, the resistance along the platinum wire is high and essentially uniform. When a droplet becomes attached to the wire and cooling begins, the resistance is reduced in proportion to the drop size. This appears as a voltage drop across the wire supports. The constant electrical energy supplied to the wire will evaporate the liquid, and the device will perform another measurement.

Mahler and Magnus (1984) suggest that the hot-wire probe will replace the time consuming and tedious method using sensitized collection substrates as well as the more elaborate optical methods. Major advantages of the system cited were that it is easily portable, requires no special alignment, and is inexpensive. Use of this approach has shown that accurate measurement for statistical values like the Sauter mean diameter (SMD) is possible. However, Bachalo (1984) states the procedure is not applicable for measuring materials which can leave a residue on the wire.

Solidification. Ferrenberg (1984) describes the hot wax technique utilized in the study of rocket engine injectors. Liquid wax is injected into the atmosphere or a large pressure vessel where the droplets rapidly cool and solidify. They are then collected and separated into size groups by a sieving operation. Each group is weighed and a plot of droplet mass versus size is constructed. Cumulative volume, volume distribution, and mass median diameter are measured directly. Temporal distribution is also measured. Analyses of sample sizes in the order of millions has shown this technique to be statistically accurate. However, the facility in which the tests are conducted must be fairly large and moderately complex.

Kim and Marshall (1971) employed the hot wax method in an analysis of the atomizing characteristics of a pneumatic atomizer. The molten wax was sprayed through the nozzle, and the dispersed material allowed to air cool. The droplets were collected and sized by a sieving operation.

Non-intrusive Methods

Non-intrusive or optical methods of droplet spectrum analysis included imaging, non-imaging or interferometry, and laser doppler techniques (Simmons, 1984). Certain devices may use the relative index of refraction of the droplet and its radius of curvature. Others may use the projected cross-section of the droplet (Bachalo, 1984). Since there is no accepted standard or method for assessing their measurement accuracy, size resolution should be adequate to characterize the given spray to be evaluated. Further, the system should be compatible with the environment in which it will be used (Bachalo, 1984).

Imaging. Ferrenberg (1984) states that imaging techniques allow the observer to actually see droplets as they exist at the point and time where knowledge of their size is desired. Thus, performance of imaging analyzers is dependent upon the optics system (Thompson, 1984). Chigier (1984) describes most imaging systems as having the light source and transmitting optics on one side of the spray with the receiving and recording systems on the other. Imaging techniques can produce erroneous results if used in applications where droplet number densities are very high or the optics system is of poor quality (Bachalo, 1984). Further, the limiting characteristic of conventional imaging systems is that resolution is inversely proportional to the distance from the droplet.

Holography relieves some of the constraints of conventional imaging techniques, but large numbers of spray distributions cannot be obtained with a high degree of confidence (Bachalo, 1984). Thompson (1984) describes the in-line, far-field holographic method used to measure droplets. The method involves a two-step procedure which captures in a permanent form the cross-sectional shape and position of each particle as it moves through a sampling area. A stationary three-dimensional image is produced for each particle in the original volume. This method can be applied to a variety of circumstances including the evaluation of fog droplets, cloud studies, and agricultural sprays.

Droplet images have been obtained using still photographs, video recordings, and photodiode arrays (Bachalo, 1984). Advantages of these imaging systems are that the projected shape of droplets is available and droplet collision and coalescence are also detectable. However, these units must sometimes be immersed in spray, so fogging of the lens can occur as well as aerodynamic deflection of small droplets. Despite attempts to shield the optical system, problems still occur under the immersed conditions.

Amberg and Butler (1970) synchronized a high speed camera with a short duration flash. Termed stroboscopic, high speed photography, this method was used for analyzing droplet formation near the nozzle orifice. Flash speed was found to be a major limitation of the technique during the qualitative tests.

Tate (1977) photographed sprays "in situ" using microflash illumination. The spectra were photographed from different directions and at different distances from the nozzle orifice. Droplet images were sized semi-automatically.

This method as well as other high speed photographic techniques gives spatial size distributions. Accurately sizing very small droplets is not possible. Thus the total number of droplets recorded in a given test is reduced. This will alter the commonly reported mean diameters, but have only a slight effect on volume median diameter (VMD). Conversion to temporal distribution requires that the droplet count or frequency be multiplied by the corresponding velocity (Tate, 1977).

Reichard et al. (1977) used an optical array spectrometer probe to measure the droplet size distribution delivered by an air blast sprayer. A laser device illuminated droplets passing through the object plane of an imaging system. Particle shadows were imaged upon a photodiode array and sized as an integral number of occulted elements. The device was positioned to evaluate the spray at various distances from the nozzle orifice.

Interferometry. Hirleman (1984) found particle sizing interferometry can provide size information independent of incident intensity. This technique is divided into two classes of measuring devices. These are ensemble or multiparticle analyzers and single particle counters. A problem associated with these instruments is the limited applicable particle size range.

Interferometry uses continuous wave devices such as low powered helium-neon or argon-ion lasers (Chigier, 1984). Helium-neon lasers are used in dilute sprays and high signal to noise systems. Argon-ion lasers increase the signal to noise ratio for dense sprays or for sprays in the presence of extraneous light and radiation interference. Research indicates these techniques are not very accurate for measuring both droplet size and velocity simultaneously. Further, past efforts at using these techniques have proved inaccurate for determining droplet size distribution. However, Rizk and Lefebvre (1984) used the helium-neon laser device and found it to agree with other techniques for measuring droplet size distribution.

Ferrenberg (1984) used an interferometry technique to measure the visibility of a signal created by light refracted through a droplet penetrating an interference region formed by the intersection of two laser beams. Scattered light was then imaged onto a photomultiplier tube located 30 degrees off the axis of the intersecting beams. Droplet size was determined from these images.

Arnold (1983) used a Malvern particle size analyzer to measure the droplet spectra for three different angled flat fan nozzles. The spectrum of each nozzle was measured laterally through the major axis of the fan and transversely at discrete points within the fan. Attention was given to the distance from the nozzle at which spectra should be analyzed.

Laser-Doppler. Chigier (1984) states that high magnification, double-pulsed laser photography is the most reliable and accurate method of simultaneously measuring particle sizes and velocities. A laser video device was used by Oberdier (1984) to analyze fuel spray images. The system formed an image using pulsed laser illumination and stored it on a magnetic video disk. Synchronization of the laser, camera, and recorder was performed by a board in the camera and a separate laser synchronized chassis. Final output is an accumulation of droplet size distributions at various sample points in the spray.

Particle Measuring

Accurate measurement of physical quantities such as droplet size is possible if recognized and well-established standards against which measuring devices can be calibrated exist (Chigier, 1984). The prescribed or desired measurement volume and time are also related to size and the number of droplets present in a given sample. Further, decisions on such parameters measured must relate to the type of atomizer, nature, and overall dimensions of the spray (Chigier, 1984).

Droplets are generally classified on the basis of the number per unit volume in each size class (Bachalo, 1984). Larger droplets will be detectable and appear to be in focus over a larger volume than the smaller ones. Thus, the number of droplets counted must be normalized to a unit area if an accurate distribution is to be obtained. In many polydisperse sprays there is little interest in the lower range of particle sizes (Chigier, 1984).

In addition, knowing if results from the measurement of droplet size distributions are dependent on the velocity of the drops is important. Devices using spatial sampling techniques give results which are velocity dependent. Those that use temporal sampling techniques are independent of velocity (Frost and Lake, 1981). Researchers prefer devices which provide the user with temporal samples.

Spectra-Characterization

Accurate knowledge of the droplet size distribution would be useful in pesticide application. Haq and Akesson (1979) claim droplet size is the principle factor affecting the efficiency of pesticide application. They suggested that droplets be small enough that a large number are produced from a fixed application volume, yet large enough to effectively impinge upon the surface of the target and provide adequate coverage. Akesson et al. (1971) indicate that the deposit of spray on a given target is primarily a function of drop size and size range. Both are affected not only by the structural features of a nozzle, but also by nozzle spacing and orientation, operating pressure, liquid properties, and atmospheric conditions (Tate and Janssen, 1966).

The droplet spectrum parameter most frequently reported by researchers and nozzle manufacturers is the volume median diameter (VMD). Sometimes the cumulative volume curve is used for representing droplet size distribution. However, a single parameter does not provide adequate information regarding the complete droplet spectrum, and a cumulative volume curve is not convenient for calculating the various mean diameters associated with the spectrum (Goering and Smith, 1978).

Heddon (1961) recognized the lack of information on droplet size and size distribution present in the spray patterns of agricultural sprayers. Mass median diameter (MMD) was used alone to express the mean droplet diameter produced by a flat fan nozzle. However, he indicated that one should be cognizant of the wide variety of droplets present in the population.

Chigier (1984) indicates that the Sauter mean diameter (SMD) is often used as a representative diameter since it represents the average surface to volume ratio and should be related to surface-dependent phenomena such as heat and mass transfer. However, the SMD alone provides insufficient information regarding the droplet spectrum and should be reported with the droplet size distribution.

Goering and Smith (1978) reviewed several mathematical equations for analyzing droplet size distributions. Equations discussed are: (1) Rosin-Rammler, (2) Nukiyama-Tanasawa, (3) Normal, (4) Square root normal, (5) Logarithmic normal, and (6) Upper Limit Logarithmic Normal. These are the distribution functions which have been discussed most frequently in the literature.

Mugele and Evans (1951) formulated and proposed the Upper Limit Logarithmic Normal (ULLN) equation as a standard for describing droplet size distribution in sprays. This relationship is based on the differential equation of the normal or Gaussian distribution. Licht (1974) applied the equations to the data of Kim and Marshall (1971), and Goering and Smith (1978) used the equations in similar atomizer analyses. Both studies indicate ULLN gave a good fit to droplet size distributions from the nozzles tested.

American Society for Testing and Materials Standard Practice E 799-81 (ASTM E 799-81) gives procedures for determining appropriate sample size, size class widths, characteristic drop sizes, and dispersion measure of drop size distribution (Anonymous, 1982a). Data are assumed to be counts by droplet size. Droplet size is assumed to be the diameter of a sphere of equivalent volume. This practice does not provide information regarding the accuracy of and correction procedures for measurement of droplets using particular equipment.

Statistical analyses of sprays should take into account the nature of the spray, its changes in space and time, the specific measurement volumes, and the accuracy of the measurement (Chigier, 1984). Progressive changes of individual input parameters such as pressures, flow rates, and nozzle geometry need to be separated and assessed for their independent or dependent influence on specific spray characteristics. Furthermore, emphasis should be focused on the accurate evaluation of the large particle size tail of droplet size distribution curves.

Droplet Forming Devices

Introduction

A variety of nozzles are used to apply agricultural chemicals. Both conventional and low volume atomizers have been evaluated in terms of effective weed and pest control as well as with regard to the effect on the ecosystem. The type of atomizer used depends upon desired coverage and ambient conditions.

Blast Atomizers

Blast atomizers use kinetic energy of a gaseous stream for spray atomization. A jet of compressed gas or air impinges on a stream of spray liquid, or the liquid is aspirated into an air stream in such a way as to cause it to disintegrate into spray droplets (Anonymous, 1984).

Fraser (1958) indicates that in certain designs of blast atomizers the mean drop size is found to change very little as the quantity of liquid is reduced for a given air mass flow in a given size atomizer. The study suggests this condition is advantageous where the same drop size is required over a range of flow rates. Further, droplet size is determined by the relative fluid velocities and their mass ratio in twin fluid atomizers. Thus droplet size is reduced as the air pressure and the air-to-liquid ratio are increased.

Bode et al. (1968) evaluated the performance of a pneumatic atomizer designed by Spraying Systems Company. A large amount of spray was lost to drift, and they suggested that the flow rate error be reduced before acceptance of the nozzle as a low volume applicator.

Gage and Seaborn (1968) evaluated the possible health risks encountered when applying chemicals with a mist blower or misting head. The research indicated that production of fine droplets was a function of the linear air flow at the atomizer head, but that these droplets were too coarse to be inhaled by the applicator.

Mullins (1968) evaluated the performances of an air mist blower and a twin fluid nozzle sprayer. The latter nozzle used air primarily to break the liquid into small droplets. A lower volume of air was required to deliver the chemical to the target than with the air mist blower since only one nozzle was used over each row.

Electrostatic Atomizers

Electrostatic atomizers have been developed which impart an electrical charge on the spray liquid. This charged liquid follows the lines of electric flux and envelopes the plant. The delivery rate is greatly reduced and virtually 100 percent of the foliage is covered (Olivo, 1984).

Law and Bowen (1966) investigated the problems encountered in charging sprays by electrostatic induction. The study indicated that this method not only improved overall foliage coverage, but significantly improved spray coverage on the underside of plant leaves. Further, Roth and Porterfield (1966) discussed the use of electric charge to create a narrow range of drop sizes. Conclusions based on this research were that production of uniform droplets of a predictable size is possible and that this atomization process is a practical means for reducing drift.

Morton (1982) evaluated the performance of the "Electrodyn" sprayer. This device provided high recovery of spray on the crop and virtually eliminated drift. This model produced a volume median diameter (VMD) of about 80 to 90 microns and delivered a fairly uniform droplet size distribution.

Law (1978) developed a mathematical model for spray-charging nozzle design. This model was derived from a theoretical analysis of droplet charging by electrostatic induction in a cylindrical-electrode field. The principles were incorporated into the design of a miniature droplet charger which performed satisfactorily under test conditions.

Concern over transport and deposition of charged spray drops resulted in the development of a mathematical model to clarify the mechanisms by which charged spray is transported to and deposited within a crop canopy (Dix and Marchant, 1984). The study suggested that to improve canopy penetration the velocity of the spray on entry to the canopy must be increased. This can be done by increasing the mass flow rate, the charge-to-mass ratio, or the drop size.

Lake and Marchant (1984) investigated the deposition of charged sprays on targets within a cereal crop. Vertical targets received greater deposits than did horizontal targets. The results suggest that broad-leaved weeds may receive lower amounts of spray, possibly because they are at or near ground level. This phenomena may happen because spray deposits become less uniform deeper into the canopy.

Pressure Atomizers

Pressure atomizers used for agricultural spraying purposes include fan spray, orifice, swirl spray, and deflector atomizers. These devices use flow energy for spray application. Liquid may be transformed into jets, fan, conical, or other patterns (Anonymous, 1984).

Conventional spray nozzles are incapable of achieving uniform atomization (Tate and Janssen, 1966). However, Bintner et al. (1977) realized significant improvements in the uniformity of spray patterns by tilting the nozzles to the horizontal position. Nozzle height and spacing was much less critical with this orientation, but they indicated that the reduced vertical component of velocity could result in hazardous drift when applying finely atomized chemicals.

The fan spray atomizer is used when applying chemicals with broadcast sprayers and planter or cultivator attachments. The tip delivers a fan shaped pattern which is tapered at each end. This permits overlapping of spray patterns to assure uniform coverage (Anonymous, 1982b).

Dombrowski (1961) observed the performance of single orifice fan spray nozzles in a moving air stream. He demonstrated that the spray produced is critically dependent on nozzle orifice design.

Decreasing nozzle spray angle while maintaining a constant output at a given pressure increased the volume median diameter (VMD) for the given spectrum (Arnold, 1983). Further, droplets at the edge of the fan were larger than those in the center.

The deflector atomizer also delivers a flat fan spray pattern, but with a wider spray angle. Flooding spray tips are included in this group. This atomizer provides for greater capacity of liquid flow, produces larger droplets, and can be more widely spaced along the boom than the flat fan nozzle. In addition, the flooding nozzle can be mounted in several different positions in order to achieve desired coverage (Anonymous, 1982b).

Bode et al. (1976) measured the effectiveness of spray atomizers in reducing drift. A flooding flat fan atomizer resulted in decreased drift when compared with conventional flat fan atomizers. This decrease is due to the increased drop size produced and the decreased operating height required by the nozzle. Tate and Janssen (1966) agree that the droplet size is larger from flooding spray nozzles, but indicate that the wide spray angle of these tips results in a thinner liquid film that might be expected to break up into smaller droplets.

Rotary Atomizers

Rotary disc and rotary wheel atomizers are devices that use rotational kinetic energy to atomize the spray (Anonymous, 1984). The rotary disc atomizer uses rotational kinetic energy to produce fluid shear and surface tension forces that adjust the thickness of the fluid sheet leaving the disc for subsequent atomization. The rotary wheel atomizer consists of a rotating circular wheel constructed with vanes, bushings, and perforated or porous openings. Liquid is fed to the inside of the wheel, moves through the constructed openings, and is broken into droplets.

Bode et al. (1972) investigated the effect of flow rate on the distribution pattern and drop size spectrum of a rotary atomizer. They found that flow rate significantly affected drop size distribution. Mean drop diameter decreased with a decrease in flow rate. In addition, atomization varied approximately inversely with atomizer speed.

Hugo (1979) described an ultra-low volume sprayer which utilized a rotating disc atomizer and a spray tube to control the droplet size spectrum. Placing a rotary atomizer inside spray tubes could successfully eliminate droplets larger than the maximum predicted sizes by requiring them to be accumulated inside the tubes and returned for re-use. The research suggested that considerable savings can be realized with this method.

Vibratory Atomizers

Acoustic and ultrasonic atomizers use kinetic energy of a vibrating member to atomize the spray (Anonymous, 1984). Acoustic atomizers use piezoelectric, magnetostrictive, other electrical, or gas-driven devices at 6 to 20 kHz to control atomization of the jet stream. Ultrasonic atomizers use electrically driven devices at 40 to 1000 kHz to control the jet stream break up.

Roth and Porterfield (1970) used a piezoelectric crystal and a magnetostrictive device to produce small, uniform droplets from a nozzle orifice. Development of the piezoelectric crystal device was discontinued because it was too delicate for field operation. Further, maintaining a stable electrical circuit under test conditions was difficult. However, the magnetostrictive device produced uniform size droplets when the vibration was applied just prior to flowing through the orifice.

Bouse et al. (1974), Bouse (1974), and Bouse (1975) studied the controlled breakup of low velocity jet streams by induced cyclic disturbances. Devices from earlier experiments were modified for these studies. The results concur with those of Roth and Porterfield (1970). Vibratory devices are an effective method for producing monodisperse spray.

Spray Pattern Analysis

The shape of a spray pattern depends partly on the type and size of the nozzle utilized (Bintner et al., 1977). Other parameters affecting the pattern profile include flow rate variation, nozzle orientation, nozzle height, and nozzle spacing. Some researchers suggest that the chemical composition of the spray liquid affects the shape of the pattern by altering such liquid properties as density, viscosity, and surface tension (Azimi et al., 1984).

Various studies have been conducted to determine the volume of liquid distributed across the spray pattern profile. Spray pattern deposits from both ground and aerial application equipment have been analyzed by direct or indirect measurement of a target area covered by droplets, by recovery and measurement of an amount of material applied to targets, and by measurement of fluorescent deposits on paper tape (Solie and Gerling, 1984). Very little information is available on analyses using a patternator.

Barger et al. (1948) performed distribution tests on individual nozzles. A patternator consisting of a sheet of corrugated aluminum roofing was used. The table was 1.83 m wide by 1.23 m deep with 6.86 cm wide corrugations. The table inclined to provide flow to graduated cylinders, one located at the lower end of each groove in the metal. Above the test tray and mounted on standards that provided height adjustment was a pipe supporting the nozzle to be evaluated.

Klingman (1964) constructed a similar device to be used for the analysis of whirl chamber nozzles. The pan measured 101.6 cm wide by 91.44 cm deep with sixteen-6.35 cm wide by 91.44 cm deep corrugations. Each channel drained into a beaker for measurement of spray. A boom holding a single nozzle was allowed to move over the center of the patternator at 0.23 km per hour.

Azimi et al. (1984) used a different style of patternator to study the shape of the pattern profile of various nozzles. The table used was 2.46 m wide by 2.44 m deep with eighty-3.0 cm wide by 2.5 cm high channels across the table width. Vertical dividers 0.5 cm wide were used to prevent particles from splashing into surrounding channels. Splatter is a problem encountered on corrugated top patternators. The nozzle was fixed to a linkage which enabled the researcher to adjust height, tilt angle, and position of the nozzle with respect to the table. Eighty 50 ml graduated cylinders were used to catch fluid from the channels. Results from the experiment indicated that spray nozzle manufacturers are not providing adequate information regarding the operation of nozzles under field conditions.

Liquid Properties

Disintegration of a liquid from a nozzle orifice is caused by several phenomena (Fraser, 1958). Disturbances in the fluid flow within the atomizer, density and viscosity of the gaseous medium into which the spray is discharged, and the physical properties of the sprayed liquid are responsible for the atomization of liquids dispersed through a nozzle. Further, disintegration into droplets requires the surface area of a sprayed liquid to be increased until it becomes unstable.

Fraser (1958) and Haq and Akesson (1979) state that the two liquid properties having the most influence in atomization are surface tension and viscosity. Fraser (1958) reports that the surface tension of most liquids, except liquid metals and fused salts, is below that of water. Further, an increase in viscosity lengthens a liquid sheet, and during the final stages of disintegration, will oppose surface tension in forming droplets. Density of a liquid has little effect, particularly over the small range of densities encountered in agricultural spraying.

During atomization, a liquid is exposed to shear and tension forces (El-Awady, 1978). Akesson et al. (1983) present data on the relationship between viscosity, surface tension, and viscoelasticity on the droplet size produced by several types of atomizers. This study suggests that viscosity changes as the rate of shear changes. With many spray mixtures, this becomes a reduction of viscosity with high shear rates. Twin fluid atomizers produce high shear rates, so viscosity effects are lessened.

Dombrowski et al. (1960) investigated the flow pattern of the liquid sheet produced from a rectangular orifice fan spray nozzle. This study concludes that the thickness of the sheet is at any point inversely proportional to its distance from the orifice. Further, the sheet thickness for a given nozzle and liquid of low viscosity at relatively low pressures is a function of surface tension, injection pressure, density, and viscosity. Sheet thickness is a function of the latter three parameters at high pressures.

Combellack and Matthews (1981) evaluated the performance of high volume sprayers using different atomizers, pressure settings, and formulations. Various emulsifiable concentrate dilutions were used during the tests. The research indicated that the effect of formulation varied among and within atomizers used. Further, one should be more cognizant of the effects of the type of formulation used rather than the concentration of one type of formulation.

Bouse (1975) studied the effects of cyclic disturbances on the surface of liquids other than water. He found that low viscosity fluids produced smaller droplets due to higher Weber frequencies for the low viscosity liquids. In addition, Williamson et al. (1979) studied liquid property effects on the droplet size distribution produced by an external mix twin fluid atomizer. Droplet uniformity was observed as a function of varying solution viscosity and surface tension, air minus liquid relative velocity, and air to liquid flow rate ratio.

CHAPTER III

MATERIALS AND METHODS

Nozzle-Design

A prototype air-assist agricultural sprayer nozzle was developed by Spraying Systems Company of Wheaton, Illinois. The nozzle design utilizes hydraulic pressure in combination with a stream of compressed air to atomize a liquid. The nozzle is made of stainless steel and uses a flooding tip (Spraying Systems Company Model TK-5) for dispersing the pre-atomized liquid. The prototype design includes several swivel points, allowing easy adjustment to many possible spraying positions.

Round orifices were used in the design to maximize free passage of a liquid through the nozzle. A manual clean-out needle for the liquid orifice was also designed for the prototype. These features facilitate the handling of highly viscous materials as well as minimize problems with clogging.

Liquid enters the nozzle body and passes through a 0.05-cm inlet leading to a mixing chamber as shown in Figure 1. Air passes through a 0.23-cm inlet into the same chamber. The liquid stream strikes a knob inside the chamber, starting the atomization process. Air impinges on the partially disintegrated liquid causing additional atomization. The fluid exits the nozzle body through the flooding tip which acts to reduce spray velocity when the pre-atomized liquid

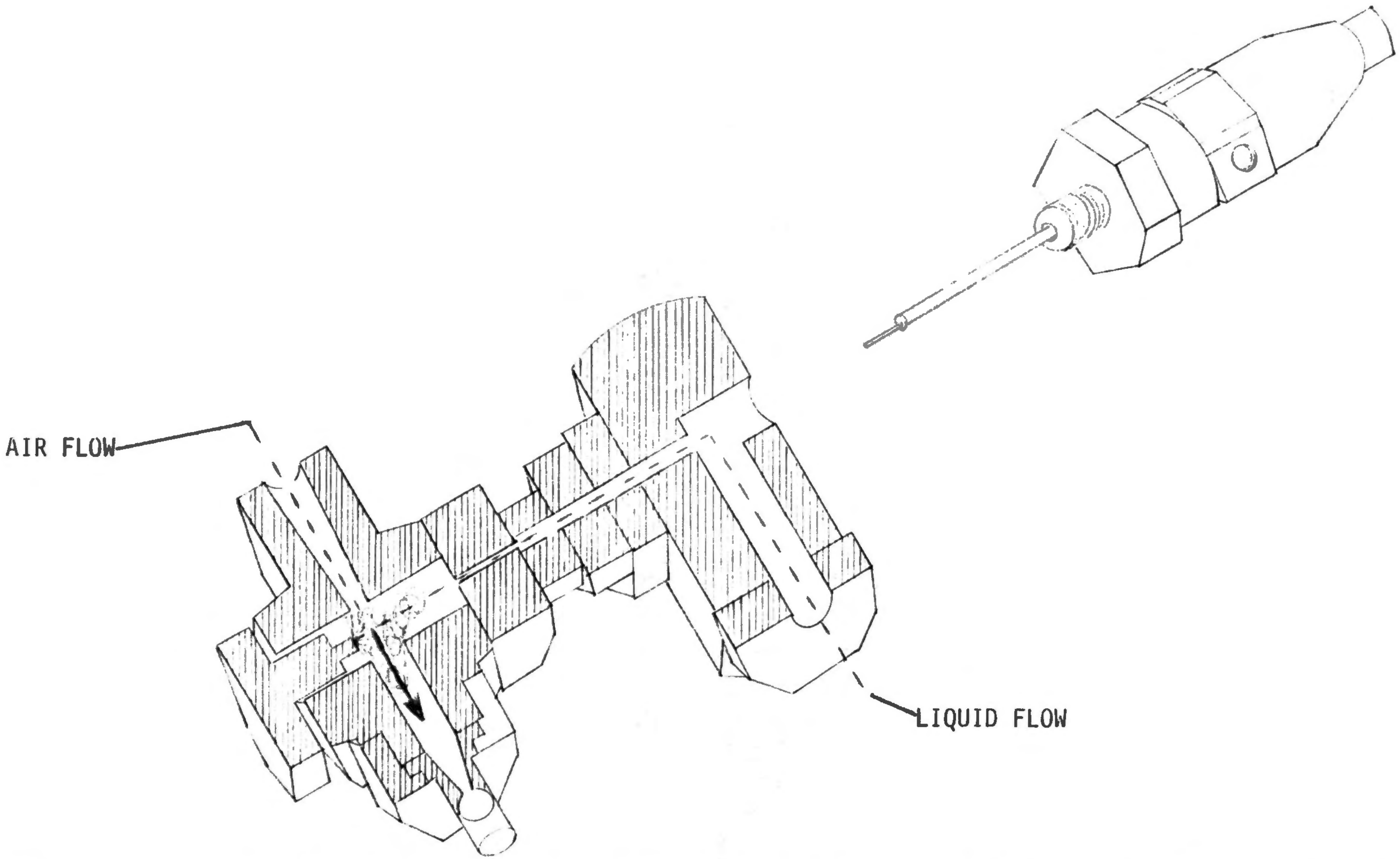

Figure 1. Cross-section of the air-assist nozzle unit showing fluid-flow paths, mixing chamber, and direction of spray discharge (not to scale).

flows across its deflection plate. The manufacturer suggests that this action aids in reducing the number of fine particles produced, thereby narrowing the droplet size spectrum. The nozzle tip produces a flat fan distribution pattern which allows for overlapping of sprays from adjacent nozzles in broadcast applications. The manufacturer reports the spray angle from this nozzle to be approximately 100 degrees plus or minus 10 degrees over the recommended liquid pressure range of 207 to 414 kPa (Spraying Systems Company, 1984).

Experimental Equipment

Droplet Spectra Analysis

The prototype air-assist nozzle was evaluated under various operating conditions. Test equipment was made available by the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) in Beltsville, Maryland. Nozzle tests were conducted in the Agricultural Equipment Building in Beltsville over a four-day period.

The nozzle was mounted inside a spraying chamber that was modified from a conventional shower stall shown in Figure 2. The nozzle was mounted so that both height and lateral adjustments could be easily made. Air and liquid lines entering the spraying chamber from remote receptacles were properly fitted on the nozzle body (Figure 3). Liquids used during the evaluation were stored in a 9.5-L pressurized container.

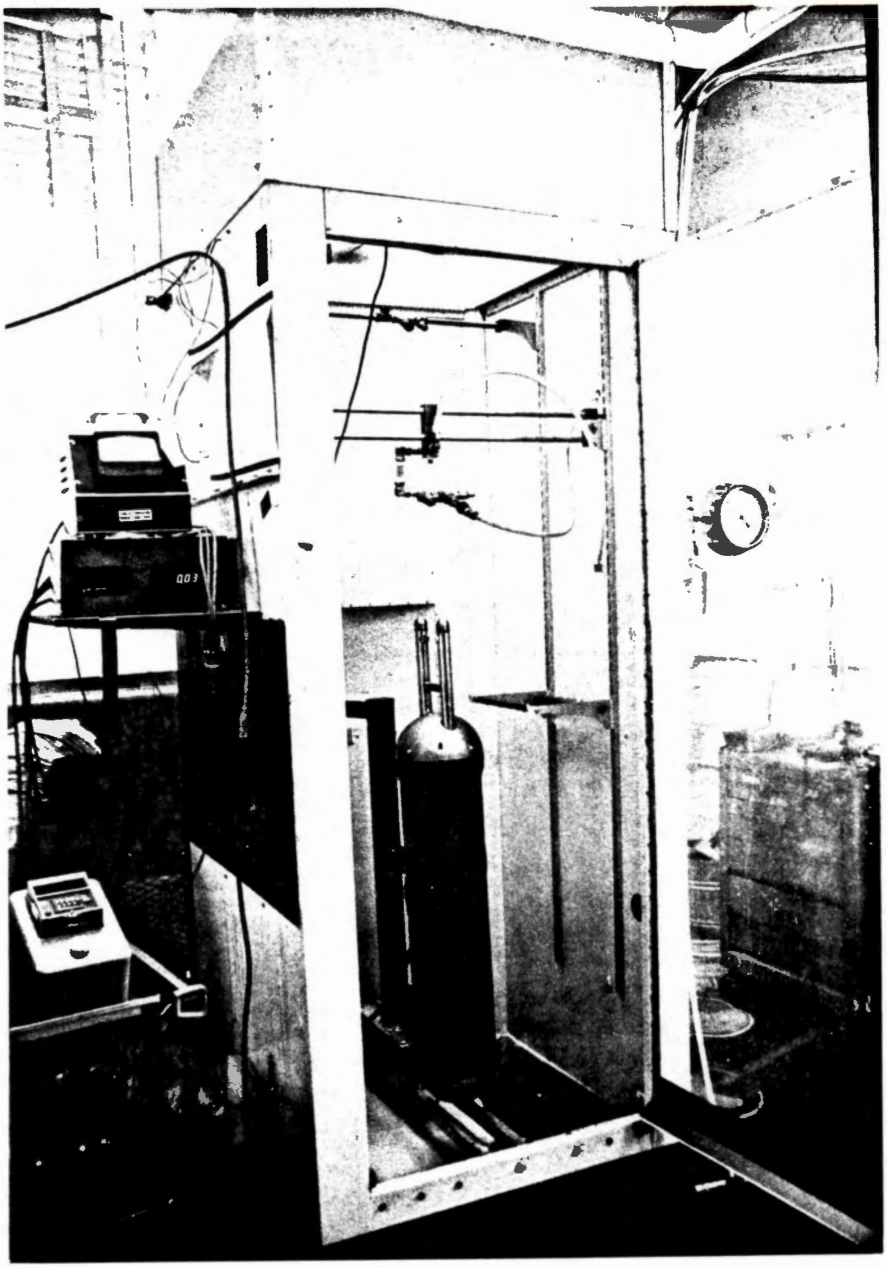

Figure 2. Spray chamber and laser spectrometer used during the droplet spectra analyses at Beltsville, Maryland.

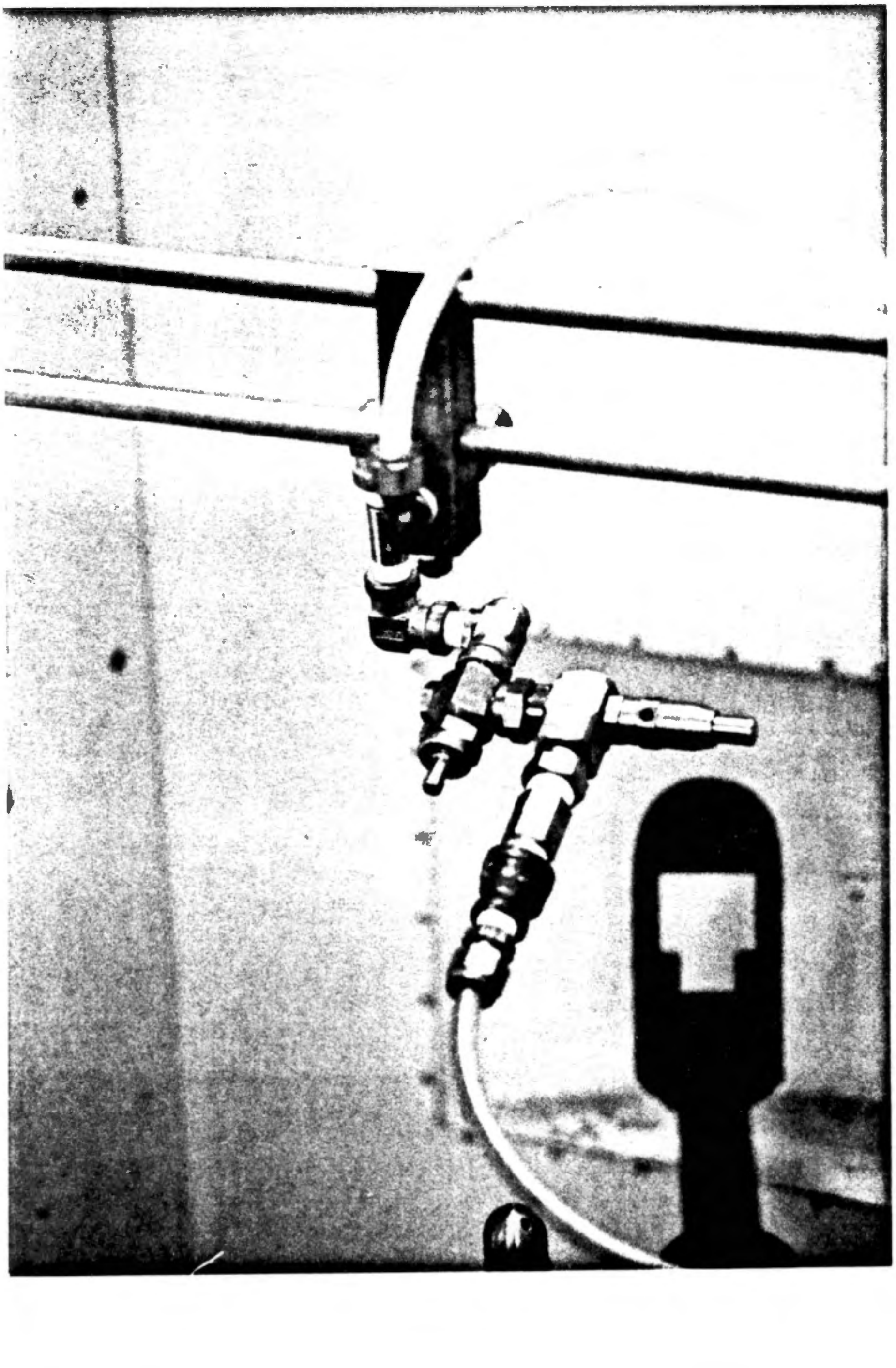

Figure 3. Air-assist unit with air and liquid lines properly fitted on the nozzle body.

Air inside the chamber was conditioned by an environmental unit (300 CFM Aminco-Aire Model No. J4S-5460A) located immediately behind the spraying chamber. The unit provided a controlled environment with high relative humidity (greater than 90 percent) and an average temperature of 25 C. A low velocity air flow system was used to produce a lateral air flow pattern downward through the test chamber. This air flow system channeled the spray fines produced during the tests so that fogging of the optical system in the spectrometer would be minimized.

Droplet size was measured by a laser spectrometer unit (Particle Measuring System Model OAP-200X) situated inside the chamber as shown in Figure 2. Droplets passing through a low-power (2 mW) helium-neon laser beam were sized by a photodiode array (24 x 1) connected to a particle counting device (Model PDS-100) that tabulated the droplets falling within the sampling area. Droplet sizes ranging from 18 to 563 microns were measured by the laser spectrometer and separated into 22 size classes or bins. Each bin increases in width by 25 microns. The mean value of each size bin was used for calculation purposes. This provided a resolution of plus or minus 12.5 microns. Droplets were rejected if they were too large or if they did not completely enter the sampling area established by the laser beam (Wilkerson et al., 1985). Data from the spectrometer were processed by a programmable Hewlett-Packard calculator. The calculator, particle data system, and a timer were located adjacent to the spraying chamber (Figure 4). Output from the calculator consisted

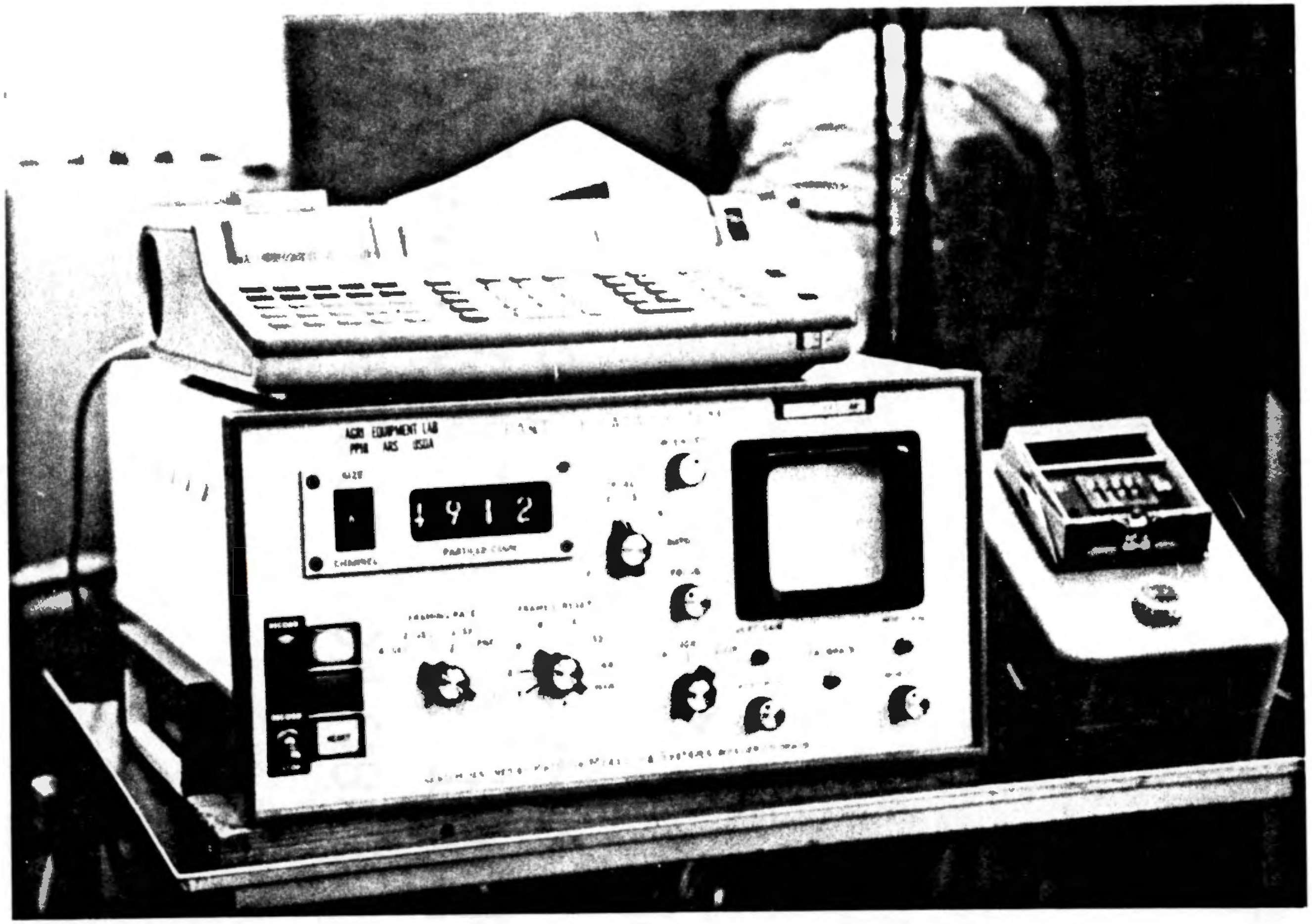

Figure 4. Calculator, particle data system, and timer used during the droplet spectra tests at Beltsville, Maryland.

of droplet counts by size bin, various mean diameters, and analyses of the cumulative volume distribution curve. Data collection time per test was 30 seconds. This collection interval was determined to be adequate for collecting an accurate droplet distribution sample.

Liquid pressure settings used during the tests were 207, 276, 345, and 414 kPa. Air pressure settings were 34, 52, and 69 kPa. These hydraulic and pneumatic pressure settings were those suggested by the manufacturer. At least four repetitions were performed for each air and liquid pressure combination.

Four liquids were tested during the experiment. Tapwater and an oil-in-water solution of 10 percent vegetable oil in water were observed at all pressure combinations. Distilled water and a hard well water were observed at 52 kPa air pressure in combination with all four liquid pressures.

Initial droplet size measurements with tapwater were taken at a position 43 cm below the center of the nozzle. The nozzle was subsequently lowered to 27 cm above the probe because of problems with fogging of the lenses in the spectrometer optical system. In addition, the nozzle was tilted slightly back from the horizontal position to allow the fan spray to be projected in a vertical plane. This correction allowed spray droplets to pass through the sampling area perpendicular to the laser beam. Further, this height agreed closely with Arnold's (1983) suggestion of a 30-cm test height for analysis of the droplet distribution. All subsequent tests were conducted at the 27-cm height.

Tests were also conducted at 7.6 cm and 15.2 cm both left and right of the center of the spray pattern. These positions were along a line 27 cm below the nozzle. Tapwater was used during these tests.

Only one nozzle tip was used for all the tests described above. Five additional tips were tested at 27 cm above the laser beam to determine variation from tip to tip. Tapwater was the only liquid used during this test of quality control among the tips. The tests are summarized in Table 1.

Spray Pattern Analysis

A patternator at The University of Tennessee Department of Agricultural Engineering in Knoxville was used to evaluate the pattern profile of a single nozzle. The spray table was designed similar to that described by Barger et al. (1948). The liquid collection surface measured 2.44 m wide by 0.91 m deep and consisted of 5.08 cm wide corrugations (Figure 5). Forty-seven test tubes across the front of the patternator were used to catch the liquid dispersed by the nozzle. A bar above the table served as a boom and provided height adjustment for the nozzle. Liquid was stored in a container beneath the spray table, and an air line from a compressed air outlet adjacent to the patternator was connected to the nozzle.

The nozzle unit was outfitted with pressure regulators at both air and liquid orifices on the nozzle body and mounted as shown in Figure 6. Liquid and air pressure settings were 207, 276, 345, and 414 kPa and 34, 52, and 69 kPa, respectively. The spray pattern

Table 1. Summary of nozzle spray droplet studies conducted at the USDA-ARS in Beltsville, Maryland, in 1984.

Liquid Pressure (kPa)	Air Pressure (kPa)	Repetitions[a] Per Liquid			
		Tapwater	Oil-in-Water	Hard Well Water	Distilled Water
207	34	4(4)[b]	4	-	-
	52	5(4)	4	4	4
	69	4(4)	4	-	-
276	34	7(3)	5	-	-
	52	4(9)[c]	4	5	5
	69	7(4)	4	-	-
345	34	6(4)	4	-	-
	52	4(4)	4	4	4
	69	4(4)	5	-	-
414	34	4(4)	4	-	-
	52	4(4)	4	4	6
	69	4(4)	4	-	-

[a] Except where indicated, all measurements were taken at a position centered 27 cm below nozzle 1.

[b] Values in parentheses are for replications taken at a position centered 43 cm below nozzle 1.

[c] Additional tests were conducted at 276 kPa liquid pressure and 52 kPa air pressure 27 cm below the nozzle unit. These tests compared distributions among six nozzle tips and positions within the spectrum along a line 27 cm below nozzle 1.

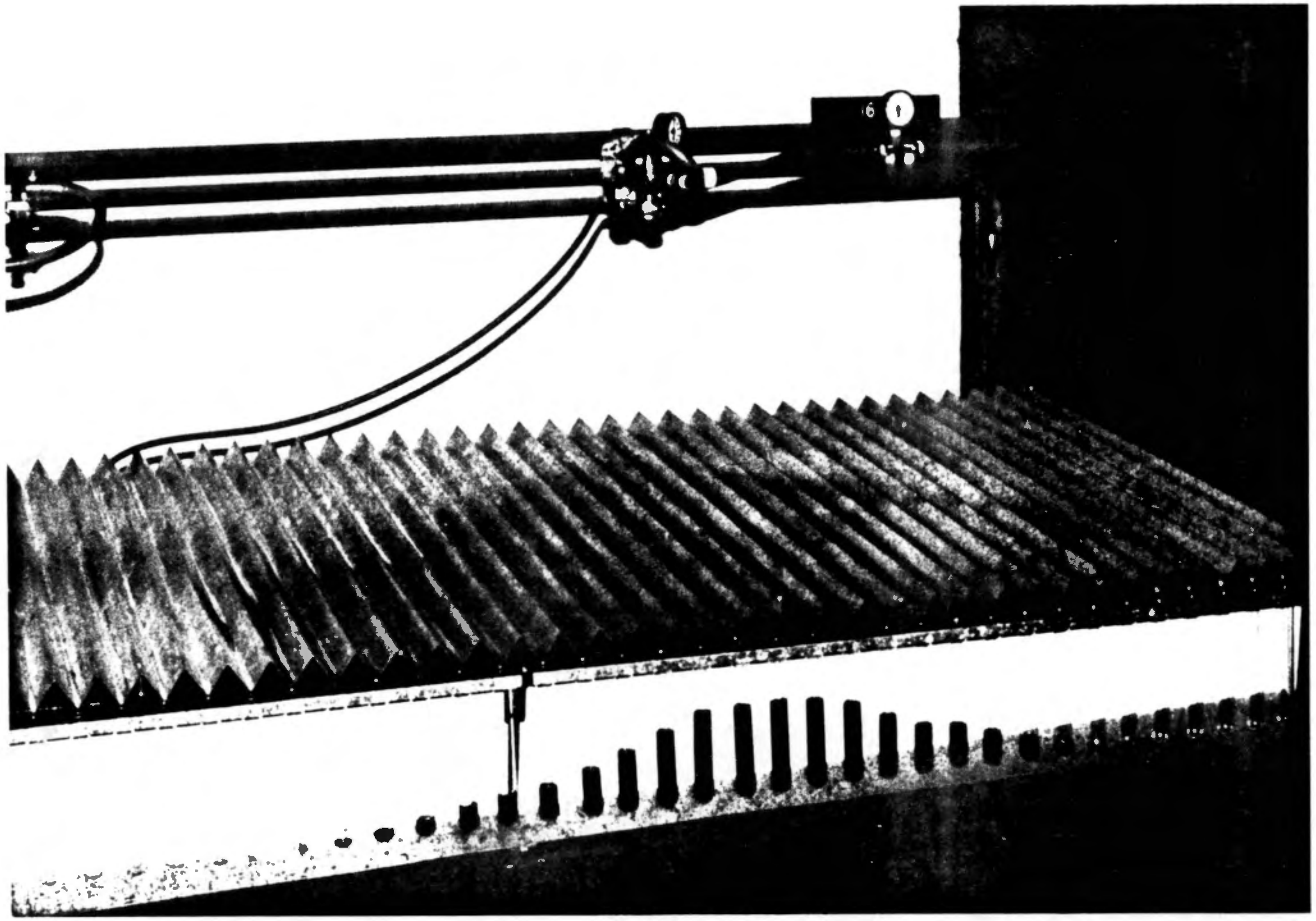

Figure 5. Patternator used to observe lateral spray distributions at The University of Tennessee Department of Agricultural Engineering in Knoxville, Tennessee.

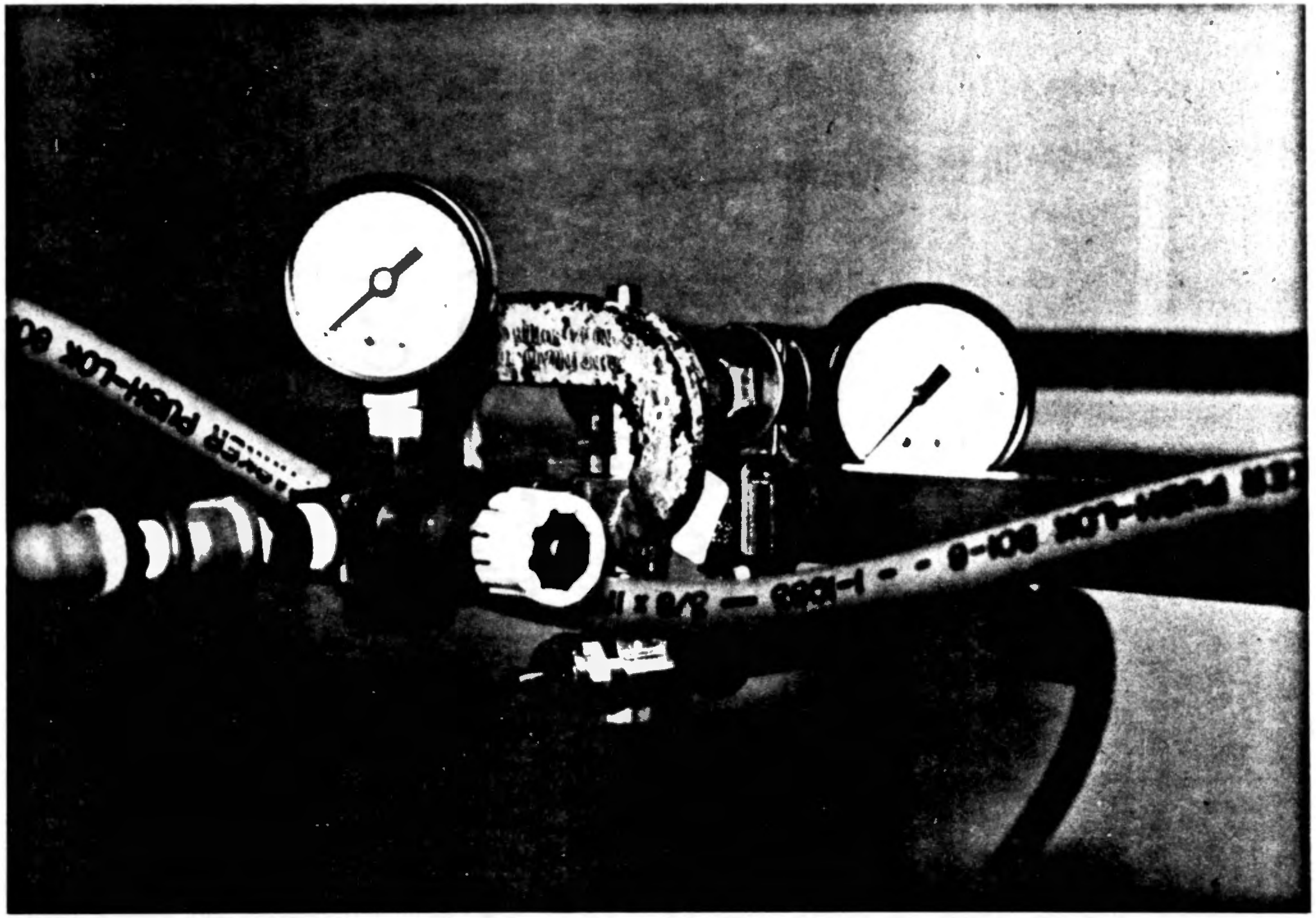

Figure 6. Nozzle outfitted with pressure regulators at both air and liquid orifices on the nozzle body.

was measured for liquids dispersed at 43, 48, and 53 cm above the spray table. Only tapwater and the oil-in-water solution were used for these tests. Measurements of liquid depth in the collection tubes were made with a scale that slipped over each test tube. The depth of liquid in each test tube was recorded for each of three repetitions performed at a given air pressure, liquid pressure, and height above the table.

Data Management

Droplet Spectra Data

Data collected at the Beltsville laboratory were initially processed on an IBM Portable Personal Computer. An electronic spreadsheet, Lotus 1-2-3 (Lotus Development Corporation, 1982), was used to place the data into files. The spreadsheet facilitated the preliminary compiling of all data collected. Only the droplet counts by size bin were stored in these files. The files have been summarized in Appendix A.

The data were then transferred to an IBM mainframe computer at The University of Tennessee. The data were sorted into separate files which contained information about the various mean droplet diameters and the cumulative volume distribution curves. These values were calculated by a Fortran program which incorporated equations from ASTM Standard Practice E 799-81 (Anonymous, 1982a) and information regarding size ranges and size class midpoints from an explanation of the USDA spray particle counter statistical printout shown in Appendix A. The final output was in the form of data sets to be used for statistical analyses.

Spray Pattern Data

The spray pattern profile data were placed on an IBM Personal Computer using Lotus 1-2-3. Worksheets and graphs were prepared to show the distribution of the spray pattern. Separate graphs were plotted for each air and liquid pressure combination at the given heights.

Statistical Analyses

Droplet Spectra Analysis

Two or more factors were investigated simultaneously using the General Linear Models (GLM) procedure of Statistical Analysis System (SAS Institute, 1982). The equations and factor arrangements used are shown in Table 2. Comparisons were made among the Sauter mean diameters (SMD), volume median diameters (VMD), and the 10 and 90 percent intercepts on the cumulative volume curves (DV1 and DV9, respectively). The Tukey-Kramer procedure for testing differences between pairs of means was employed since the sample sizes were unequal (Sokal and Rohlf, 1981). This is a conservative yet powerful method for testing all differences between pairs of means when unequal sample sizes are to be evaluated. GLM provided this technique as a procedure under the Means statement (SAS Institute, 1982). In addition, graphs of the statistical values were used to illustrate comparisons among the parameters test.

Table 2. General Linear Models from Statistical Analysis Systems (SAS) used for the analyses of the statistical values.[a]

Model	Description
D.V.[b] = LIQ LP LIQ*LP	Analysis of the liquid physical properties.
D.V. = HT LP AP HT*LP HT*AP LP&AP HT*LP*AP	Analysis of the two test heights (27 cm versus 43 cm).
D.V. = LIQ LP AP LIQ*LP LIQ*AP LP*AP LIQ*LP*AP	Analysis of the tapwater and oil-in-water solution.
D.V. = NOZ	Analysis of six different nozzle tips.
D.V. = POS	Analysis of positions within the spectrum along a plane 27 cm below the nozzle.

[a] Symbols on the right-hand side of the equation represent the following: LIQ = Liquid Type, LP = Liquid Pressure, AP = Air Pressure, HT = Height, NOZ = Nozzle Tips, POS = Position within spectrum.

[b] D.V. represents the dependent variables analyzed. They are Sauter Mean Diameter (SMD), Volume Median Diameter (VMD), 10% Cumulative Volume (DV1), and 90% Cumulation Volume (DV9).

Spray Pattern Analysis

Graphs of the spray pattern distribution were used to compare differences within the given heights for every air and liquid pressure combination tested. These graphs showed the percent of total spray that accumulated inside each test tube.

The coefficient of variation was calculated for various samples using the following equation:

$$\text{Coefficient of Variation (\%)} = \frac{\text{Standard Deviation} \times 100}{\text{Mean}}$$

Assuming identical spray profiles, the values obtained were used to compare variations among lateral spray distributions for different nozzle spacings.

CHAPTER IV

RESULTS AND DISCUSSION

Droplet Spectra Analyses

Data from droplet spectra produced by the prototype air-assist sprayer nozzle were analyzed to determine any differences or similarities among the effects of liquid pressure, air pressure, and other operational variables on mean droplet size and the distribution of droplet sizes. The Sauter mean diameters (SMD), volume median diameters (VMD), and the 10 and 90 percent intercepts on the cumulative volume curves (DV1 and DV9, respectively) were evaluated separately for a variety of test conditions. All statistical tests were performed at an alpha level of 0.05.

The SMD, DV1, VMD, and DV9 values were not reported alone since none of these values, considered individually, adequately represented the variations observed in the sample distributions being compared. For instance, the DV1's for a certain set of test conditions may not be significantly different for the sample distributions tested while the VMD's from the same samples may be significantly different. This probably resulted from shape differences among the cumulative volume curves which were calculated from the number of droplets in each size class. Examples of curve shape differences are shown in Figures 7 and 8. In this instance the VMD's for the samples were not significantly different; however,

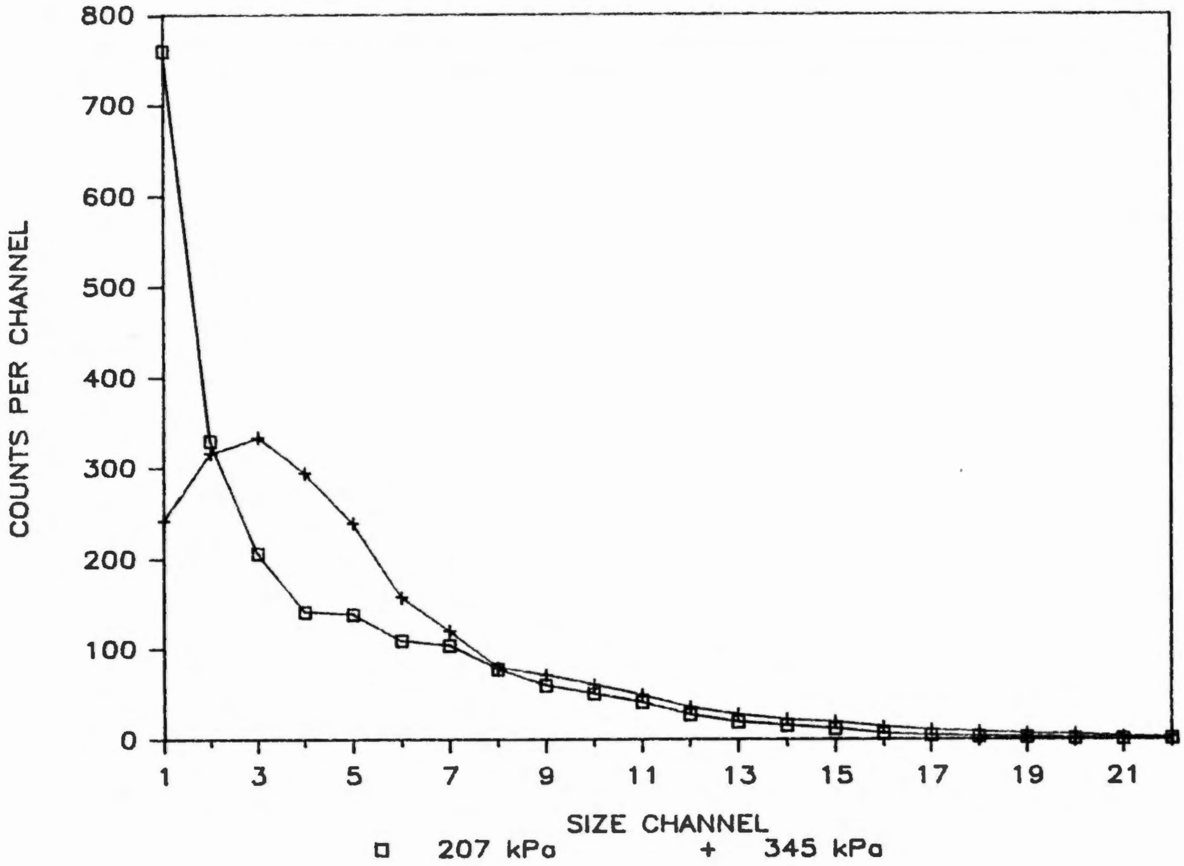

Figure 7. Mean droplet counts per size channel of tapwater at 52 kPa air pressure in combination with 207 kPa and 345 kPa liquid pressures for spectra with the same volume median diameter (VMD).

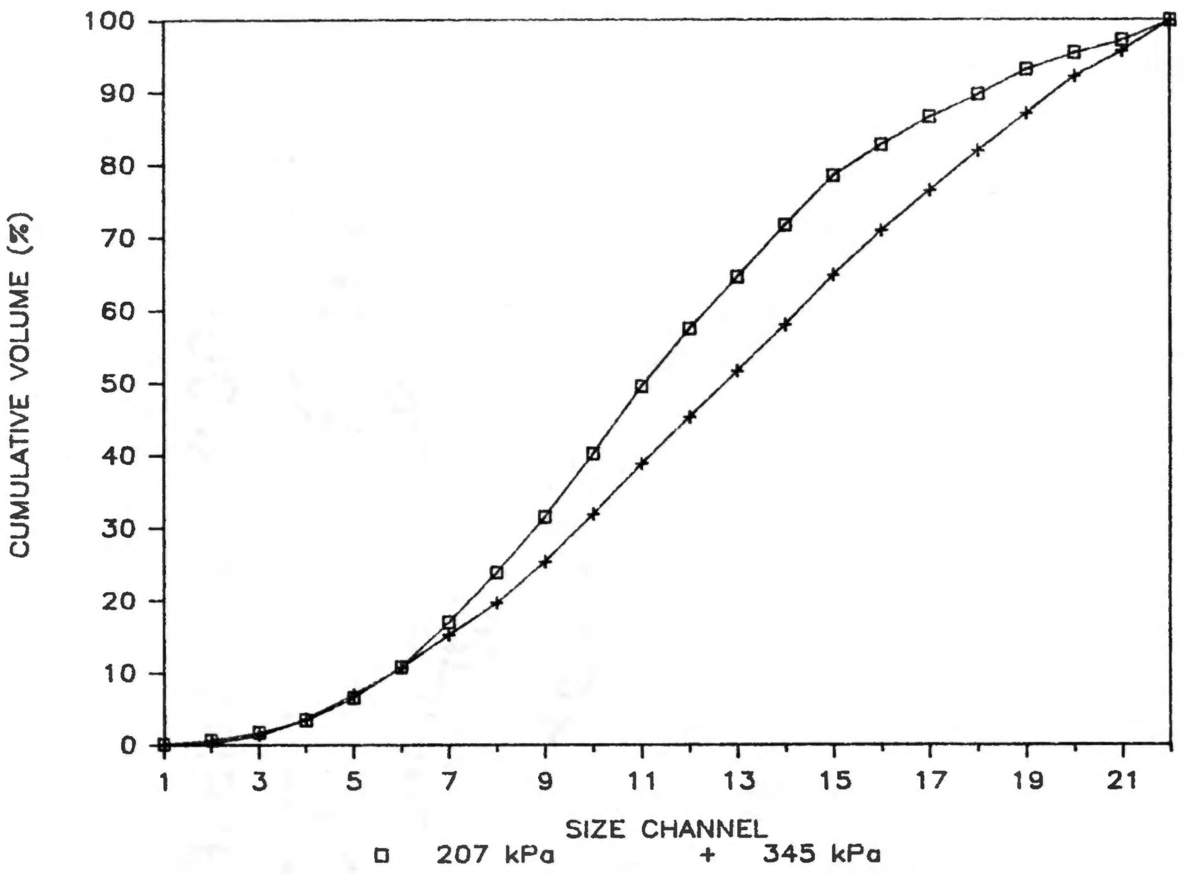

Figure 8. Mean cumulative volume curve of tapwater at 52 kPa air pressure in combination with 207 kPa and 345 kPa liquid pressures for spectra with the same volume median diameter (VMD).

the other values (SMD, DV1, and DV9) tested were different. Further, the SMD's are affected by the number of droplets in each size class. Two SMD's may not be significantly different for the sample distributions tested, yet the droplet counts may vary widely.

Caution is required when reporting droplet spectra data using only the SMD, DV1, VMD, or DV9. Consideration should be given to the number and size of droplets present in the spectrum. A high VMD may be as much the result of an accumulation of many small droplets as opposed to the accumulation of a few large droplets in the distribution. Thus, a single parameter should not be reported and used alone to describe the characteristics of a droplet spectrum. These values can, however, provide information about the general operating trends of nozzles such as the air-assist unit.

Effect of Air Pressure

Figures 9 through 12 suggest that as air pressure was increased, the mean droplet size produced by the nozzle decreased for any of the liquid pressures considered. This trend occurred in the samples using both tapwater and the oil-in-water solution. The pair-wise comparison of the droplet means by the Tukey-Kramer method indicated significant differences existed for this trend among some of the sample distributions tested (Tables 3 and 4). The DV9 values exhibit the least variation across the range of air pressures for the samples tested.

The rate of decrease in droplet size was generally greater from 34 kPa to 52 kPa than for the next higher pressure increment.

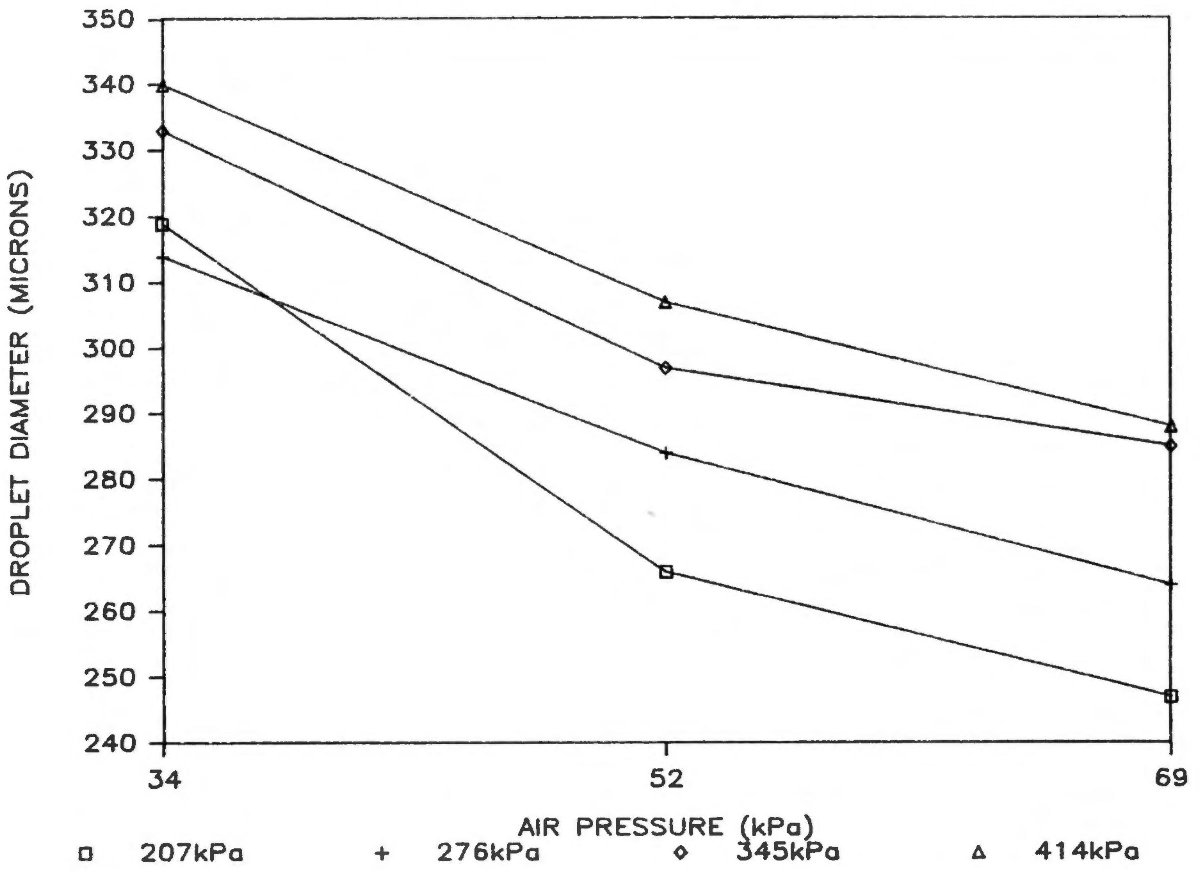

Figure 9. Effect of changing air pressure for each liquid pressure on the Sauter mean diameter (SMD) for the oil-in-water solution.

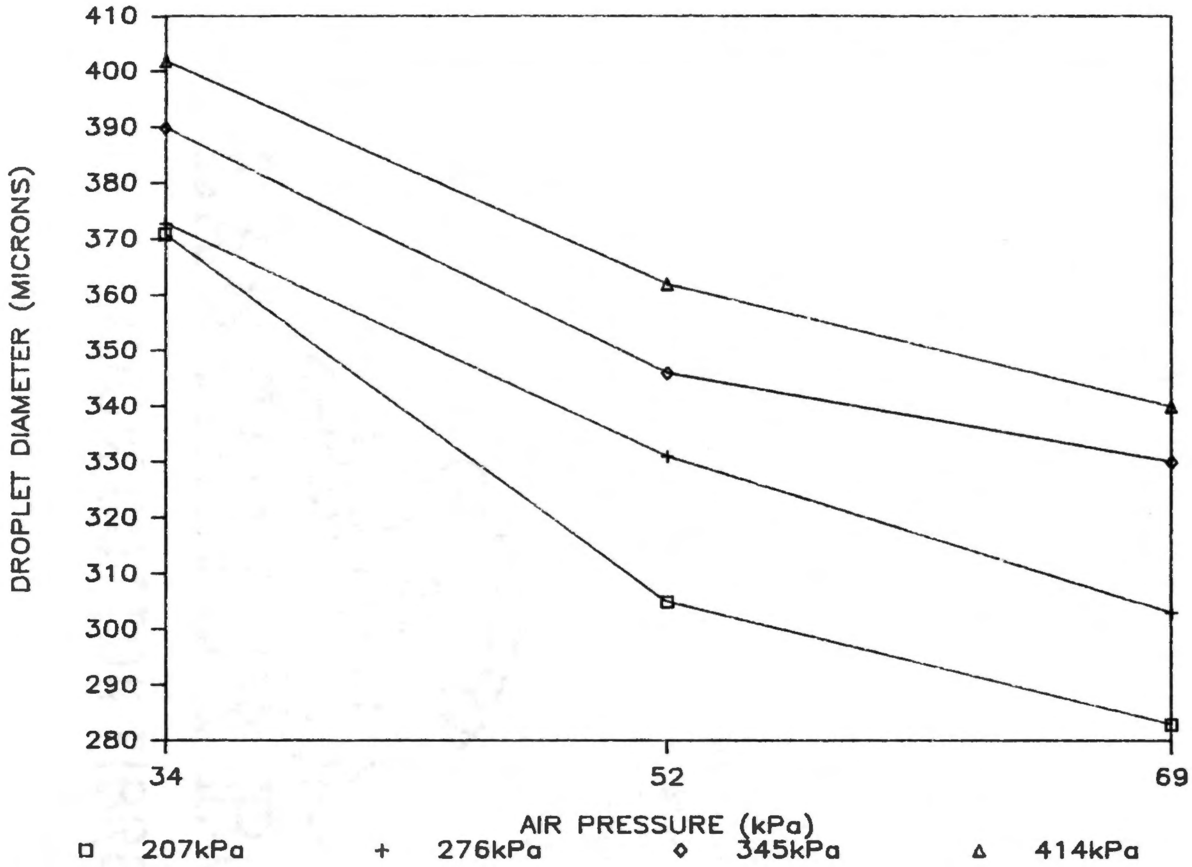

Figure 10. Effect of changing air pressure for each liquid pressure on the volume median diameter (VMD) for the oil-in-water solution.

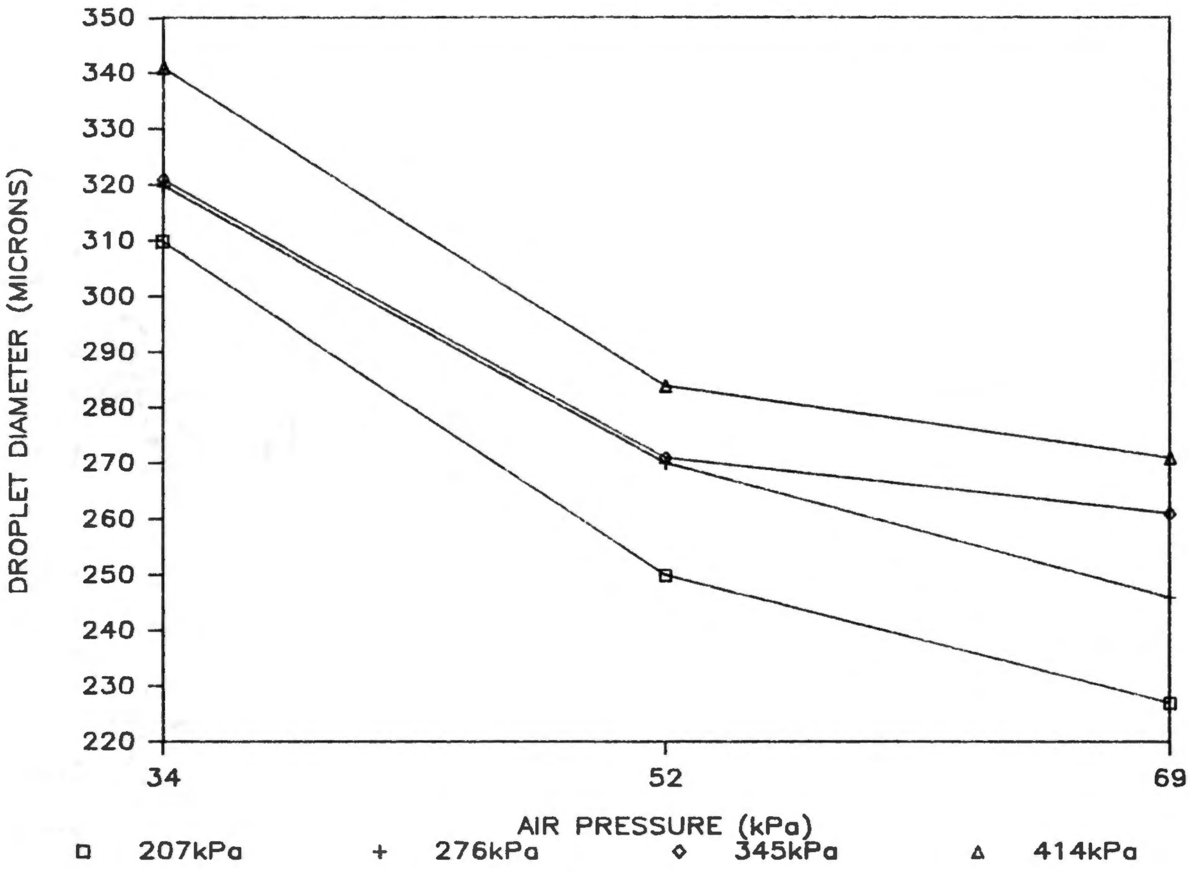

Figure 11. Effect of changing air pressure for each liquid pressure on the Sauter mean diameter (SMD) for tapwater at 27 cm below the nozzle.

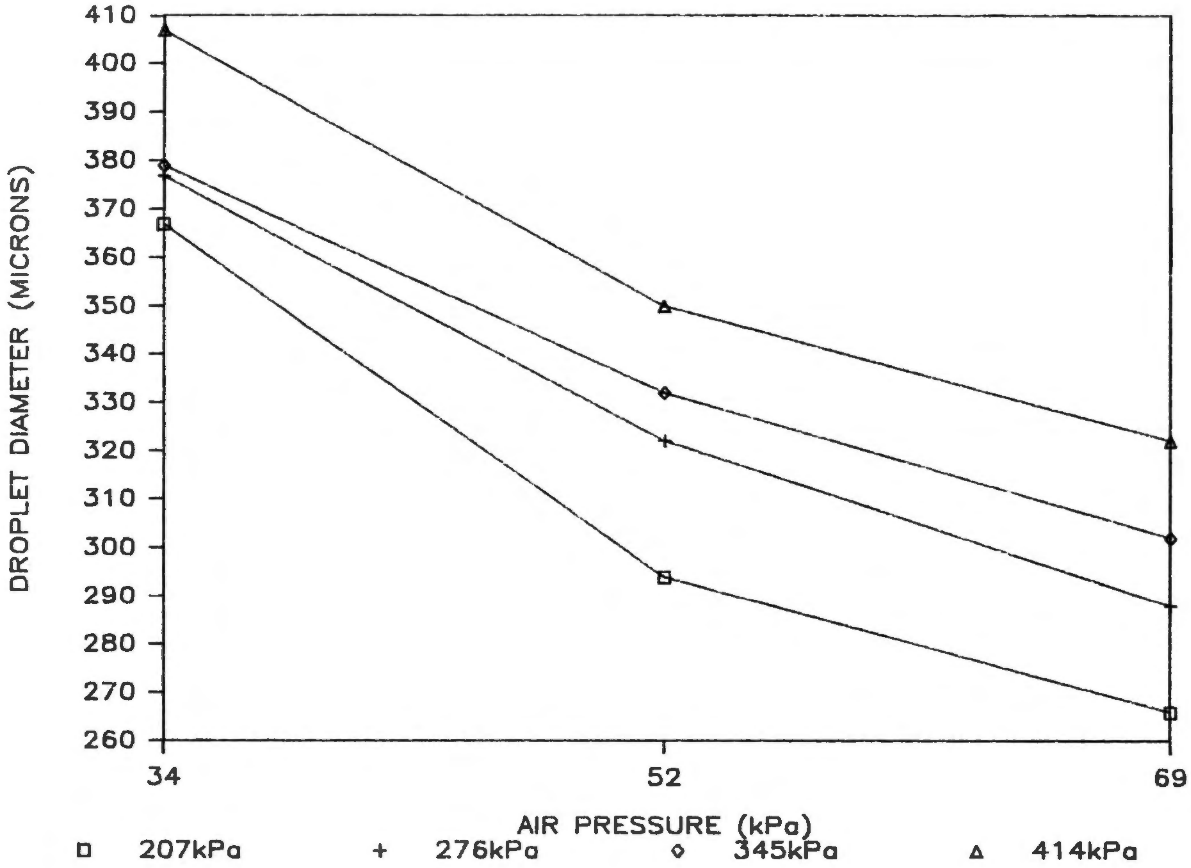

Figure 12. Effect of changing air pressure for each liquid pressure on the volume median diameter (VMD) for tapwater at 27 cm below the nozzle.

Table 3. Effect of changing air pressure while maintaining a constant liquid pressure for tapwater at 27 cm below the nozzle.

Liquid Pressure (kPa)	Air Pressure (kPa)	Statistical Droplet Diameters (Microns)			
		Sauter Mean Diameter	10% Cumulative Volume Diameter	Volume Median Diameter	90% Cumulative Volume Diameter
207	34	310a*	198a	367a	522a
	52	250b	161b	294b	456b
	69	227c	146c	266c	421c
276	34	320a	206a	377a	520a
	52	270b	170b	322b	492a
	69	246c	158c	288c	451b
345	34	321a	213a	379a	527a
	52	271b	161b	332b	500a
	69	261b	169b	302c	465b
414	34	341a	226a	407a	535a
	52	284b	178b	350b	516a,b
	69	271b	171b	322c	490b

*Means followed by same letter for the given statistical droplet diameter within a given liquid pressure are not significantly different at the alpha level = 0.05.

Table 4. Effect of changing air pressure while maintaining a constant liquid pressure for the oil-in-water solution at 27 cm below the nozzle.

Liquid Pressure (kPa)	Air Pressure (kPa)	Statistical Droplet Diameters (Microns) Sauter Mean Diameter	10% Cumulative Volume Diameter	Volume Median Diameter	90% Cumulative Volume Diameter
207	34	319a*	205a	371a	526a
	52	266b	171b	305b	467b
	69	247c	163b	283c	447b
276	34	314a	199a	373a	573a
	52	284b	180b	331b	495a,b
	69	264c	172b	303c	464b
345	34	333a	215a	390a	536a
	52	297b	188b	346b	511a,b
	69	285b	182b	330b	488b
414	34	340a	223a	402a	542a
	52	307b	197b	362b	523a,b
	69	288c	183c	340c	505b

*Means followed by same letter for the given statistical droplet diameter within a given liquid pressure are not significantly different at the alpha level = 0.05.

The actual rate varies among the statistical values plotted and appears to be related to the liquid pressure at which the three air pressures were tested. This droplet size trend was similar for both tapwater and the oil-in-water solution.

Effect of Liquid Pressure

Figures 13 through 16 show the effect of increasing liquid pressure when air pressure is held constant. Both tapwater and the oil-in-water solution generally showed an increase in droplet size for an increase in liquid pressure. This behavior is opposite that of a conventional hydraulic atomizer.

Increases in the droplet size for increases in liquid pressure is attributed to the mechanism by which the liquid is atomized. If a constant flow of air into the mixing chamber is maintained, any increase in liquid pressure will increase the amount of liquid entering the chamber to be atomized. As the liquid-flow to air-flow ratio is increased, droplet size will increase since a constant volume of air impinges on an increasing quantity of liquid.

Statistical analyses indicated no significant differences existed among droplet size trends for tapwater at liquid pressures of 276 kPa and 345 kPa in combination with air pressures of 34, 52, and 69 kPa (Table 5). The same is true for the oil-in-water solution at liquid pressures of 276 kPa and 345 kPa, but only at 52 kPa air pressure (Table 6).

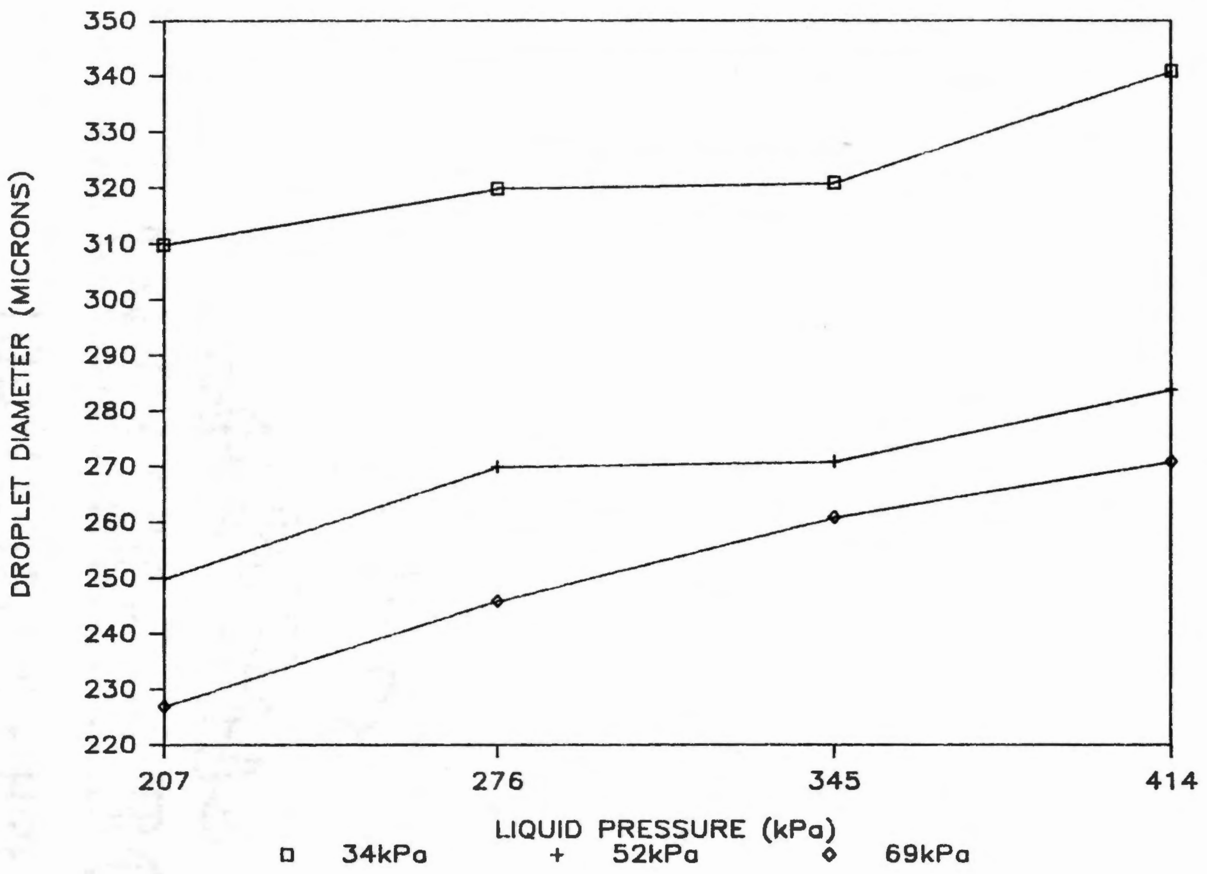

Figure 13. Effect of changing liquid pressure for each air pressure on the Sauter mean diameter (SMD) for tapwater at 27 cm below the nozzle.

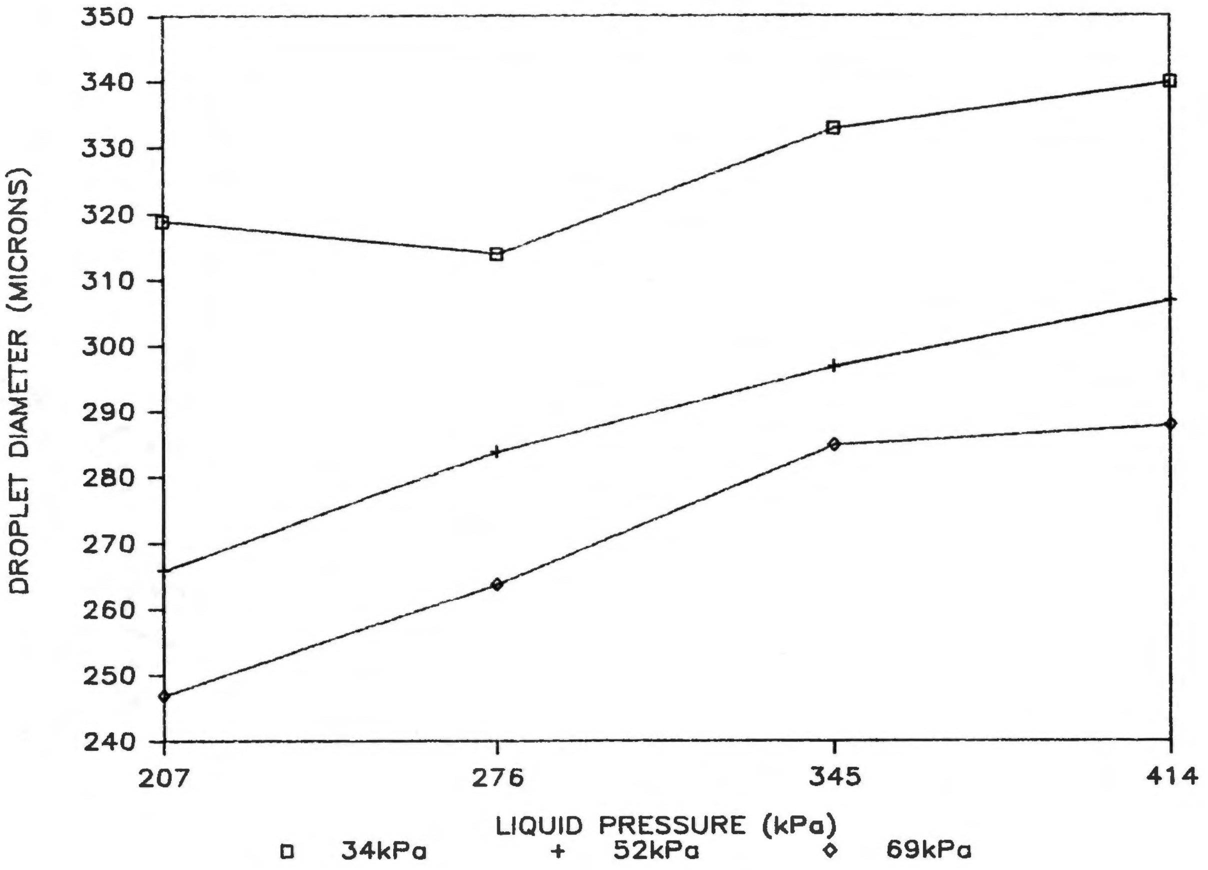

Figure 14. Effect of changing liquid pressure for each air pressure on the Sauter mean diameter (SMD) for the oil-in-water solution.

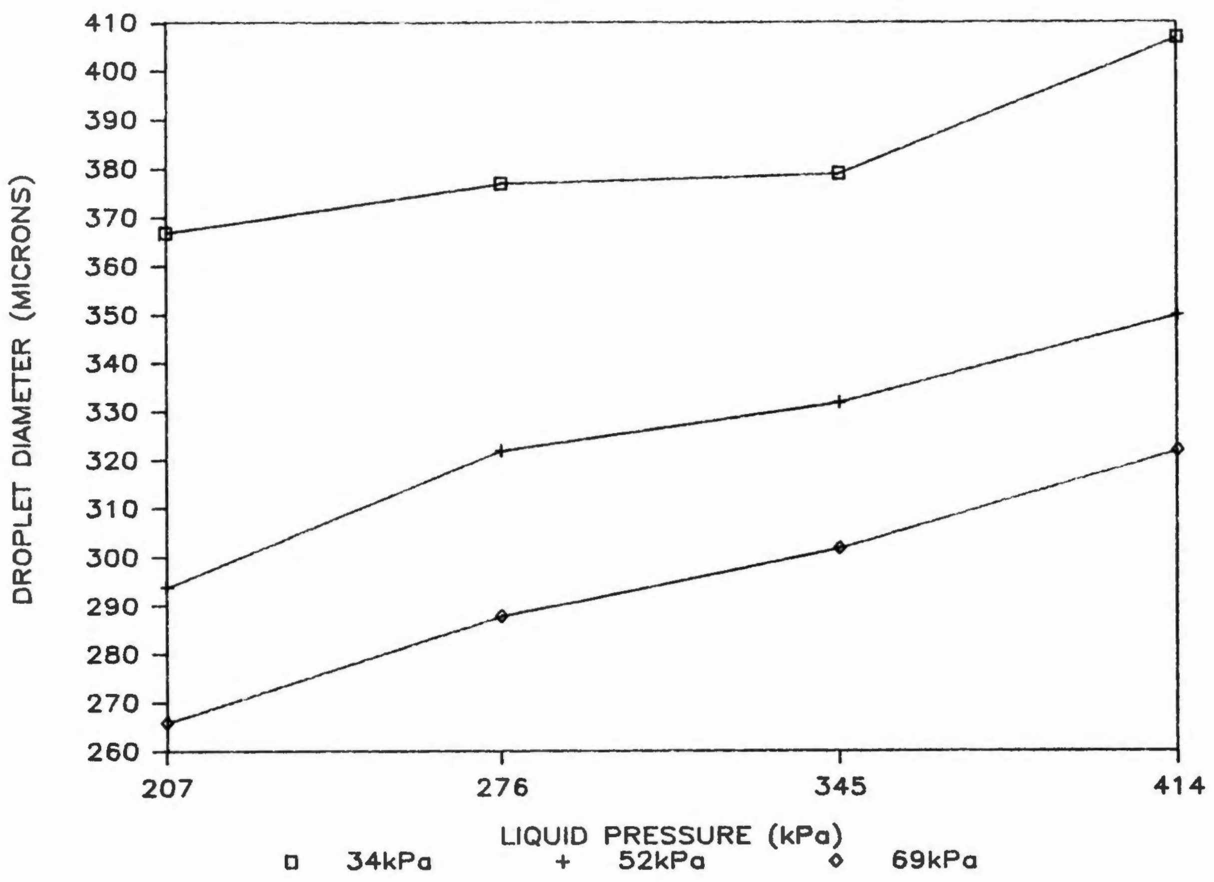

Figure 15. Effect of changing liquid pressure for each air pressure on the volume median diameter (VMD) for tapwater at 27 cm below the nozzle.

Table 5. Effect of changing liquid pressure while maintaining a constant air pressure for tapwater at 27 cm below the nozzle.

		Statistical Droplet Diameters (Microns)			
Liquid Pressure (kPa)	Air Pressure (kPa)	Sauter Mean Diameter	10% Cumulative Volume Diameter	Volume Median Diameter	90% Cumulative Volume Diameter
34	207	310a*	198a	367a	522a
	276	320a	206a,b	377a	520a
	345	321a	213b	379a	527a
	414	341b	226c	407b	535a
52	207	250a	161a	294a	456a
	276	270b	170a,b	322b	492b
	345	271b	161a	332b,c	500b
	414	284b	178b	350c	516b
69	207	227a	146a	266a	421a
	276	246b	158b	288b	451a,b
	345	261b,c	169b,c	302b,c	465b,c
	414	271c	171c	322c	490c

*Means followed by same letter for the given statistical droplet diameter within a given air pressure are not significantly different at the alpha level = 0.05.

Table 6. Effect of changing liquid pressure while maintaining a constant air pressure for the oil-in-water solution at 27 cm below the nozzle.

Liquid Pressure (kPa)	Air Pressure (kPa)	Statistical Droplet Diameters (Microns)			
		Sauter Mean Diameter	10% Cumulative Volume Diameter	Volume Median Diameter	90% Cumulative Volume Diameter
34	207	319a,b*	205a,b	371a	526a
	276	314a	199a	373a	513a
	345	333b,c	215b,c	390a,b	536a
	414	340c	223c	402b	542a
52	207	266a	171a	305a	467a
	276	284a,b	180a,b	331b	495a,b
	345	297b,c	188b,c	346b,c	511b
	414	307c	197c	362c	523b
69	207	247a	163a	283a	447a
	276	264a	172a,b	303a	464a,b
	345	285b	182b	330b	488b,c
	414	288b	183b	340b	505c

*Means followed by same letter for the given statistical droplet diameter within a given air pressure are not significantly different at the alpha level = 0.05.

Effects of Liquid Physical Properties

The model used to analyze the differences between droplets formed from tapwater and the oil-in-water solution across all liquid and air pressure combinations indicated the oil-in-water solution did not always exhibit the same characteristics as tapwater. This may be due in part to separation of the oil from the solution during atomization which would cause surface tension to change, thus producing many varied droplets. Differences were observed for the SMD, DV1, and VMD values when the air pressure was set at 69 kPa in combination with all liquid pressures. However, when air pressure was 34 kPa in combination with all liquid pressures, no significant differences existed between the two liquids for these same values. In addition, there were no significant differences among the DV9 values between tapwater and the oil-in-water solution at all air and liquid pressure combinations.

The experimental model used for evaluating the effect of tapwater, distilled water, a hard well water, and the oil-in-water solution at the four liquid pressures in combination with 52 kPa air pressure was inappropriate for testing differences among the liquids. In effect, the liquids were blocks and each liquid pressure was restricted to a given liquid (block) in the analysis of variance (ANOVA). This added variance or restriction error resulted in there being no suitable mean square to use in the denominator for testing the liquid mean square (Sokal and Rohlf, 1981). Further, there was the added possibility of systematic error in the experiment set-up similar to that which may have existed during the comparisons of tapwater and the oil-in-water solution. However, since the blocks were not replicated as they were for the tapwater and oil-in-water solution, comparisons among the liquid physical properties were not pursued.

Graphs were produced which show the relationship between distilled water and the oil-in-water solution, and a similar relationship between the hard well water and tapwater (Figures 17-20). The droplets formed from distilled water and the oil-in-water solution appear to be larger than those from the other liquids tested; however, as stated earlier, it was not possible from the given model to determine statistically if the size differences are significant. All liquids tested generally exhibited the trend of increasing droplet size with increasing liquid pressure.

Effect of Height

Differences among the statistical values tested for the sample distributions existed for certain air and liquid pressure combinations at the two different heights at which tapwater was tested (Table 7). The trends reported indicated that droplets measured 43 cm below the nozzle were larger than those measured 27 cm below the nozzle; however, this varied among the liquid and air pressure settings used. None of the pressure combinations yielded DV9 values that were significantly different between the two heights.

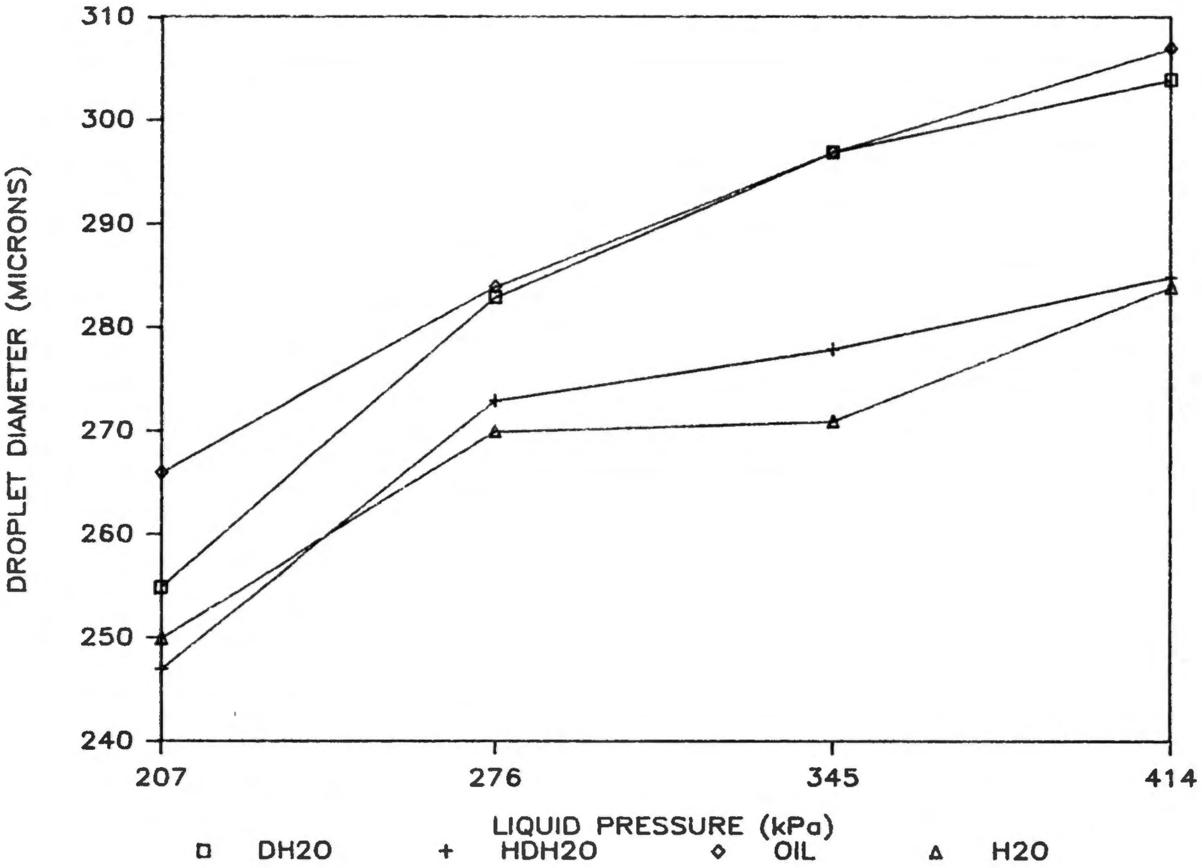

Figure 17. Effect of distilled water (DH20), hard well water (HDH20), the oil-in-water solution (OIL), and tapwater (H20) on Sauter mean diameter for changes in liquid pressure at 52 kPa air pressure.

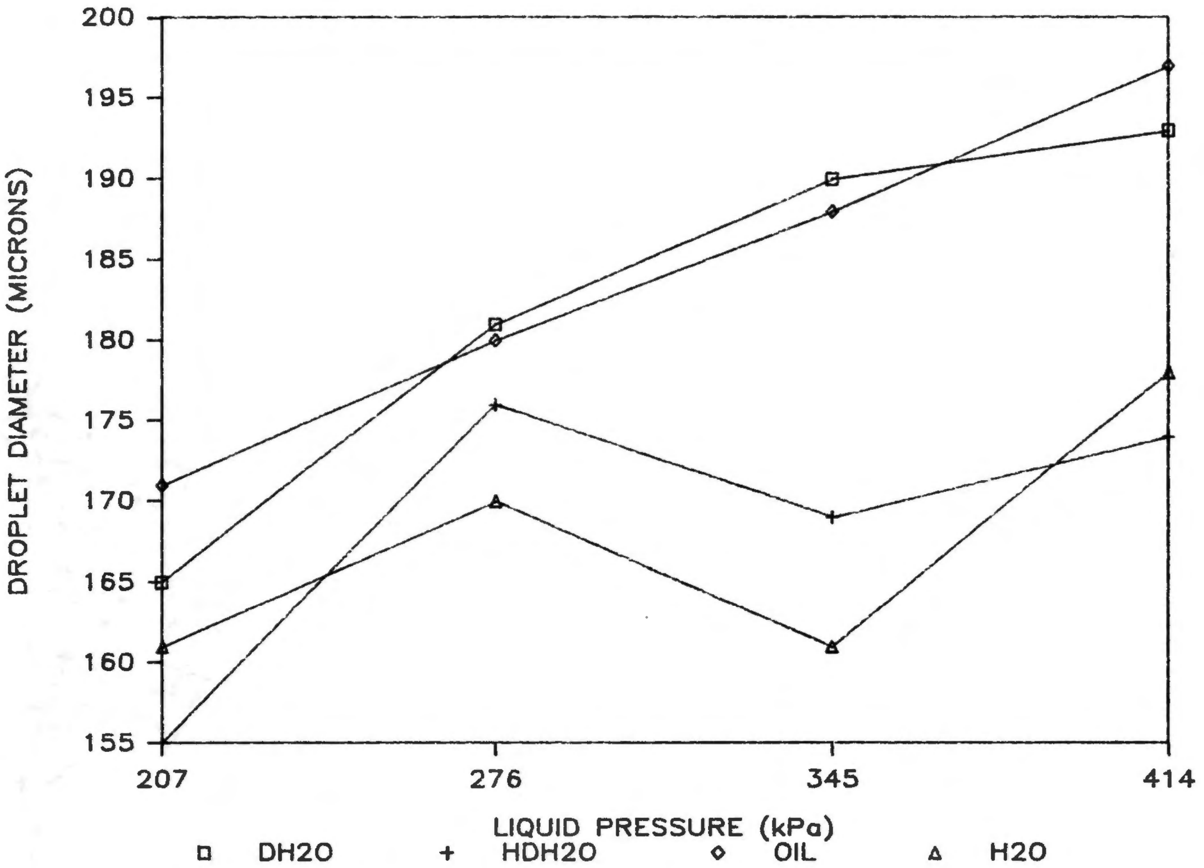

Figure 18. Effect of distilled water (DH2O), hard well water (HDH2O), the oil-in-water solution (OIL), and tapwater (H2O) on the droplet diameter at 10% of the cumulative volume curve (DV1).

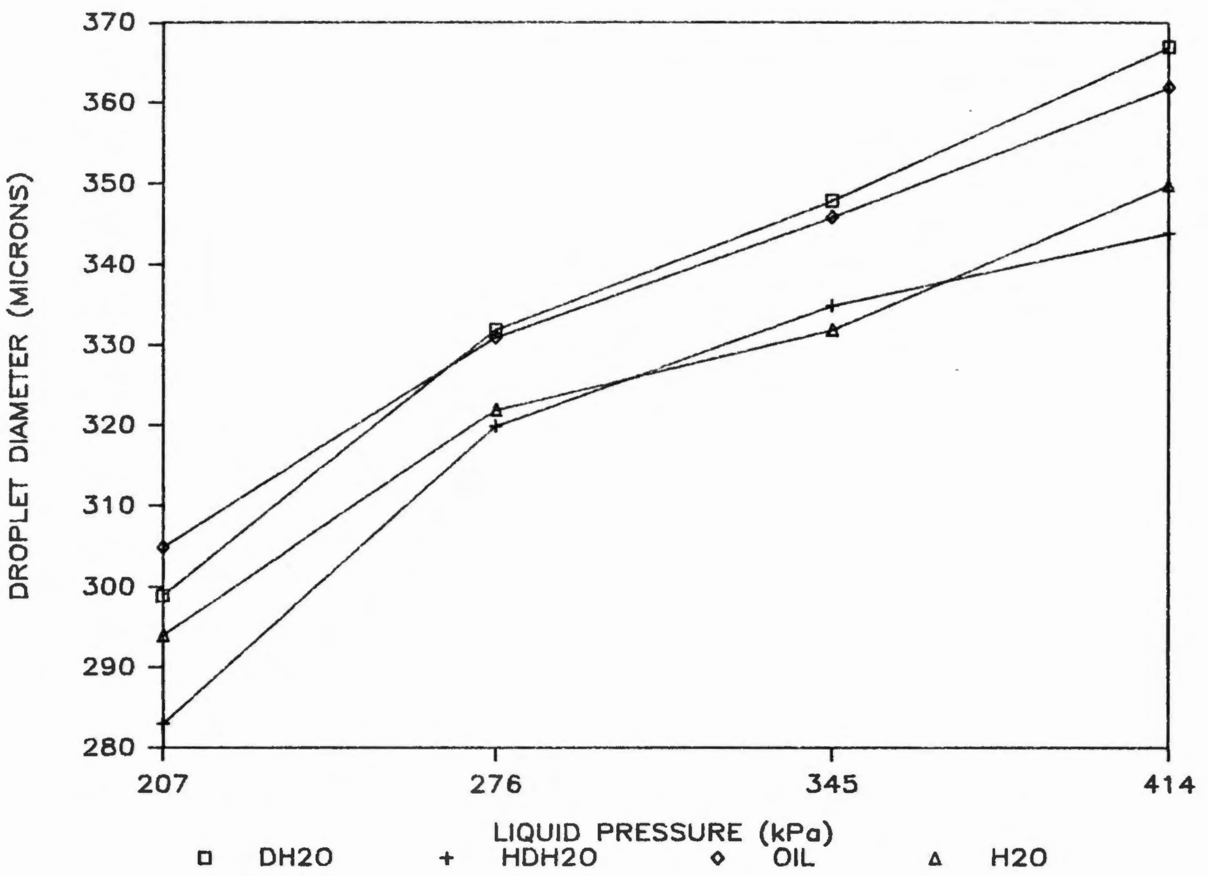

Figure 19. Effect of distilled water (DH2O), hard well water (HDH2O), the oil-in-water solution (OIL), and tapwater (H2O) on the volume median diameter (VMD).

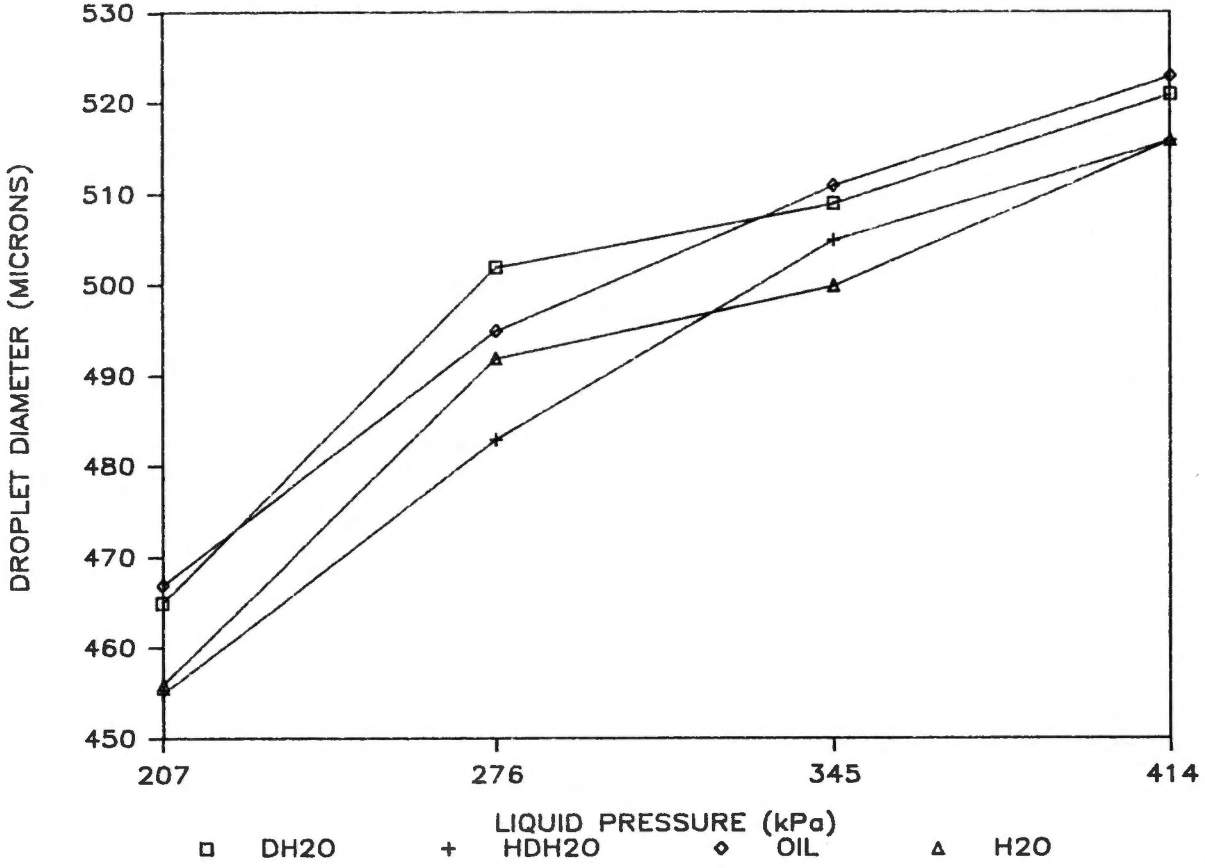

Figure 20. Effect of distilled water (DH2O), hard well water (HDH2O), the oil-in-water solution (OIL), and tapwater (H2O) on the droplet diameter at 90% of the cumulative volume curve (DV9).

Table 7. Effect on droplet size measurements when data is taken 27 cm below the nozzle versus 43 cm below the nozzle.[a]

Air Pressure (kPa)	Liquid Pressure (kPa)	Height (cm)	Statistical Droplet Diameters (Microns)			
			Sauter Mean Diameter	10% Cumulative Volume Diameter	Volume Median Diameter	90% Cumulative Volume Diameter
34	276	27	---[b]	---	377a	---
		43	---	---	403b	---
	345	27	321a[c]	---	379a	---
		43	336b	---	406b	---
52	276	27	270a	170a	322a	---
		43	282b	184b	335b	---
	345	27	---	161a	---	---
		43	---	178b	---	---
	414	27	284a	178a	---	---
		43	306b	202b	---	---

[a] Tapwater was used during these tests.

[b] Values and additional pressure combinations not listed were not significantly different for the samples tested.

[c] Means followed by same letter for the given statistical droplet diameter within each air pressure and liquid pressure combination are not significantly different at the alpha level = 0.05.

Position Evaluation

Table 8 and Figures 21 through 24 show the variation in droplet size produced at various positions left and right of center along a line 27 cm below the nozzle tip. Mean droplet size decreased from 15.2 cm left-of-center to the center of each spectrum. Mean droplet size continued to decrease to 7.6 cm right-of-center before increasing at 15.2 cm right-of-center. This trend was observed for the SMD, DV1, VMD, and DV9; however, the mean droplet size for 15.2 cm right-of-center was not always greater than the mean droplet size at other positions within the spectrum except for the position 7.6 cm right-of-center.

Nozzle Tip Evaluation

Table 9 and Figures 25 through 28 show the variation in droplet size produced by the six nozzle tips tested. There were no significant differences observed among the VMD and DV9 values for any of the tips tested; however, differences were observed for the SMD and DV1 values. Despite efforts to maintain a high degree of quality control during production runs, differences among the droplet spectra emitted by the nozzle tips do exist. This may occur because of changes in liquid physical properties, ambient conditions, and/or operating conditions in addition to any structural differences among nozzle tips. Since droplet spectra can change due to these external phenomena, evaluation of nozzle tip production practices based on spectra differences may not be totally reliable.

Table 8. Droplet sizes measured at various positions left and right of center along a line 27 cm below the nozzle tip.[a]

Position Within Spectrum	Statistical Droplet Diameters (Microns)			
	Sauter Mean Diameter	10% Cumulative Volume Diameter	Volume Median Diameter	90% Cumulative Volume Diameter
Left-of-center (15.2 cm)	325a[b]	214a	365a	531a
Left-of-center (7.6 cm)	298b	193b	247b	510a,b
Center	272c	173c	324c	491b,c
Right-of-center (7.6 cm)	262c	167c	311c	474c
Right-of-center (15.2 cm)	308b	210a	340b	489b,c

[a] Liquid pressure and air pressure were 276 kPa and 52 kPa, respectively.

[b] Means with the same letter for the given statistical droplet diameter are not significantly different at the alpha level = 0.05.

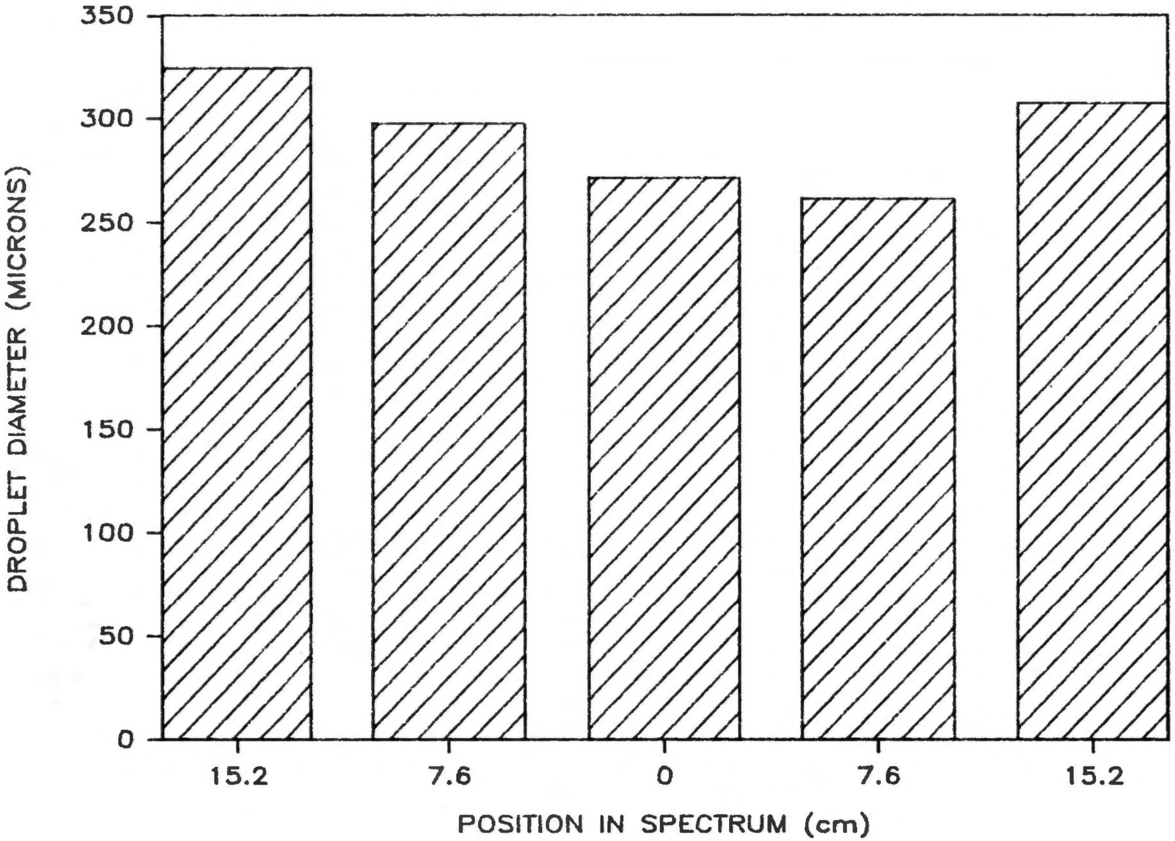

Figure 21. Sauter mean diameters (SMD) for five positions along a line 27 cm below the nozzle for tapwater at 52 kPa air pressure and 276 kPa liquid pressure.

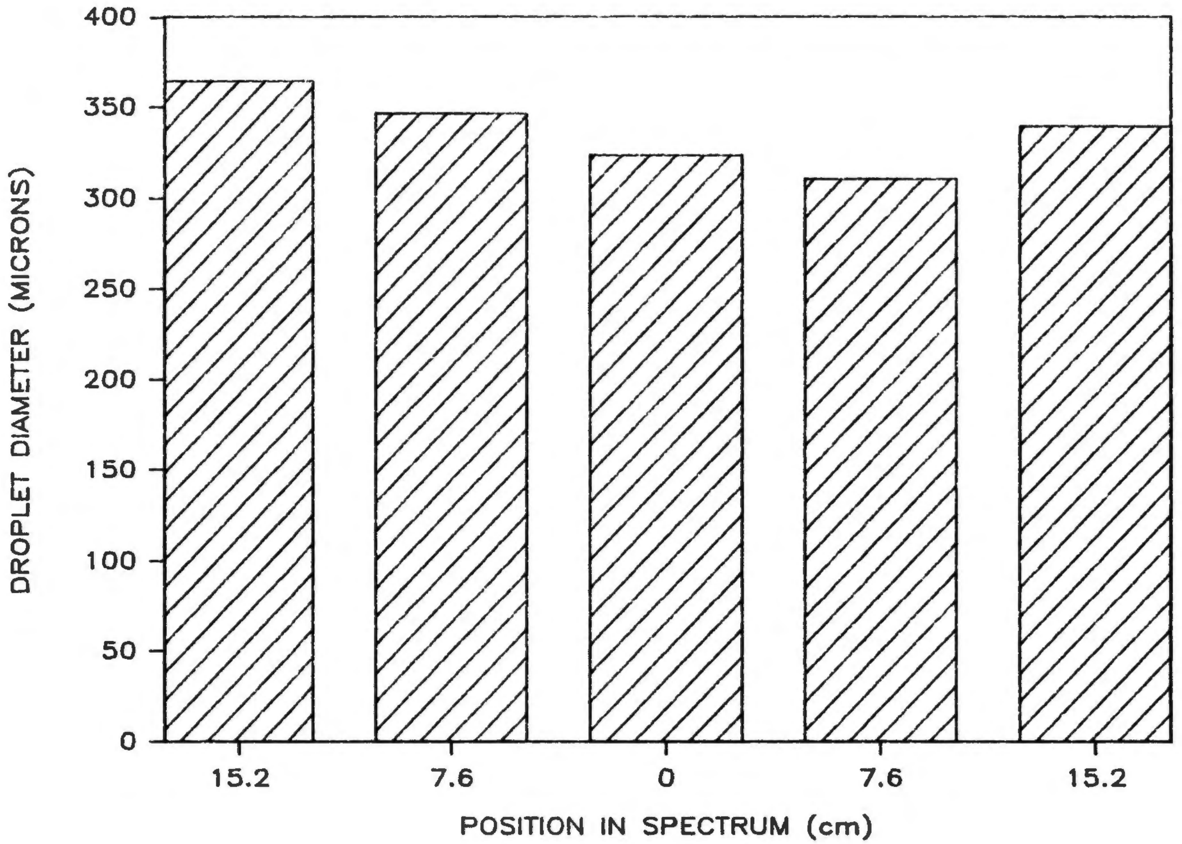

Figure 22. Volume median diameters (VMD) for five positions along a line 27 cm below the nozzle for tapwater at 52 kPa air pressure and 276 kPa liquid pressure.

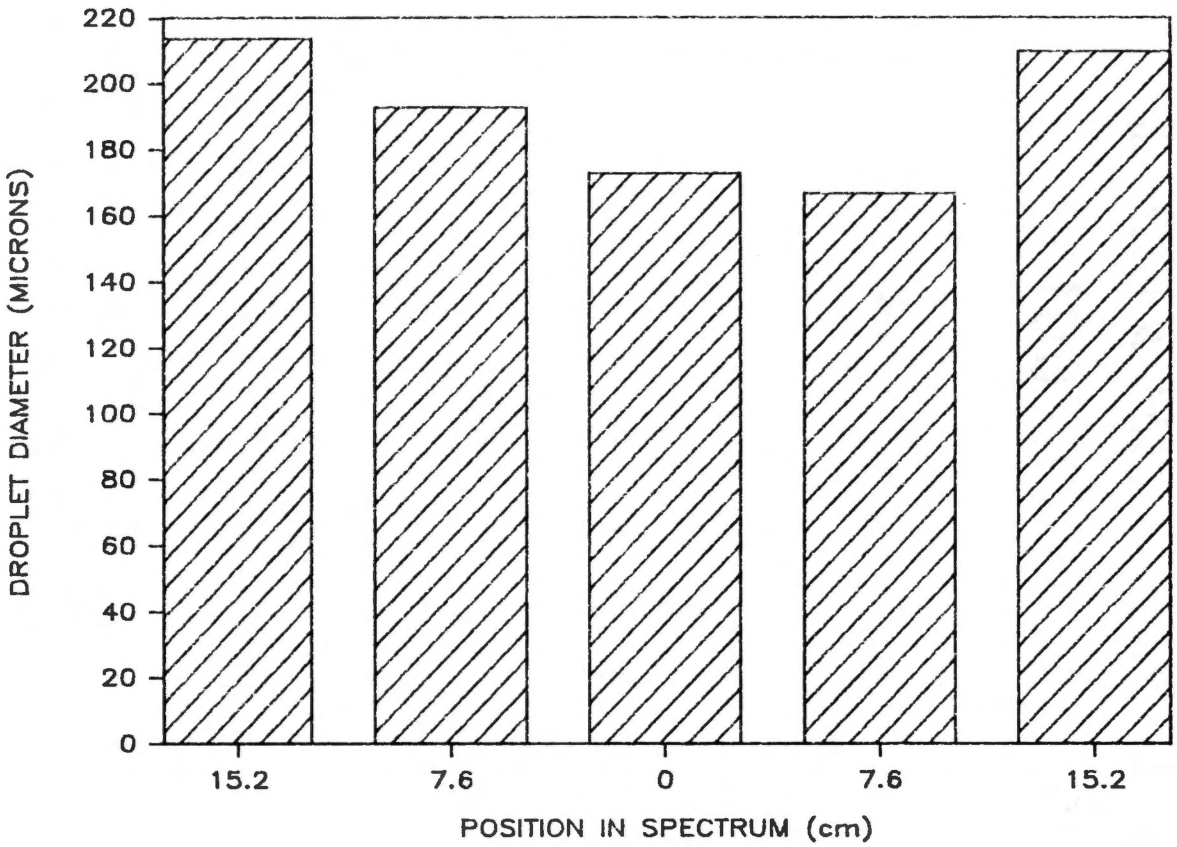

Figure 23. Droplet diameters at 10% of the cumulative volume curve (DV1) for five positions along a line 27 cm below the nozzle for tapwater at 52 kPa air pressure and 276 kPa liquid pressure.

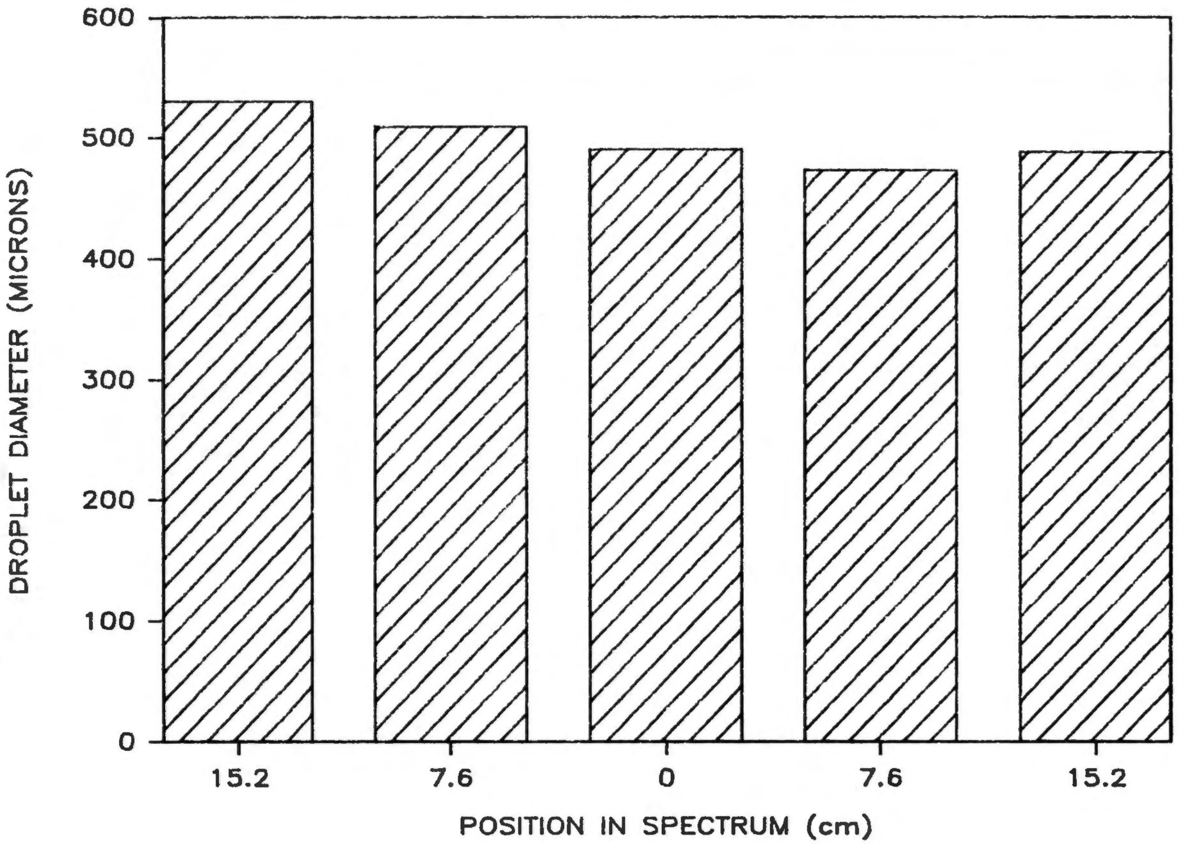

Figure 24. Droplet diameters at 90% of the cumulative volume curve (DV9) for five positions along a line 27 cm below the nozzle for tapwater at 52 kPa air pressure and 276 kPa liquid pressure.

Table 9. Variation in droplet sizes produced from six different nozzle tips.[a]

	Statistical Droplet Diameters (Microns)			
Nozzle Tip	Sauter Mean Diameter	10% Cumulative Volume Diameter	Volume Median Diameter	90% Cumulative Volume Diameter
1	281a[b]	182a	329a	494a
2	277a	177a,b	328a	493a
3	263a,b	164b,c	320a	491a
4	262a,b	165b,c	317a	486a
5	254b	157c	317a	499a
6	272a,b	173a,c	319a	477a

[a] Liquid pressure and air pressure were 276 kPa and 52 kPa, respectively.

[b] Means followed by the same letter for the given statistical droplet diameter are not significantly different at the alpha level = 0.05.

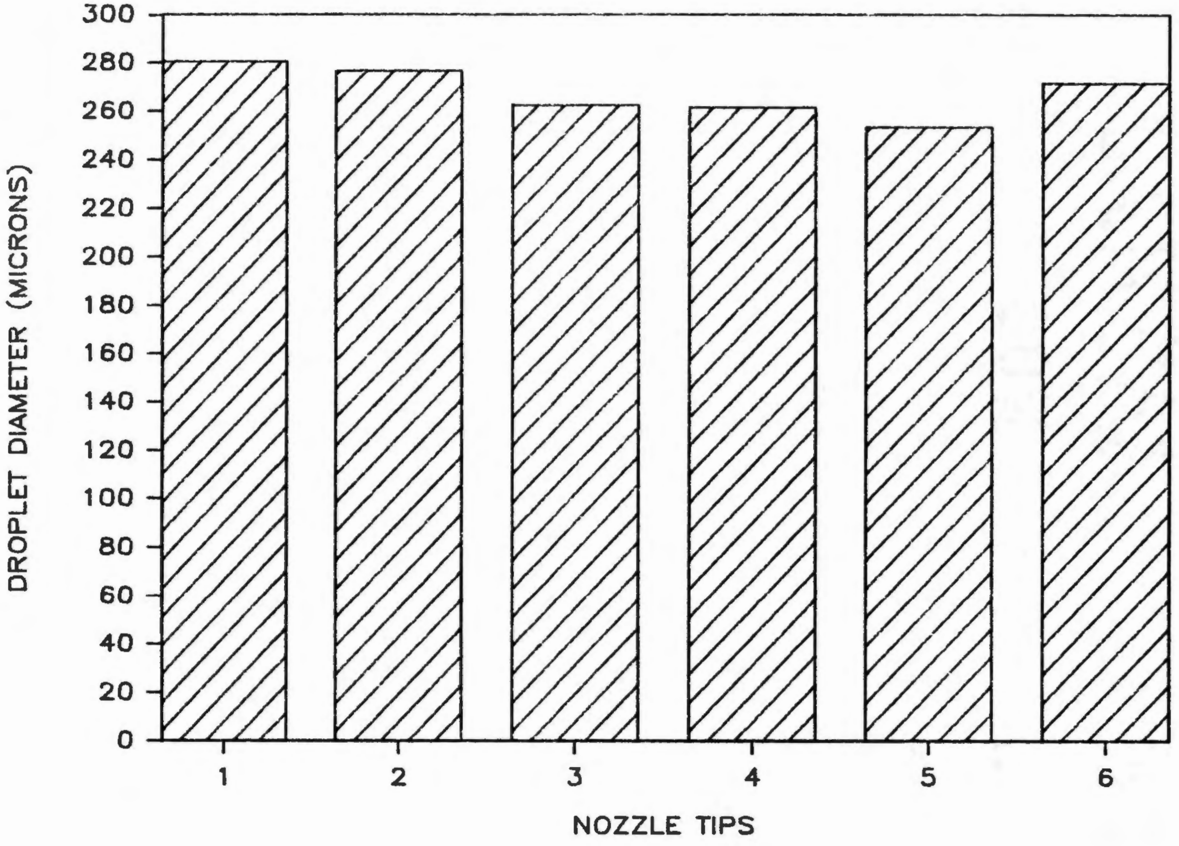

Figure 25. Sauter mean diameters (SMD) for six nozzle tips tested with tapwater at 52 kPa air pressure and 276 kPa liquid pressure.

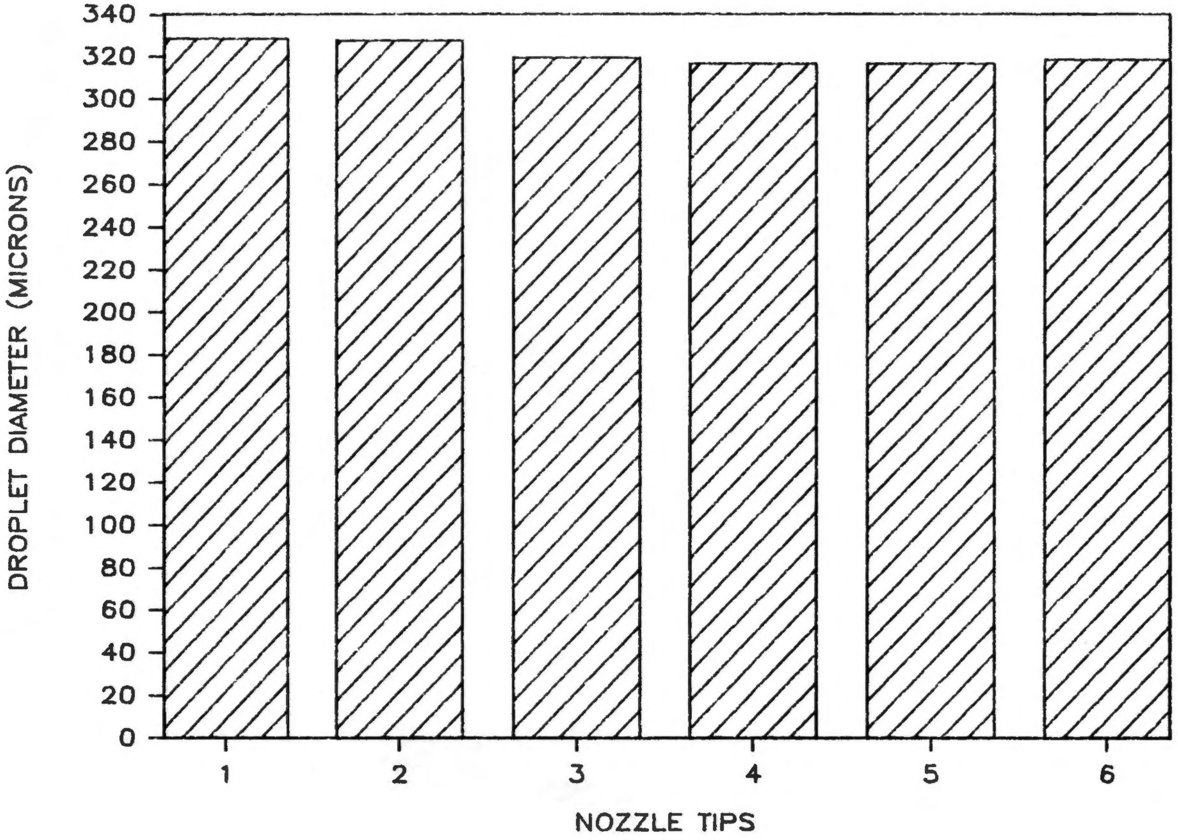

Figure 26. Volume median diameter (VMD) for six nozzle tips tested with tapwater at 52 kPa air pressure and 276 kPa liquid pressure.

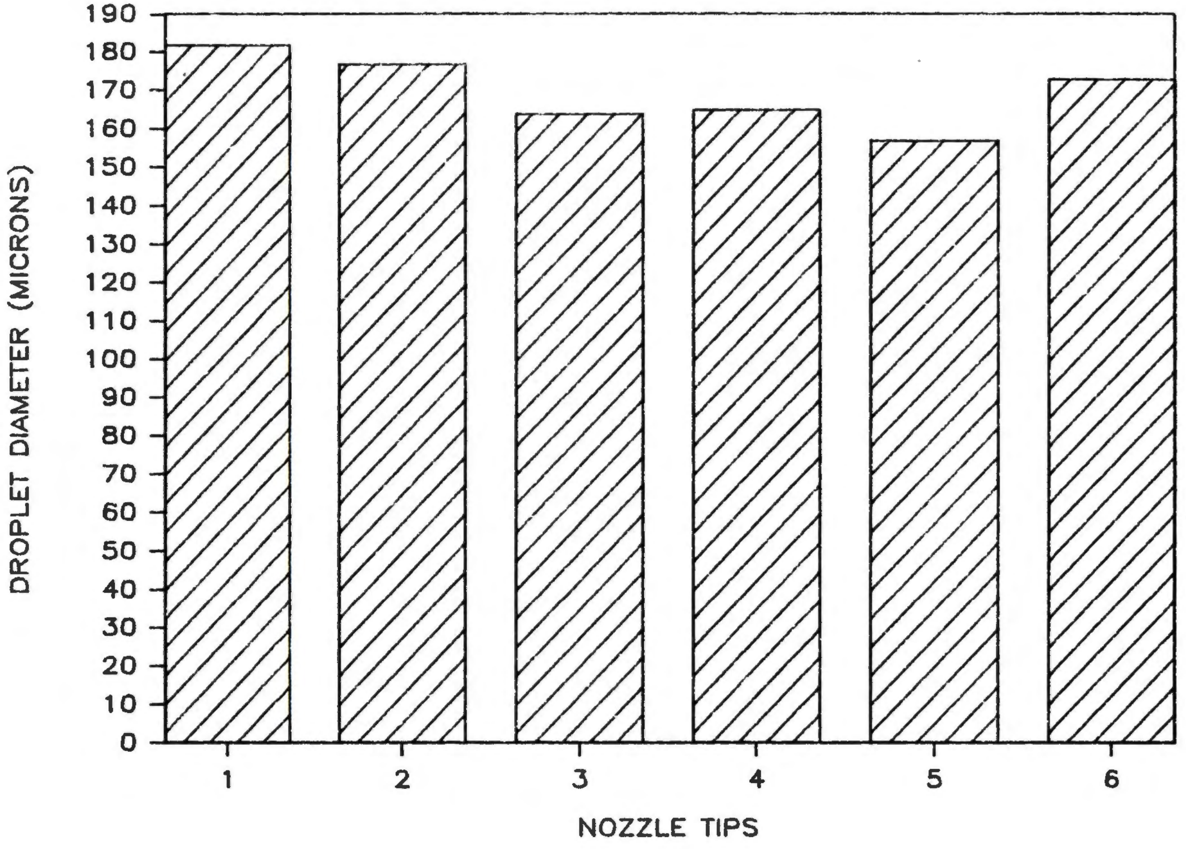

Figure 27. Droplet diameters at 10% of the cumulative volume curve (DV1) for six nozzle tips tested with tapwater at 52 kPa air pressure and 276 kPa liquid pressure.

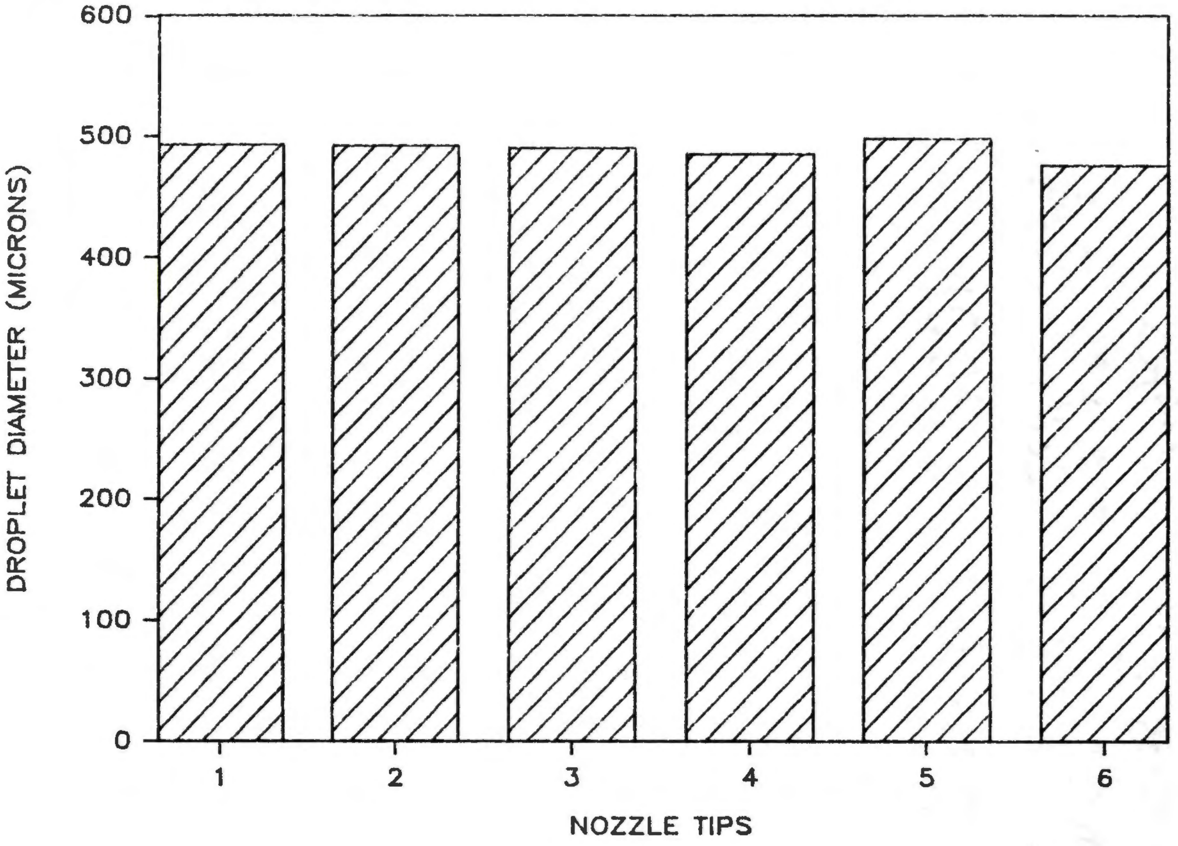

Figure 28. Droplet diameters at 90% of the cumulative volume curve (DV9) for six nozzle tips tested with tapwater at 52 kPa air pressure and 276 kPa liquid pressure.

Spray Pattern Analysis

Analyses of the coefficient of variation (CV) among lateral spray distributions for tapwater and the oil-in-water solution at a height of 48 cm and an air pressure of 52 kPa in combination with liquid pressures of 276 kPa and 345 kPa were performed. Figures 29 and 30 give the distribution coefficients of variation for nozzle spacings between 20 cm and 120 cm along the boom. Based on these figures, spacing the nozzles between 40 cm and 60 cm along the boom would be adequate for most application operations. Figures 31 through 34 are corresponding graphical representations of the lateral spray distributions analyzed.

Figures 35 through 54 in Appendix B were selected to show the pattern distributions for some of the samples of tapwater and the oil-in-water solution that were not significantly different at 276 kPa and 345 kPa as shown in Tables 5 and 6, pages 58 and 59, respectively. The lower two air pressure settings used, 34 kPa and 52 kPa, at the boom height of 53 cm appear to produce the most uniform distributions of spray from the nozzle for tapwater when liquid pressures were 276 kPa and 345 kPa. The oil-in-water solution patterns vary widely for the same liquid pressures at an air pressure of 52 kPa, but appear to be more uniform at the lower boom heights.

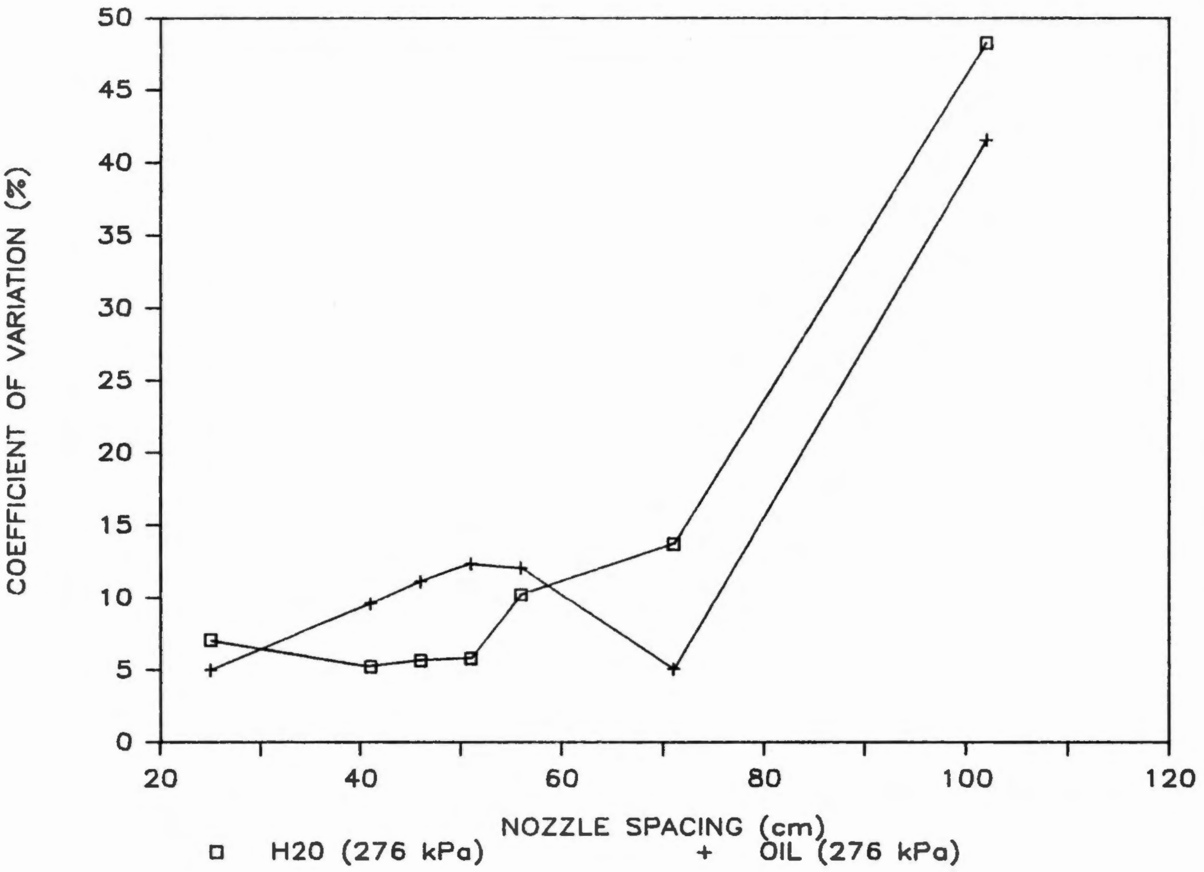

Figure 29. Coefficients of variation (CV) of the lateral spray distribution at various nozzle spacings for tapwater and the oil-in-water solution at 52 kPa air pressure, 276 kPa liquid pressure, and 48 cm above the patternator.

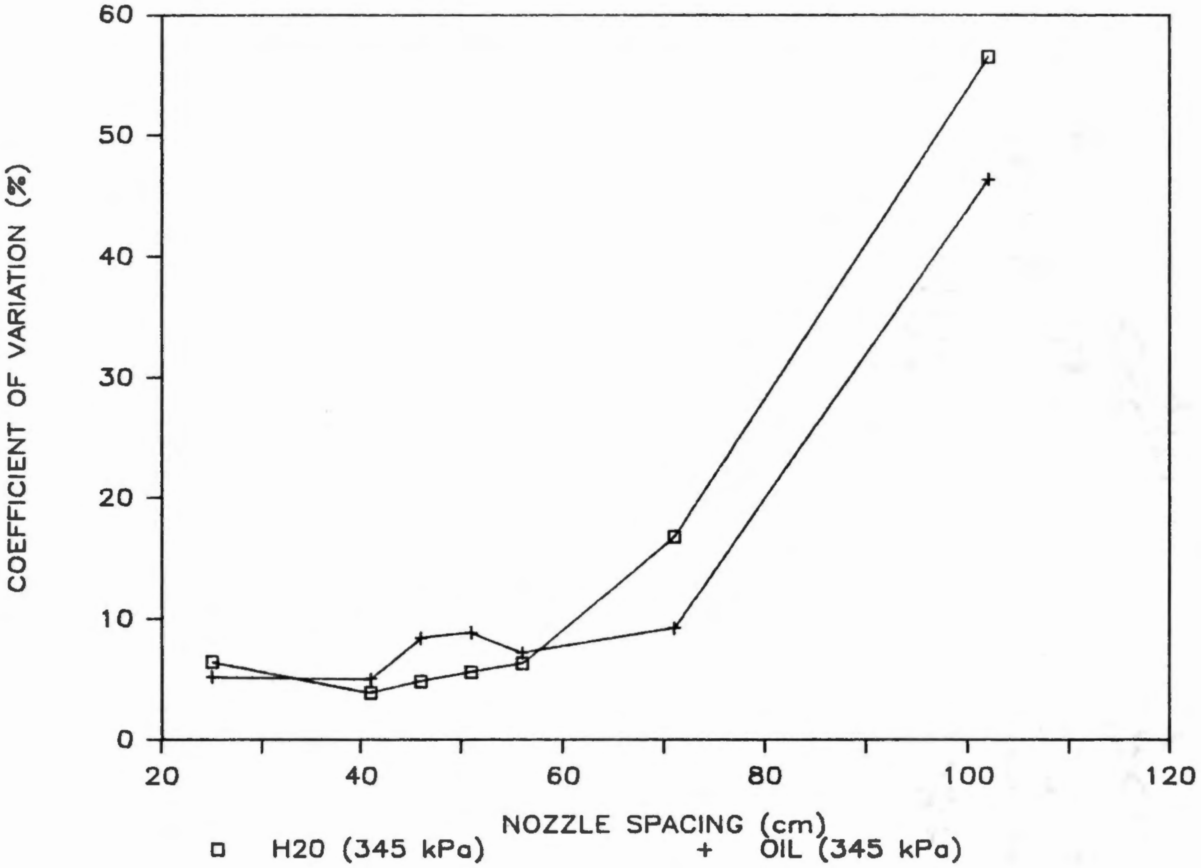

Figure 30. Coefficients of variation (CV) of the lateral spray distribution at various nozzle spacings for tapwater and the oil-in-water solution at 52 kPa air pressure, 345 kPa liquid pressure, and 48 cm above the patternator.

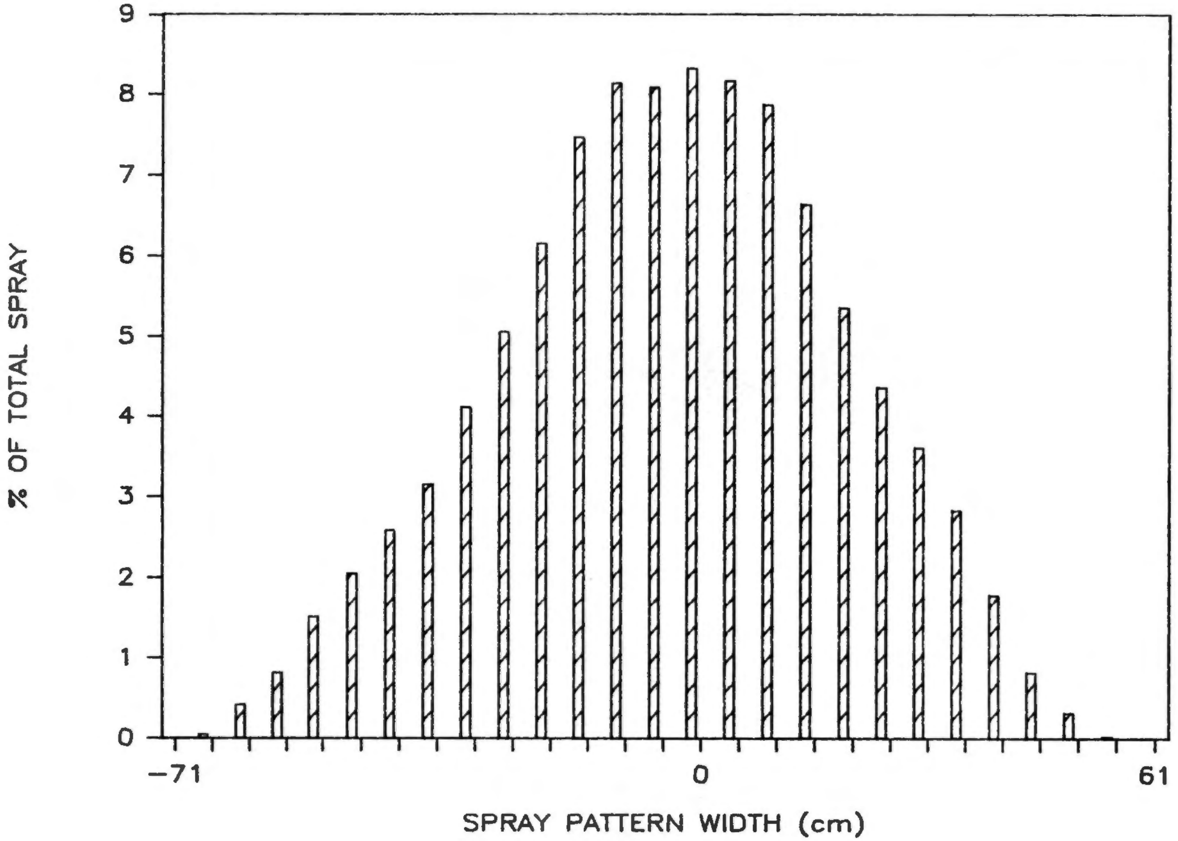

Figure 31. Lateral spray distribution for tapwater at 52 kPa air pressure, 276 kPa liquid pressure, and 48 cm above the patternator.

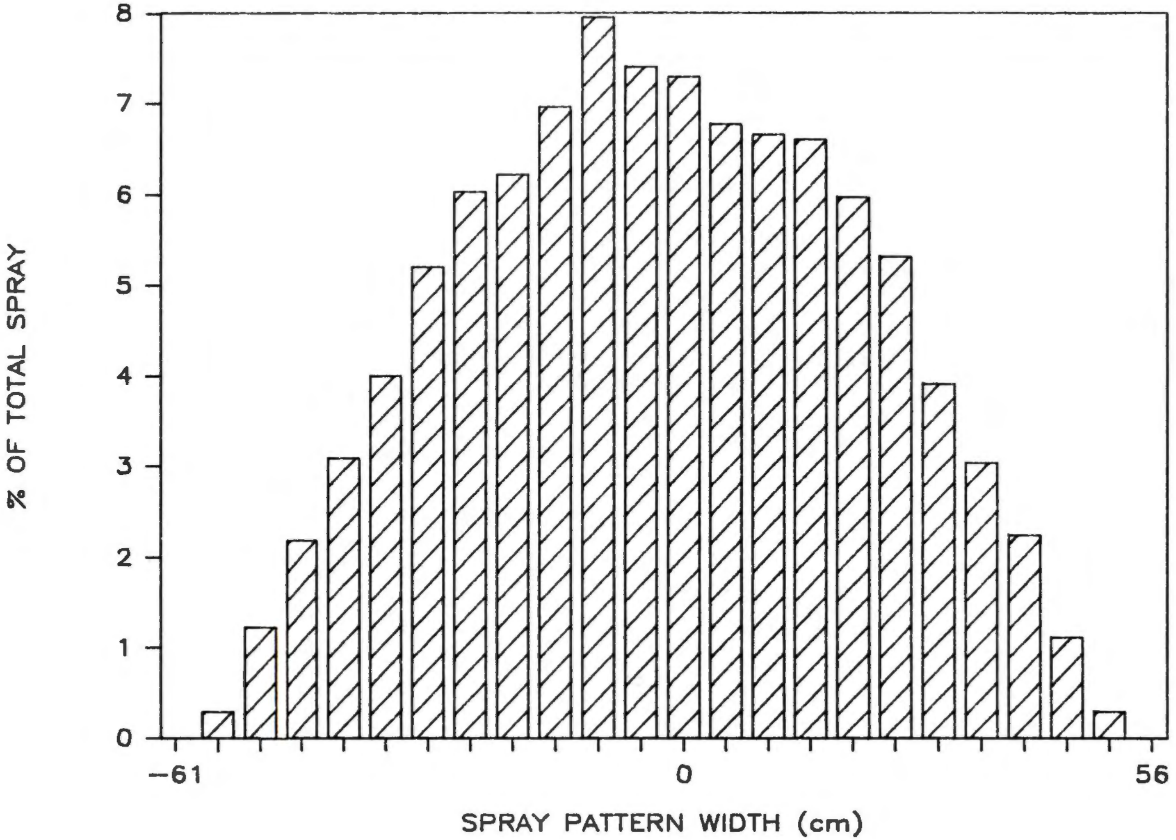

Figure 32. Lateral spray distribution for the oil-in-water solution at 52 kPa air pressure, 276 kPa liquid pressure, and 48 cm above the patternator.

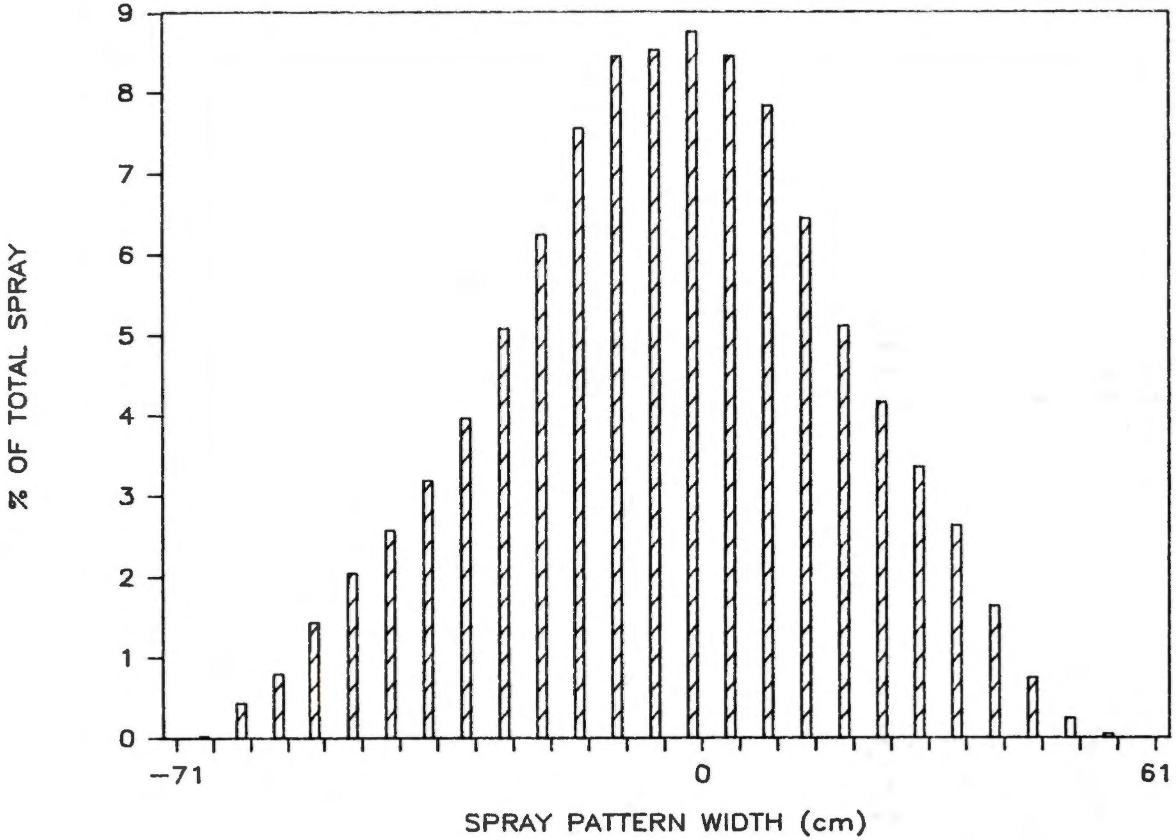

Figure 33. Lateral spray distribution for tapwater at 52 kPa air pressure, 345 kPa liquid pressure, and 48 cm above the patternator.

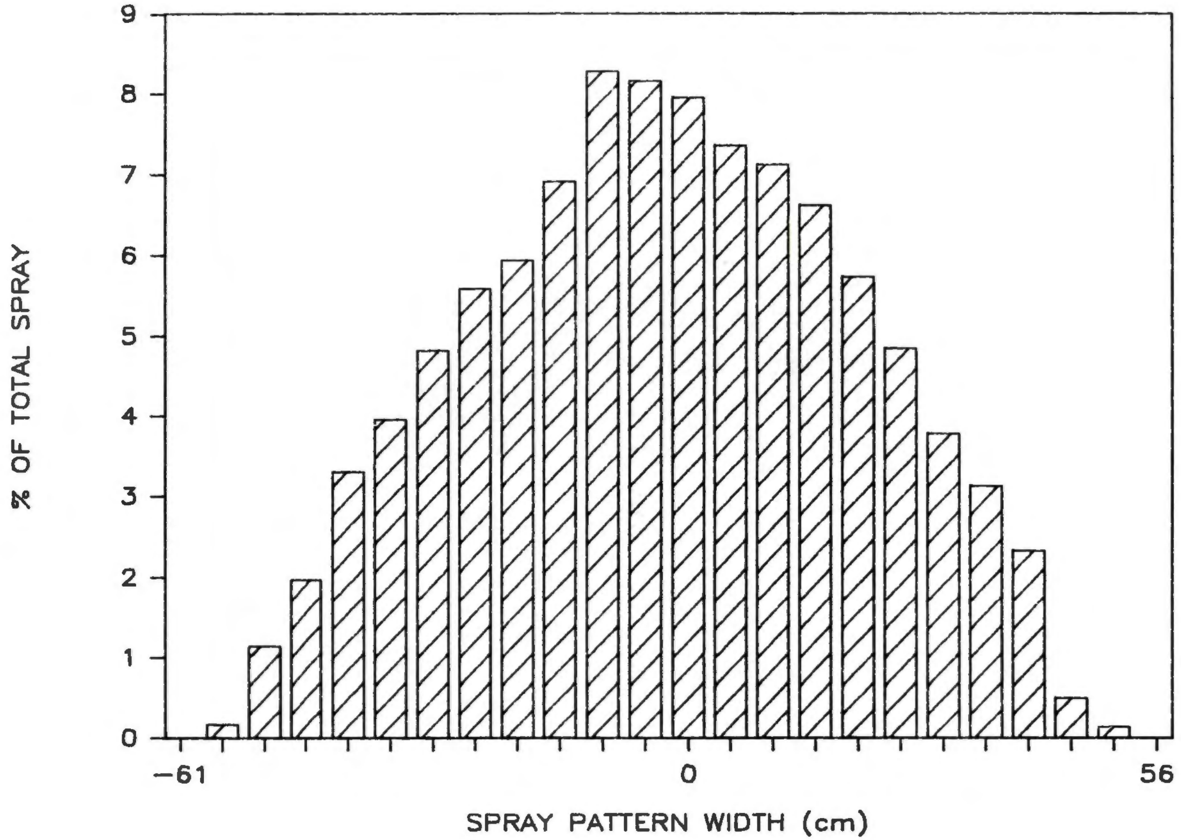

Figure 34. Lateral spray distribution for the oil-in-water solution at 52 kPa air pressure, 345 kPa liquid pressure, and 48 cm above the patternator.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

A prototype air-assist agricultural sprayer nozzle was evaluated at the USDA-ARS facilities in Beltsville, Maryland and at the Department of Agricultural Engineering of The University of Tennessee, Knoxville. The objectives of this evaluation were to analyze the droplet spectra over the range of liquid and air pressures recommended by the manufacturer, to evaluate the uniformity of lateral spray distribution produced by the nozzle, to determine appropriate liquid and air pressure settings for operation with water and an oil-in-water solution, and to evaluate nozzle performance with four liquids at a single air pressure setting in combination with several liquid pressure settings.

Droplet spectra data were collected using a laser spectrometer unit. Various operating parameters including liquid pressures of 207, 276, 345, and 414 kPa in combination with air pressures of 34, 52, and 69 kPa, four liquid types, and two different nozzle heights were observed. Trends among the volume-surface (Sauter) mean diameters, and the 10, 50, and 90 percent intercepts on the cumulative volume curves were analyzed for these parameters. In addition, analyses of the lateral spray distributions produced by the nozzle were performed using the coefficient of variation across the distribution. A patternator which allowed boom height to be adjusted was used for these studies. The air and liquid pressures listed above were used with tapwater and an oil-in-water solution during the analyses.

Conclusions

Evaluation of the trends observed during operation of an air-assist agricultural sprayer nozzle resulted in the following conclusions:

1. Single statistical values such as the volume-surface (Sauter) mean diameter and the 10, 50, and 90 percent intercepts on the cumulative volume curve do not completely characterize the droplet spectrum emitted from a nozzle. Analysis of the droplet counts per size class and the cumulative volume curves should be considered during spectra evaluations. Certain trends may be identified, however, using single statistical values.

2. The air-assist nozzle operated at liquid pressures of 276 kPa and 345 kPa appeared to produce a nearly constant mean droplet size for tapwater across the range of air pressures considered. The same was true for the oil-in-water solution at the same liquid pressures, but only when the air pressure was 52 kPa.

3. Mean droplet size produced by the air-assist nozzle generally decreased as air pressure was increased for a given liquid pressure setting. For example, both the Sauter mean diameter and volume median diameter decreased 30 percent for tapwater as air

pressure was increased from 34 kPa to 69 kPa at a liquid pressure of 276 kPa. Furthermore, the Sauter mean diameter and volume median diameter decreased 19 percent and 23 percent, respectively, for the oil-in-water solution as air pressure was increased similarly at a liquid pressure of 276 kPa.

4. Mean droplet size produced by the air-assist nozzle generally increased as liquid pressure was increased for a given air pressure setting. This occurred for all liquids tested. For example, Sauter mean diameter increased 12 percent for tapwater as liquid pressure increased from 207 kPa to 414 kPa at an air pressure of 52 kPa. Likewise, the volume median diameter increased 16 percent for the oil-in-water solution as liquid pressure was increased similarly at an air pressure of 52 kPa.

5. Mean droplet size within the spray pattern tended to increase from the center directly below the nozzle to positions 15.2 cm left- and right-of-center along a horizontal line. For example, volume median diameter increased 11 percent from the center position to a position 15.2 cm left-of-center and increased 5 percent from the center position to a position 15.2 cm right-of-center.

6. Mean droplet size differed slightly among the nozzle tips tested. However, since these differences may result from external phenomena such as ambient conditions or operating parameters in addition to any structural differences among the tip orifices or deflection plates, quantitative assessment of production quality control would be inappropriate.

7. Data collected from various distances below the point of fluid discharge should be evaluated separately when comparing the effects of test parameters on droplet spectra. Differences can exist among mean droplet sizes even when the same liquids are tested. During this evaluation, droplets collected at 43 cm below the nozzle tended to be larger than those collected at 27 cm below the nozzle. For example, the volume median diameter for the spray sample collected at the 43 cm height was 335 microns compared to 322 microns at the 27 cm height for tapwater at 52 kPa air pressure and 276 kPa liquid pressure.

8. Distilled water and the oil-in-water solution appeared to produce larger mean droplet sizes than do tapwater and a hard well water.

9. Nozzle spacings between 40 cm and 60 cm along the boom would be appropriate for most application operations. Coefficients of variation for broadcast application with this range of nozzle spacings were below 15 percent. For example, the coefficients of variation both for tapwater and the oil-in-water solution at 52 kPa air pressure, 276 kPa liquid pressure, and 48 cm above the surface are between 5 and 15 percent for nozzle spacings from 40 cm to 60 cm along the boom.

LITERATURE CITED

LITERATURE CITED

Akesson, N. B., S. E. Wilce, and W. E. Yates. 1971. Atomization control to confine sprays to treated fields. ASAE Paper No. 71-662. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Akesson, N. B., K. Haq, and W. E. Yates. 1983. Pesticide spray drop spectra correlated with fluid physical properties. ASAE Paper No. 83-1014. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Amberg, A. A. and B. J. Butler. 1970. High-speed photography as a tool for spray-droplet analysis. TRANSACTIONS of the ASAE 13(5):541.

Anonymous. 1982a. Standard practice for determining data criteria and processing for liquid drop size analysis. ASTM Designation: E 799-81. pp. 1230-1235. In: 1982 Annual Book of ASTM Standards. Part 41. American Society for Testing and Materials, Philadelphia, PA 19103.

Anonymous. 1982b. 1982 Delavan Agspray Products Catalogue. Delavan Corporation, West Des Moines, IA 50265.

Anonymous. 1984. Terminology and definitions for agricultural chemical application. ASAE S327.1. pp. 224-225. In: ASAE Standards 1984. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Arnold, A. C. 1983. Comparative droplet-size spectra for three different-angled flat fan nozzles. Crop Protection 2(2): 193-204.

Azimi, A. H., T. G. Carpenter, and D. L. Reichard. 1984. Analysis of nozzle spray distribution and spacing requirements for various operating parameters. ASAE Paper No. 84-1004. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Bachalo, W. D. 1984. Droplet analysis techniques: Their selection and applications. pp. 5-21. In: J. M. Tishkoff, R. D. Ingebo, and J. B. Kennedy (ed.). Liquid Particle Size Measurement Techniques. ASTM STP 848. American Society for Testing and Materials, Philadelphia, PA 19103.

Barger, E. L., E. V. Collins, R. A. Norton, and J. B. Liljedahl. 1948. Problems in the design of chemical weed-control equipment for row crops. Agricultural Engineering 29(9):381-383.

Bintner, D. W., S. E. Conrad, and R. W. Tate. 1977. Effect of nozzle positioning on spray deposit uniformity. ASAE Paper No. 77-1038. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Bode, L. E., M. R. Gebhardt, and C. L. Day. 1968. Spray-deposit patterns and droplet sizes obtained from nozzles used for low-volume application. TRANSACTIONS of the ASAE 11(6):754.

Bode, L. E., T. L. Zimmerman, C. E. Goering, and M. R. Gebhardt. 1972. The effects of flow rate on the distribution pattern and drop-size spectrum of a spinning atomizer. TRANSACTIONS of the ASAE 15(1):86-90.

Bode, L. E., B. J. Butler, and C. E. Goering. 1976. Spray drift and recovery as affected by spray thickener, nozzle type, and nozzle pressure. TRANSACTIONS of the ASAE 19(2):213.

Bouse, L. F., D. G. Haile, and O. R. Kunze. 1974. Cyclic disturbance of jets to control spray drop size. TRANSACTIONS of the ASAE 17(2):235.

Bouse, L. F. 1974. Properties of water jet stream sprays related to cyclic disturbance. TRANSACTIONS of the ASAE 17(5):814.

Bouse, L. F. 1975. Use of pulsed jets to atomize various liquids. TRANSACTIONS of the ASAE 18(4):618.

Chigier, N. 1984. Comparative measurements using different particle size instruments. pp. 169-186. In: J. M. Tishkoff, R. D. Ingebo, and J. B. Kennedy (ed.). Liquid Particle Size Measurement Techniques. ASTM STP 848. American Society for Testing and Materials, Philadelphia, PA 19103.

Combellack, J. H., and G. A. Matthews. 1981. The influence of atomizer, pressure, and formulation on the droplet spectra produced by high-volume sprayers. Weed Research 21(2):77-86.

Dix, A. J., and J. A. Marchant. 1984. A mathematical model of the transport and deposition of charged spray drops. Journal of Agricultural Engineering Research 30(1):91-100.

Dombrowski, N., D. Hasson, and D. E. Ward. 1960. Some aspects of liquid flow through fan spray nozzles. Chemical Engineering Science 12(1):35-50.

Dombrowski, N. 1961. Some flow characteristics of single-orifice fan-spray nozzles. Journal of Agricultural Engineering Research 6(1):37-44.

El-Awady, M. N. 1978. An atomization theory for swirl nozzles. TRANSACTIONS of the ASAE 21(1):70.

Elbanna, H., M. I. I. Rashed, and M. A. Ghazi. 1984. Droplets from liquid sheets in an airstream. TRANSACTIONS of the ASAE 27(3):677.

Ferrenberg, A. J. 1984. Liquid rocket injector atomization research. pp. 82-97. In: J. M. Tishkoff, R. D. Ingebo, and J. B. Kennedy (ed.). Liquid Particle Size Measurement Technique. ASTM STP 848. American Society for Testing and Materials, Philadelphia, PA 19103.

Fraser, R. P. 1958. The fluid kinetics of application of pesticidal chemicals. pp. 1-106. In: R. L. Metcalf (ed.). Advances in Pest Control Research. Volume II. Interscience Publishers, Inc., New York, NY.

Frost, A. R., and J. R. Lake. 1981. The significance of drop velocity to the determination of drop size distributions of agricultural sprays. Journal of Agricultural Engineering Research 26(4): 367-370.

Gage, J. C., and D. J. Seaborn. 1968. Size distribution of fine droplets produced by a mistblower. Journal of Agricultural Engineering Research 13(2):120-126.

Goering, C. E., and D. B. Smith. 1978. Equations for droplet size distributions in sprays. TRANSACTIONS of the ASAE 21(2): 209-216.

Haq, K. A., and N. B. Akesson. 1979. An analysis of rheological properties of pesticide solutions as they affect atomization and drop size distribution. ASAE Paper No. 79-1504. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Heddon, O. K. 1961. Spray drop sizes and size distribution in pesticide sprays. TRANSACTIONS of the ASAE 4(2):158-159, 163.

Hirleman, E. D. 1984. Particle sizing by optical, nonimaging techniques. pp. 35-60. In: J. M. Tishkoff, R. D. Ingebo, and J. B. Kennedy (ed.). Liquid Particle Size Measurement Techniques. ASTM STP 848. American Society for Testing and Materials, Philadelphia, PA 19103.

Hugo, F. 1979. An ultra low volume sprayer with a controlled droplet size spectrum. ASAE Paper No. 79-1008. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Kim, K. Y., and W. R. Marshall, Jr. 1971. Drop-size distribution from pneumatic atomizers. AIChE Journal 17(3):575.

Klingman, G. C. 1964. Whirl chamber nozzles compared to other herbicide nozzles. Weeds 12(1):10-14.

Kohl, R. A. 1974. Drop size distribution from medium-sized agricultural sprinklers. TRANSACTIONS of the ASAE 17(4):690.

Lake, J. R., and J. A. Marchant. 1984. Wind tunnel experiments and a mathematical model of electrostatic spray deposition in barley. Journal of Agricultural Engineering Research 30(2):185-195.

Law, S. E., and H. D. Bowen. 1966. Charging liquid spray by electrostatic induction. TRANSACTIONS of the ASAE 9(4):501-506.

Law, S. E. 1978. Embedded-electrode electrostatic-induction spray-charging nozzle: Theoretical and engineering design. TRANSACTIONS of the ASAE 21(6):1096-1104.

Licht, W. 1974. Maximum drop size produced by pneumatic atomization. AIChE Journal 20(3):595.

Lotus Development Corporation. 1982. Lotus 1-2-3 Spreadsheet and Graphics Software, 161 First Street, Cambridge, MA 02142.

Mahler, D. S., and D. E. Magnus. 1984. Hot-wire technique for droplet measurements. pp. 153-165. In: J. M. Tishkoff, R. D. Ingebo, and J. B. Kennedy (ed.). Liquid Particle Size Measurement Techniques. ASTM STP 848. American Society for Testing and Materials, Philadelphia, PA 19103.

Morton, N. 1982. The "Electrodyn" sprayer: first studies of spray coverage in cotton. Crop Protection 1(1):27-54.

Mugele, R. A., and H. D. Evans. 1951. Droplet size distribution in sprays. Industrial and Engineering Chemistry 43(6):1317.

Mullins, J. A. 1968. Ultra-low volume, row crop ground sprayer research. ASAE Paper No. 68-149. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Oberdier, L. M. 1984. An instrumentation system to automate the analysis of fuel-spray images using computer vision. pp. 123-136. In: J. M. Tishkoff, R. D. Ingebo, and J. B. Kennedy (ed.). Liquid Particle Size Measurement Techniques. ASTM STP 848. American Society for Testing and Materials, Philadelphia, PA 19103.

Olivo, L. E. 1984. Evaluation of low-volume herbicide application technology for no-till soybeans. Unpublished Master's Thesis, The University of Tennessee, Knoxville, TN.

Reichard, D. L., H. J. Retzer, L. A. Liljedahl, and F. R. Hall. 1977. Spray droplet size distributions delivered by air blast orchard sprayers. TRANSACTIONS of the ASAE 20(2):232.

Rizk, N. K., and A. H. Lefebvre. 1984. Measurement of drop-size distribution by a light-scattering technique. pp. 61-71. In: J. M. Tishkoff, R. D. Ingebo, and J. B. Kennedy (ed.). Liquid Particle Size Measurement Techniques. ASTM STP 848. American Society for Testing and Materials, Philadelphia, PA 19103.

Roth, L. O., and J. G. Porterfield. 1966. Liquid atomization for drift control. TRANSACTIONS of the ASAE 9(4):553.

Roth, L. O., and J. G. Porterfield. 1970. Spray drop size control. TRANSACTIONS of the ASAE 13(6):779.

SAS Institute, Inc. SAS User's Guide: Statistics, 1982 Edition. Cary, NC: SAS Institute, Inc., 1982. 584 pp.

Skoog, F. E., T. L. Hanson, A. H. Higgins, and J. A. Onsager. 1976. Ultra-low-volume spraying: Systems evaluation and meteorological data analysis. TRANSACTIONS of the ASAE 19(1):2.

Simmons, H. C. 1984. Investigating the commercial instrument market. pp. 22-32. In: J. M. Tishkoff, R. D. Ingebo, and J. B. Kennedy (ed.). Liquid Particle Size Measurement Techniques. ASTM STP 848. American Society for Testing and Materials, Philadelphia, PA 19103.

Sokal, R. R., and F. J. Rohlf. 1981. Biometry. Second Edition. W. H. Freeman and Company, San Francisco. 859 pp.

Solie, J. B., and J. F. Gerling. 1984. A spray pattern analysis system for ground application. ASAE Paper No. 84-1002. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Spraying Systems Company. 1984. Unpublished literature describing design and recommended operation of prototype air-assist nozzles.

Tate, R. W. 1961. Immersion sampling of spray droplets. AIChE Journal 7(4):574.

Tate, R. W., and L. F. Janssen. 1966. Droplet size data for agricultural spray nozzles. TRANSACTIONS of the ASAE 9(3):303.

Tate, R. W. 1977. Droplet size distributions for drift reduction nozzles. ASAE Paper No. 77-1503. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Tate, R. W., S. I. Ahmad, L. E. Bode, and H. I. Retzer. 1980. Droplet size characteristics of bypass nozzles. ASAE Paper No. 80-1058. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Thompson, B. J. 1984. Droplet characteristics with conventional and holographic imaging techniques. pp. 111-122. In: J. M. Tishkoff, R. D. Ingebo, and J. B. Kennedy (ed.). Liquid Particle Size Measurement Techniques. ASTM STP 848. American Society for Testing and Materials, Philadelphia, PA 19103.

Wilkerson, J. B., R. D. von Bernuth, L. R. Wilhelm, and F. D. Tompkins. 1985. Microcomputer interface for measurement of water droplets. Proceedings of the Agri-Mation 1 Conference and Exposition. Palmer House Hotel, Chicago, IL.

Williamson, J. R., F. Wheaton, L. A. Liljedahl, and H. Ritzer. 1979. Liquid property effects on droplet size distribution for twin-fluid atomization. ASAE Paper No. 79-1501. American Society of Agricultural Engineers, St. Joseph, MI 49085.

APPENDIXES

APPENDIX A

DROPLET COUNT (CORRECTED) DATA

DROPLET COUNT (CORRECTED) DATA

The droplet count data contained in this Appendix was collected at the USDA-ARS in Beltsville, Maryland in 1984. All statistical droplet diameters and cumulative volume curves were calculated from this data. The calculations were performed using ASTM Standard Practice E 799-81 (Anonymous, 1982a) along with the information contained in the description of the USDA Spray Particle Counter Statistical Printout which follows the data sets.

The information contained in the data sets is Test Number, Sample Repetition, Liquid Type, Spectra Position, Liquid Pressure (psig), and Air Pressure (psig). The values following the preceding information are the corrected droplet counts by size bin for each of the 22 size channels, and are read from left to right. The last value is the total number of droplets counted in the distribution.

Test Numbers 28 through 78 and 131 through 136 are for tap-water at 43 cm below the nozzle. Test Numbers 84, 85, 99, and 100 are for the position 7.6 cm right-of-center. Test Numbers 86, 87, 101, 102, and 103 are for the position 15.2 cm right-of-center. Test Numbers 88, 89, 92, and 96 are for the position 7.6 cm left-of-center. Test Numbers 90, 91, 93, and 94 are for the position 15.2 cm left-of-center. Test Numbers 82, 83, 97, and 98 were used in the position tests and represent data collected at the center position. Test Numbers 104 through 110 are for Nozzle Tip 1; 111 through 114 are for Nozzle Tip 2; 115 through 118 are for Nozzle Tip 3; 119

through 122 are for Nozzle Tip 4; 123 through 126 are for Nozzle Tip 5; and 127 through 130 are for Nozzle Tip 6. The aforementioned tests used tapwater and were taken 27 cm below the nozzle unit unless otherwise indicated. The remaining tests are clearly labeled and were taken 27 cm below the nozzle.

```
28  1  W  C 40  7.5  256.25  139.59   84.96   44.44   42.00   35.83   34.80
   26.62   25.71   24.87   19.95   14.49   11.87    8.60    5.66    5.43
    3.72    2.62    2.30    1.53    1.31    1.97  794.52
29  1  W  C 30  7.5  390.63  242.45  146.24   69.94   57.89   43.43   37.79
   25.09   21.55   20.38   15.63    8.65    7.02    4.45    4.43    2.72
    2.62    0.92    0.49    0.66    0.66    0.66 1104.30
30  2  W  C 30  7.5  206.25  115.92   79.72   42.19   43.66   44.03   41.35
   32.65   25.67   22.65   17.92   11.81    7.87    7.36    4.67    3.84
    3.17    2.10    1.97    0.22    0.33    0.66  716.01
31  2  W  C 40  7.5  278.13  128.16   78.58   39.95   45.52   41.60   41.23
   36.49   30.21   29.47   21.31   13.83   13.05   10.64    7.38    5.15
    5.36    4.33    2.30    1.97    0.98    1.32  836.96
32  3  W  C 40  7.5  328.13  182.86   85.53   51.31   42.96   38.81   37.70
   33.17   34.61   28.91   22.35   14.43   11.67   10.35    6.56    5.90
    4.26    3.67    2.62    2.18    1.31    1.32  950.61
33  1  W  C 50  7.5  271.88  131.43   87.94   47.45   46.16   42.60   41.52
   34.00   33.26   33.50   25.79   15.44   14.16   10.06    8.52    6.09
    4.48    4.59    2.95    3.93    2.66    0.66  869.07
34  1  W  C 60  7.5  118.75  108.57   67.87   35.32   33.16   32.52   33.73
   31.16   32.46   29.87   22.62   15.80   13.44   11.44   10.16    7.77
    8.20    4.85    2.95    2.62    2.62    3.29  629.17
35  2  W  C 60  7.5  190.63  123.27   74.04   41.34   33.32   32.52   37.34
   34.70   32.51   30.37   24.86   16.52   13.05   12.32   10.49    7.02
    6.12    5.64    4.43    3.06    2.59    1.97  738.11
36  2  W  C 50  7.5  190.63  248.98  106.38   55.72   47.12   40.05   39.75
   30.86   28.76   27.50   23.28   15.74   12.59   10.42    9.75    5.90
    4.59    3.93    2.95    2.40    1.64    0.66  909.60
37  3  W  C 50  7.5  618.75  428.57  191.77   95.29   72.76   53.50   42.70
   35.18   33.07   27.50   19.40   13.95   11.80   10.20    8.28    6.74
    4.48    5.37    2.95    2.62    1.31    1.97 1688.16
38     W  C  0  0.0    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00    0.00    0.00    0.00
39  4  W  C 50  7.5  371.88  178.78  114.04   76.58   76.65   67.44   61.27
   45.54   36.86   32.29   27.98   19.26   16.00   12.46    9.18    1.69
    2.30    0.66    1.15    0.87    0.98    0.00 1153.86
40  4  W  C 40  7.5  293.75  171.84   98.01   72.64   76.92   60.51   57.62
   42.48   31.85   28.76   26.01   16.82   12.59    9.55    8.28    6.55
    5.57    3.28    1.80    1.09    1.64    0.00 1027.56
41  3  W  C 30  7.5  434.38  221.63  132.06   88.18   78.14   61.70   55.33
   38.81   29.74   24.77   21.20   14.31   11.87    6.56    5.16    5.06
    2.40    1.70    0.49    0.87    0.00    0.00 1234.36
42  4  W  C 30  7.5  478.13  214.29  121.84   87.25   79.21   64.09   57.99
   43.79   32.32   25.48   20.27   15.86   10.03    8.31    5.08    4.78
    2.73    2.10    1.31    1.09    0.98    2.63 1279.56
43  3  W  C 60  7.5  300.00  136.73  102.13   64.37   73.29   67.79   63.20
   46.72   41.73   37.99   30.05   21.94   17.11   15.82   12.79    9.36
    6.89    5.24    3.93    4.37    3.93    1.97 1067.35
```

```
44  4  W  C 60  7.5  268.75  137.55   98.30   62.60   74.73   65.33   61.15
   44.58   38.45   36.53   26.28   22.60   18.56   16.55   12.38    8.99
    8.20    7.08    5.90    5.02    1.64    4.61 1025.78
45  1  W  C 60  5.0   65.63   51.84   36.88   21.72   22.44   27.03   26.31
   23.16   19.02   17.76   15.36   11.57    9.11    8.31    7.05    4.87
    6.56    5.90    4.43    3.06    3.93    7.24  399.18
46  2  W  C 60  5.0   65.63   50.61   40.14   18.01   20.20   20.98   23.77
   20.24   16.81   17.71   14.70    8.94   10.69    9.26    7.13    7.02
    5.03    5.11    3.93    4.59    3.28    5.92  379.70
47  1  W  C 50  5.0   84.38   81.63   58.44   37.17   35.18   29.74   29.55
   22.25   20.42   18.01   15.14   10.73    8.20    8.53    5.98    4.59
    3.83    4.33    3.61    2.18    5.25    3.95  493.09
48  2  W  C 50  5.0   59.38   58.37   52.20   25.58   25.16   26.23   25.94
   20.94   17.85   14.73   14.37   10.14    8.59    7.94    6.56    5.62
    4.37    4.85    3.61    3.49    1.97    5.92  403.81
49  1  W  C 40  5.0   59.38   86.94   60.57   32.23   30.22   29.02   28.48
   22.16   16.96   14.73   13.93    9.66    8.13    6.49    7.30    4.78
    4.59    4.59    3.44    3.28    3.61    1.97  452.46
50     W  C  0  5.0    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00    0.00    0.00    0.00
51  1  W  C 30  5.0  112.50   53.88   43.40   21.17   21.54   20.86   20.74
   16.00   13.40   12.51    9.40    7.39    7.41    4.45    3.85    3.75
    2.84    2.62    2.95    0.66    0.98    2.63  384.93
52  2  W  C 30  5.0  121.88   55.51   51.63   31.14   28.78   26.31   24.43
   17.66   13.35   12.21   12.02    7.99    6.89    5.83    4.51    4.21
    3.61    3.15    2.30    1.53    1.64    0.66  437.24
53  3  W  C 40  5.0  125.00   60.00   41.42   26.43   28.57   28.86   27.87
   21.15   16.25   16.90   12.24    9.96    8.07    7.29    6.72    5.34
    3.17    3.80    5.25    3.28    1.97    3.95  463.49
54  3  W  C 30  5.0  184.38   75.10   53.90   32.92   31.50   27.55   29.55
   17.09   14.61   14.03   11.64    7.33    7.28    5.39    3.52    3.18
    2.62    1.83    0.66    0.87    0.66    1.97  527.58
55  4  W  C 30  5.0  131.25   71.43   40.71   26.58   25.05   24.68   24.39
   18.40   14.61   15.14   10.49    7.45    5.97    6.49    4.84    3.46
    3.39    2.62    1.64    2.18    0.98    0.66  442.41
56  4  W  C 40  5.0  165.63   65.71   51.49   27.59   33.58   29.70   27.50
   20.63   16.77   15.74   12.30   10.38    8.72    7.22    6.39    4.87
    5.68    3.01    2.62    2.62    4.92    5.26  528.33
57  3  W  C 50  5.0  231.25   98.78   56.31   18.32   21.22   20.42   22.42
   17.00   15.74   14.48   12.68    8.35    7.28    7.51    6.39    5.99
    5.36    4.19    2.62    2.84    4.92    3.95  588.02
58  4  W  C 50  5.0   65.63   36.73   34.89   15.92   21.70   23.17   23.28
   19.36   16.96   16.35   13.55   11.03    8.85    7.80    5.82    6.93
    4.04    4.85    4.26    3.49    3.28    0.66  348.55
59     W  C  0  5.0    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00    0.00    0.00    0.00
```

```
60  3  W  C 60  5.0   59.38   49.39   36.17   23.88   31.13   32.96   30.70
   22.55   19.72   17.10   16.56   10.97    9.31    7.94    8.44    7.30
    5.36    4.98    2.95    3.71    2.95    4.61  408.06
61  4  W  C 60  5.0   87.50   48.57   38.58   24.65   29.80   31.01   28.52
   24.43   19.95   16.70   16.12   12.10    9.77    8.75    8.11    8.24
    7.43    4.33    5.74    4.59    3.28    5.92  444.09
62  1  W  C 60 10.0  500.00  237.14  152.34  114.53  114.45  110.19   92.79
   72.07   58.50   51.87   38.58   29.16   25.31   18.95   14.59    8.61
    8.63    7.99    3.77    4.15    4.26    3.29 1671.17
63  2  W  C 60 10.0  431.25  209.39  152.34  112.36  111.99  100.84   95.53
   70.32   54.52   49.60   41.37   29.76   22.69   18.59   15.49   10.96
    7.54    6.03    5.90    2.84    4.26    0.66 1554.23
64  1  W  C 50 10.0  562.50  313.06  195.18  121.25  119.67   97.37   86.11
   64.12   52.27   44.55   33.99   23.20   18.95   14.36    9.92    6.55
    6.34    3.41    2.79    3.49    0.66    0.66 1780.40
65  2  W  C 50 10.0  515.63  283.67  184.11  110.90  107.30   94.79   85.00
   60.23   52.13   44.80   37.65   25.16   19.21   13.56   11.72    7.58
    4.26    4.06    3.93    2.84    1.31    2.63 1672.47
66     W  C  0 10.0    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00    0.00    0.00    0.00
67  1  W  C 40 10.0  603.13  271.43  180.14  121.95  115.19  100.92   86.89
   61.32   48.76   43.54   33.77   23.02   17.51   13.41    9.67    6.84
    3.50    2.75    1.64    1.97    1.31    0.00 1748.66
68  2  W  C 40 10.0  628.13  268.57  175.32  120.02  120.79   99.12   85.29
   62.41   50.73   42.99   31.37   21.59   14.89   13.85    9.26    4.78
    3.61    4.19    1.64    1.75    0.66    1.32 1762.28
69  1  W  C 30 10.0  456.25  264.49  164.26  105.72   96.48   70.74   56.39
   43.75   34.71   28.81   18.69   13.77    8.59    6.71    5.08    3.18
    1.64    2.10    1.64    1.09    0.00    0.00 1384.09
70  2  W  C 30 10.0  509.38  221.63  149.08   97.84   90.30   64.89   57.99
   40.03   32.41   25.13   19.23   13.60    8.66    5.83    3.93    3.00
    2.08    1.05    0.33    0.66    0.33    0.00 1347.38
71  3  W  C 40 10.0  412.50  228.98  147.52  105.10  103.52   83.64   69.92
   51.09   42.81   38.45   29.07   20.16   15.21    9.69    8.85    6.18
    2.73    3.01    2.46    0.44    0.66    0.00 1381.99
72  3  W  C 30 10.0  403.13  224.08  150.21   95.98   81.88   64.77   51.64
   38.90   30.54   25.43   20.98   12.10    7.80    5.10    4.51    3.18
    1.75    0.39    0.66    0.66    0.00    0.00 1223.69
73  4  W  C 30 10.0  412.50  212.24  135.46   85.16   76.60   61.27   50.78
   37.33   31.62   26.08   17.76   10.91    8.85    5.69    4.34    2.34
    1.97    0.92    1.64    0.00    0.00    0.00 1183.46
74  4  W  C 40 10.0  406.25  222.45  149.65  100.70   85.87   73.61   59.75
   45.76   41.78   35.17   28.25   18.66   13.77   10.06    8.44    5.99
    2.62    2.23    1.31    1.09    0.98    0.66 1315.05
75  3  W  C 50 10.0  228.13  197.96  137.73   96.45   94.88   73.53   68.57
   50.39   44.96   36.02   30.66   21.35   16.07   13.99    9.92    7.21
    3.50    4.33    2.46    1.75    0.98    1.32 1138.16
```

```
76  4  W  C 50 10.0  262.50  173.88  146.95   94.98   95.15   77.03   63.52
   48.95   39.81   34.56   30.27   21.94   17.38   12.68   11.23    6.84
    3.28    3.28    2.30    1.75    0.66    1.32 1150.26
77  3  W  C 60 10.0   93.75  165.31  171.77  107.65   98.77   78.26   73.16
   52.80   43.00   38.55   31.75   20.51   17.70   12.76   13.20    9.36
    6.45    4.33    2.79    2.18    1.97    1.97 1047.99
78  4  W  C 60 10.0  112.50  196.33  189.08   85.63   68.44   63.65   58.36
   42.35   36.25   29.87   26.83   18.43   15.28   11.22    6.97    6.09
    5.46    5.11    3.44    1.53    1.64    1.32  985.78
79  1 H20  ROC 40  7.5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00    0.00    0.00    0.00
80 2a H20  ROC 40  7.5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00    0.00    0.00    0.00
81  2 H20  ROC 40  7.5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00    0.00    0.00    0.00
82  1 H20   C  40  7.5  846.88  368.16  238.30  201.08  190.72  142.04  127.38
  101.01   75.69   65.59   54.70   38.76   32.85   25.00   19.84   13.01
   10.96    9.04    6.23    4.80    1.97    1.97 2575.98
83  2 H20   C  40  7.5  406.25  232.24  161.42  153.17  157.89  131.61  125.08
   90.78   71.62   64.38   54.43   36.02   30.16   24.64   19.67    9.83
   10.27    8.91    6.07    4.80    3.93    3.95 1807.12
84  1 H20 ROC3 40  7.5  415.63  187.35  152.77  113.52  110.71   97.49   85.78
   65.82   54.66   40.77   34.48   27.19   20.85   15.74   11.07    8.99
    6.99    4.59    5.08    2.62    1.64    1.97 1465.71
85  2 H20 ROC3 40  7.5  265.63  153.47  121.99  102.78   93.60   80.97   80.41
   72.29   54.94   44.55   36.34   24.27   18.03   13.92   11.72    8.15
    7.43    5.90    3.61    1.97    1.31    1.97 1205.25
86  1 H20 ROC6 40  7.5   21.88   14.69   19.86   18.86   24.15   24.96   24.47
   23.78   19.91   18.11   16.34   13.36    7.61    7.29    7.13    4.78
    3.39    1.57    2.46    0.87    2.62    0.00  278.09
87  2 H20 ROC6 40  7.5   34.38   19.59   19.15   20.56   23.61   24.56   27.34
   22.64   21.64   18.77   16.07   15.21   13.51    8.53    5.82    5.15
    3.17    2.62    1.97    1.31    0.98    1.32  307.90
88  1 H20 LOC3 40  7.5  334.38  130.20  106.52   88.64  104.26  103.38  112.54
   85.05   65.39   55.10   49.67   37.15   25.51   22.52   19.51   16.20
    8.85    8.52    7.54    3.06    3.28    4.61 1391.88
89  2 H20 LOC3 40  7.5  343.75  157.14  105.39   83.38  102.99   98.21  106.27
   86.10   64.12   54.74   48.69   35.12   27.21   23.54   18.28   15.54
   13.44    7.21    5.74    4.80    5.57    3.95 1411.18
90  1 H20 LOC6 40  7.5   93.75   49.39   35.32   27.28   33.80   46.10   55.29
   59.09   47.35   39.86   32.40   26.06   25.64   17.42   15.74   10.49
   10.49    6.03    5.90    3.71    1.31    7.89  650.31
91  2 H20 LOC6 40  7.5   65.63   41.63   26.24   18.62   28.14   36.86   50.33
   58.65   47.40   39.00   31.53   28.21   21.44   17.49   14.10   12.27
    9.29    6.16    4.92    3.93    2.30    3.95  568.09
```

```
 92  3 H20 LOC3 40  7.5  268.75  141.63  108.37   74.19   89.39   94.79   99.67
    84.44   66.51   55.15   43.99   35.72   29.97   21.28   20.00   14.42
    11.58   10.62    7.05    5.02    4.26    0.66 1287.46
 93  3 H20 LOC6 40  7.5   37.50   22.86   24.26   19.47   25.75   33.88   50.86
    55.81   44.17   34.66   30.71   27.01   18.56   17.71   13.85   10.58
     7.21    6.29    4.10    3.71    4.59    9.21  502.75
 94  4 H20 LOC6 40  7.5   65.63   52.24   43.69   35.47   36.25   38.54   55.45
    58.92   46.60   39.61   29.62   23.61   20.07   16.69   12.54   10.67
     7.21    7.47    4.75    5.68    2.95    4.61  618.27
 95 4a H20 LOC3 40  7.5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00
 96  4 H20 LOC3 40  7.5  337.50  164.90  104.82   83.85  100.64  103.03  104.96
    81.56   64.64   53.94   48.36   34.29   26.89   23.32   21.89   16.29
    11.58    9.04    6.23    5.90    4.92    7.89 1416.44
 97  3 H20   C  40  7.5  946.88  416.73  242.55  172.18  153.46  121.14  117.58
    87.24   69.23   60.49   50.33   34.94   26.75   22.23   19.26   11.33
     9.62    8.78    6.23    5.02    3.61    5.26 2590.84
 98  4 H20   C  40  7.5  946.88  446.94  264.68  178.59  149.57  124.08  121.52
    90.38   66.09   62.06   51.31   37.15   27.15   22.08   18.11   11.42
    10.60    6.68    7.70    3.06    1.97    0.66 2648.68
 99  3 H20 ROC3 40  7.5  981.25  457.55  297.59  218.93  167.75  119.67  106.02
    84.31   64.17   53.28   42.40   30.95   25.77   19.90   16.56    8.24
     6.67    4.85    3.77    2.84    1.31    1.32 2715.10
100  4 H20 ROC3 40  7.5  812.50  442.86  261.56  202.55  165.62  119.47  102.95
    81.16   64.22   50.61   42.90   31.01   24.20   20.70   15.49    8.71
     6.89    6.03    5.41    2.84    1.64    0.66 2469.98
101 3a H20 ROC6 40  7.5    9.38   11.43   14.47   10.36   16.90   19.43   20.57
    19.80   19.34   15.84   15.30   12.46   10.95    7.07    6.15    4.21
     3.61    3.15    1.31    2.18    0.98    0.00  224.89
102  3  W ROC6 40 7.5    9.38    5.31    6.38    5.56   10.39   12.82   17.87
    19.62   21.59   16.09   14.04   12.94   10.30   10.06    5.25    5.71
     3.83    2.88    1.97    0.87    0.66    0.66  194.18
103  4  W ROC6 40 7.5   37.50   15.10   12.06   13.06   20.68   24.08   30.70
    27.53   26.46   23.66   16.23   15.92   13.77    8.97    6.97    6.37
     3.39    3.93    1.15    1.09    1.97    0.00  310.59
104  1  W    C  40 7.5  693.75  286.12  167.09  115.22  114.13  106.53   99.14
    82.69   67.21   57.57   50.66   33.21   26.30   21.06   18.44    6.37
     4.48    3.41    2.95    2.18    1.64    1.97 1962.12
105 2A  W    C  40 7.5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00
106  2  W    C  40 7.5  571.88  231.02  151.21  108.96  128.30  112.90  115.29
    84.53   65.29   61.05   53.39   38.88   29.84   26.09   20.49   15.26
    12.13    7.60    5.57    4.15    3.93    2.63 1850.39
107 3A  W    C  40 7.5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00
```

```
108  3  W   C  40 7.5  637.50  313.47  169.65  137.64  150.32  122.49  115.94
    92.57   72.79   68.26   55.46   41.74   31.28   27.04   24.34   15.45
    11.26    8.52    8.03    5.24    4.92    5.26 2119.17
109  4  W   C  40 7.5  621.88  328.16  169.22  145.05  149.09  124.56  113.73
    94.01   73.58   63.67   57.16   39.42   33.51   24.71   20.25   14.98
     9.29   10.62    8.52    4.80    4.59    4.61 2115.41
110  5  W   C  40 7.5  821.88  315.92  187.23  148.69  155.54  127.59  117.17
    91.87   76.35   66.60   55.36   38.76   33.31   24.93   18.52   16.39
    14.21    9.70    8.20    5.90    4.92    0.66 2339.70
111  1  W   C  40 7.5  981.25  414.29  250.35  189.95  182.89  138.26  125.29
    96.90   78.88   66.30   55.08   38.22   30.36   24.13   21.07   15.07
     8.85    9.04    6.23    5.68    2.95    3.29 2744.33
112  2  W   C  40 7.5  825.00  336.73  202.41  168.47  167.06  135.55  122.50
    95.85   77.19   68.72   57.32   40.55   33.38   23.83   19.43   15.92
    10.60    7.99    6.07    3.93    4.26    2.63 2425.39
113  3  W   C  40 7.5  896.88  379.18  227.09  186.17  175.43  131.33  124.96
    95.98   77.61   68.01   55.03   39.77   29.97   26.53   18.93   14.98
    13.11   11.14    6.56    4.15    4.26    3.29 2590.36
114  4  W   C  40 7.5  396.88  252.65  190.50  143.04  154.85  130.61  117.83
    95.67   75.36   71.44   59.84   44.25   35.87   26.68   23.61   14.79
    11.15   10.48    7.38    4.37    5.25    2.63 1875.13
115  1  W   C  40 7.5 1284.38  524.08  328.09  265.61  212.31  142.32  122.50
    94.89   79.53   66.30   55.68   36.73   30.23   23.32   19.26   13.39
    10.60    7.21    7.21    5.02    2.95    4.61 3336.22
116  2  W   C  40 7.5 1137.50  489.39  293.90  238.72  206.50  136.69  116.84
    94.23   77.38   66.20   50.38   36.31   29.64   21.65   20.00   14.04
    11.26    7.47    7.21    5.68    2.62    1.32 3066.93
117  3  W   C  40 7.5 1190.63  529.80  316.17  257.57  206.02  144.15  118.77
    96.46   77.80   63.07   53.66   36.73   29.70   24.34   17.87   10.96
    10.71    7.73    5.41    4.37    2.95    1.97 3206.84
118  4  W   C  40 7.5 1143.75  498.37  291.49  238.33  201.65  139.05  117.99
    91.04   77.85   64.18   53.83   38.82   29.70   22.81   20.00   12.83
     9.40    6.95    8.03    5.02    2.30    4.61 3078.00
119  1  W   C  40 7.5 1125.00  502.86  309.65  246.45  208.69  143.19  122.01
    95.19   80.23   65.74   53.93   36.43   29.38   22.96   18.77   12.83
    10.27   10.35    5.41    2.62    2.62    5.26 3109.84
120  2  W   C  40 7.5 1212.50  560.00  341.56  265.07  223.13  145.42  125.82
    95.67   80.14   66.90   57.10   40.07   31.87   27.84   18.93   11.70
     7.65    9.17    6.56    3.49    4.26    1.97 3336.82
121  3  W   C  40 7.5 1106.25  453.06  294.47  236.94  196.70  140.80  122.13
    93.44   79.77   68.87   55.85   38.94   31.80   23.62   20.08   12.17
    11.04    7.86    6.56    4.59    2.95    1.97 3009.86
122  4  W   C  40 7.5 1103.13  478.37  275.04  239.03  205.65  142.79  122.75
    96.68   78.27   67.15   53.77   39.65   27.74   24.49   19.26   12.55
     8.63    8.65    8.03    2.84    2.95    3.29 3020.71
123  1  W   C  40 7.5 1206.25  537.55  298.16  227.20  200.96  149.76  132.87
   100.04   85.57   69.78   55.90   41.20   34.30   26.02   20.00   12.45
     9.84    8.26    5.41    3.93    3.61    3.95 3233.01
```

```
124  2  W   C  40 7.5 1128.13  565.71  378.72  253.48  209.12  149.88  128.85
   104.63   81.22   72.15   60.00   38.34   33.84   27.19   20.49   14.33
     8.85    8.91    7.38    4.15    3.28    1.97 3300.62
125  3  W   C  40 7.5  693.75  520.00  415.74  251.55  185.23  132.29  118.89
    89.12   79.95   65.04   52.73   36.31   26.75   21.79   18.03   11.99
     8.31    7.34    7.38    3.49    5.90    3.29 2754.87
126  4  W   C  40 7.5 4821.88 1453.06  635.89  311.51  207.89  128.86  105.86
    77.19   66.09   57.06   42.95   28.98   24.13   15.52   12.70   12.36
     8.96    6.82    5.90    3.93    4.92    3.29 8035.75
127  1  W   C  40 7.5   93.75  159.59  259.72  208.27  177.88  124.08  108.73
    84.18   72.55   62.97   50.82   38.28   30.62   23.98   19.18   12.92
    10.93    6.82    6.89    3.71    3.93    1.97 1561.77
128  2  W   C  40 7.5  137.50  208.57  281.70  198.69  163.59  116.68  103.03
    86.01   70.77   62.51   54.54   40.49   31.48   24.56   17.95   13.39
    10.16    7.47    4.92    3.28    3.28    3.29 1643.86
129  3  W   C  40 7.5   93.75  204.90  298.44  204.10  158.90  111.03   95.70
    81.29   71.85   64.58   52.40   39.24   29.90   25.00   20.66   11.89
     8.09    7.86    5.57    1.97    1.31    1.32 1589.75
130  4  W   C  40 7.5  190.63  245.71  287.94  204.79  164.13  113.30   98.24
    77.62   71.43   61.35   50.16   34.05   30.30   21.65   18.20   11.70
     8.09    6.42    6.23    3.06    1.64    1.32 1707.96
131  1 H20   C  40   7.5  456.25  169.80  105.67   74.96   66.95   52.83   51.35
    36.19   29.18   25.13   21.31   15.32   11.15   10.20    6.64    5.90
     4.70    2.75    4.59    3.06    1.64    2.63 1158.20
132 2a H20   C  40   7.5    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00
133  2 H20   C  40   7.5  343.75  151.84   89.08   58.73   57.41   50.88   49.14
    39.60   30.73   26.94   21.91   16.04   12.00   10.57    8.20    6.84
     5.25    3.28    2.46    2.18    2.30    1.32  990.45
134  3 H20   C  40   7.5  309.38  144.08   84.26   58.11   50.53   39.85   40.98
    34.53   27.96   23.97   20.44   14.43   11.34    9.84    6.64    7.02
     5.79    3.67    3.77    1.53    2.62    1.97  902.71
135  4 H20   C  40   7.5  387.50  145.31   90.50   60.36   52.93   46.06   45.37
    36.98   28.85   26.03   21.26   14.07   10.95    9.40    7.87    5.34
     3.61    2.10    3.11    2.18    1.31    3.29 1004.38
136  5 H20   C  40   7.5  275.00  150.20   91.63   60.59   44.03   38.50   38.16
    30.55   24.36   23.26   19.07   12.58   10.89    8.67    6.39    6.09
     4.59    3.15    2.46    2.40    2.30    0.66  855.53
137  1 H20   C  40   7.5  715.63  335.10  269.93  217.54  194.30  143.15  124.92
    93.27   74.57   65.94   50.00   36.20   27.41   22.30   18.44   12.92
    10.38    8.91    6.07    4.59    2.62    3.29 2437.48
138  2 H20   C  40   7.5  678.13  306.94  265.53  208.42  185.50  139.77  126.43
    90.78   72.88   62.26   53.61   37.98   28.92   25.44   19.84   14.04
    11.37    8.13    6.72    4.37    3.93    0.00 2350.99
139  3 H20   C  40   7.5  546.88  301.63  235.46  197.76  176.55  136.43  124.84
    91.56   71.99   60.95   52.13   33.33   28.20   21.57   18.03   12.55
     9.84    6.55    5.25    4.80    3.93    5.26 2145.49
```

```
140  4 H20   C  40  7.5  725.00  329.80  188.09  153.48  155.70  122.25  113.73
    91.52   70.21   60.60   48.63   35.72   26.62   24.78   18.52   10.96
     9.07    6.16    5.25    4.59    2.62    1.97 2205.27
141  1 H20   C  30  7.5  700.00  271.02  154.75  110.28  124.31  107.68  104.92
    77.58   61.26   53.23   43.11   28.26   20.52   15.82   13.28    9.64
     6.34    4.06    4.43    3.28    1.64    3.95 1919.36
142  2 H20   C  30  7.5  868.75  345.31  177.45  126.97  133.58  107.52  107.70
    82.08   63.09   53.68   45.52   29.22   21.25   15.38   11.72    7.21
     5.68    4.19    3.44    1.97    1.97    1.32 2215.00
143  3 H20   C  30  7.5  834.38  298.37  169.22  111.44  115.99   99.32  107.25
    79.90   64.45   52.52   44.10   28.62   21.31   16.25   14.10    7.58
     6.45    4.46    3.93    2.62    0.98    1.97 2085.21
144 4a H20   C  30  7.5  468.75  220.82  149.50  116.69  121.00  101.83  100.08
    79.33   57.99   49.34   41.69   26.18   17.11   16.03   12.21    0.75
     0.66    0.26    0.00    0.22    0.00    0.00 1580.44
145  1 H20   C  50  7.5  340.63  448.16  423.83  338.95  255.70  161.23  121.15
    82.26   72.74   59.69   50.60   32.44   28.39   20.99   19.26   13.67
    12.02    9.44    7.05    7.21    3.61    5.26 2514.28
146  2 H20   C  50  7.5  175.00  262.45  297.02  275.89  235.71  155.81  120.12
    77.58   73.72   58.58   47.76   36.73   28.07   22.74   20.25   15.26
    10.60    9.44    6.07    6.77    4.59    2.63 1942.79
147  3 H20   C  50  7.5  171.88  248.57  296.60  271.87  221.11  152.03  117.17
    78.28   69.56   62.41   49.40   34.59   29.51   21.87   19.75   13.76
    10.71    8.78    7.38    3.06    2.62    2.63 1893.54
148  4 H20   C  50  7.5  284.38  310.20  321.28  293.51  244.88  161.90  122.91
    84.48   71.05   64.68   51.04   40.01   26.16   23.40   20.00   15.36
    10.38    8.52    8.69    8.08    3.93    5.26 2180.10
149  4 H20   C  30  7.5  931.25  515.10  379.86  241.73  200.05  131.49  102.30
    72.16   53.82   46.82   33.66   26.83   18.10   14.58   10.08    8.99
     5.90    4.46    4.59    1.31    1.64    1.32 2806.04
150  1 H20   C  60  7.5 1968.75 1112.65  739.29  258.11  152.35  101.47   86.15
    62.33   54.24   48.03   37.16   26.60   21.44   16.03   12.54   12.36
    11.15    7.86    8.03    5.68    6.56    5.26 4754.04
151  2 H20   C  60  7.5  690.63  286.12  172.91  170.94  176.81  130.81  121.89
    96.24   77.75   69.53   61.58   41.62   35.67   28.64   23.93   19.19
    13.99   11.14    7.54    6.33    6.89    6.58 2256.73
152  3 H20   C  60  7.5  481.25  248.16  164.82  158.89  171.70  127.43  114.47
    92.48   79.44   65.19   61.86   39.71   36.00   29.45   25.98   18.35
    13.33   11.40    9.18    7.64    5.57    7.24 1969.54
153  4 H20   C  60  7.5  600.00  303.67  187.80  191.34  185.34  137.22  120.53
    96.90   83.04   71.59   58.42   45.56   35.87   30.39   25.00   18.07
    17.16    9.70   10.00    6.11    3.28    5.26 2242.25
154  1 DH20  C 60  7.5   78.13  124.90  110.64   90.73  105.44   90.17   90.41
    69.76   63.89   59.03   46.01   35.60   31.48   25.58   18.20   17.98
    11.37   11.80   10.98    8.30    7.21    9.87 1117.48
155  2 DH20  C 60  7.5  356.25  235.51  173.90  142.81  150.91  115.45  104.47
    83.48   72.27   62.82   55.74   36.26   33.44   26.17   19.67   14.98
    15.63   10.62    8.69    6.99    4.92    5.26 1736.24
```

```
156 3a DH20  C 60  7.5  453.13  455.10  267.23  117.93   84.65   61.03   56.11
     38.85   31.99   25.03   20.55   15.44   10.43   10.64    7.30   15.26
     14.43    9.44    8.36    5.90    8.52    5.92 1723.24
157  3 DH20  C 60  7.5  600.00  275.92  183.83  178.83  187.85  131.77  121.27
     95.10   80.42   69.88   58.80   43.65   34.69   28.64   24.02   17.79
     14.54   12.32   11.64    6.33    4.26    3.95 2105.50
158  4 DH20  C 60  7.5  578.13  242.04  163.55  173.72  175.11  137.94  119.80
     97.68   79.86   72.65   62.02   41.68   37.55   29.88   26.07   16.85
     13.55   11.66   11.31    6.77    4.92    7.89 2110.63
159  5 DH20  C 60  7.5  696.88  284.49  177.59  180.68  183.37  136.86  119.88
     97.81   83.51   70.94   63.66   45.92   33.77   30.32   27.46   22.00
     13.88   13.11   11.15    7.86    5.57    8.55 2315.26
160  1 DH20  C 30  7.5 1006.25  394.69  239.01  178.28  151.92  116.84  102.01
     69.23   56.72   50.05   39.56   27.85   19.61   15.96   14.10    9.08
      6.01    4.33    2.79    1.97    0.98    0.66 2507.90
161  2 DH20  C 30  7.5  596.88  294.29  164.11  123.88  129.80  109.36  104.18
     76.62   65.01   55.45   44.15   29.87   22.43   18.15   12.54    8.33
      6.01    4.06    3.61    2.40    2.62    0.66 1874.41
162  3 DH20  C 30  7.5  806.25  365.31  189.65  147.06  145.90  117.16  111.52
     83.74   66.93   55.75   45.57   31.90   23.41   18.15   12.30    9.64
      5.14    3.93    3.93    3.06    0.33    1.97 2248.60
163  4 DH20  C 30  7.5  690.63  268.98  141.70  115.53  131.98  109.28  108.32
     80.90   64.12   52.93   42.51   31.37   23.87   15.89   13.03    9.83
      6.78    4.59    4.92    2.62    0.98    0.66 1921.42
164  1 DH20  C 40  7.5  696.88  273.86  161.84  151.85  161.46  130.93  117.95
     89.42   74.38   66.25   53.55   38.88   29.70   24.42   20.98   13.11
      9.73    7.73    7.21    5.02    4.59    1.97 2141.73
165  2 DH20  C 40  7.5  709.38  312.24  167.09  156.72  165.99  123.81  117.79
     89.69   73.02   64.58   55.74   37.45   30.95   23.91   20.08   13.58
     10.71    9.44    6.39    6.55    5.25    1.32 2201.68
166  3 DH20  C 40  7.5  512.50  220.82  141.13  129.21  143.98  119.75  117.01
     87.46   69.70   60.29   50.87   38.28   32.33   22.01   17.95   14.61
      7.98    9.04    7.54    4.37    2.30    3.29 1812.42
167  4 DH20  C 40  7.5  318.75  182.45  107.52  101.16  133.32  120.94  116.43
     88.46   72.37   62.51   49.62   35.42   28.20   23.47   19.84   13.95
     10.05    9.31    6.56    5.46    4.26    7.24 1517.29
168  1 DH20  C 50  7.5  315.63  155.92  109.65  126.66  156.45  131.73  121.84
     99.34   79.34   68.82   58.03   43.47   35.15   27.11   23.20   17.42
     15.52    9.83   11.15    7.64    3.61    4.61 1622.12
169  2 DH20  C 50  7.5  375.00  179.18  125.39  130.76  160.39  131.33  124.10
     98.38   83.28   68.97   58.25   43.59   32.13   28.72   24.59   16.76
     13.88   11.93   10.33    7.21    4.26    2.63 1731.06
170  3 DH20  C 50  7.5  340.63  202.04  158.72  150.46  153.14  122.77  116.64
     93.27   78.59   67.76   57.32   41.44   33.11   27.41   20.49   17.42
     15.08   11.01    8.52    7.42    7.21    6.58 1737.03
171  4 DH20  C 50  7.5  343.75  237.96  175.60  152.47  152.03  123.93  116.80
     96.59   78.97   66.09   58.20   42.34   32.79   25.44   23.93   15.17
     14.54   11.66    7.38    6.99    6.56    5.92 1795.11
```

```
172  5 DH20  C 40  7.5  756.25  369.80  232.20  162.52  150.27  116.36  108.40
    86.63   71.52   62.61   53.33   38.10   27.54   21.50   18.11   12.08
     9.73    9.17    7.21    5.24    3.93    3.29 2325.79
173  1 HARDH20 C 40 7.5  587.50  251.84  134.18  133.46  160.18  127.75  115.82
    94.14   69.51   60.34   48.74   39.65   31.54   22.74   16.89   13.95
    11.91    6.95    7.38    4.15    1.31    1.97 1941.90
174  2 HARDH20 C 40 7.5  609.38  261.63  149.22  142.50  155.01  125.48  120.00
    92.44   72.69   63.98   53.77   34.70   29.84   26.60   21.07   12.45
     9.84    8.91    5.41    3.71    3.61    3.95 2006.19
175  3 HARDH20 C 40 7.5  753.13  318.37  187.09  152.47  157.25  130.73  124.51
    93.53   74.66   64.98   52.90   38.70   28.92   26.17   20.66   11.14
     9.73    6.95    4.75    3.93    1.97    1.97 2264.51
176  4 HARDH20 C 40 7.5  800.00  350.20  208.51  150.62  158.37  129.34  120.49
    94.10   74.05   66.50   54.15   39.00   30.62   22.74   18.28   12.64
    10.49    6.82    5.90    5.46    2.62    1.97 2362.87
177  5 HARDH20 C 40 7.5  628.13  265.71  151.06  134.08  144.78  125.40  120.94
    93.97   71.99   61.60   49.73   37.69   27.08   21.79   18.77   11.14
     9.18    7.08    4.26    4.80    2.62    0.66 1992.46
178  1 HARDH20 C 30 7.5  237.50  181.22  149.36  150.46  178.62  161.11  132.99
    73.95   62.90   50.00   34.26   26.54   19.15   13.34    9.84    8.61
     6.12    3.01    2.46    1.97    0.66    0.66 1504.73
179  2 HARDH20 C 30 7.5  206.25  171.43  149.65  143.51  171.59  147.17  125.41
    75.52   58.12   47.83   37.92   24.09   19.28   12.17   10.49    7.68
     6.01    5.11    3.61    0.66    0.66    1.32 1425.48
180  3 HARDH20 C 30 7.5  237.50  186.12  138.44  132.69  167.64  149.24  124.26
    73.78   57.80   45.06   37.54   26.00   18.75   12.76    8.20    6.93
     4.15    4.19    3.44    2.18    2.30    1.97 1440.94
181  4 HARDH20 C 30 7.5  218.75  176.33  142.98  140.80  166.36  154.46  126.27
    77.14   60.52   49.65   39.40   23.55   20.79   13.19   10.90    5.24
     3.28    3.01    1.97    0.87    0.98    0.66 1437.10
182  1 HARDH20 C 50 7.5  243.75  348.98  277.02  239.95  224.25  166.08  134.84
    91.13   77.00   59.99   49.67   37.21   31.48   24.64   22.05   13.20
    12.13    9.31    5.57    6.11    6.56    2.63 2083.55
183  2 HARDH20 C 50 7.5  168.75  238.78  225.82  202.01  208.85  157.84  131.60
    90.82   72.32   60.75   47.81   33.39   26.03   22.59   18.69   14.61
    11.04    9.31    6.56    3.93    6.56    1.97 1760.03
184  3 HARDH20 C 50 7.5  171.88  227.35  212.34  200.70  211.78  164.37  135.94
    96.33   75.50   61.30   48.52   36.02   29.18   24.13   21.23   15.64
    10.49   10.48    6.89    6.33    3.61    4.61 1774.62
185  4 HARDH20 C 50 7.5  153.13  224.49  201.70  202.40  210.87  162.26  126.02
    87.54   70.63   59.69   49.18   34.35   29.38   23.83   20.00   15.54
    12.79    8.78    7.54    6.55    2.95    5.26 1714.88
186  1 HARDH20 C 60 7.5  200.00  306.94  281.99  236.01  223.77  150.64  125.49
    93.23   78.59   66.30   51.04   37.98   32.26   26.24   20.33   15.17
    14.10   10.35    7.54    6.33    6.56    7.24 1998.10
187  2 HARDH20 C 60 7.5  187.50  340.82  318.30  248.38  219.30  148.57  123.69
    95.37   77.52   64.08   52.68   37.92   31.67   26.82   18.85   16.76
    11.04   12.98    8.69    6.77    4.26    6.58 2058.55
```

```
188  3 HARDH20 C 60 7.5  215.63  265.31  238.87  213.29  208.58  154.02  122.70
     93.49   78.64   60.90   54.15   38.28   31.28   25.00   21.89   14.79
     11.48   10.75    6.89    7.42    6.23    5.26 1884.85
189  4 HARDH20 C 60 7.5  143.75  238.78  238.58  212.98  198.88  153.03  122.17
     91.30   75.55   64.33   51.64   41.09   32.98   21.72   23.44   16.67
     12.24   11.14    9.67    7.21    4.26    5.26 1776.67
190  1 TAPH20 C 60 5.0  246.88  118.78   71.63   64.14   67.96   54.74   51.11
     43.97   36.91   36.83   31.37   26.36   19.41   18.44   13.20   12.45
     12.46    8.78    8.03   10.92    7.54    5.92  967.83
191  2 TAPH20 C 60 5.0  225.00   89.39   60.00   57.57   63.27   53.74   50.66
     41.17   35.74   34.21   30.00   23.85   22.82   18.22   12.70   13.95
     11.91   11.66    8.36    9.61    4.59    5.92  884.34
192  3 TAPH20 C 60 5.0  231.25  123.27   72.62   62.67   66.63   52.67   50.57
     41.61   38.17   36.33   33.06   22.00   20.39   18.59   17.46   14.42
     10.49   11.40    7.05    6.55    8.85    7.89  953.94
193  4 TAPH20 C 60 5.0  331.25  125.71   77.87   69.78   68.66   55.65   50.86
     41.17   36.44   37.34   30.11   25.64   20.13   18.00   16.56   14.51
     11.48   10.09    8.85    9.61   10.82    9.87 1080.40
194  1 TAPH20 C 30 5.0  215.63   84.90   47.52   38.41   52.93   53.90   57.25
     47.07   33.40   33.30   30.11   18.84   15.61   12.54   12.21    9.36
      8.42    6.95    3.61    4.15    6.56    3.29  795.96
195  2 TAPH20 C 30 5.0  203.13   68.16   42.27   40.11   50.75   53.34   60.04
     47.90   33.11   32.29   26.99   20.63   17.64   14.58    9.92    8.71
      8.96    7.08    3.11    4.80    5.57    1.32  760.41
196  3 TAPH20 C 30 5.0  321.88  162.45   95.46   67.93   70.47   61.31   64.88
     50.04   39.11   32.74   30.87   21.47   16.85   12.24   10.82    9.55
      8.31    6.55    4.26    5.46    5.90    1.97 1100.52
197  4 TAPH20 C 30 5.0  331.25  155.92   93.05   68.01   65.99   61.62   63.07
     47.29   35.55   33.30   27.10   22.06   16.85   13.99   11.07   11.42
      6.56    6.42    4.75    4.80    4.92    3.29 1088.28
198  1 TAPH20 C 40 5.0  187.50   86.53   62.98   49.15   55.65   59.24   59.10
     44.36   35.93   36.93   31.37   24.09   19.02   16.91   13.36   11.42
      9.95    8.52    4.92    7.21    6.56    4.61  835.31
199  2 TAPH20 C 40 5.0  268.75  141.22   81.70   62.83   68.76   55.53   54.67
     42.44   33.26   30.02   25.90   21.88   17.77   17.35   15.90   11.05
     10.71    8.52    5.41    4.80    3.93    5.92  988.32
200  3 TAPH20 C 40 5.0  181.25  103.67   70.07   55.72   65.30   60.15   59.92
     51.22   40.80   35.37   31.53   24.75   21.77   16.69   14.02   10.39
     12.35    8.91   10.49    5.68    1.31    0.66  882.02
201  4 TAPH20 C 40 5.0  228.13   81.63   56.88   52.86   60.98   56.61   58.57
     51.18   40.98   34.11   29.89   24.33   19.34   16.55   12.62   10.77
      8.31    7.73    6.23    3.71    3.28    1.97  866.66
202 1A TAPH20 C 50 5.0    0.00    0.00    0.00    0.00    0.00    0.00    0.00
      0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
      0.00    0.00    0.00    0.00    0.00    0.00    0.00
203  1 TAPH20 C 50 5.0  271.88  167.35   95.32   64.61   56.34   45.58   48.03
     44.89   38.92   35.22   30.11   22.18   21.57   18.29   12.54   12.08
     11.48    9.17    6.23    4.59    3.61    9.87 1029.86
```

```
204 2A TAPH20 C 50 5.0    0.00     0.00     0.00     0.00     0.00     0.00     0.00
      0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
      0.00     0.00     0.00     0.00     0.00     0.00     0.00
205  2 TAPH20 C 50 5.0  153.13   131.43   103.69    76.35    60.02    44.03    43.98
     40.91    37.75    34.46    28.69    21.94    19.41    17.57    13.61    10.49
      9.51     7.99     5.90     2.62     2.95     3.29   869.72
206  3 TAPH20 C 50 5.0  118.75   135.51   106.52    73.88    64.02    46.10    47.30
     43.44    36.16    35.47    29.73    24.15    20.66    16.03    14.34    12.64
     11.48     6.42     6.89     4.37     2.62     4.61   861.09
207  4 TAPH20 C 50 5.0  106.25   120.82   108.65    73.11    58.37    41.56    43.07
     41.56    38.08    33.25    30.44    23.08    20.33    16.47    12.54    10.77
     10.60     8.78     7.05     3.71     3.93     2.63   815.05
208     TEST     0 0.0    0.00     0.00     0.00     0.00     0.00     0.00     0.00
      0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
      0.00     0.00     0.00     0.00     0.00     0.00     0.00
209  5 TAPH20 C 50 5.0  193.75    87.76    61.84    53.25    68.28    60.03    61.89
     45.85    39.67    37.13    31.20    24.75    19.54    18.08    15.90    14.79
     11.26     8.65     5.41     4.80     6.56     7.24   877.63
210  6 TAPH20 C 50 5.0  212.50    87.35    54.47    59.81    70.74    60.43    57.83
     46.85    41.36    39.56    29.78    25.28    22.30    17.13    14.43    13.67
     11.37     8.13     8.85     5.46     4.92     5.26   897.48
211  5 TAPH20 C 40 5.0  200.00    92.24    58.58    47.14    60.39    62.10    62.75
     48.95    38.27    34.26    30.49    21.65    21.05    17.86    12.30    10.21
     10.05     8.52     6.56     5.24     5.90     3.95   858.46
212  6 TAPH20 C 40 5.0  225.00    87.76    63.40    55.56    66.47    65.61    63.44
     48.99    37.00    36.48    32.40    22.78    20.79    17.35    13.03     9.83
     10.38     8.65     4.75     6.99     7.21     5.92   909.79
213  7 TAPH20 C 40 5.0  200.00    84.08    47.94    45.90    60.61    55.69    61.39
     48.51    38.36    31.33    27.81    22.48    18.43    15.96    10.66    11.24
      9.29     7.73     6.23     5.68     6.89     3.29   819.50
214  1 OIL    C  40  7.5  581.25  229.39  147.38  152.78  177.13  155.57  152.58
    115.25    92.51    82.19    64.15    49.31    39.54    30.54    24.92    18.26
     15.63    11.93     9.51     6.33     6.56     3.29 2166.00
215  2 OIL    C  40  7.5  550.00  230.61  140.00  145.36  181.24  156.20  147.99
    115.56    93.63    79.72    69.95    48.78    39.54    30.54    27.13    18.26
     14.43    11.27     8.52     6.11     3.61     3.29 2123.74
216  3 OIL    C  40  7.5  346.88  188.16  155.04  208.35  247.49  204.66  171.31
    120.24    92.18    81.23    73.93    52.53    43.02    35.42    29.18    17.42
     13.66    10.88     7.38     5.46     6.56     7.89 2118.87
217  4 OIL    C  40  7.5  534.38  199.18  136.31  159.66  205.97  184.43  156.48
    109.57    82.86    73.56    62.68    48.30    39.93    33.24    26.48    16.20
     12.68     9.70     7.05     4.80     3.61     1.32 2108.39
218  1 OIL    C  30  7.5  581.25  241.22  150.78  145.90  187.31  171.10  161.15
    108.30    77.94    69.42    62.84    40.79    33.05    23.76    17.54    12.27
      9.51     6.82     4.75     1.97     2.62     4.61 2114.90
219  2 OIL    C  30  7.5  453.13  185.71  118.72  121.17  164.45  157.84  154.84
    103.58    76.77    66.85    58.25    43.53    30.75    24.64    16.64    10.58
      8.85     4.98     4.10     2.84     1.31     1.32 1810.85
```

```
220  3 OIL   C  30  7.5 596.88 211.84 146.52 142.66 171.16 159.59 152.99
    105.59  75.41  66.65  58.80  41.50  33.97  23.62  20.41  13.39
      9.07   8.13   3.61   2.84   2.95   1.97 2049.55
221  4 OIL   C  30  7.5 543.75 212.65 127.94 120.02 153.94 147.21 146.68
    106.16  80.37  67.51  59.89  40.19  28.92  23.25  16.80  10.67
      7.10   5.77   5.90   1.53   1.64   1.32 1909.21
222  1 OIL   C  50  7.5 487.50 227.76 159.86 174.19 206.02 162.78 153.89
    114.16  90.63  78.36  72.73  53.25  43.80  37.46  30.82  23.60
     19.23  12.32  10.82   8.73   7.54   5.92 2181.37
223  2 OIL   C  50  7.5 571.88 258.78 188.09 187.87 213.81 184.75 161.43
    120.85 100.42  87.24  79.29  56.71  47.80  40.01  30.82  22.00
     17.05  14.94  13.61  11.35   6.23   9.21 2424.14
224  3 OIL   C  50  7.5 443.75 241.22 161.42 167.54 209.01 177.03 155.45
    119.71  98.08  86.43  77.76  54.74  45.97  38.85  31.80  22.94
     19.13  14.42  10.49   7.64   8.20   5.92 2197.50
225  4 OIL   C  50  7.5 618.75 244.90 179.72 187.79 212.58 174.00 155.20
    114.20  99.77  84.26  73.11  58.02  46.16  10.09  30.74  20.97
     16.83  14.02  12.30   9.17   7.21   5.26 2375.05
226  1 OIL   C  60  7.5 478.13 255.10 193.90 197.06 218.28 167.60 149.59
    116.61 100.33  86.78  75.46  57.78  49.51  39.43  33.77  23.41
     17.92  16.38  14.43  10.04  11.15  13.82 2326.48
227  2 OIL   C  60  7.5 584.38 268.98 204.82 196.83 209.22 157.96 153.61
    117.40  94.94  88.24  79.45  59.51  43.93  41.47  34.67  24.91
     18.58  16.51  14.10  12.23   6.89  13.16 2441.79
228  3 OIL   C  60  7.5 509.38 254.29 193.62 196.68 210.02 166.48 148.52
    115.43 100.80  88.45  79.23  57.66  48.20  39.43  30.98  26.97
     18.03  16.78  13.61  10.26  11.15   3.29 2339.26
229  4 OIL   C  60  7.5 590.63 294.29 166.10 185.16 203.62 159.12 147.17
    118.88  97.24  92.58  79.40  60.29  51.67  41.40  36.97  28.09
     20.77  16.64  14.43  14.63   8.85   9.87 2437.80
230  1 OIL   C  60  5.0 221.88 155.10 113.05 105.72 103.73  78.03  65.78
     57.17  48.99  47.07  39.45  32.62  29.77  25.29  20.98  18.07
     14.86  13.63  10.82  11.79   7.87  13.82 1235.49
231  2 OIL   C  60  5.0 200.00  99.59  83.55  82.92  84.43  74.76  68.11
     57.47  49.18  46.87  41.26  31.78  28.07  22.45  22.62  16.10
     12.24   9.44  10.00   8.08   9.51  15.13 1073.56
232  3 OIL   C  60  5.0 215.63 116.73  86.95  84.62  93.02  76.43  67.62
     55.46  49.70  46.22  40.00  33.21  28.79  28.50  23.11  17.60
     15.52  14.29  10.16   8.52  10.49   9.87 1132.44
233  4 OIL   C  60  5.0 228.13 139.18  99.86  95.13  95.52  77.87  70.04
     54.06  45.81  45.96  41.04  32.44  27.21  22.01  22.54  18.07
     14.10  14.68  10.00   6.99  10.49  11.84 1182.97
234  1 OIL   C  30  5.0 200.00  91.43  66.81  55.10  65.94  69.51  76.72
     60.23  44.12  41.68  37.54  26.18  24.98  19.61  14.59  12.36
     10.49   7.99   7.54   5.68   4.59   1.97  945.06
235 2a OIL   C  30  5.0   0.00   0.00   0.00   0.00   0.00   0.00   0.00
      0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
      0.00   0.00   0.00   0.00   0.00   0.00   0.00
```

```
236  2 OIL   C  30  5.0 175.00   80.00   63.12   53.32   67.22   76.19   80.45
     58.04   47.78   40.16   37.16   26.06   24.98   18.22   15.90   10.96
      7.87    7.73    5.41    4.59    2.62    4.61  907.39
237  3 OIL   C  30  5.0 150.00   65.71   66.81   49.23   68.76   76.27   79.92
     59.27   45.25   43.54   40.82   29.64   23.15   20.34   16.48   13.01
     11.91    9.70    9.02    8.08    5.25    9.21  901.37
238  4 OIL   C  30  5.0 140.63   79.59   63.55   50.54   70.20   78.22   79.30
     58.83   46.04   45.76   37.10   29.76   23.15   21.65   18.61   13.58
     10.16    9.70   10.16    6.11    7.21    8.55  908.40
239    OIL   C   0  5.0   0.00    0.00    0.00    0.00    0.00    0.00    0.00
      0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
      0.00    0.00    0.00    0.00    0.00    0.00    0.00
240  1 OIL   C  40  5.0 153.13   88.16   91.06   98.84  112.15  100.52   85.49
     61.41   49.09   46.72   42.62   32.20   26.43   21.65   17.54    7.87
      4.04    2.10    1.64    2.18    0.98    0.00 1045.82
241  2 OIL   C  40  5.0 165.63   92.65   72.20   85.09   99.73   98.73   90.37
     60.40   50.40   47.28   42.51   27.91   26.69   20.99   18.85   15.17
     13.22    9.70    8.85    9.39    8.85   11.18 1075.79
242  3 OIL   C  40  5.0 171.88  116.33   87.66   99.07  109.86  102.99   92.13
     61.06   52.32   52.72   42.79   31.01   27.15   22.52   19.18   13.76
     14.54   11.80   11.64    8.95    7.21    3.29 1159.86
243  4 OIL   C  40  5.0 150.00   85.31   81.13   94.74  106.45   99.12   88.93
     61.80   51.90   47.12   41.53   30.89   25.57   19.61   21.31   16.67
     12.35   11.53    8.36    8.95    9.51    8.55 1081.33
244  5 OIL   C  40  5.0 131.25   89.39   90.92   88.25  100.75  103.03   89.67
     63.02   50.73   49.19   43.55   31.66   25.90   21.57   18.61   15.36
     10.60   10.35    9.84    8.08    8.52   15.13 1075.37
245  1 OIL   C  50  5.0 134.38   75.51   66.81   63.37   86.62   87.26   79.47
     63.02   52.74   48.18   41.37   34.11   31.34   23.98   24.34   17.60
     13.11   13.24    9.51    9.17    7.87    8.55  991.55
246  2 OIL   C  50  5.0 281.25  122.04   86.81   79.44   99.84   88.61   83.98
     64.42   55.27   49.90   45.52   36.08   28.79   28.28   22.46   16.01
     16.50   11.53    9.34    9.83    7.54    8.55 1251.99
247  3 OIL   C  50  5.0 300.00  140.41  109.65   91.65  113.49   94.27   91.07
     64.25   53.07   50.50   44.75   34.59   30.23   26.97   23.03   16.67
     13.77   12.71    8.20   10.92    9.51   11.18 1350.89
248  4 OIL   C  50  5.0 184.38   91.84   66.38   61.13   83.05   89.25   83.07
     61.67   51.52   49.50   40.77   33.57   29.11   25.73   23.28   19.19
     14.86   12.71   11.15    7.86   11.80   11.18 1063.00
249  1 OIL   C  50 10.0 840.63  313.88  193.33  193.89  273.13  249.28  226.15
    162.28  129.65  122.50  107.16   76.27   62.30   53.13   40.74   25.94
     21.53   16.78   15.25    7.64    5.57    4.61 3141.64
250  2 OIL   C  50 10.0 534.38  323.27  217.87  196.29  273.40  242.24  229.67
    160.49  132.37  119.93  108.58   72.57   58.75   49.85   40.25   23.78
     20.44   16.25   15.90    8.52    7.21    3.95 2855.96
251  3 OIL   C  50 10.0 718.75  337.14  207.38  210.66  275.43  254.66  227.13
    167.35  144.64  126.59  109.73   77.76   65.18   50.07   46.48   27.53
     20.11   18.09   14.59    8.95    4.59    7.89 3120.70
```

```
252  4 OIL   C  50 10.0    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00
253  5 OIL   C  50 10.0 1006.25  447.35  260.99  264.22  318.39  264.85  234.39
   179.72  144.54  131.38  110.44   80.74   63.67   56.27   46.80   23.88
    18.58   14.29   12.79    6.77    4.26    5.26 3695.83
254  6 OIL   C  50 10.0 1153.13  469.39  300.99  295.05  343.34  265.80  231.27
   178.58  151.90  130.17  116.01   80.80   64.92   52.99   41.31   26.97
    21.20   19.53   13.28    7.64    7.21    8.55 3980.03
255  1 OIL   C  60 10.0    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00
256  1 OIL   C  30 10.0 1134.38  431.02  226.10  184.23  220.90  195.62  192.21
   140.52  107.45   85.22   66.83   43.23   28.46   22.96   17.13   11.99
     4.92    7.73    2.30    0.87    1.64    1.32 3127.03
257  2 OIL   C  30 10.0 1412.50  522.86  260.14  190.57  204.26  197.81  191.60
   144.62  104.68   85.02   69.18   42.64   32.13   26.46   19.75   10.96
     6.99    5.64    5.25    2.62    1.64    0.66 3537.98
258  3 OIL   C  30 10.0 1106.25  413.06  231.91  185.70  214.02  202.83  198.32
   146.46  110.02   89.35   75.03   43.41   32.85   25.15   20.33   10.39
     5.57    6.03    4.59    1.53    0.98    1.97 3125.75
259  4 OIL   C  30 10.0 1262.50  453.06  249.50  198.22  218.98  199.96  202.66
   147.55  107.92   85.62   71.31   44.96   31.74   25.58   20.25   12.27
     9.73    5.90    3.77    2.18    2.30    2.63 3358.59
260  1 OIL   C  40 10.0  993.75  404.49  278.44  221.56  254.74  226.19  205.49
   158.04  129.93  110.34   92.08   63.74   45.38   38.85   29.10   15.07
    12.24    7.60    8.36    4.37    2.30    1.97 3304.03
261  2 OIL   C  40 10.0  912.50  405.31  261.42  210.82  260.07  225.80  218.32
   153.67  126.14  109.03   88.36   61.60   46.56   33.53   30.00   18.45
     9.73    9.96    6.89    3.49    3.93    1.97 3197.55
262  3 OIL   C  40 10.0  778.13  342.86  231.06  195.83  240.09  217.87  212.95
   160.31  123.04  103.53   88.31   59.63   49.77   35.28   28.20   15.54
    13.99    8.13    6.89    2.84    4.59    1.32 2920.16
263  4 OIL   C  40 10.0  906.25  371.43  238.58  202.55  240.83  221.58  214.34
   154.76  131.05  108.93   88.85   61.36   48.13   37.24   29.67   18.45
    13.55   11.01    8.03    5.02    3.93    1.97 3117.51
264  2 OIL   C  60 10.0 1037.50  455.92  359.15  339.10  345.52  256.25  231.56
   171.68  151.57  132.59  115.74   77.28   65.25   55.03   46.64   32.68
    25.57   18.09   15.90    7.86   12.13    9.87 3962.88
265  3 OIL   C  60 10.0  968.75  474.69  357.45  341.58  349.52  260.67  229.92
   176.88  150.12  129.87  112.62   78.53   64.33   56.78   48.36   26.12
    26.12   20.05   17.70   10.04    7.87    8.55 3916.52
266  4 OIL   C  60 10.0 1003.13  471.43  365.53  339.95  341.79  253.14  226.31
   176.49  147.73  133.25  112.90   82.41   66.62   56.20   47.46   30.90
    24.92   17.43   17.87    9.17    8.20   10.53 3943.36
267  5 OIL   C  60 10.0  962.50  448.98  324.54  309.04  325.27  249.76  224.02
   168.44  150.82  131.79  112.46   80.02   63.15   54.30   48.20   29.21
    21.42   19.79   13.61    8.95    6.89    8.55 3761.71
```

```
268  1 H20   C  60 10.0  875.00  478.37  338.44  303.55  299.47  223.01  199.06
   150.96  122.86  104.34   86.89   57.19   45.84   37.76   31.72   21.35
    15.08   12.71   11.80    5.68    4.26    3.29 3428.63
269  2 H20   C  60 10.0 1125.00  512.24  368.94  328.44  304.90  219.23  199.39
   145.67  118.88  103.08   88.52   54.80   44.46   34.55   33.11   19.94
    15.96   11.66   11.64    7.42    3.61    5.92 3757.36
270  3 H20   C  60 10.0  965.63  457.96  326.52  289.64  284.75  217.56  196.07
   145.24  113.86  101.01   82.24   60.94   41.64   37.46   31.64   19.19
    15.19   13.50   10.33    5.46    3.93    6.58 3426.34
271  4 H20   C  60 10.0  878.13  449.80  335.04  271.87  270.04  203.18  185.61
   137.50  109.27   95.56   79.02   54.08   46.69   33.38   28.61   19.19
    14.86   10.75    8.52    5.02    7.87    3.29 3247.28
272  1 H20   C  30 10.0  650.00  357.14  216.31  160.36  170.79  155.89  142.25
   100.79   72.18   59.84   44.64   27.85   19.28   12.68    9.92    5.71
     4.04    2.10    2.79    1.53    0.33    0.66 2217.08
273 2a H20   C  30 10.0    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00
274  2 H20   C  30 10.0  387.50  361.22  275.46  267.47  282.68  221.42  179.14
   114.38   84.31   68.31   55.96   33.81   24.85   15.16   14.59    6.65
     5.68    4.59    2.13    1.75    1.97    0.66 2409.69
275  3 H20   C  30 10.0 1253.13  824.90  482.70  336.71  378.57  297.33  231.93
   129.46   93.30   79.82   64.75   35.24   27.93   17.27   15.57    6.09
     6.01    2.75    2.13    1.09    0.66    0.00 4287.34
276  4 H20   C  30 10.0    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
     0.00    0.00    0.00    0.00    0.00    0.00    0.00
277  5 H20   C  30 10.0 1334.38  472.65  256.45  202.70  216.90  178.07  161.02
   115.52   84.96   67.66   56.12   31.96   24.13   17.06   12.05    8.43
     4.92    3.01    2.79    1.53    0.98    0.00 3253.29
278  1 H20   C  40 10.0  884.38  382.86  212.77  204.87  234.75  195.22  174.92
   134.44  105.15   83.91   71.20   45.14   35.80   26.09   19.67   11.99
    10.60    6.16    6.89    2.18    2.62    1.97 2853.58
279  2 H20   C  40 10.0  862.50  501.22  311.35  238.18  217.22  163.18  149.47
   110.88   91.15   75.38   63.44   37.45   26.56   21.57   17.87   12.36
     7.76    6.16    3.93    3.49    1.31    1.97 2924.40
280  3 H20   C  40 10.0  996.88  737.14  467.66  287.40  210.55  155.25  135.49
    92.18   79.11   63.02   52.95   33.27   24.13   18.59   13.69    8.05
     6.01    4.85    3.61    1.31    1.64    0.00 3392.78
281  4 H20   C  40 10.0  878.13  635.51  419.15  254.64  198.35  145.18  128.89
    89.25   73.02   66.25   53.93   30.05   23.74   17.93   14.10    6.74
     5.68    4.33    2.79    1.09    1.31    0.00 3050.06
282  5 H20   C  40 10.0 1168.75  611.84  354.47  260.66  228.04  173.49  158.03
   118.01   92.18   79.82   62.08   40.97   32.07   19.61   19.18   13.76
    10.16    8.13    5.41    2.18    2.95    1.97 3463.76
283  6 H20   C  40 10.0  712.50  337.96  194.33  165.38  193.87  165.64  156.43
   111.80   90.91   75.88   59.95   39.71   29.11   22.16   17.87    9.55
     7.21    5.50    3.61    1.75    0.98    1.97 2404.07
```

```
284  7 H20   C  40 10.0  637.50  272.24  167.66  132.69  159.38  142.75  143.48
  100.66   84.68   71.64   53.17   36.31   28.79   22.52   15.16    8.61
    4.26    4.72    3.44    1.53    1.97    0.00 2093.16
285  1 H20   C  50 10.0  743.75  363.67  242.98  189.64  197.44  166.24  156.02
  117.48   98.31   86.48   67.60   43.05   36.26   27.04   20.82   13.48
    8.52    6.95    5.08    3.06    2.95    0.66 2597.48
286  2 H20   C  50 10.0  681.25  386.94  256.31  212.98  207.89  163.89  156.72
  118.53   97.75   82.74   68.47   45.20   34.56   26.68   21.56   12.36
    9.07    7.34    5.74    1.97    2.62    0.66 2601.23
287  3 H20   C  50 10.0  631.25  334.29  237.87  205.64  209.91  169.27  155.04
  118.14   97.94   83.40   69.02   44.19   34.16   26.97   23.69   14.70
   12.68    6.03    4.92    4.80    2.30    4.61 2490.82
288  4 H20   C  50 10.0  596.88  375.92  279.29  208.73  200.05  163.85  156.39
  111.28   89.18   78.36   65.90   36.85   32.72   23.54   20.66   13.67
    9.95    7.86    5.90    3.06    1.64    0.66 2482.34
```

USDA SPRAY PARTICLE COUNTER STATISTICAL PRINTOUT

```
NOW RUN PROBE #2
     FILE #  8
TEST #
     605

   PROBE      3

CHNL         COR. COUNTS

 1              590.63
 2              101.63
 3               46.52
 4                7.73
 5                7.89
 6               11.62
 7               19.51
 8               21.55
 9               24.64
10               25.78
11               26.28
12               17.17
13               19.48
14               17.64
15               17.62
16               11.89
17                9.62
18                6.55
19                2.13
20                1.09
21                0.00
22                1.32
SUM             988.29

ARITHMETIC
    MN DIAM      97.52
    SD          115.10
CV = SD/MN        1.18

DIAMETER WGTD
    MN DIAM     233.36
    SD          142.42
CV = SD/MN        0.61

SURFACE WGTD
    MN DIAM     320.28
    SD          105.81
CV = SD/MN        0.33

VOLUME WGTD
    MN DIAM     355.23
    SD           87.80
CV = SD/MN        0.25

MEAN VOLUME
DIAM =          193.89
MICRONS

CUMULATIVE   VOL   %
CHNL
 1                 0.2
 2                 0.5
 3                 0.8
 4                 0.9
 5                 1.1
 6                 1.7
 7                 3.3
 8                 5.8
 9                 9.8
10                15.7
11                23.4
12                29.9
13                39.3
14                49.9
15                62.8
16                73.4
17                83.6
18                91.9
19                95.1
20                97.0
21                97.0
22               100.0

DIAM  @  10%    VOL =
     243      MICRONS

DIAM  @  50%    VOL =
     368      MICRONS

DIAM  @  90%    VOL =
     457      MICRONS
```

⇦ Key in up to 8 digits for test conditions

⇦ Probe(s) used

⇦ Counts or frequency corrected for variable sampling area, actually counts/mm^2

SIZE RANGE	SIZE CLASS MIDPOINT
18-42 μm	30 μm
42-67	55
67-92	80
92-117	104
117-142	129
142-166	154
166-191	178
191-215	203
215-242	229
242-265	253
265-289	277
289-314	301
314-338	326
338-363	351
363-388	375
388-413	400
413-438	425
438-463	450
463-488	475
488-513	500
513-538	525
538-563	550

⇦ Total Particles in all 22 size classes

⇦ $\bar{D}_{10} = \frac{\sum Df}{\sum f}$, also known as Arithmetic Mean Diameter

SD = Standard deviation CV = Coefficient of variation

⇦ $\bar{D}_{21} = \frac{\sum D^2 f}{\sum Df}$, also known as Surface-Diameter Mean Diameter

⇦ $\bar{D}_{32} = \frac{\sum D^3 f}{\sum D^2 f}$, also known as Volume-Surface ("Sauter") Mean Diameter

⇦ $\bar{D}_{43} = \frac{\sum D^4 f}{\sum D^3 f}$, also known as "DeBrouckere" Mean Diameter

⇦ $\bar{D}_{30} = \left[\frac{\sum D^3 f}{\sum f}\right]^{1/3}$, also known as Volume Mean Diameter, VMD <

⇦ CUMULATIVE VOLUME PRINTOUT

⇦ $\bar{D}_{v.1}$ = 10% intercept of Cumulative Volume Curve.

⇦ $\bar{D}_{v.5}$ = 50% intercept of Cumulative Volume Curve, Volume (or Mass) Median Diamet (MMD).

⇦ $\bar{D}_{v.9}$ = 90% intercept of Cumulative Volume Curve.

Prepared by Henry J. Retzer
Agricultural Equipment Lab., FPHI
Beltsville, Maryland 1/16/79

APPENDIX B

LATERAL SPRAY DISTRIBUTIONS

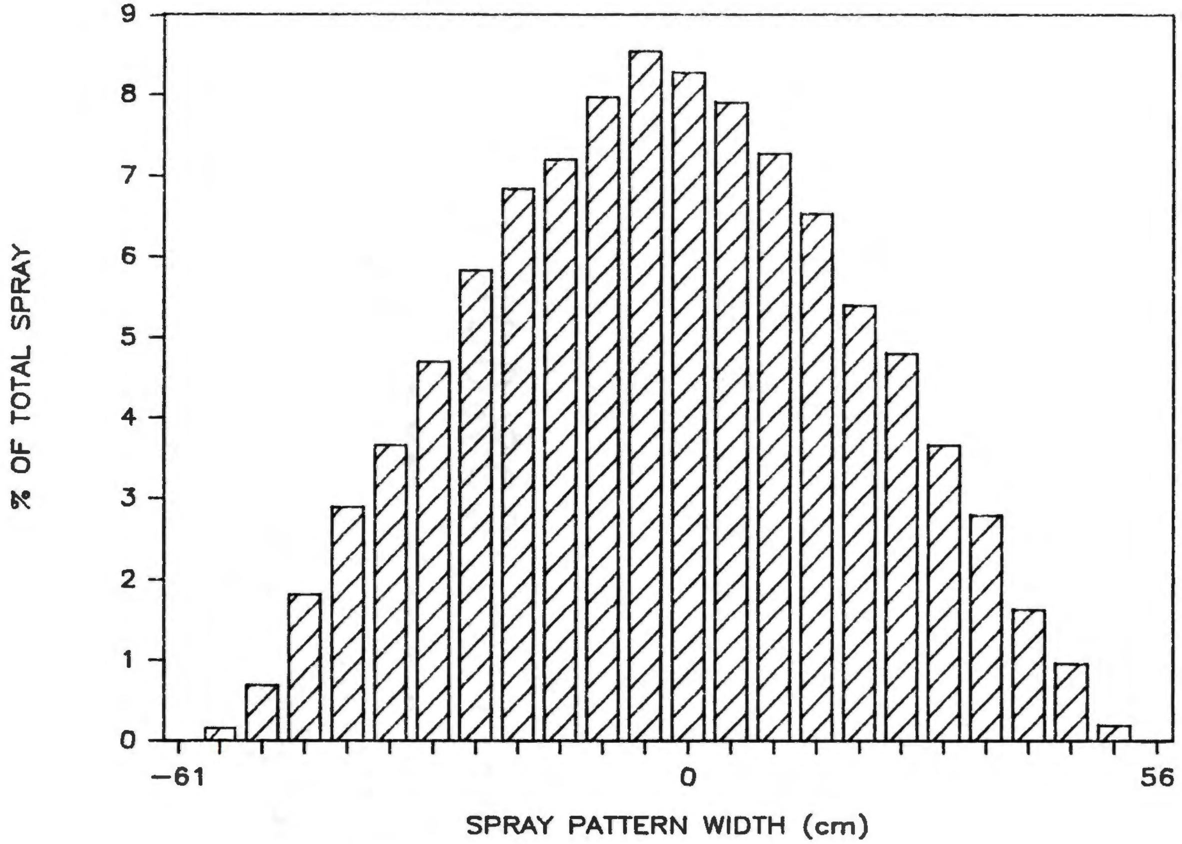

Figure 35. Lateral spray distribution for the oil-in-water solution at 52 kPa air pressure, 276 kPa liquid pressure, and 43 cm above the patternator.

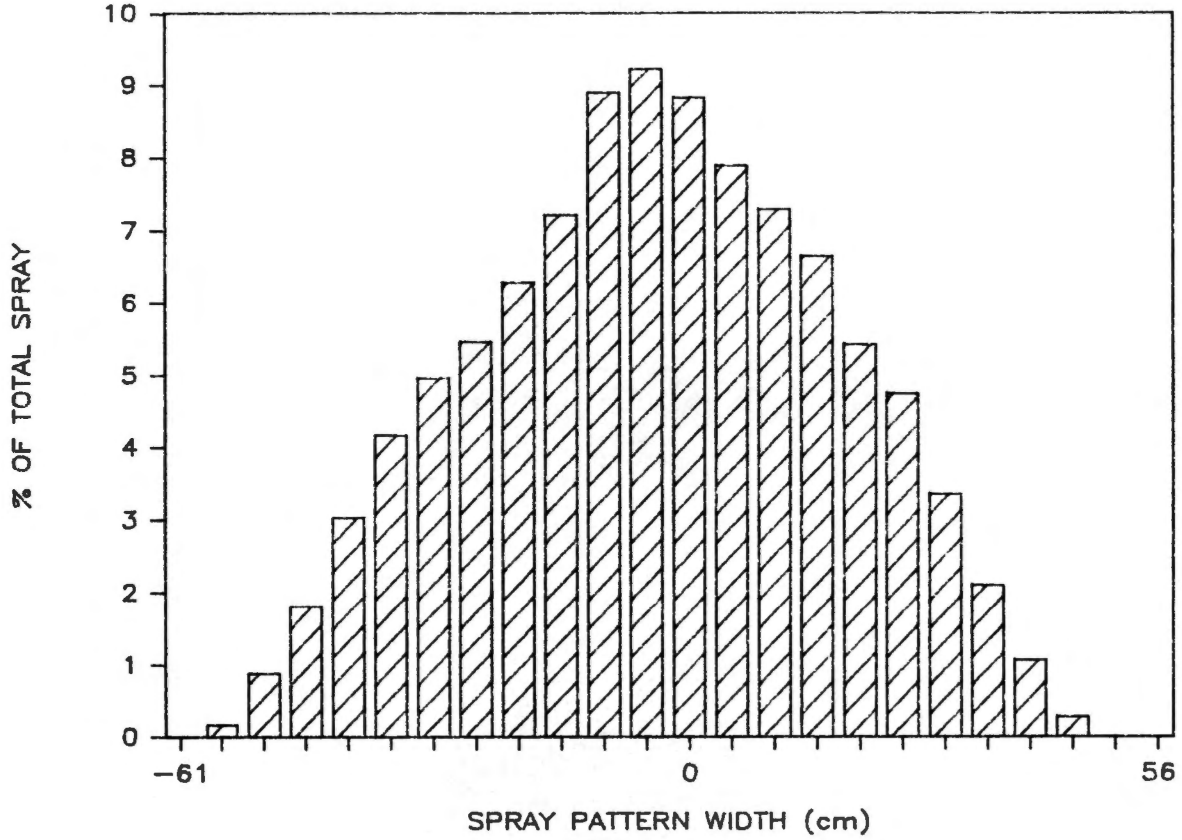

Figure 36. Lateral spray distribution for the oil-in-water solution at 52 kPa air pressure, 345 kPa liquid pressure, and 43 cm above the patternator.

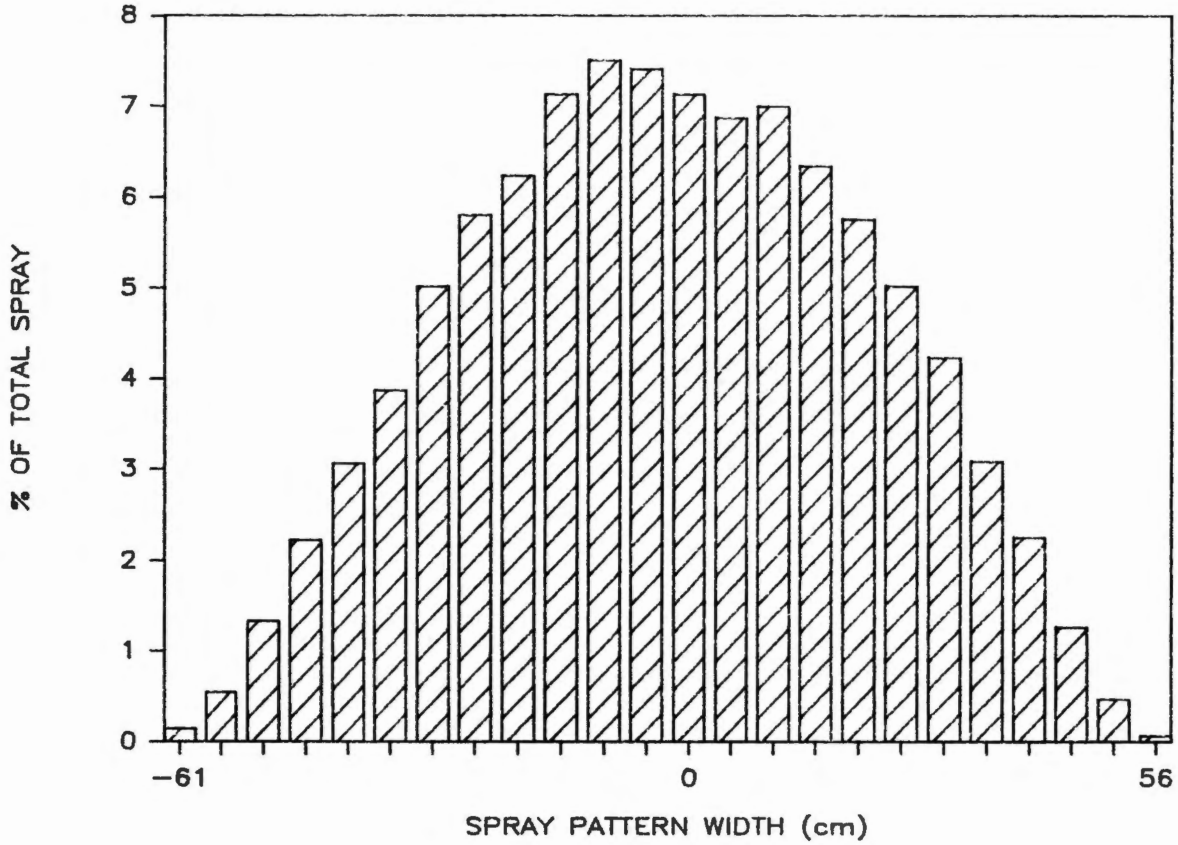

Figure 37. Lateral spray distribution for the oil-in-water solution at 52 kPa air pressure, 276 kPa liquid pressure, and 53 cm above the patternator.

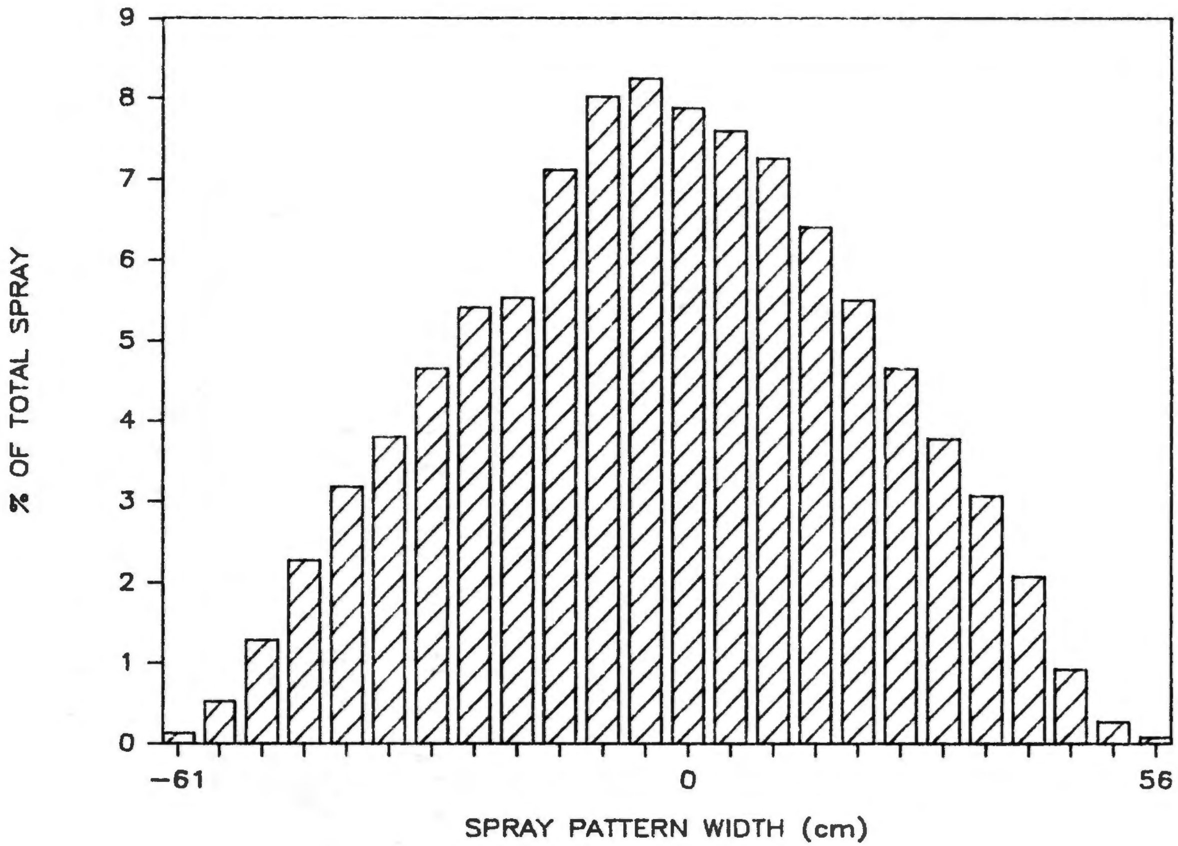

Figure 38. Lateral spray distribution for the oil-in-water solution at 52 kPa air pressure, 345 kPa liquid pressure, and 53 cm above the patternator.

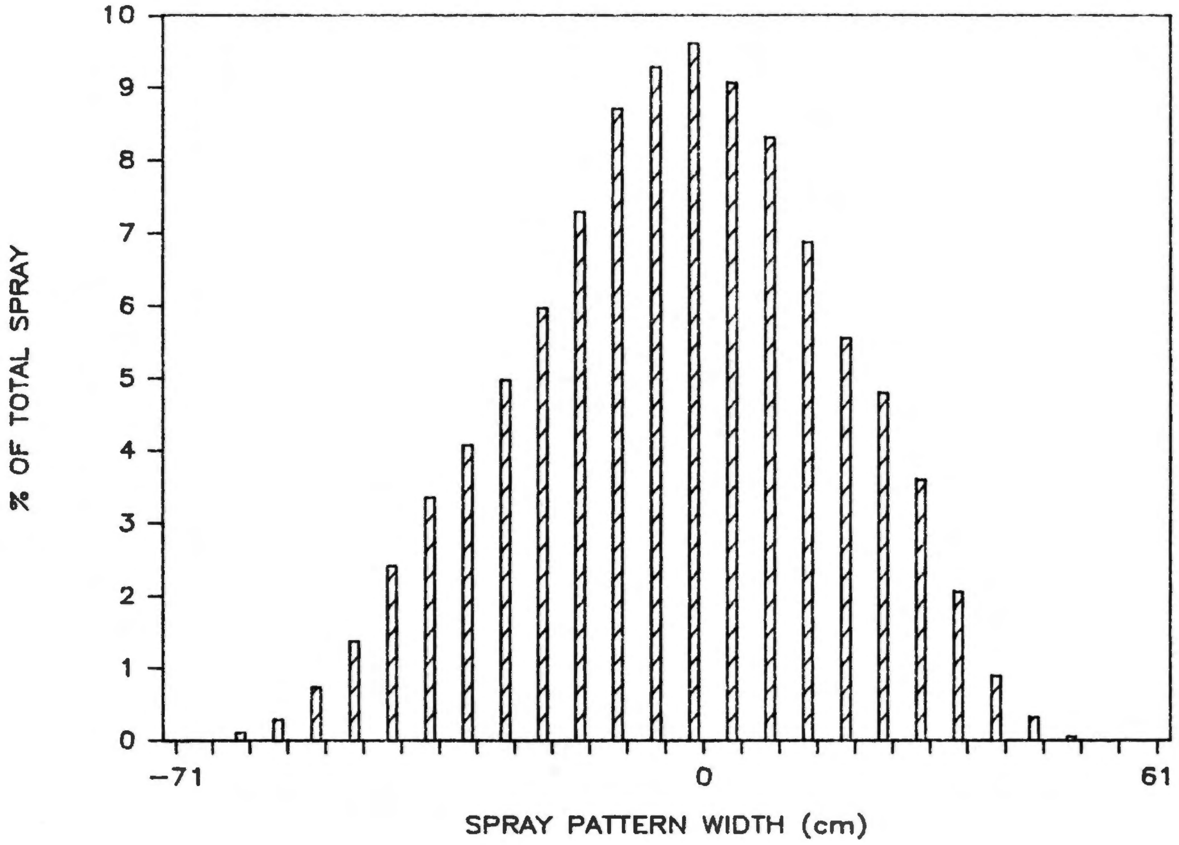

Figure 39. Lateral spray distribution for tapwater at 34 kPa air pressure, 276 kPa liquid pressure, and 43 cm above the patternator.

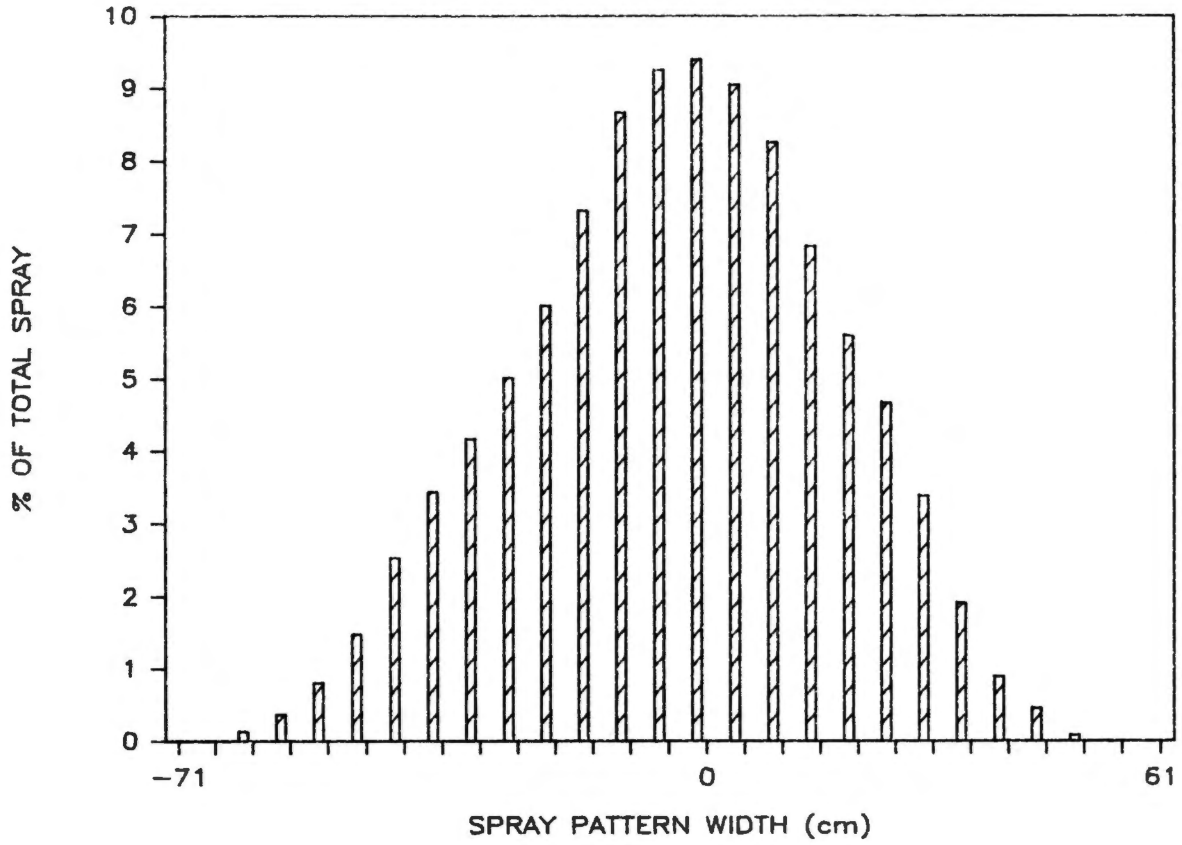

Figure 40. Lateral spray distribution for tapwater at 34 kPa air pressure, 345 kPa liquid pressure, and 43 cm above the patternator.

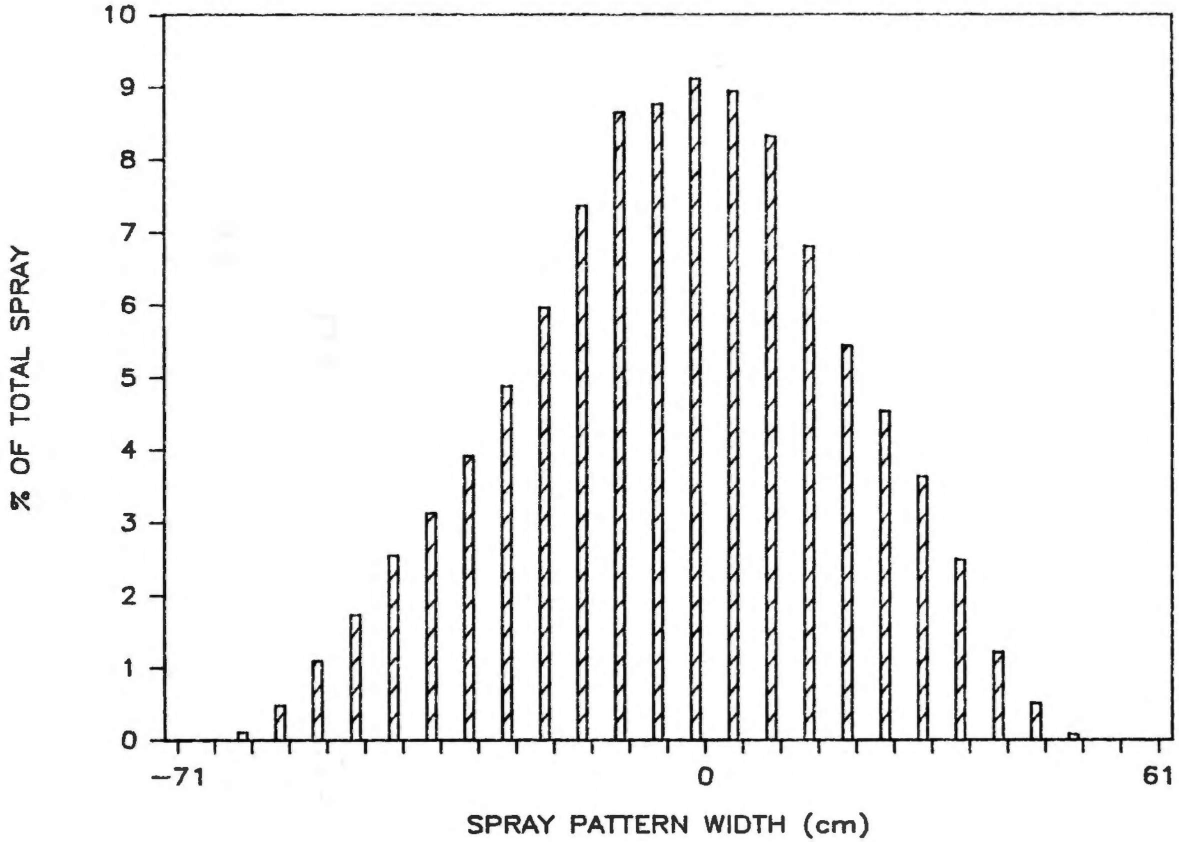

Figure 41. Lateral spray distribution for tapwater at 52 kPa air pressure, 276 kPa liquid pressure, and 43 cm above the patternator.

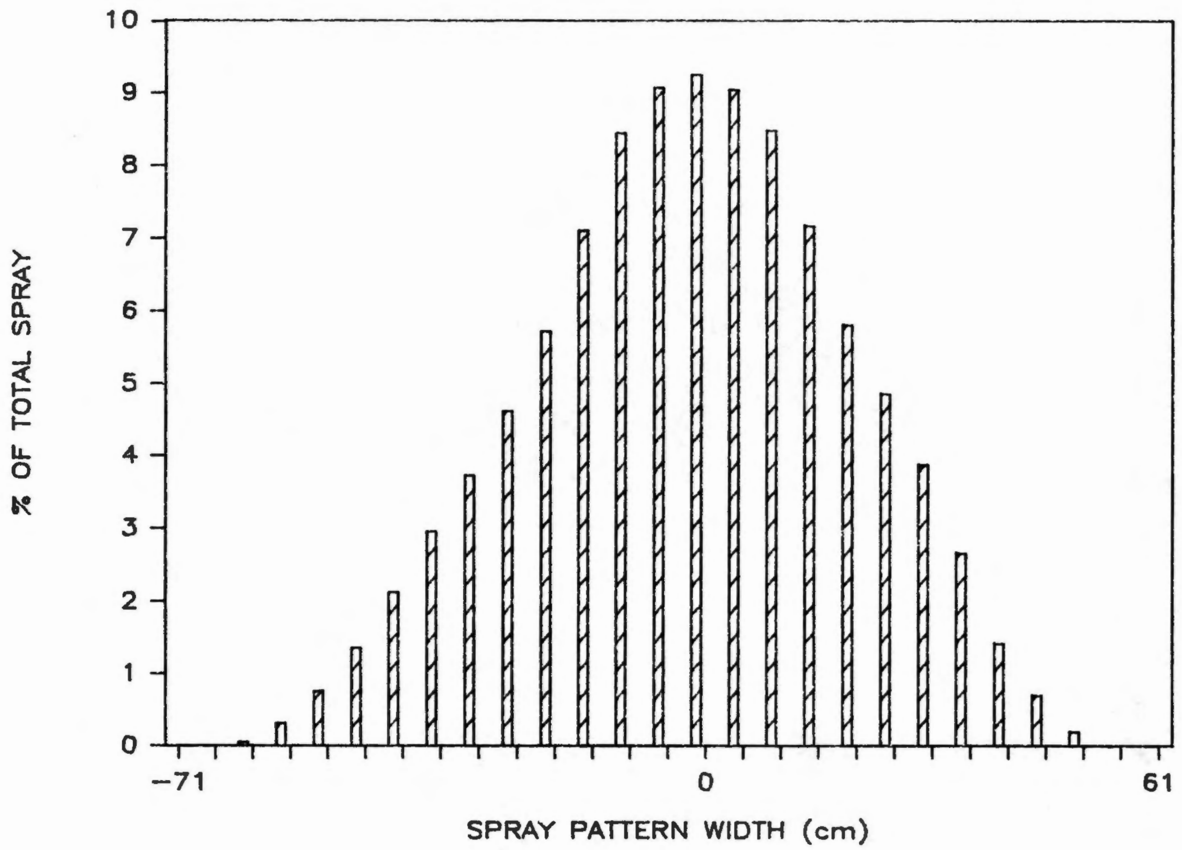

Figure 42. Lateral spray distribution for tapwater at 52 kPa air pressure, 345 kPa liquid pressure, and 43 cm above the patternator.

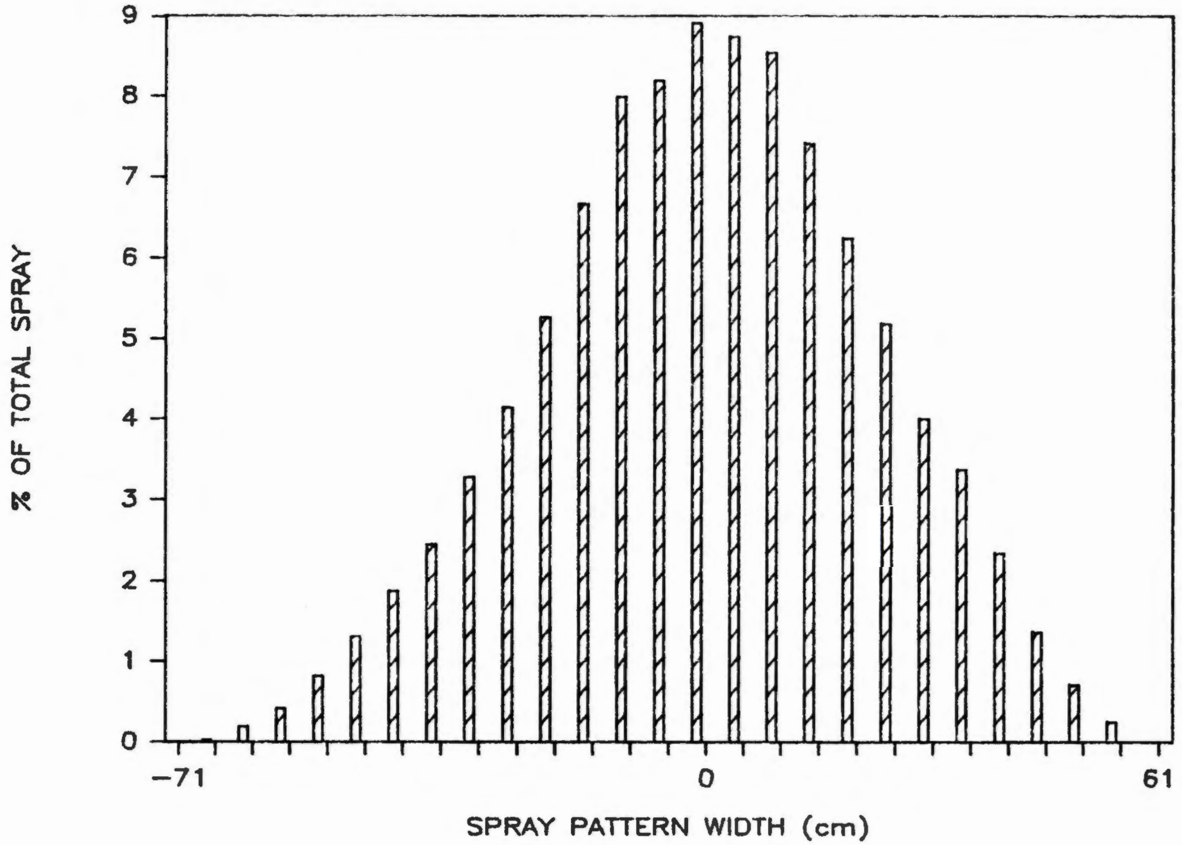

Figure 43. Lateral spray distribution for tapwater at 69 kPa air pressure, 276 kPa liquid pressure, and 43 cm above the patternator.

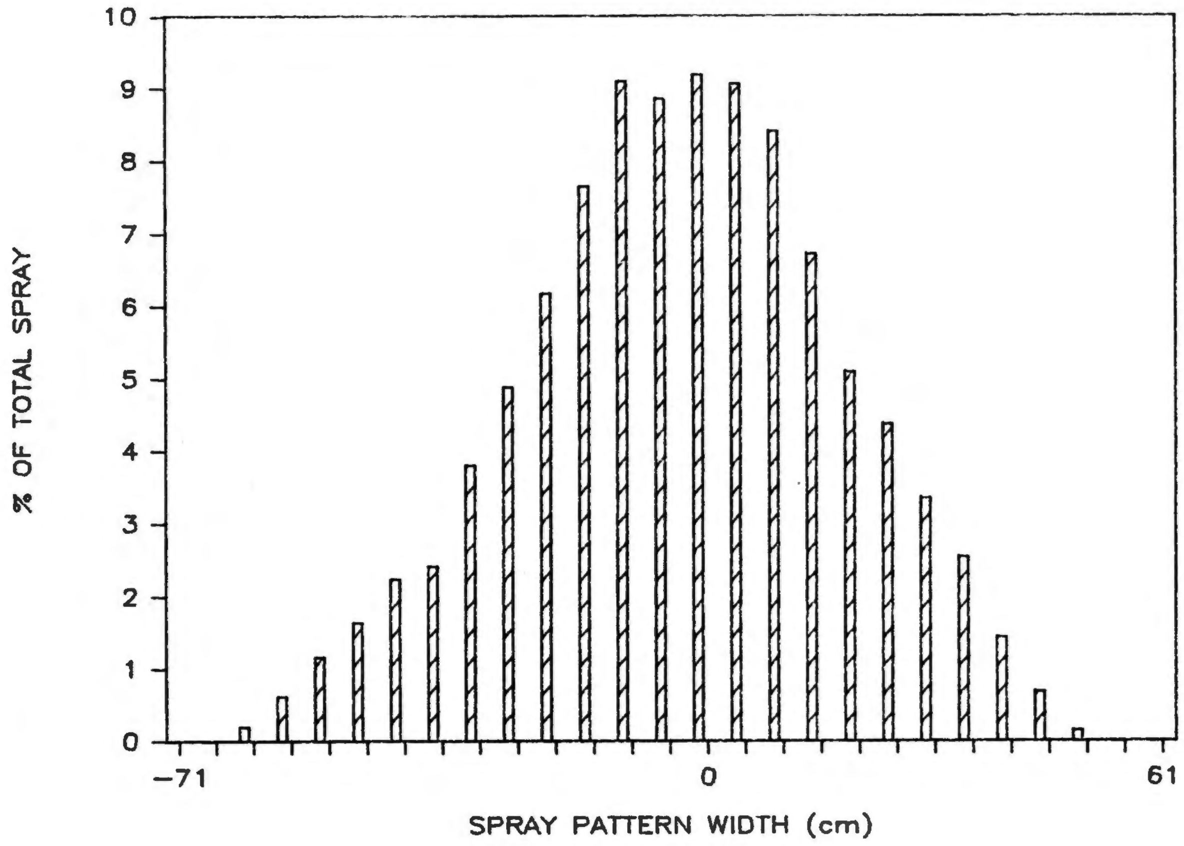

Figure 44. Lateral spray distribution for tapwater at 69 kPa air pressure, 345 kPa liquid pressure, and 43 cm above the patternator.

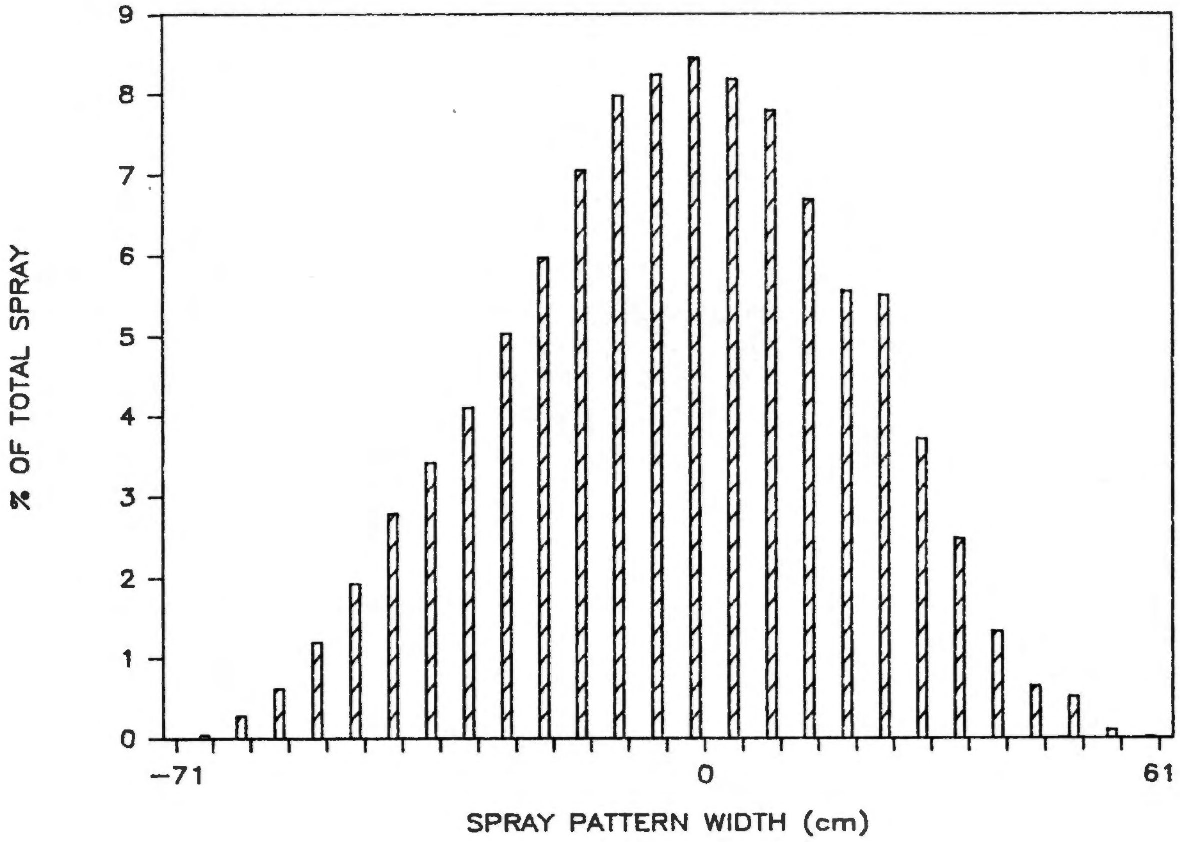

Figure 45. Lateral spray distribution for tapwater at 34 kPa air pressure, 276 kPa liquid pressure, and 48 cm above the patternator.

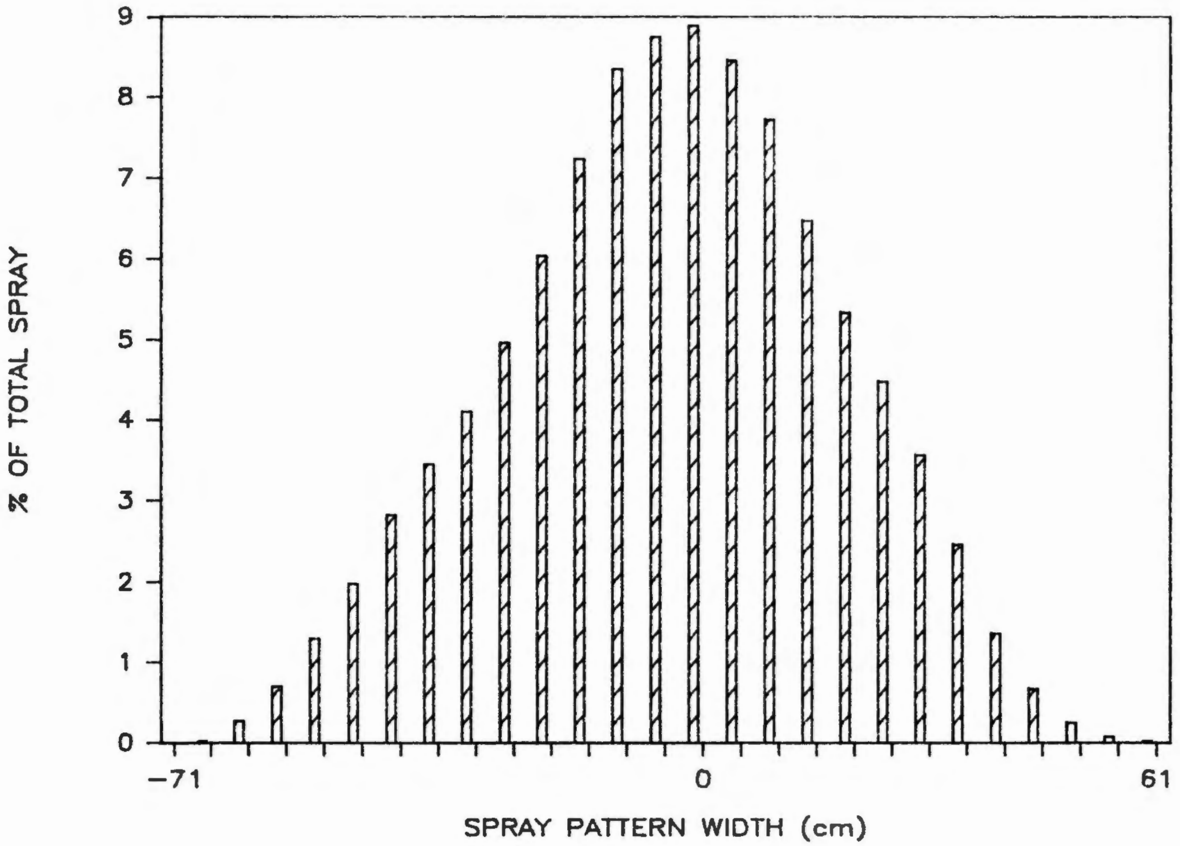

Figure 46. Lateral spray distribution for tapwater at 34 kPa air pressure, 345 kPa liquid pressure, and 48 cm above the patternator.

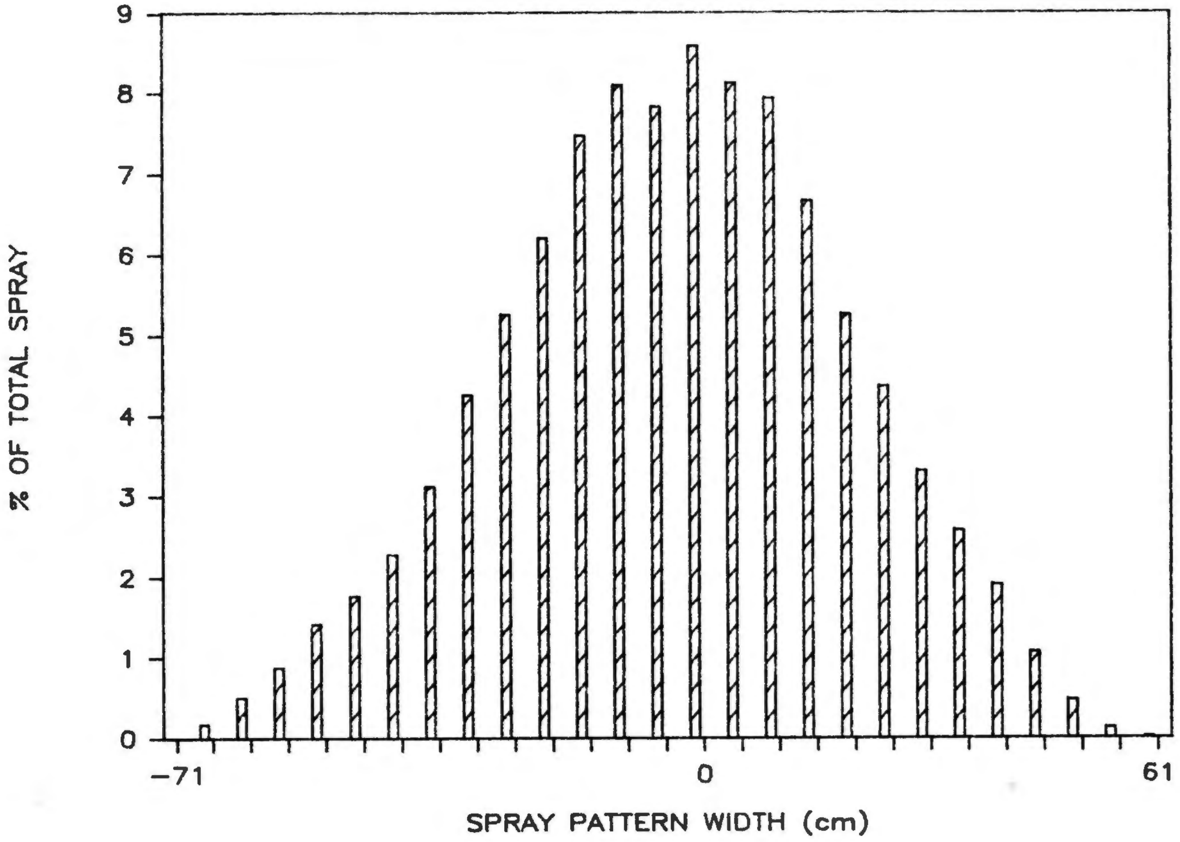

Figure 47. Lateral spray distribution for tapwater at 69 kPa air pressure, 276 kPa liquid pressure, and 48 cm above the patternator.

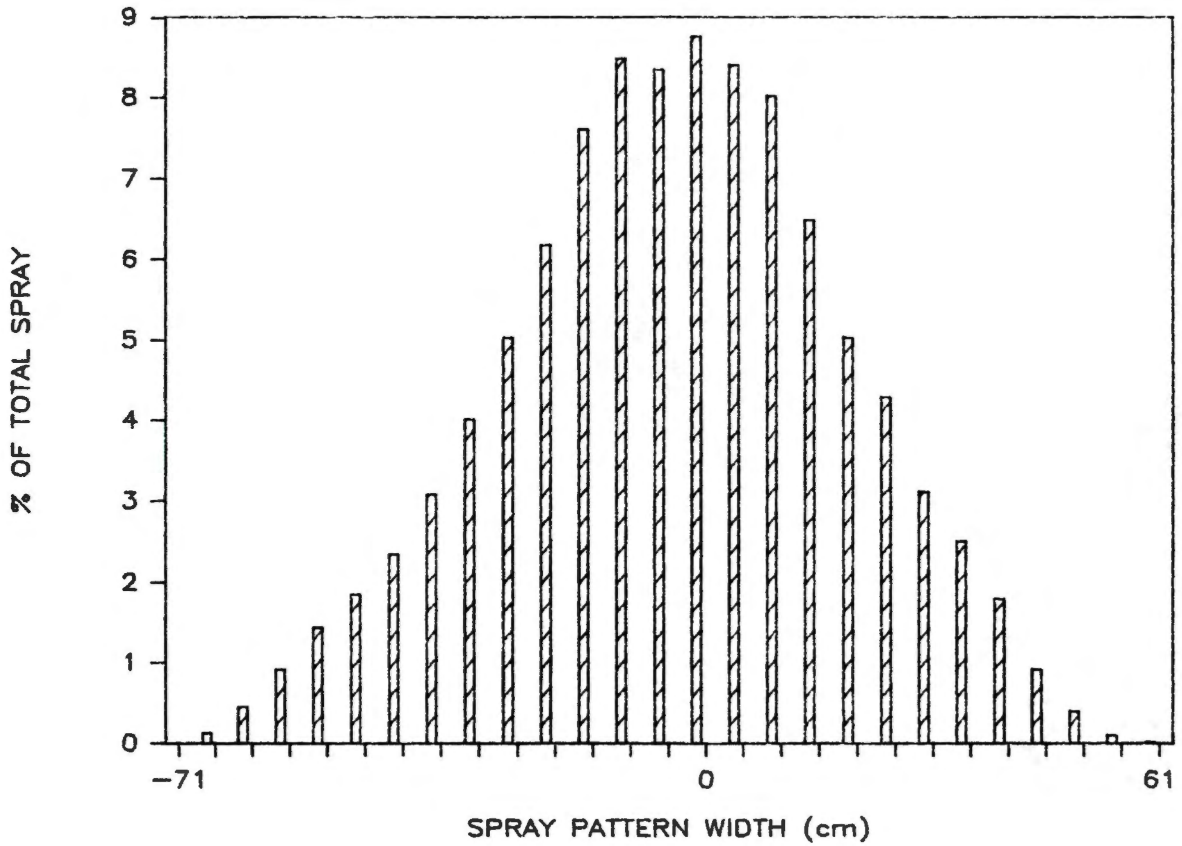

Figure 48. Lateral spray distribution for tapwater at 69 kPa air pressure, 345 kPa liquid pressure, and 48 cm above the patternator.

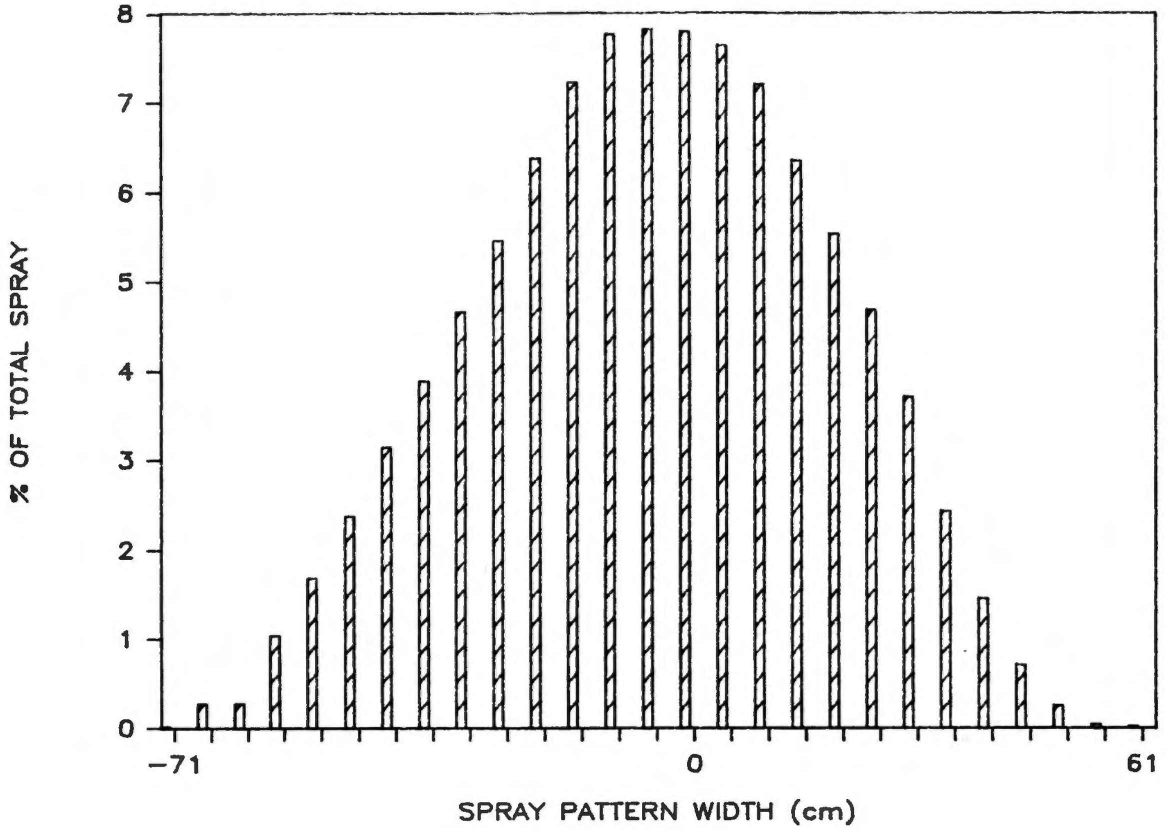

Figure 49. Lateral spray distribution for tapwater at 34 kPa air pressure, 276 kPa liquid pressure, and 53 cm above the patternator.

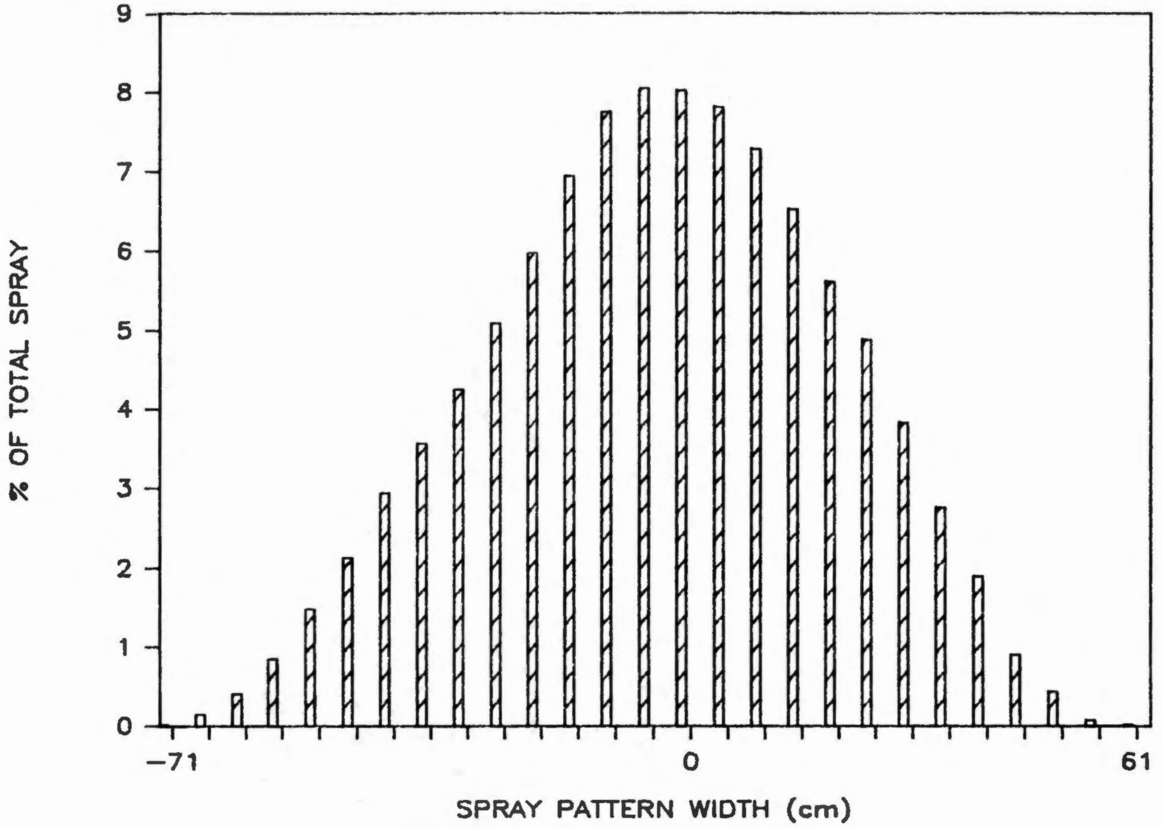

Figure 50. Lateral spray distribution for tapwater at 34 kPa air pressure, 345 kPa liquid pressure, and 53 cm above the patternator.

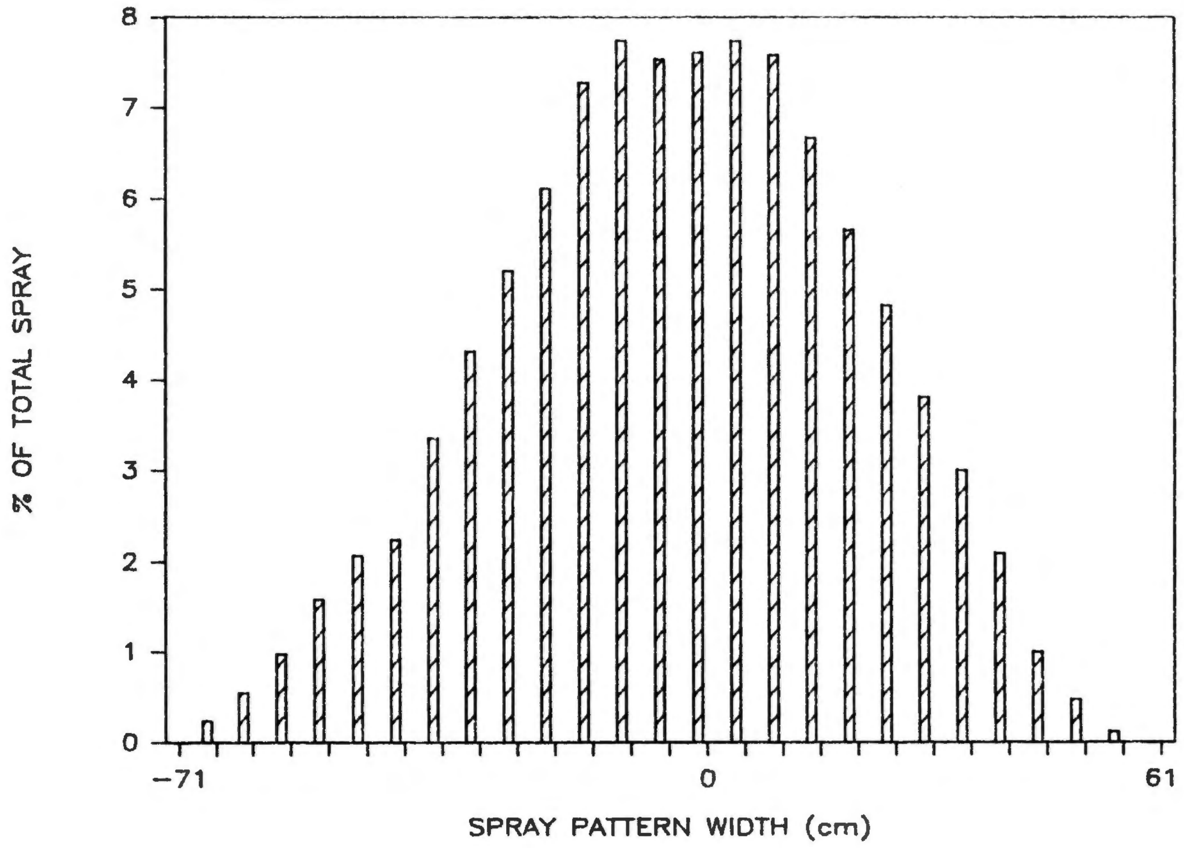

Figure 51. Lateral spray distribution for tapwater at 52 kPa air pressure, 276 kPa liquid pressure, and 53 cm above the patternator.

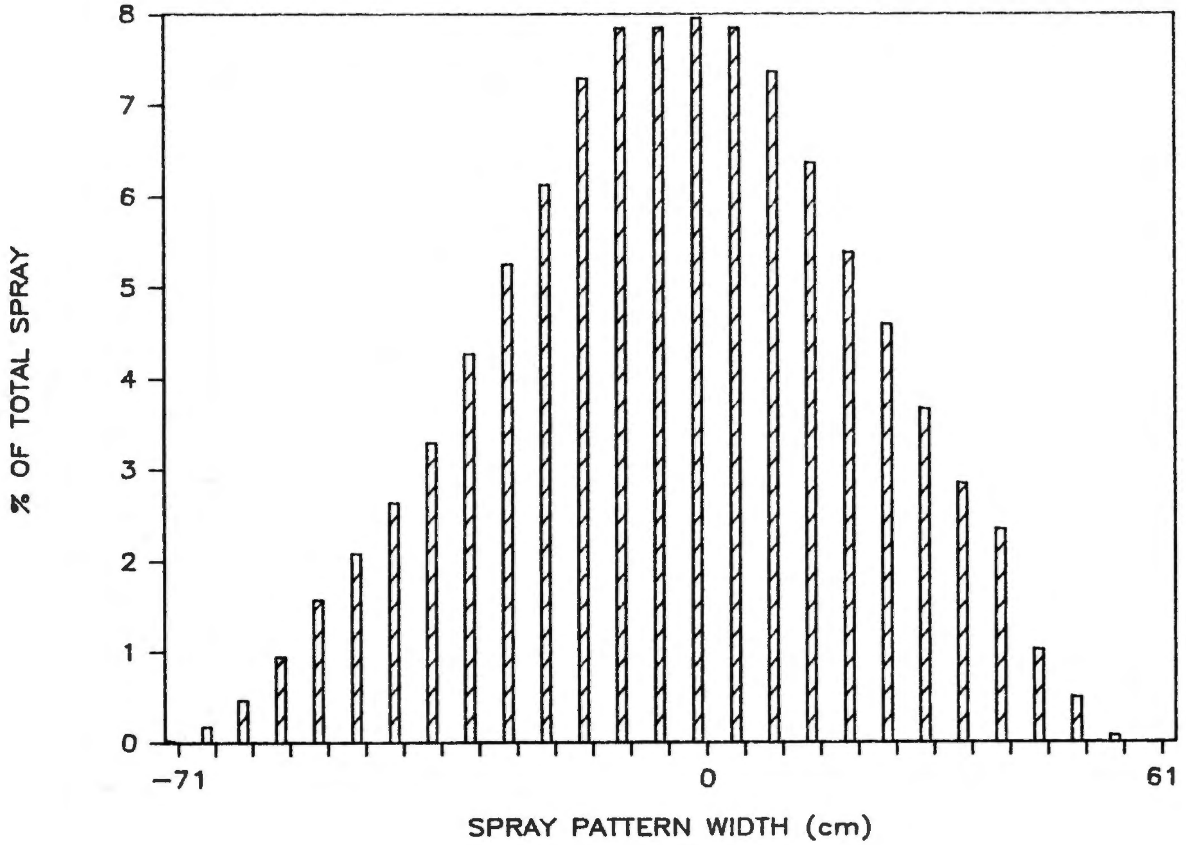

Figure 52. Lateral spray distribution for tapwater at 52 kPa air pressure, 345 kPa liquid pressure, and 53 cm above the patternator.

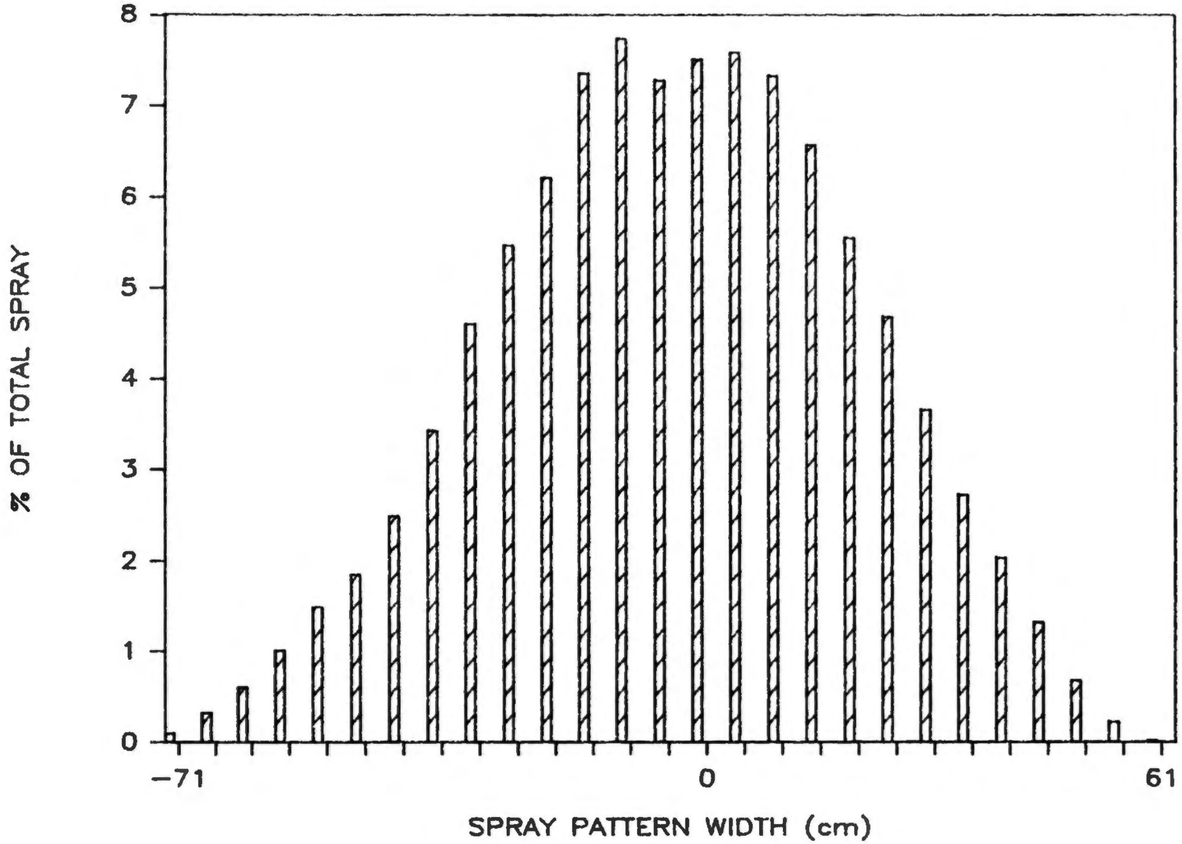

Figure 53. Lateral spray distribution for tapwater at 69 kPa air pressure, 276 kPa liquid pressure, and 53 cm above the patternator.

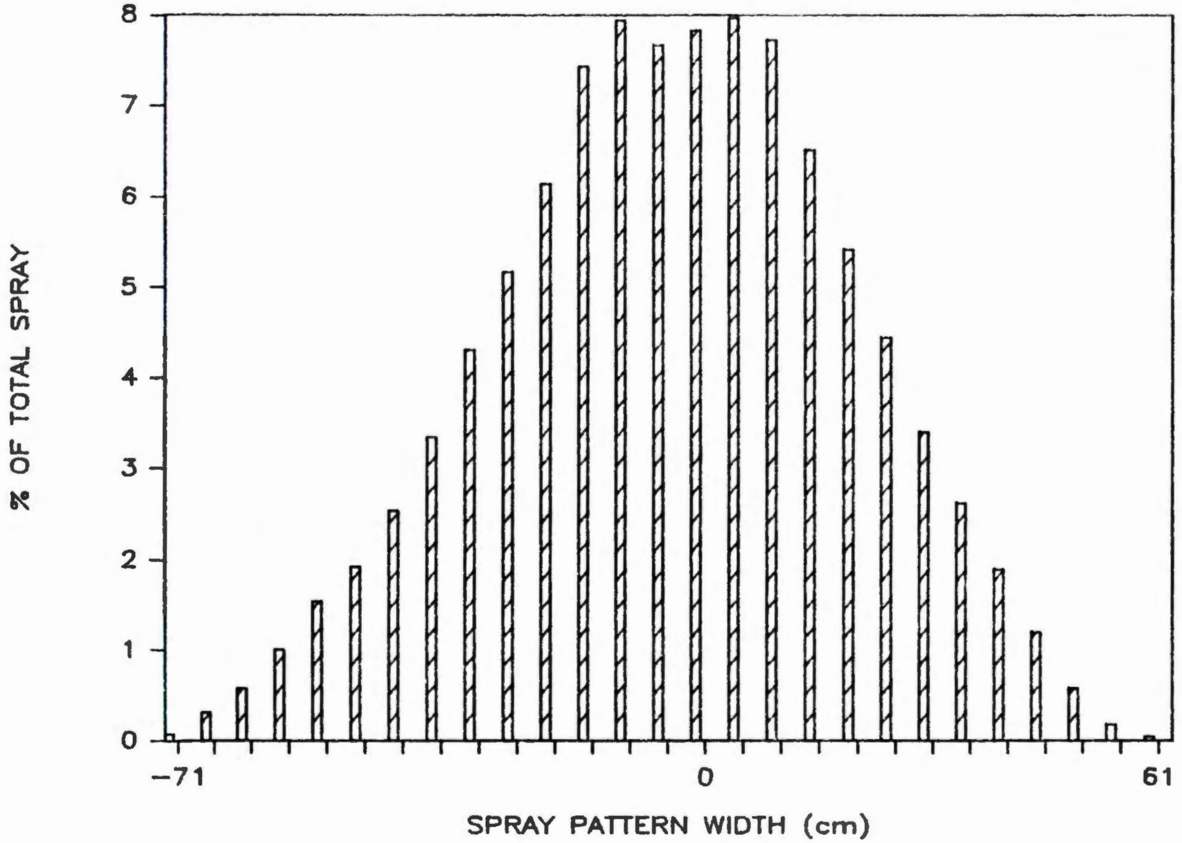

Figure 54. Lateral spray distribution for tapwater at 69 kPa air pressure, 345 kPa liquid pressure, and 53 cm above the patternator.

VITA

Steven P. Manos was born January 21, 1961, in Greeneville, Tennessee. He resided in East Tennessee for most of 16 years before moving to Gahanna, Ohio.

He graduated from Gahanna-Lincoln High School in June of 1979 and entered The Ohio State University the following September. The author received his Bachelor of Science degree in Agriculture with a major in Agricultural Mechanization and Systems in June of 1983. The following fall he entered The Graduate School at The University of Tennessee, Knoxville. He completed his graduate studies in August of 1985 and received a Master of Science degree in Agriculture with a major in Agricultural Mechanization. The author has accepted a position with the Agricultural Group of Spraying Systems Company in Wheaton, Illinois.