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# BARD

## FINAL REPORT

PROJECT NO. US-1282-87

### Aerodynamic Dispersion and Electric-Force Deposition of Pesticide Sprays in Greenhouses

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**Title**

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in Greenhouses

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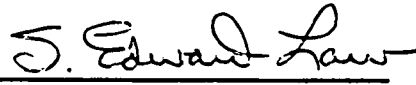
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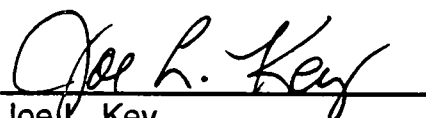
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## I. ABSTRACT

Electrostatic-induction spray-charging nozzles were developed into both laboratory-scale and full-size greenhouse equipment for low-volume, air-assisted, electrostatic application of conductive pesticide sprays. Successful operational characteristics of the aerodynamic-electrostatic method typically encompassed: 5-8 mC/kg spray charge-to-mass ratio at 1/2 - 1 kV electrode voltage as electronically derived from a 9 V transistor-radio battery; 50-250 mL/min liquid throughput to provide ca. 50 L/ha finished spray application having conductivity in the  $10^{-4}$  - 10 siemens/m range; 3-6 m/s canopy - penetration air velocity from the 207 - 276 kPa inherent pneumatic air-carrier jet; and liquid viscosity up to that of 25% wettable-powder loadings. Hand-directed sprayers of both backpack and pushcart designs were included, as well as self-propelled vehicle-mounted units developed to provide uniform application speed and automated guidance (e.g., ultrasonic and electromagnetic) in unmanned greenhouse operation.

Computer simulation of aerodynamically delivered charged spray and field evaluations of air-carrier sprayer equipment assisted in system development and pulsed charged-cloud improvements. Advanced methodology for quantitatively assessing spray deposits was established *via* mathematical modelling of spray coverage on leaves and by the development of a fully operational, light-intensified, machine-vision, image-analysis system incorporating a computer-controlled x-y positioning stage. Significant new documentation resulted regarding the micro-deposition characteristics and spatial distribution of deposits, especially onto leaf undersides and at deep-canopy penetration. Other theoretical and experimental studies confirmed the electrostatic deposition process to be appropriate for spraying plastic-potted plants having even greater than  $10^9$  ohms resistance to earth, and demonstrated beneficial modifications of dielectric boundaries (e.g., plastic greenhouse films) which enhance target deposition of charged sprays.

Laboratory and greenhouse spraying tests documented both the droplet deposition efficiency (*via* tracer fluorometry, GC foliar residue analysis and computer image analysis) and the insect-control efficacy achieved by three spray application methods: a) reduced-volume, air-assisted charged spray; b) reduced-volume, air-assisted uncharged spray; and c) conventional high-volume, hydraulically-automized spray. The aerodynamic-electrostatic method (a) was confirmed to increase active-ingredient deposition between 2- to 4-fold as compared with the other two methods (b and c). Underleaf and deep-canopy deposition were especially enhanced by electrostatic forces. Using the directed air-assistance to inject sprays into plant canopies, electrostatic charging did not significantly alter deposition onto the operator or greenhouse structural surfaces. Insect-control efficacy achieved with the reduced-volume aerodynamic-electrostatic method was at least equal to the other application methods tested when using label rates of pesticide, and it performed significantly better at lower rates of 1/4 and 1/2 label. Additionally, application time was halved and potential for phytotoxicity reduced as compared with the conventional high-volume greenhouse spraying method.

## II. OBJECTIVES

Quality assurance is critically important in high-value floricultural and greenhouse vegetable crops which rely not only upon biological soundness, but also appearance, for market acceptance. Pest control is a major factor contributing to quality assurance. Certain greenhouse pests present special control problems because of their niche within the canopy of the host. Aphids, spider mites and whiteflies feed on the lower surface of leaves. Mealybugs and some aphids feed on stems and leaf petioles well protected by the surrounding canopy. Thrips inhabit especially secluded plant regions such as leaf folds and flowers. Satisfactory control of these pests within greenhouses is often unattained due to basic difficulties in spray-application methodology. Fundamentally, these deficiencies relate first to poor dispersion of the pesticide spray throughout the plant-canopy requiring treatment, and subsequently to gross inefficiency in the basic droplet-deposition process effecting mass-transfer onto the nearby biological-target surfaces. The consequential problems may be exhibited as inadequate pesticide dosage, nonuniform surface coverage, and often overdose of easily coated plant regions while attempting to adequately coat the more interior and obscured regions. Such inefficient and ineffective usage of expensive toxic pesticides gives rise to valid concerns from economic, environmental, personnel-safety, and crop-residue viewpoints.

Common practice attempts to attain adequate plant surface coverage through large-volume applications of dilute sprays; much inconvenience and labor cost is associated with handling these large diluent volumes. Efforts to utilize low-volume sprays (e.g., 5-50 L/ha) require more finely atomized droplets in order to achieve coverage; major problems exist in maintaining control over the movement and deposition of such small-mass droplets which are ineffectively managed by conventional gravitational and inertial forces. These droplet forces depend upon particle volume; in contrast, electrical forces can be made dependent upon particle surface area. Thus, the ratio of electrical to gravitational or inertial forces will depend inversely upon droplet radius, and calculations confirm electrical forces to become dominant in the small-droplet realm generally under 150  $\mu\text{m}$  diameter. Fortunately, this size realm coincides both with that required by low-volume spraying for coverage and with that demonstrated in many instances to provide enhanced biological efficacy per unit volume of the pesticide active ingredient actually deposited. A firm rationale thus exists for seeking a solution to greenhouse pesticide application problems through the incorporation of electric forces for efficient deposition of low-volume, finely atomized, charged sprays which have been uniformly dispersed by aerodynamic means throughout the desired target-plant canopies. The overall objective of this proposed research was, therefore, the development and evaluation of such an aerodynamic-electrostatic pesticide sprayer having the several type applied droplet forces appropriately balanced for achieving improved greenhouse pest control.

**Specific objectives were:** 1) to theoretically and experimentally define the appropriate energy balance between aerodynamic and electrical forces which will provide the desired dispersion and electrodeposition of charged sprays uniformly and efficiently throughout target-plant canopies; 2) based upon the guidance established in objective 1,

to design and fabricate a small-scale aerodynamic-electrostatic sprayer prototype especially suited for greenhouse applications of low-volume, finely atomized, charged sprays; 3) to investigate the basic electrical-biological-environmental interactions occurring during the prototype's application of charged droplet clouds to indoor greenhouse plants, and to optimize these interactions for maximum deposition attributes; and 4) to evaluate the biological efficacy of the optimally applied aerodynamic-electrostatic pesticide sprays within full-size greenhouse situations with special emphasis on achieving acceptable efficacy at increased application speed, reduced active ingredient, and enhanced operator safety.

**Hypotheses** - The hypotheses of this study for improving greenhouse pest control were:

- a.) An appropriate balance of aerodynamic and electric forces can be beneficially incorporated into greenhouse low-volume spray application to significantly improve the uniformity of surface coverage and the efficiency of droplet deposition, respectively, throughout plant canopies. A canopy-entry air velocity of 5 m/sec and a 2 mC/kg spray charge intensity represent reasonable initial conditions from which to commence this investigation.
- b.) As contrasted with previous electrostatic spray applications onto field crops, the optimal force ratios determined for plants within the protected indoor conditions afforded by greenhouse spraying will remain constant in the absence of wind disturbances, thus making possible a more consistent and greater level of exploitation of electrostatic deposition as has been accomplished by indoor industrial systems for over four decades.
- c.) A robust and highly effective greenhouse prototype sprayer based upon aerodynamic dispersion and electric-force deposition of finely atomized, low-volume, charged sprays can be expediently and economically down-scaled from existing low-voltage electronic droplet-charging systems having over ten years of testing and improvements in outdoor row-crop agriculture.
- d.) The indoor charged-spray methodology and aerodynamic-electrostatic sprayer prototype developed in this proposed work will be useful for extending improved spray application technology to the poultry and animal-housing sectors and to other agricultural requirements for efficient spraying within enclosed spaces.

**Description of Research Plan** - The research was conducted with the goal of developing both the process and the prototype machine for aerodynamic-electrostatic spraying of pesticides within greenhouses. The work was performed by U.S. and Israeli engineers and biological scientists in the following eight stages over a period of three years with individual responsibilities as indicated by the accompanying table:

**Stage 1** - Develop a computer simulation model of air-assisted charged-droplet motion within plant canopies, and determine theoretically the optimal ratio of droplet charge to air velocity and turbulence.



**Stage 2** - Devise a laboratory system for measuring the droplet deposition and the uniformity of coverage in a model canopy. The system will provide simultaneous reading at 32 locations in the canopy utilizing currently developed computer-interfaced charge transfer instrumentation methods.

**Stage 3** - Experimentally validate the spray dynamics of the simulation model developed in stage 1.

**Stage 4** - Develop a laboratory size aerodynamic-electrostatic spray applicator based on the findings in stages 1, 2 & 3. The pneumatic-atomizing, induction charging nozzle previously developed at the University of Georgia will provide the core component for this system.

**Stage 5** - Experimentally evaluate, via fluorometric droplet-tracer techniques, the uniformity of surface coverage and the amount of spray deposition achieved by the laboratory applicator when treating idealized targets and representative greenhouse plant canopies. If variation from the recommended spray dosage encountered using a hand-directed spray applicator is deemed intolerable, then either incorporate a temporarily visible spray marker (e.g., foam) to gauge spray application, or commit to a mobilized system (e.g., overhead track-mounted).

**Stage 6** - Design and fabricate a full-size aerodynamic-electrostatic sprayer prototype for greenhouse usage. Units for both Israel and the U.S. will be built.

**Stage 7** - Test the uniformity of coverage and the material deposition achieved by the prototype in full-size greenhouse settings utilizing tracer-tagged sprays. Evaluate the effects which environmental humidity and leaf tip electrical discharges exert upon this deposition and coverage.

**Stage 8** - Determine the insect-control efficacy achieved by the prototype aerodynamic-electrostatic sprayer in comparison with efficacy obtained with conventional low-volume and high-volume equipment used in commercial greenhouses, with special emphasis given to pests inhabiting lower leaf surfaces, leaf undersides, and deep plant-canopy regions which are difficult to reach with application of pesticides. Plants will also be observed for phytotoxicity which can be associated with spray-application method.

Time schedule and location for individual stages of work.

Year	Responsibilities and locations				
	U.S.		Israel		
	Athens	Griffin	FAE	AEI	PPD
First	4		3	1, 2	
Second	5, 6, 7		6, 7		
Third		8			8

### III. RESEARCH ACTIVITIES AND RESULTS

#### A. UNIVERSITY OF GEORGIA (S.E. Law):

Application of pesticides has been included among the top ten ecological and human health risks recently identified by the Scientific Advisory Board of EPA [ 15 ]. While pesticides remain absolutely essential for protection of crops against insect, disease and weed pests, much opportunity exists for engineering improvements into the spray-application process. Both increased deposition efficiency and improved spatial distribution of droplets, especially onto deep-canopy underleaf surfaces, are needed. The latter need is especially evident from the inability to control current widespread infestations of the underleaf-dwelling whitefly on numerous greenhouse and field crops [ 16 ].

Conventional spray-application technology which relies upon gravitational and inertial forces often achieves less than 50% mass transfer of the dispensed pesticide onto the desired plant targets with the loss presenting economic and environmental concerns; the actual quantity reaching the insect or disease pest is estimated to be as low as *ca.* 0.01% [ 7,14.]. Considering the *ca.* \$7 billion direct materials cost for the *ca.* 400 million kg of pesticide active ingredient utilized annually in the USA [ 1 ], the significance of appreciable engineering improvements in spray application becomes obvious.

The droplet velocity vector *vis-a-vis* the target for conventionally applied sprays is essentially fixed by the gravitational field and the momentum imparted upon departing the spray source. Air-assisted sprays provide for some beneficial in-flight redirection of droplets in response to viscous and turbulent interactions with the air-carrier stream as it flows in the target vicinity, yet provide no attractive force *per se*. In contrast,

appropriate development of air-assisted electrostatic spraying can simultaneously exploit both the benefits of aerodynamic and electric force fields in which the electric-force vector continuously redirects itself toward the earthed plant surfaces as the spray cloud traverses the crop. To achieve penetration of charged pesticide spray droplets for deposition deeply within electrically-shielded plant canopies, such a hybrid aerodynamic-electrostatic design is the appropriate approach for both greenhouse/nursery and field crops.

Of the four distinct modes for incorporating electric forces into spray application as illustrated in Figure A1, only the one driven by the space-charge electric field of the charged spray cloud itself can be exploited over any appreciable droplet-attraction distance within the canopy [ 13 ]. While important for charged-droplet transport across target boundary layers, the inverse-square image-charge-force mode generally only acts over very close millimeter droplet-to-leaf spacings. The mode utilizing the applied electric-field force is most commonly relied upon for electrostatic coating of external product surfaces in industry; crop-sprayer design should generally minimize this mode of force since it would primarily deposit charged spray onto the periphery of the grounded plant canopy where the applied electric field lines terminate.

This BARD project on aerodynamic dispersion and electric-force deposition of pesticide sprays in greenhouses has fully benefitted from the embedded-electrode, electrostatic-induction, pneumatic-atomizing, spray-charging nozzle developed at the University of Georgia [ 12 ] and commercially refined and produced under patent license [ 11 ] by Electrostatic Spraying Systems, Inc. This charging nozzle uniquely meets the design requirements for electrostatic applications of conductive, aqueous-based, pesticide sprays onto greenhouse crops. A high droplet charge-to-mass ratio (*viz.*, 8-10 mC/kg) can routinely be imparted to sprays over the nozzle's typical operational range of : 50-150 mL/min liquid flowrate;  $10^{-1}$  -  $10^4$   $\Omega$ m liquid resistivity; 207-276 kPa atomizing air pressure; 0.5-1.5 kV charging voltage at less than 50 mW electronic power input from a 9-12 Vdc battery; and liquid viscosity up to that of 25% wettable powder loadings. The inherent air-carrier stream from this pneumatic nozzle both generates finely atomized sprays in the 30  $\mu$ m volume-median diameter range and provides for their air-assisted conveyance (*ca.* 4-6 m/s canopy entry velocity) and turbulent dispersal within the plant canopy. Droplet size is highly compatible both with effective electrostatic control [ 13 ] and with enhanced biological efficacy per unit mass of active ingredient [8,9,10] and greater persistence of deposit [ 3 ].

This section of the report summarizes the development and operational performance of several air-assisted electrostatic crop-sprayer machines incorporating this specific type pesticide spray-charging capability. Laboratory and greenhouse documentation of increased deposition efficiency and insect-control efficacy attributable to this reduced-volume aerodynamic-electrostatic application technology is presented. Fluorometric and image-analysis measurements of improvements in deep-canopy penetration and underleaf deposition are included as well as G.C. analysis of foliar deposits of active ingredient achieved in greenhouse tests.

## **1. Laboratory Electrostatic Sprayer Development**

A self-contained, lab-scale aerodynamic-electrostatic spray applicator (Fig. A2) was developed and provided in Year 1 to the Technion and Volcani Center for supporting the experimental phase of this cooperative study. A similar system was retained at the University of Georgia for comparative work. The design of the purpose-built electrostatic sprayer controller permits operation of multiple charging nozzles at remote locations with only a 12 Vdc electrical input from a small battery. It also provides an input to an operational amplifier circuit for measuring the small microampere-range currents imparted to the charged spray cloud; a needle-type ionization probe collects the droplet charge for this purpose. Both a solid-cone and a flat-fan pattern pneumatic-atomizing electrostatic-induction spray-charging nozzle of University of Georgia design were included in the laboratory system provided. Figure A3 documents the excellent droplet charge-to-mass ratios achieved by the several type charging nozzles developed. This laboratory sprayer also incorporates an air-carrier stream for determining the appropriate balance between electrostatic and aerodynamic energies for greenhouse spraying.

## **2. Full-Size Electrostatic Sprayer Development**

Conceptual and engineering design criteria were established for electrostatic pesticide sprayers appropriate for greenhouse use. Through licensing of the University's patents to the local company Electrostatic Spraying Systems, Inc., full-scale aerodynamic-electrostatic sprayers for greenhouse usage were developed and refined for application on this project. Backpack and pushcart configurations (Figures A4 and A5) were fabricated as originally proposed. The former requires only an input of pressurized air from a centrally installed greenhouse compressor system while the latter is self-contained as powered by either a small 4 hp gasoline engine or an electric motor. Both configurations utilize the same design of hand-held charged-spray gun. The handgun incorporates dual induction-charging orifices in the forward end and a solid-state DC-to-DC converter high-voltage power supply of U.Ga. design within the handgrip. Typically, this electronic circuitry can be operated continuously for over 30 hours from an easily replaced 9 volt transistor-radio battery. An ESS, Inc. circuit refinement provides a low-battery warning signal by an economical operational-amplifier comparator circuit.

Figures A6, A7 and A8 summarize numerous laboratory experiments conducted to evaluate the spray-charging capability of the dual-orifice induction nozzle as developed for greenhouse usage. Spray droplet charge-to-mass ratio values are presented as functions of the following ranges of operational conditions: a) charging-electrode voltage @ 0-1.4 kV; b) atomizing air pressure @ 15, 30, 45 and 60 psig; and c) liquid flow rate @ 50-350 ml/min. Successful greenhouse application appears assured by the excellent spray charging of nearly -8 mC/kg carried on 200 ml/min of total spray-gun output.

### 3. Charged Spray Dispersion/Deposition Experiments

Laboratory tests utilizing idealized targets evaluated, via fluorometric droplet-tracer techniques, the amount and distribution of spray deposition achieved at various distances by the aerodynamic-electrostatic applicator. An electronically-controlled "spray robot" was designed and fabricated to provide a consistent angular sweeping (in the vertical plane) of the charging nozzle past a linear array of targets positioned horizontally at 1, 2, 3, 4, 5 and 6 m from the dual orifices. At a constant 200 ml/min liquid flow rate, the other operational conditions were varied as follows: a) spray-cloud current @ 0, -6, -12, -18 and -22  $\mu\text{A}$ ; and b) atomizing air pressure @ 30, 45 and 60 psig. For the case of 45 psig, Figure A9 presents typical experimental results for the quantity of deposition achieved (*i.e.*, ng of tracer deposited per unit area of target surface) and its distribution with respect to the distance of targets from the nozzle. As compared with uncharged spray, droplet charging increased deposition onto the two nearest targets by approximately 4-fold and more than doubled the deposition onto the target at the 3 m distance. Lesser improvements were achieved at greater distances, and at 6 m the charged vs. uncharged deposition values did not differ. While spray charging significantly increased deposition at the 1, 2, 3 and 4 m distances, no significant differences in deposition could be declared among the four non-zero spray-charging levels tested; all charging levels of -6  $\mu\text{A}$  and above provided equal electrodeposition benefits.

Results of these charged-spray deposition experiments indicated: a) a modified action should be utilized for sweeping the gun past the targets at an angular velocity which reduces for the distant targets (as is common practice with conventional hand-held spraying operations); and b) for the idealized target array, the non-dependency of charged-spray deposition upon the specific charging level utilized (*i.e.*, 6  $\mu\text{A}$  and greater) likely resulted from space-charge suppression of the induction nozzle's charging ability. The measured response underscores the importance of proper charged-spray injection into the nearby electrically-shielded plant canopies as would be the usual case with actual electrostatic spraying of greenhouse plants.

### 4. Beneficial Effects of Dielectric Boundary

A mathematical model and computer simulation were developed to better understand the effects upon charged-droplet motion caused by electric charge captured on dielectric surfaces such as plastic films underlying plants and greenhouse coverings. This active dielectric boundary concept may readily be applied to reduce the unwanted deposition onto boundary surfaces underlying plants (*e.g.*, tables) while redirecting the charged spray back upward onto plant-leaf undersides. Electrical charging of the aerodynamically-delivered spray droplets, in combination with beneficial manipulation of the dielectric boundary, resulted in an 84%/16% ratio of target surface-to-nontarget film deposition compared to a corresponding 44%/56% ratio for uncharged spray.

## 5. Greenhouse Plant Grounding Requirements

An experimental study was completed to determine what constitutes adequate electrical grounding of plastic containerized greenhouse plants if they are to satisfactorily undergo the electrostatic spraying process.

During the typical 600 ms - 1 s electrostatic crop-spraying event, the flow of transient current to earth is required if electrodeposition is to occur unimpeded. Target capacitance  $C$  and electrical resistance  $R$  to earth control the flow. Theoretically, it was shown that target charge-dissipation time constants  $RC < 0.1$  s should facilitate adequate grounding for this process. Experimental analysis of a 120 pF spray target, simulating plastic-potted greenhouse plants, confirmed that the 5-fold increase in charged vs. uncharged droplet deposition did not significantly depend upon the resistance imposed in the grounding path over a 0 -  $10^{12}$  ohm range (Fig. A10). A survey of hanging and table-supported plastic-containerized living plants in commercial greenhouses indicated plant-to-earth resistances of only  $10^7$  -  $10^9$  ohms. It may be concluded that electrical grounding of such plants should be adequate for satisfactory implementation of electrostatic crop-spraying for greenhouse culture.

## 6. Laboratory Tests

This and the following sections experimentally document the performance of electrostatic crop sprayers (Fig. A11-A14) based upon University of Georgia technology and developed under patent license by Electrostatic Spraying Systems, Inc. Mass-transfer studies quantifying deposits of both spray tracer and pesticide active ingredient in laboratory and greenhouse tests are presented as well as results of machine-vision image analysis of underleaf deposits. Comparisons include the three following methods of application: a) reduced-volume, air-assisted, charged sprays; b) reduced-volume, air-assisted, uncharged sprays; and c) conventional high-volume, hydraulically-atomized sprays.

For laboratory tests potted plants of cotton and chrysanthemums, which were greenhouse grown, were compactly positioned for deposition studies in the spray room of the University of Georgia Applied Electrostatics Laboratory. Details of these experiments are provided by Dai *et al.* [ 2 ]; summary results are presented here for cotton only since it provided the largest canopy-type to be penetrated.

The target-plant array was comprised of three 60 cm spaced rows having five potted plants at 40 cm spacings within each row. The mid-season cotton plants typically had a canopy leaf zone measuring ca. 60 cm vertically by 40 cm maximum diameter horizontally. Measured leaf area (one side) per plant was 5,700 cm<sup>2</sup> and calculated canopy volume was 74,200 cm<sup>3</sup>; thus, an index of the compactness of foliar spray-surface was 0.077 cm<sup>-1</sup> leaf area to canopy volume ratio.

Tracer-tagged sprays were applied from a motorized boom traveling 4 km/h over the plants at a 45 cm nozzle-to-crop vertical spacing. Depending upon the treatment, the boom carried either nine air-assisted spray-charging nozzles (Fig. A14) angled forward 30° or nine Spraying Systems Company™ TX-3 hydraulic nozzles, all on 20 cm spacing along the boom. All air-assisted charged spray treatments in the laboratory used a constant -5.2 mC/kg spray charge-to-mass ratio; air-assisted uncharged spray treatments were simply made with the charging nozzles' electrostatic power supply turned off.

Charging nozzles were operated at various atomizing-air pressures to determine the effect of increased air delivery volume and velocity on spray deposition; liquid flowrate was held constant at 80 mL/min per nozzle. Hydraulic nozzles were operated at 350 kPa liquid pressure producing a liquid flowrate of 340 mL/min each. Spray application rates were thus 60 L/ha (6.4 gal/acre) and 255 L/ha (27.2 gal/acre), respectively, for the charging and the hydraulic nozzle treatments. The concentration of fluorescent tracer in water was adjusted for liquid flowrate so an identical mass of tracer particles was sprayed over the plant array for each treatment in order to simulate a common active-chemical dispense rate.

Several types of brass targets were hidden among the leaves of plants at the center of the test plots, then removed after spraying and washed for fluorometric analysis. Brass targets were used because they could be repeatedly placed at the same location within the plant canopy for numerous spray treatments and could be much more reliably washed than delicate leaf surfaces. Nine stacked, segmented cylinders of 41.6 cm<sup>2</sup> area each (7.62 cm length x 1.75 cm dia.) were placed vertically in the canopy center, well obscured by leaves, to quantify deposition as a function of depth of spray penetration measured from the top of the canopy. Also, a 60 cm<sup>2</sup> facsimile of a cotton leaf was made by clipping together two thin brass leaf-shaped plates, positioned at the plant canopy's center for spraying, and then separated to fluorometrically determine topside and underleaf spray coverage independently. In addition, finer spatial resolution of deposition characteristics on these leaf-facsimile surfaces was determined *via* light-intensified machine-vision image analyses as reported in detail by Evans *et al.* [ 4 ].

**Fluorometric Results** - Figure A15 documents deposition results from a completely randomized test consisting of four replications of hydraulic spray at 340 kPa liquid pressure, and air-assisted charged and uncharged sprays at 138, 172, 207 and 276 kPa atomizing-air pressure. Average underleaf deposition density is shown for two brass-leaf targets placed midway down into the canopy (35 cm from its top). One leaf target was placed among canopy leaves toward the front side of the plant, the other was similarly placed toward the canopy backside. Air-assisted charged sprays delivered an average tracer deposit of 90 ng/cm<sup>2</sup> onto underleaf surfaces of these targets, which was 2.5-fold greater than uncharged or hydraulic treatments. There was no difference between uncharged and hydraulic spray treatments. The underleaf electrostatic-deposition benefit increased with atomizing-air pressure within the range tested. Conversely, uncharged spray deposition was found to decrease as air pressure was increased above 172 kPa.

Figure A16 documents, as a function of depth of penetration into the canopy from the top, the quantity of tracer deposited onto vertical surfaces of the individual target-cylinder segments positioned near the cotton-plant's central stalk when using a moderate 207 kPa atomizing-air pressure. Air-assisted charged spray achieved the greatest tracer deposition on all cylinder segments, and provided the most uniform spatial distribution from top to bottom. Maximum hydraulic-spray deposition occurred on the lower target cylinders, perhaps due to material run-off onto these lower target sections. When averaged vertically over all target segments and all atomizing-air pressures, air-assisted charged spray achieved 2-fold greater tracer deposition onto vertical surfaces along the canopy centerline than did air-assisted uncharged spray and 2.3-fold greater than did hydraulically applied spray.

**Image-Analysis Results** - Spatial distribution of underleaf deposits was independently documented by a light-intensified machine-vision image-analysis methodology developed in collaboration with Dr. M.D. Evans of this department and Mr. S.C. Cooper of ESS, Inc. with SBIR partial funding. Figure A17 illustrates the percentages of the brass-leaf-target underside area covered by fluorescent tracer particles when treated by the three spray-application methods and then image analyzed. These representative contour plots are generated by interpolating from image analyses of 1.8 x 2.4 mm fields of view centrally located in 18 leaf subareas. Approximately 200,000 pixels within each field of view (providing resolution of ca. 5  $\mu$ m deposited particles) were analyzed for presence/absence of fluorescent radiation, and a weighted value for percent target area covered was calculated for each respective subarea. When taken over the entire underleaf surface, the weighted percent area covered values determined by image analysis correlated very well ( $R^2 = 0.96$ ) with those measured by the widely accepted fluorometric method.

Table A1 summarizes results from imaging of brass-leaf targets placed within cotton canopies. The average number of underleaf deposits and the average percent target area covered for each of the three spray treatments are included. Air-assisted charged spray achieved 4-fold more individual sites of deposit per unit leaf area than did air-assisted uncharged spray and 68-fold more than hydraulic spray. Charged spray deposits covered 2.6 times more leaf area than uncharged and 48 times more than hydraulic spray. Imaging results clearly show a spatial-distribution benefit on a micro-scale attributable to electrostatic deposition forces. Likewise, Fig. A17 and Table A1 emphasize the tremendous deficiency of conventional hydraulic spraying for achieving underleaf deposition of pesticides.



Table A1. Image analysis of the spatial characteristics of tracer particles deposited by three spray-application methods onto undersides of brass-leaf targets placed within cotton canopy.

Spray method	Average number of underleaf deposits per 10 mm <sup>2</sup>	Average area covered by deposits, $\mu\text{m}^2$	Percentage of target area covered
Air-assisted charged spray (207 kPa)	425.0	569	2.42%
Air-assisted uncharged spray (207 kPa)	105.8	881	0.93%
Hydraulic spray (350 kPa)	6.3	749	0.05%

## 7. Greenhouse Tests

The deposition efficiency, insect-control efficacy, and off-target deposition loss of reduced-volume air-assisted charged sprays were evaluated in comparison with reduced-volume air-assisted uncharged sprays and conventional high-volume hydraulic sprays applied in greenhouse floriculture by hand-directed guns. All non-hydraulic sprays were applied by dual-orifice electrostatic handguns (Fig. A11) operating at *ca.* 250 mL/min liquid flow, 345 kPa atomizing-air pressure, and zero or -6 mC/kg spray charge-to-mass ratio.

**Fluorometric Results** - Spray targets (six 7.6 cm metal spheres) were positioned well down in the canopy zone of mature potted chrysanthemum plants in a full-scale commercial greenhouse in Ringgold, Georgia. Additionally, three 7.6 x 15 cm strips of Tyvek™ polyethylene fabric were pinned to the spray operator's Tyvek™ spraysuit, and three brass foil strips were placed on greenhouse structural members near the spray area to measure off-target deposits. The two treatments applied were charged and uncharged, both from the same electrostatic air-assisted spray gun; for uncharged applications, spray charging was simply deactivated without the operator's knowledge. Five replications of each spray treatment were conducted over a three-day period. Spray application rate was 5.3 mL/m<sup>2</sup> or 53 L/ha (5.7 gal/acre).

Rolling plant benches in the test area permitted grouping three together for a 6.4 m wide x 23 m long spray swath. This resulted in every third aisle being walked, spraying one side of the swath on the way in and the other on the way out as a time-saving benefit. Targets were well obscured and not readily visible to the operator as he passed.

As seen in Table A2, deposition within the plant canopy was consistently greater using charged sprays. Tracer deposits averaged 23 net fluorometer units for charged sprays compared to 7 for uncharged giving an overall 3.3-fold benefit from charged sprays. Spray deposition onto side targets (ca. 1.5 m from the operator) was greater than onto targets placed along the centerline of the spray swath. The charged-to-uncharged deposition ratio was 3.8 onto side targets and 2.0 onto centerline targets. Deposition onto the greenhouse structure and the operator was found to be negligible for both the charged and the uncharged spray applications with means statistically not significantly different. (One exception was increased charged-spray deposition onto the metal support posts immediately adjacent to the sprayed swath).

Table A2. Treatment means for charged and uncharged air-assisted spray deposition onto targets within a commercial chrysanthemum greenhouse.

Deployment of spray targets	Relative tracer deposition (net fluorometer readings <sup>1</sup> )	
	Charged spray	Uncharged spray
Spheres in plant canopies:		
Right side of swath	28	8
Centerline of swath	12	6
Left side of swath	30	8
Strips on greenhouse structure:		
Distant post off right of swath	0.2	0.5
Beam above swath centerline	2.3	0.5
Nearby post off left of swath	1.0	0.5
Strips on operator's spraysuit:		
Forearm of spray hand	1.0	0.4
Center of chest	0.5	1.0
Forehead of hood	1.0	0.8

<sup>1</sup>Net readings less than 2 are considered negligible since repeated readings from the same wash sample can vary by this amount.

**Gas Chromatography Results** - While this section reports results not creditable directly to this BARD project, they are included as corroborating data since they were conducted with the U.Ga.-ESS, Inc. aerodynamic-electrostatic greenhouse sprayer.

Giles [ 6 ] measured foliar and non-target deposition of permethrin sprays applied to commercial greenhouse-grown chrysanthemums in the Sacramento, California area by a conventional high-volume (2300 L/ha) hydraulic sprayer (termed "wet sprayer") and by

the reduced-volume (46 L/ha), air-assisted electrostatic handgun sprayer (Fig. A11) based on University of Georgia technology. The potted plants sprayed, closely spaced on greenhouse benches, measured ca. 20 cm high with 4500 cm<sup>2</sup> of leaf area (one side) each.

For both spray methods, a common active chemical rate of 1.15 kg/ha was dispensed. A commercial FMC Corporation<sup>TM</sup> high-pressure (2 MPa) handgun sprayer with cone-type hydraulic nozzle was used for the conventional high-volume spray applications. Following spray treatment, permethrin deposition was analyzed by G.C. using extractions taken from leaf punches of foliage and from off-target surfaces at the benchtop, under the bench, and on the aisle floor.

The air-assisted charged spray was found to deposit significantly more insecticide onto plant foliage than did the high-volume conventional spray method; the values were 1.29 µg/cm<sup>2</sup> and 0.35 µg/cm<sup>2</sup>, respectively, giving a 3.7-fold electrodeposition benefit.

Figure A18 inventories the foliar and various off-target permethrin deposition components as measured by Giles [ 6 ] on a mass-balance basis. On all off-target surfaces except under the bench, the reduced-volume air-assisted charged spray method desirably deposited considerably less pesticide than did the high-volume conventional method; 73% and 49%, respectively of the dispensed permethrin could be accounted for as sprayed in the greenhouse by the two application methods.

**Insect-Control Results** - Insect efficacy was determined in collaboration with Dr. R.D. Oetting by comparing the reduced-volume (65 L/ha) air-assisted electrostatic sprayer with standard high-volume (1304 L/ha) hydraulic and fixed-position ultra-low volume (65 L/ha) mist-blower application equipment. The high-volume hydraulic sprayer operated at 690 kPa using a solid-cone nozzle. The mist blower was a Ball Fast-Sprayer<sup>TM</sup> which directed the spray cloud in one direction and was not air-assisted. A horizontal fan was used to circulate the air and distribute the mist throughout the greenhouse. The high-volume hydraulic applicator was considered the standard and the same amount of active ingredient (a.i.) was applied to a given greenhouse area by each spraying method. The four treatments applied were: no chemical, ¼ a.i., ½ a.i., and the full recommended active ingredient for the pest being treated (i.e., 1 a.i.).

Efficacy experiments were conducted by placing marigold plants evenly, but not touching, on greenhouse benches and treating them using the above procedures. The test plants were placed randomly on the bench by removing a plant and replacing it with the experimental one. The pest population was determined before spray application by a standard method and post-application populations were determined by the same method to assess population reduction achieved by that a.i. rate and spray method.

Aphids are a major pest of greenhouse crops and an experiment was conducted evaluating the application techniques with cyfluthrin (Tempo<sup>TM</sup> 2E at 220 mL/ha) against green peach aphids (*Myzus persicae*) (Fig. A19). The aphids were present on the new growth and all application techniques were effective at full a.i. rate. The air-assisted electrostatic applications were more efficacious at the lower rates.

While these treatments required good penetration of the plant canopy, a better test of application efficiency is the management of pests which are present on the undersides of leaves. An experiment was conducted with abamectin (Avid™ 2E at 430 mL/ha) to test efficacy against two-spotted spider mites (*Tetranychus urticae*) which are primarily present on the under-leaf surface. Marigolds infested with mites were treated once and population evaluations of mites and eggs present on the under-leaf surface were made on the eighth day following spray application (Fig. A20). All application methods were effective at the standard full a.i. rate, but the air-assisted electrostatic sprayer was again more efficacious against mites and their eggs at the lower a.i. rates. These experiments conducted at the Georgia Agricultural Experiment Station in Griffin indicate that the reduced-volume air-assisted electrostatic sprayer was more effective in penetrating the foliage than both the standard high-volume hydraulic sprayer and the fixed-position mist-blower sprayer.

## 8. Summary and Conclusions

Aerodynamic and electrostatic droplet forces have been shown to be conveniently incorporated into greenhouse crop spraying by pneumatic-atomizing, electrostatic-induction, spray-charging nozzles. The resulting air-assisted charged-droplet spraying method has proven especially appropriate for penetrating charged conductive-pesticide sprays to inner plant-canopy regions and electrostatically depositing droplets onto leaf undersides by action of the spray's own space-charge field.

This air-assisted electrostatic crop-spraying technology has been developed into a variety of full-scale improved pesticide-application machines for greenhouse crops. Laboratory and field-tests have been presented which document the technology's contribution to consistently greater than 2-fold increases in droplet-deposition efficiency and insect-control efficacy--especially for spray treatments requiring good underleaf deposition of pesticide. Corroborating experimental results recently obtained from spray-tracer deposition analysis by both fluorometry and machine-vision imaging, active-ingredient deposition analysis by gas chromatography, and insect-control efficacy by bioassay all support the hypothesis that the reduced-volume air-assisted electrostatic method of spray application can be utilized to halve the quantity of pesticide active ingredient dispensed into a given crop area as compared with that being dispensed for economic pest control by conventional high-volume hydraulic spraying. Profound environmental, economic and energy-related benefits would accrue from widespread adoption of this technology by the greenhouse industry and agriculture in general.

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## **B. UNIVERSITY OF GEORGIA (R.D. Oetting):**

### **1. Insect-Control Efficacy**

The final stage of this BARD project was to determine pest-control efficacy for insects and mites on greenhouse-grown ornamentals. This research included a comparison of standard application methods, other low-volume application equipment, and the reduced-volume prototype aerodynamic-electrostatic sprayer of this study. Observations included efficacy, dilution of finished spray, amount of time required for application, phytotoxicity, and rate of active ingredient (AI) used.

***Development of Experimental Techniques*** - Application rates were determined by spraying a 9.29 m<sup>2</sup> area with standard high-volume (HV) application equipment and using the same amount of pesticide active ingredient over the same area with low-volume (LV) application. The HV method was a hydraulic Hy-Pro™ pump sprayer operated at 100 psi liquid pressure using a solid-cone nozzle. The rate of application was maintained consistent by timing initial applications and maintaining this time in all future HV applications.

The same amount of active ingredient was applied with the prototype electrostatic sprayer using 45 psi atomizing-air pressure at the gun with a liquid flow rate of ca. 250 ml/min. through the twin-orifice nozzle of the handgun. The active ingredient was mixed in 5% (varied in some experiments) of the total volume of finished spray as used with the high-volume sprayer. The time required for application was recorded and maintained constant during an experiment.

Two other commercial low-volume sprayers were compared to the electrostatic prototype. The first was a Pulsefog™ model, and the second was a Ball Fast Sprayer™ model kept in a fixed position in the greenhouse (denoted FP). Both units were used as fixed-position sprayers by placing them either in the doorway (Pulsefog) or inside the greenhouse (Fast Sprayer) and allowing a measured amount of finished spray to be delivered to the greenhouse. A horizontal air flow fan was used to keep the air moving in the greenhouse to obtain even coverage of the test plants. These two LV sprayers were compared to the electrostatic sprayer by applying the same amount of active ingredient per unit area of bench or greenhouse. The Ball Fast Sprayer was set by a timer to discharge the spray for 2 hours (ample time to empty tank); the horizontal air flow fan was on during application and for 4 hours following. The fans were then deactivated and at least 4 hours of settling was allowed before the exhaust fans were activated to clear the greenhouse for reentry.

Efficacy experiments were conducted by placing test plants on a greenhouse bench and treating them using the above procedures. The test plants were placed randomly on the bench by removing a plant from a grouping already on the bench and substituting the experimental one. The pest population was determined before application by a standard method and post-application counts were made by the same method to determine population reduction by the application method.

**Results of Spray Dilution Experiment** - Several experiments were conducted to determine the effect of pesticide dilution on efficacy; it was concluded that as long as good coverage is obtained, it was not significant what quantity of water the active ingredient (AI) was mixed in. These dilutions were based on recommended dosage per 100 gallons of water. In one experiment acephate 75S was applied against green peach aphid at different dilutions from 0.5 lb AI/5 gallons (a 1/1 dilution of water) to 0.5 AI/100 gallons (a 1/20 dilution of water) without any significant difference in control (Table B1).

It was concluded that a mix of the recommended amount of AI in 5 gallons of water was the minimum amount of water which practically can be used. At this dilution, an applicator must keep a constant pace of movement and could not move any faster and get good coverage. This dilution was used in the experiments conducted to compare application methods. If application was made to large plants or an area where coverage was more difficult, the AI could be mixed in 10 gallons of water and application made twice at different angles to increase the probability of good coverage.

**Time Required for Application** - An important part of insecticide application is the actual time spent by applicators in a spray suit treating a greenhouse area. To the applicator it is time spent in a very uncomfortable suit, and the shorter the period of time in a spray suit, the less the chance for exposure to chemicals. To the owner, time is money and the fewer hours spent treating an area, the less will be the cost. In addition, the time for application is often after working hours when other employees are out of the greenhouses, and time is short for completing the treatment of a large area before dark.

The fixed-position air-blast sprayers obviously have the advantage in this regard because they are activated by a timer mechanism and they do not require the presence of a worker. These sprayers apply the active ingredient in the form of an ultra-low volume mist propelled through the air by a fan. However, the plume of spray is only directed in one direction and the mist must be aided by horizontal fans to get distribution throughout the house. There are newer commercial models on the market that have rotating heads to propel the spray plume in all directions.

The electrostatic sprayer and the standard high-volume application equipment require a worker to carry the hose and spray wand and to direct the spray plume toward the foliage. These application techniques require a substantial amount of applicator time and any time savings decreases both the potential for exposure and the money required for wages.

In all experiments the air-assisted electrostatic LV sprayer required much less time for spray application than did the standard HV sprayer. The time savings obtained with LV application were usually about one-half the time required by HV and even greater savings in some experiments (Table B2).

**Phytotoxicity Related to Spray Application Method** - Phytotoxicity experiments were conducted comparing standard HV and electrostatic LV spraying methods. No experiments were conducted with the fixed position sprayers. However, there was no phytotoxicity observed with these sprayers during efficacy experiments.

Bedding plants are often used for phytotoxicity experiments because of ease of obtaining plants from seed with no chemical application history, and new tender plants are very susceptible to chemical injury. An experiment was conducted using ten bedding-plant species to evaluate the potential for phytotoxicity associated with insecticide application method (Table B3). Applications of a given amount of AI by the prototype electrostatic sprayer resulted in much less plant damage than sprays applied by the standard HV unit. Both methods were safe to the bedding plants evaluated following one application at the recommended rate. However, an increase in rate and repeat applications increased the amount of phytotoxicity and degree of damage (Tables B4-B5). The amount of damage observed, and the number of species with damage, were much less following application with the electrostatic LV than with standard HV application. The only species with moderate-to-severe phytotoxicity with LV application were celosia, tomato, and salvia (Table B5). When the same species were treated with HV, all but the aster and pinks had at least moderate damage (Table B4). The type of phytotoxicity was similar with both techniques with tip and marginal necrosis the first indication of damage. In other experiments and discussions with growers and researchers, this reduction of phytotoxicity with LV application is typical.

**Insecticide/Miticide Efficacy** - The key to any pesticide application is delivery of the active ingredient to the desired site such that control of the target pest is achieved. All application methods were effective in delivering the active ingredient and reducing pest populations. In 1989-90, preliminary experiments were conducted to develop experimental technique and become familiar with each application device. It was decided to use the HV sprayer as the guide or standard in determining the amount of active ingredient to dispense to a given area and this was followed throughout the testing period.

In early trials the spray cloud was applied over the top of the canopy without making an effort to get good penetration. Abamectin (Avid™) was chosen as an insecticide/acaricide for these trials because of consistent efficacy results and quick knockdown of pests. Abamectin had a disadvantage of not being target-sensitive because it has some transluminal activity and will penetrate the leaf not requiring as thorough coverage. In the first test abamectin was used against *Tetranychus urticae* Koch, two-spotted spider mites, and HV and LV efficacy was similar (Table B6). Other experiments were conducted on other greenhouse pests that are not as sensitive to abamectin. In these experiments the LV application was significantly more efficacious against both immature and adult thrips (*Frankliniella occidentalis* (Pergande)) on foliage (Table B7). Similar results were obtained with abamectin against aphids (*Myzus persicae* (Sulzer), green peach aphid) (Table B8). In these experiments the insecticides were applied at the recommended dosage based on HV application and double that dosage. In 1990-91 more rates were applied and more testing was conducted comparing the fixed position (FP) mist blower with HV and air-assisted electrostatic LV application.



In all experiments, in 1990-91, good control was obtained with the rate recommended on the pesticide label. However, the electrostatic LV sprayer consistently was more effective in reducing insect and mite populations in our experiments, and reduction was more significant at lower application rates (Tables B9-B11), thus potentially facilitating economic pest control with reduced AI rates as compared with conventional HV and mist blower application methods.

In the first 1990 experiment a population of green peach aphid (GPA) was selected to compare application equipment. The GPA population was high with a mean of 44.6 aphids per terminal on chrysanthemum plants grown in 15 cm plastic pots, with 2 pots per plot, and 4 replications. The majority of the population was in the upper canopy and not as difficult to reach as a population located well within the canopy and on the underside of leaves. In this experiment all application methods should be effective. All methods were effective at the label rate (Table B9), but the aerodynamic-electrostatic method was more effective at the lower AI rates. Data were transformed using square-roots and the means compared. Pest populations treated with the electrostatic low-volume sprayer were significantly less post-treatment than with the other two techniques.

Mites are more difficult to reach when the population is on the underside of leaves within the canopy. However, they are often found around the periphery of the plant. An experiment was conducted with abamectin (Avid 0.15EC) to compare HV and LV applications. In this experiment two-spotted spider mites on marigolds were well established and both methods were effective in reducing populations (Table B10). However, a much greater efficacy was achieved in controlling pest populations treated with  $\frac{1}{4}$  normal AI rate applied by the electrostatic LV method than in controlling populations treated with the hydraulic HV method at the same insecticide rate. Data were transformed using square-root and were significantly different for the two application methods on both mites and eggs.

In our experiments, the insect that was the most difficult to control was the sweetpotato whitefly (*Bemisia tabaci* (Gennadius)). These insects lay their eggs on the new growth but they can require 1 to 2 months to develop to adult and in this period of time new plant growth obscures the developing immatures deep within the canopy. In addition, they often remain on the lower leaves of the plant and a significant population can develop on the lowest leaves. When the canopy is close and dense, it is very difficult to reach these individuals. Thus, an experiment was conducted to evaluate the different application methods against sweetpotato whitefly. Poinsettias infested with whiteflies were treated with three applications of a mixture of acephate (Orthene 75S) and fenprothrin (Tame 2.4EC) to evaluate efficacy. In this experiment all application methods significantly reduced whitefly populations two weeks after the treatment series (Table B11). However, population levels were still not as low as would be desired in commercial production. There was not any significant difference among application equipment in this experiment.

Experiments were conducted at commercial grower greenhouses to compare efficacy with the electrostatic LV sprayer and the hydraulic HV sprayer. In these trials it was difficult to get replication in one greenhouse and maintain a pest population. Two rates

were applied in each location using a recommended label rate of active ingredient and 2X that rate. The experiments were established with a greenhouse bench as a split plot with one end sprayed with HV and the opposite end sprayed with LV. In all experiments the two methods were similar in performance. An experiment was conducted in cooperation with Dr. Will Hudson in south Georgia using cyfluthrin against an aphid (believed to be a *Aphis* sp.) on oleander. In all chemical plots there was 100% reduction of aphids when compared to the water check. The oleander was not dense and penetration of the canopy was easily obtained.

Two experiments were conducted in north Georgia, in cooperation with Dr. Beverly Sparks, using soaps, oils, and azadirachtin against sweetpotato whiteflies on small-to-medium-sized poinsettias. In these experiments significant reduction was obtained on the poinsettias but not commercially acceptable control. On medium-growth poinsettias (approx. 7-10 cm) and on unbranched poinsettias with moderate-to-heavy infestation of whiteflies, we were not able to obtain significant reduction of the whitefly population. In all trials the reduction in insect population was similar with both application methods.

**Conclusions** - The use of air-assisted electrostatic LV application at label rates of AI proved to be equal to or better than conventional HV and fixed-position (FP) mist-blower applications. Low-volume application required less time in all experiments, cutting the time in at least half as compared with the hydraulic HV method. The FP mist-blower system saved the most application time because an operator is not required during pesticide application. There was a reduction in the potential for phytotoxicity using electrostatic LV application on bedding plants. In commercial ornamental plant production the danger of phytotoxicity is a very important factor in the application of pesticides. Efficacy achieved with the air-assisted electrostatic LV method was at least equal to the other application methods tested using label rates of pesticide in all experiments, and it performed significantly better than the other application methods in some experiments with lower IA rates.

## C. VOLCANI CENTER (S. Gan-Mor):

Improving the understanding and the techniques of electrostatic crop spraying, via computer simulation, was the major objective of the collaborators from the Volcani Center. This simulation showed that in order to get uniform spray deposition, the size of the charged spray cloud outside the canopy should equal the gaps and clouds inside the canopy. In addition, fast and turbulent air streams should penetrate the canopy and carry the droplets to the target vicinity, but then the air velocity should be minimized to enable the electrostatic forces to help the droplets deposit onto the targets. Some modification in the research plan of the Israeli collaborators was undertaken, after consultation with all the collaborators, to include the recommendations for improved deposition uniformity which resulted from the simulation.

Uniform application of the spray requires a constant speed for the nozzle motion along the target. This goal is easy to achieve utilizing a self-propelled vehicle. But safety measures dictate that in a sealed environment, as proposed by the computer simulation, no operator should be present and this calls for automatic guidance. Three generations of automatic guidance systems were developed and tested during the course of this research.

To reduce the cloud size outside the canopy and to facilitate its penetration, a previously developed pulsed air-stream device was utilized and the operating parameters were selected for maximum uniformity of the spray distribution.

### 1. Improving Electrostatic Spray Distribution In Greenhouses Utilizing Computer Simulation

#### Analytical Considerations

Trajectories of charged and non-charged particulates being conveyed in an air-carrier stream were simulated in order to reveal the dominant factors affecting spray droplet final deposition.

The amount of material deposited on the surface of two parallel plates was simulated by Lake and Marchant (1984) when they tried to evaluate the spraying of the outer surface of two parallel rows. In the present study more emphasis was given to the inner plant surfaces where the amount of material deposited might be less than the required levels. Deposition onto one-, two- and three-dimensional bodies was simulated.

**Two Parallel Surfaces** - The model for two parallel surfaces presented by Lake and Marchant used Poisson's equation (Moore, 1973) for the one-dimensional situation as

$$E = \frac{\rho}{\epsilon_0} x \quad (1)$$

were  $E$  is the electrostatic field in the  $x$ -direction,  $\rho$  is the space charge density, and  $\epsilon_0$  is the air permittivity. Coordinate  $x$  is measured from the plane of symmetry between the parallel surfaces.

For the present investigation, the two surfaces can represent relevant parallel surfaces within the plant canopy, such as two adjacent leaves. In this case the electrostatic field will be smaller by an order of magnitude compared with the field outside the canopy.

**Cylinders and Spheres** - Poisson's equation for cylindrical coordinates (Moore, 1973) serves for analyzing cases of cylindrical bodies such as plant stems. Using the equation for spherical coordinates may quantify the electrostatic field around a sphere surrounded by a charged spray cloud as

$$E = \frac{\rho}{3\epsilon_0} \left( -r + R_1^3 \frac{1}{r^2} \right) \quad (2)$$

where the electrostatic field is in only the  $r$ -direction because of symmetry. Here  $R_1$  is the radius to the envelop of zero electrostatic field.

## Results and Discussion

Figures C1 and C2 show trajectories of particulates initiated at different heights relative to the horizontal central plane of a spherical target. Both gravitational force and drag forces due to the air flow were considered. The uniform air-carrier velocity for the above figures is 5 m/sec. The sphere radius is 4 cm which leads to a Reynolds Number far greater than 8. This means that the boundary layer separation phenomenon is fully developed for most of the rear part of the sphere. Thus, a unique trajectory for a particulate is non-evident and impossible to predict within this region. Values for air viscosity and permittivity are those of standard conditions, particulate mass density is 1000 kg/m<sup>3</sup> and diameter is 130  $\mu$ m, and the field-reversal radius  $R_1 = 0.1$  m.

Figure C1 is for a particulate charge-to-mass ratio of  $1 \times 10^{-3}$  C/kg and a space charge density of  $3.1 \times 10^{-6}$  C/m<sup>3</sup>. Figures C2 is for the uncharged particle condition.

Comparing the two figures shows that even at such high air velocity and relatively low droplet charges, an increase of a few percent of material deposition is predicted for the front part of the sphere. However, the charging increases the amount of material which gets into the wake at the rear of the sphere by several fold and likely will provide even greater material deposition within this region.

## Conclusions

- a) Electrostatic charging can increase the amount of material deposited onto surfaces of spherical bodies which face the oncoming spray cloud, but it has greater influence in increasing deposition onto the rear part.
- b) The increased deposition onto outer plant parts which directly face the spray may result in a decrease in the material left for the inner canopy parts. This is partly responsible for the order of magnitude smaller electric forces within the canopy which result from the smaller spaces between the inner surfaces, and which yield smaller electrostatic deposition at these regions.
- c) An increased deposition at the inner surfaces may partly be achieved by reducing the size of the cloud of the charged particulates at the plant outer space. A cloud having pulsed mass flow of proper frequency may provide a promising strategy.

## References

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## 2. Uniform Vehicle Speed and Automated Guidance For The Greenhouse Sprayer

A self-propelled vehicle for greenhouse spraying was designed and constructed, but since the design did not require any major innovations, this part is not reported here in detail.

Automatic guidance of a sprayer was primarily tested utilizing a steel rail. A special weigh-carrying wheel, routed by four ball bearings, was designed for a smooth and safe ride, to make sure that the guidance system could not be detached from the rail (Fig. C3). A commercially available sprayer was modified for use in a tomato greenhouse (Fig. C4). The guidance system was designed and constructed to track the rail along the rows as shown. At the end of each row the vehicle automatically turns into the next row.

The rail presented several advantages with high reliability including no guidance defaults for over 300 working hours. However, the high construction cost of approximately \$4/m<sup>2</sup>, and the need for removal every year in most greenhouses to enable soil cultivation, present major disadvantages.

No construction costs and no yearly removal were required for a guidance system which utilized ultrasonic sensors which measured the distance to each side of the canopy. A feasibility study showed that such a system may satisfactorily guide the vehicle in well organized tomato greenhouses. Figure C5 shows two ultrasonic sensors in front of the test vehicle. However, missing plants and other such disorders required the development of additional guidance means, such as a gyroscopic system. This additional development would have required a long research period which was not available in the present research study.

Thus, a simpler system was chosen, utilizing sensors which measure the electromagnetic field generated by wires implanted in the bottom of the canopy. These wires are easy to install and of low cost. An electronic system was developed for processing the signal. The system was able to guide the vehicle in the middle of the passage with accuracy of  $\pm 0.5$  cm. Figure C6 shows the sensors' arrangement. The end of the row was sensed and an automatic free turn was performed into the next row. The cost of the guidance system for each vehicle is estimated at \$1000 and the wires at \$0.04/m<sup>2</sup>. A schematic diagram of the wire arrangement in the greenhouse is presented in Fig. C7.

### **3. Uniform Spray Application Utilizing Small Clouds Of Charged Droplets (In collaboration with Dr. Eli Dubitzki)**

The optimal location of the electrostatic spray nozzle in relation to the outlet of a pulsed air jet source was investigated. The pulsed air jet was generated by a system originally developed for pollinating tomato flowers (ASAE Paper 82-1076). The air pulsator was mounted on a source of fast air stream (approximately 70 m/s velocity from a 65 mm diameter hose). Figure C8 shows the air pulsator, the electrostatic spray nozzle and its electronic controller, and a five degrees-of-freedom table which was utilized for determining the nozzle location. The schematic diagram in Fig. C9 describes the directions of the table scales and clarifies the parameters which influence the droplet deposition densities shown in Tables C1 and C2. Table C1 shows the droplet deposition densities for charged spray and Table C2 gives that of non-charged spray. The density was evaluated from a strip of water-sensitive paper, across which the system was passing. Figures C10 a,b and c graphically demonstrate selective results from these tables.

The system arrangement for the greenhouse experiments is shown in Fig. C11 a and b. Numerous tests were conducted to maximize the uniformity of the droplet deposition density. Recent results are given in Table C3 and represent the best arrangement achieved at this time for relatively dense canopies in a rose greenhouse. High supplemental pulsating air velocity of about 3 m/s on entering the canopy is not yet enabling to demonstrate the full advantage of the electrostatic charging. Better results are anticipated and are under investigation, since in experiments with less-dense canopies, the spray deposition uniformity was far better and the advantage in spray charging was much more significant.

## D. TECHNION (G. Manor):

### 1. Development of Experimental Capability

Electronic instrumentation necessary for conducting project-related experiments was appropriately selected and purchased including: a) measuring instruments for low-level currents, charge accumulation, and electric fields (*i.e.*, Keithley electrometer and Monroe vibrating-capacitor fieldmeter); b) high-voltage dc power supplies; c) air velocity sensors; and d) air-blast sprayer for facilitating laboratory and greenhouse spray tests.

### 2. Development Of Mathematical Model For Spray Coverage Of Leaves

It is usual to protect plants from insects or diseases by spraying them and especially their leaves. In order to be effective, the sprayed chemicals must come into contact with the insect or with the areas affected by the disease. For each combination chemical/leaf-condition there is an *effective radius* within which the spray can kill an insect or a fungal organism (Fig. D1).

When the insect is moving, the probability that it will contact a droplet is increased. Also, it is obvious that the probability is larger when there are more droplets on one leaf. The best coverage is achieved when the distance between any point on the leaf and the nearest droplet center is equal to or less than the effective radius. If the droplets lie closer than required by the above criterion, some chemical is wasted. The smaller the droplets, the larger the leaf area that can be covered by the same spray quantity.

The distribution patterns of chemicals applied by sprayers are usually evaluated by measuring the amount of tracer material recovered from the collectors (ASAE Standard S 386.1) or from the leaves (Law, 1981). Sister *et al.* (1982) used an image analyzer to measure the area of a target card covered with chemicals, but gave no information about the spatial density of the droplets. Carlton *et al.* (1981) measured the leaf area covered by the chemical itself, but not the density distribution of the droplets.

It was proposed on this project to measure the distances between the droplets and their sizes. It may be hypothesized that for every type of insect or disease there exists a relationship between the size of the droplet, its chemical concentration, and the effective distance.

If the coordinates of the droplet centers and the radii of the droplets are known, the area covered by the spray can be readily calculated, and the percentage of the leaf that is *effectively* covered determined.

A computer program for evaluating the influence of the effective radius upon pest control is in the stage of debugging and testing. The input of the program consists of:

- a) the array of (x, y) coordinates of the leaf contour;
- b) the array of (x, y) coordinates of droplet centers;
- c) the radius R of the droplets, assumed constant throughout the sprayed area.

Input items a) and b) are obtained from optical devices. The set listed under a) needs not be convex; that is, more than two x-values may be entered for one y-value, subject to the obvious constraint that there is either one or an even number of x-values of one y-value.

The user may provide the minimum and the maximum values of R; the program will run a loop of R values - for one combination of the input arrays listed under a) and b) - and yield:

- a) the leaf area A (constant);
- b) the area S over which the spray is effective (function of R);
- c) the S/A ratio.

This latter output is conceptually illustrated by a graph (Fig. D2) of the S/A ratio versus radius R.

The algorithm employed by the program counts each sprayed point only once, even when it lies within the intersection of several overlapping droplets. Also, the algorithm does not take into account the droplet areas that protrude beyond the leaf boundaries. The program is written in MATLAB, an interpreter which allows for concise and well structured code.

## References

- Carlton, J.B., L.F. Bouse, H.P. O'Neal, and W.J. Walls. 1981. Measuring spray coverage on soybean leaves. *Trans. of the ASAE*. p. 1108.
- Law, S.E. and M.D. Lane. 1981. Electrostatic deposition of pesticide spray onto foliar targets of varying morphology. *Trans. of the ASAE*. p. 1441.
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### 3. Aerodynamic Spray Applicator

**Introduction** - Spraying with help of air streams is well known from the 1940's in orchards and groves. The air streams are used to carry the chemical droplets to targets which are high and far from the sprayer.

In the last few years the advantage of air-stream-assistance spraying in penetrating into the plant canopy of row crops and preventing drift was recognized. Because of the complication of the phenomena that are concerned with the air-blast spraying process, most of the studies are based on statistical analyses of the spraying results.

One of the most important parameters is the air jet, its direction and velocity outside and inside the plant canopy, and its ability to carry the spray droplets to the leaves. In most cases the air jet is perpendicular to the sprayer's travel direction, a situation which influences the real velocity of the air jet measured at an exact point. In order to study the effect which sprayer travel speed has upon the air velocity pattern, laboratory experiments were carried out.

**Hardware** - An Imperial sprayer equipped with a P.T.O.-driven centrifugal blower having eight 38 mm diameter air output pipes was mounted on a MF 135 tractor. A gearbox with a 1:8 ratio was mounted between the tractor's 540 rpm P.T.O. and the blower.

Measurements were made on one outlet of the eight, with the other seven outlets directed such that they would not interfere with the measurements.

**Measurement Instrumentation** - The air velocity measurements for zero travel speed were made by a pilot tube which in turn was connected to a Schaevitz p-3061 differential pressure transducer having a pressure range of 0-50 inches of water. The data were collected by a GULTON recorder.

Air velocity measurements while the sprayer traveled forward were made using a KURZ 490 series hot-wire anemometer. The data from the anemometer were collected by a DASH-16 board and HSDAS program which were installed in an IBM XT compatible computer. The signals from the anemometer were amplified before they were entered into the computer. The system was calibrated in the low-speed wind tunnel of the Aerodynamical Engineering Department at the Technion.

**Zero Forward Speed** - Measurements were made at distances which changed in steps of five diameters (*i.e.*, the air outlet diameter was used as the measurement unit) from the nozzle out to the distance where the pilot tube became ineffective. The air velocity profile was detected across the jet diameter for seven blower speeds: 1520, 2030, 2540, 3080, 3570, 4080 and 4320 rpm. One repetition was made for all combinations of blower speed and distance from the nozzle. A jet velocity of 64 m/s was measured at a distance of 5 diameters (*i.e.*, 19 cm) from the nozzle.

**Measurements at a Point Within a Moving Jet Source** - The air jet was directed toward the probe of the KURZ anemometer. The cross-section of the jet was set-up when the sprayer moved across the measurement point. Measurements were taken at four sprayer travel speeds: 0.498, 0.737, 1.389 and 1.998 m/s using one engine speed of 1700 rpm.

The distance between the anemometer's probe and the air nozzle was incremented in steps of five outlet diameters from 1 diameter up to 66 diameters for all four travel speeds. Three repetitions were made for all combinations of distance and travel speed.

As expected from momentum and energy considerations, the measured air velocity became lower as the sprayer travel speed was increased. However, smaller differences occurred as the distance between the jet source and the target was increased (Figure D3).

**Plant Spraying** - Because of absence of greenhouse plants, cotton field plants were used for field testing. The plants were 1 m tall and provided enough space for the air pipes to move between rows without interference.

Fluorescent tracer in aqueous concentration of 1.5% was sprayed at rates of 190 and 380 l/ha. The two application rates were achieved by driving the sprayer at travel speeds of 2.000 and 0.956 m/s. KON-JET™ type X-3 hydraulic-atomizing spray nozzles (Spraying Systems Co.) were used at an operating pressure of 2 bars. Thirteen spray nozzles were used for each row - one pointed downward above the row and six on each side as seen in Figure D4.

The aerodynamic spray applicator tested is based on a new design (patent pending) of air nozzles. The main advantage is pulsating side nozzles on vertical air ducts.

After spraying, four leaves were taken from twelve locations, from ten plants in every row, at three elevations in every plant (Figure D5). Analysis of the sprayed leaves showed that 100% of the upper surfaces of the leaves from all sites were covered, 100% of the lower surfaces of the leaves from the locations of the upper layer, 99% of the lower surfaces of the leaves from the middle layer, and 97% of the lower surfaces of the leaves from the lower layer were covered.

#### **4. Evaluation Of Electrostatic Sprayer Nozzle**

Electrostatic charge method for getting better coatings in the paint industry is popular in use. The same method is being used with agricultural sprayers for getting better coverage of plant foliage by the sprayer droplets. Because the electrostatic charging method is more efficient than conventional spraying methods, less dangerous chemicals are expected to be used and less spray drift to neighboring fields is likely as compared with the other methods.

An aerodynamic-electrostatic spray-charging nozzle was tested by us at the Technion. Coverage quality, with and without electrostatic charge, was tested. The results show a significant advantage of the electrostatic sprayer.

Between the dates 11/12/90 - 11/26/90 the first electrostatic nozzle, which was designed and fabricated by Prof. S.E. Law of the University of Georgia, was tested at the Agr. Dept. of the Technion. Five additional nozzles of the new generation along with a new high-voltage amplifier, as fabricated in their commercially developed designs by the University of Georgia's patent licensee (Electrostatic Spraying Systems, Inc.) were received in 1991 for testing on a greenhouse sprayer. After some failures because of using too high a voltage rate causing electrode damage, successful tests were conducted in a tomato greenhouse at the agricultural high school of Kfar Galim. [Editorial Note - The charging-nozzle units were incorporated into locally fabricated experimental sprayers and did not utilize the air pressure-sensing cutoff for the electronics which is a standard feature on the ESS-engineered system for precluding this problem of electrode-shortening].

**Test Sites** - The nozzle's flow rate, the droplets size, and droplets traveling distance were measured in the power and machinery laboratory of the Agricultural Engineering Faculty of the Technion. Spraying tests of the first generation nozzle were made in the agricultural high school in Kfar Hasidim, in study's greenhouse (1990). Plant pots were arranged in groups of 1 m x 1 m, 0.2 m between the groups. The pots stood on stoney ground. In every group of 20 pots, five pots were chosen and electrically grounded. The other pots were used as a control group. Another group at the opposite side of the greenhouse was sprayed with uncharged spray and also used also as a control group.

The five nozzles of the new generation with a new high-voltage amplifier were tested in a rose greenhouse in Moshav Nir Banim. The nozzles' properties were checked at the Institute of Agricultural Engineering of the A.R.O. (1991). The tests failed because of too high voltage which caused damage to the nozzles (see test results).

Spraying tests of three new nozzles, after electrode replacement, were made in a laboratory of the Agricultural Engineering Faculty of the Technion for the nozzles' properties and in a tomato greenhouse in the agricultural high school Kfar-Galim for checking the spray coverage properties (1992). The tomato plants were planted in pots which were arranged in rows. Plant height was 2.5 m and they made a regular green wall perpendicular to the floor. Eight pots, about 2 m from the beginning of the rows, were electrically connected to the ground for the charged test. The uncharged repetitions took place in the other end of the rows about 40 m away from the charged repetitions site.

**Instrumentation** - The nozzle was connected to an air pressure bottle and to a liquid bottle. The liquid was sucked by the air stream according to the Bernoulli principle. An electrostatic electrode which was mounted within the outlet of the nozzle charged the fluid droplets with negative electrical charge.

Electric power was supplied by two 6V 3425-ICE-41r20 "TEDICEL" batteries which were connected in series. This voltage was raised by a ratio of approximately 1:100 by

a voltage amplifier which was developed by Prof. S.E. Law. An AVO-meter was used to determine the voltage between the batteries poles and between ground and the electrode.

An electric carriage which had been designed in the Agricultural Engineering Institute in Bet Dagan was used as a basis with a vertical rod mounted on it for holding the nozzles. Diving compressed air bottles were connected to the nozzles for air supply. A carriage, pushed by hand, was designed and built for carrying the nozzles between the tomato rows while spraying in the tomato greenhouse. The carriage was pushed at a steady walking velocity of 1 m/s along the tomato rows (1992).

The effective distance, the number of droplets per unit area, and the droplets diameter were measured in the laboratory by spraying horizontally for five seconds from a height of 0.6 m above water-sensitive papers which were spread along a straight line out from the nozzle. The droplet diameters were measured under a microscope with an enlargement of 15.5. [Editorial Note - Some uncertainty exists as to whether the typical 30-50  $\mu\text{m}$  droplets produced by U.Ga./ESS charging nozzle cause adequate reaction to create droplets spots for detection on the water-sensitive paper.].

A SAS language, PC version, was used to analyze the test observations. ANOVA procedure was used to find any significant difference between charged and uncharged sprayed droplets.

**Nozzle Construction and Operation** - The fluid principle of the nozzle, of both generations, is based on a venturi tube. A high velocity air stream causes a low pressure which draws the liquid up from its container and breaks it into droplets. Six 2 mm diameter air nozzles are drilled around the 1 mm liquid nozzle. An air stream from a pressure bottle sucks up the sprayed liquid from the container, breaks it into droplets and carries it to the foliage through a 3 mm hole which was drilled in a toroidal electrode (Law, 1978).

The electrode was assembled in the nozzle outlet for charging the droplets with negative charge. A high-voltage amplifier multiplies the low voltage by approximately 100-fold getting its energy from two series-connected alkaline 6V batteries.

Three nozzles were mounted, with 250 mm distance between them, on a vertical rod of 2 m height which was welded to a four-wheel carriage. The air supply was from a 150 bar compressed air bottle which stood outside the rows in the passage. A pressure of 2 bars was kept by a pressure regulator which was mounted on the air bottle. A long flexible tube connected the air bottle and the sprayer. The spray jets made a 45° angle with the rows (Fig. D6).

**Testing Method** - Liquid flow rate was measured in the laboratory by filling a probe tube for 10 seconds. Three repetitions were made for every nozzle from the three and the average value was calculated.

For measuring the spray distance, a nozzle was located 60 cm above the floor and was connected to the laboratory air supply through a pressure regulator. The liquid

suction tube was immersed in one liter water pot. Water-sensitive papers (76 mm x 52 mm) were spread in the spraying direction, 0.5 m between the papers, from 0.5 m up to 4 m. The air was opened for 5 seconds. A pressure of 2 bars was kept in the inlet of the nozzle.

In the tomato greenhouse 10 m of two rows were sprayed, one with charged mode in a row with eight pots grounded electrically and the other row sprayed with uncharged mode. The distance between the nozzles and the row was kept at 600 mm. "Lunar Yellow" fluorescent tracer was used in the spraying tests. After spraying, thirty leaves were taken randomly from every test location. Estimations of the area of the leaf which was covered and the density of the coverage were visually made in the laboratory. The covered area was qualitatively estimated on 0 to 5 grades, and the coverage quality was estimated by eye on 0 to 3 grades. The quantitative grades were translated to percentages. The "relative spray quantity" as a product of the relative covered area and the relative coverage quality was calculated.

**Test Results** - The first nozzle flow rate was found to be 70 ml/min. Flow rate measurements of the three nozzles after exchanging the burnt electrodes gave 62 ml/min for two of the nozzles. The third nozzle gave 112 ml/min.

The spray traveling distance as measured was 4 m in both the first and second generations of nozzles. The droplets diameters and the number of droplets in cm<sup>2</sup> are given in Table D3 for the new nozzles. It can be seen from the table that most of the liquid reached the distances between 2 m to 3 m. [Editorial Note - laser measurements of airborne droplets produced by the U.Ga./ESS charging nozzle document a 30-50  $\mu$ m volume - median diameter for the spray at the air pressures used. The large sizes of Table D3 are not consistent with all previous droplet size analysis.]

The tests which were conducted in the rose greenhouse of Nir Banim failed because of the electric arc formation. But the leaf coverage by the charged spray applied by the new nozzles was better than the uncharged spray in spite of the arc which was formed between the electrode and the nozzle while spraying.

The arc was not formed while the nozzle was dry. Electrode voltage of 1.2 kV in the outlet of the dry nozzles was measured. Water flow through the nozzles lowered the voltage which was measured to 0.5 kV. The maximum current measured in the fluid jet, nearby the nozzles, was 3  $\mu$ A. An arc between the electrode and the nozzle could be seen when the nozzles were wet (after water flow was terminated). The burnt electrode assemblies were replaced by new ones and the voltage was lowered to 0.9 kV, by using 9V battery, to prevent this phenomenon.

The covered area and coverage quality as visually examined in the tomato greenhouse trails, were much better by the electrostatic method (Table D4). Better coating, the product of coverage area and coverage quality, was found on the leaf undersides while spraying with the electrostatic charging method than with the regular method, but most of the underside area still was not covered.

**Conclusions** - The electrostatic spraying is much better than the uncharged spraying. The electrostatic spraying devices can be mounted on regular sprayers with no difficulties and change of the old sprayers. The air stream has not enough energy to penetrate the canopy and coating the undersides of the leaves. The gap between the electrode and the fluid nozzle was not large enough and the maximum voltage without arc was 0.9 kV.

#### **IV. DESCRIPTION OF COOPERATION**

Good collaboration occurred in Year-1 among engineering researchers at the Volcani Center, the Technion and the University of Georgia. Common instrumentation needs were jointly evaluated and recommended purchases made. Specialized electronic circuits of U.Ga. design for transient charge-transfer measurement systems were fully shared, and fabricated spray-charging systems were provided in both the U.S. and Israel. Throughout Year-2 and Year-3, excellent collaboration in evaluations of biological efficacy was provided to this project by the entomologist co-investigators.

Collaborative visits of researchers to both nations occurred. Under funding from other sources, G. Manor spent approximately three weeks in July 1989 at the Agricultural Engineering Department of the University of Georgia conferring with S.E. Law and others. During ten days in early September 1989 in Israel, S.E. Law conferred on project matters with S. Gan-Mor at the Volcani Center and G. Manor at the Technion. A good insight was provided into Israeli methods of greenhouse vegetable production during visits to a number of facilities throughout the country. Visits of Israeli researchers to the University of Georgia also occurred during Year-2. Both Dr. G. Manor and Dr. S. Gan-Mor visited with Dr. S.E. Law during the June-July 1990 period for research discussions regarding this BARD work. Dr. Gan-Mor spent approximately ten days on site for BARD-related conferences.

No binationally-authored publications have resulted from this three-year US-Israeli cooperative project.

#### **V. EVALUATION OF RESEARCH ACHIEVEMENTS**

Section II has presented the originally proposed project objectives and the Stages 1-8 of research and development tasks with indicated responsibilities. The overall objective was accomplished in successfully developing and evaluating an aerodynamic-electrostatic pesticide sprayer providing improved greenhouse pest control at increased application speed, reduced active ingredient in many cases, and operator safety. Especially important improvements in underleaf and deep-canopy deposition were achieved in meeting the overall objective.

The *Stage-1* development of a computer simulation model for air-assisted charged-droplet motion within plant canopies was completed for research guidance; however, its explicit validation (*Stage-3*) was deferred to permit experimental investigation of the pulsed-cloud concept suggested by the model.

Several methodologies and systems for measuring droplet deposition, quantity and spatial uniformity, were successfully devised in *Stage-2*. These included improvements on an existing multi-channel electronic instrumentation system for measuring transient charge exchanges occurring between spray clouds and targets, a mathematical model for spray coverage of leaves, and a computer-interfaced, light-intensified, machine-vision, image-analysis system for assessing deposition characteristics of deposited particles as small as 5  $\mu\text{m}$  at a multitude of leaf locations.

The *Stage-4* development of a laboratory-size aerodynamic-electrostatic spray application was completed and identical systems provided in both Israel and the US for facilitating charged-spray experimentation. The full-size aerodynamic-electrostatic sprayer of *Stage-6* was developed in both backpack and self-contained pushcart models in conjunction with the U.Ga. patent licensee (ESS, Inc.). Completely engineered ESS systems were evaluated in US greenhouse and laboratory tests while ESS charging nozzles alone were provided to Israeli cooperators for their inclusion into locally fabricated experimental sprayers.

The achievements of *Stage-5* and *Stage-7* generally documented (*via* both fluoroanalysis and image analysis) improved amounts and spatial distributions of air-assisted charged sprays - especially onto leaf undersides and inner-canopy regions. Tracer mass-transfer tests were completed in the laboratory on both idealized targets and potted-plant targets, as well as in full-scale commercial greenhouses. Additional corroborating results of GC analysis of the improved pesticide foliar deposition achieved by the University of Georgia/ESS technology were provided (*viz.*, by Dr. D. K. Giles, U.Calif./Davis). The proposed mobilized system was accomplished as based upon fixed-track, ultrasonic, and electromagnetic guidance methods. Also achieved were the basic investigations regarding various electrical interactions occurring during the charged crop-spraying process including those studies of electrical grounding requirements for plastic-potted greenhouse crops and the effects of dielectric boundaries upon the process. A portable air-ion monitor was designed and built for more fully investigating environmental effects upon electrostatic spraying, but only abbreviated experiments were possible.

*Stage-8* was fully accomplished for determining the insect-control efficacy achieved on common greenhouse plants by the reduced-volume aerodynamic-electrostatic sprayer in comparison with non-charged air-assisted spray and with high-volume conventional hydraulic spray. Documentation was also completed regarding the labor-saving and reduced phytotoxicity benefits associated with the developed spraying method.

## VI. LIST OF PUBLICATIONS FROM THIS WORK

- Law, S. Edward, Steven C. Cooper and Adrian G. Bailey. 1988. Transient analysis of charged-droplet motion and corona-induced velocity perturbations during electrostatic deposition processes. *IEEE Trans. IA-24*(5):913-921.
- Law, S. Edward. 1989. Electrical interactions occurring at electrostatic spraying targets. *Jour. of Electrostatics* 23:145-156.
- Law, S. Edward. 1989. Charge and mass flux in the radial electric field of an evaporating charged water droplet: an experimental analysis. *IEEE Trans. IA-25*(6):1081-1087.
- Law, S. Edward and Henry D. Bowen. 1989. Effects of liquid conductivity upon gaseous discharge of droplets. *IEEE Trans. IA-25*(6):1073-1080.
- Law, S. Edward and Steven C. Cooper. 1989. Target grounding requirements for electrostatic deposition of pesticide sprays. *Trans. of ASAE* 32(4):1169-1172.
- Cooper, Steven C. and S. Edward Law. 1990. Computer-based charge transfer data acquisition from multiple targets undergoing electrostatic spraying. *Trans. of ASAE* 33(2):666-670.
- Giles, D. Kenimer and S. Edward Law. 1990. Dielectric boundary effects on electrostatic crop spraying. *Trans. of ASAE* 33(1):2-7.
- Giles, D.K., Y. Dai and S.E. Law. 1991. Enhancement of spray electrodeposition by active precharging of a dielectric boundary. *Proceedings of the 1991 Oxford University Conference on Electrostatics. British Inst. of Phys. Conf. Ser. No. 118* (Section 1):33-38. ISBN 0-85498-407-0.
- Manor, G., R. Hedvati, E. Kalter and A. Geva. 1991. Aerodynamic spraying of cotton plants for better coverage and lower drift. *ASAE Paper No. 91-1032* (microfiche), St. Joseph, MI.
- Dai, Y., S.C. Cooper and S.E. Law. 1992. Effectiveness of electrostatic, aerodynamic and hydraulic spraying methods for depositing pesticide sprays onto inner plant regions and leaf undersides. *ASAE Paper No. 92-1094* (microfiche), St. Joseph, MI.
- Law, S.E., S.C. Cooper and R.D. Oetting. 1992. Advances in air-assisted electrostatic crop spraying of conductive pesticides. *ASAE Paper No. 92-1062* (microfiche), St. Joseph, MI.
- Evans, M.D., S.E. Law and S.C. Cooper. 1992. Image analysis of particulate spray deposits using light-intensified machine vision. *ASAE Paper No. 92-7015* (microfiche), St. Joseph, MI.



**FIGURES FOR SECTION IIIA**  
**(S.E. Law)**

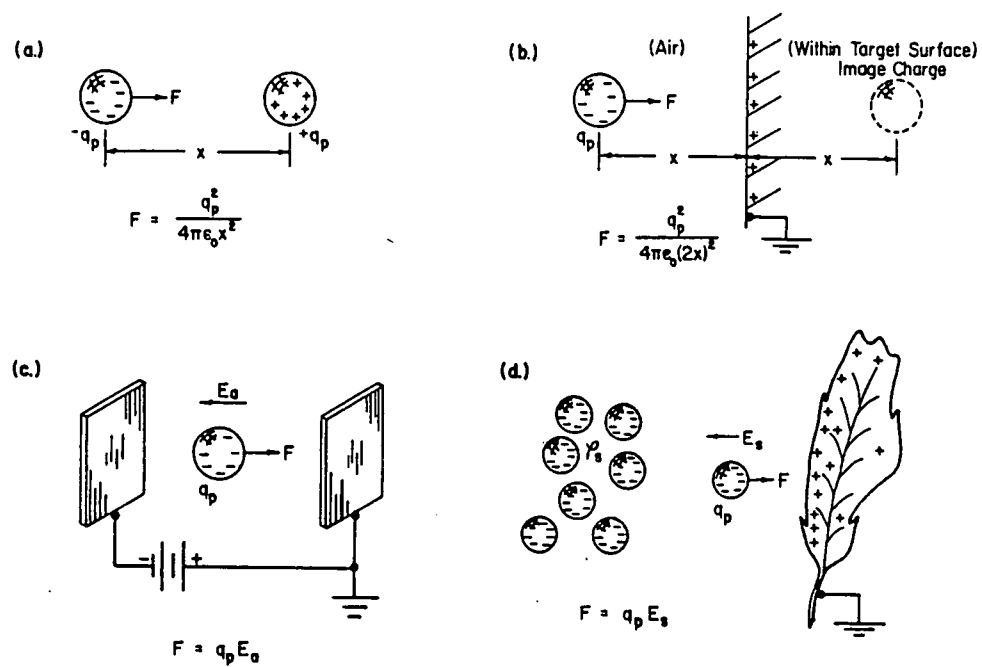


Figure A1. Electric-force options for charged-droplet crop spraying. a) inverse-square droplet-to-droplet force, b) induced image-charge force, c) externally applied electric-field force, d) spray-cloud space-charge force.

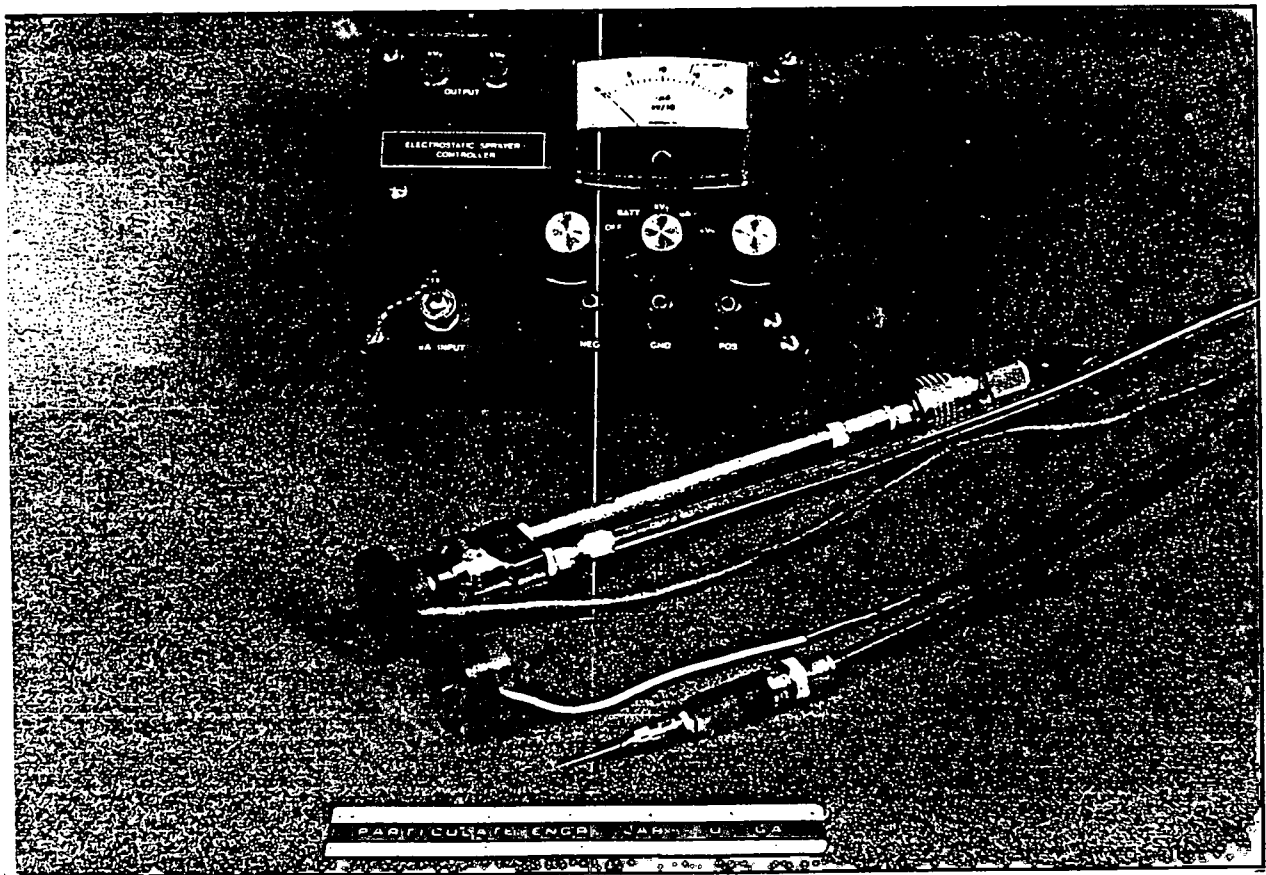


Figure A2. Laboratory-scale aerodynamic-electrostatic spray application system.

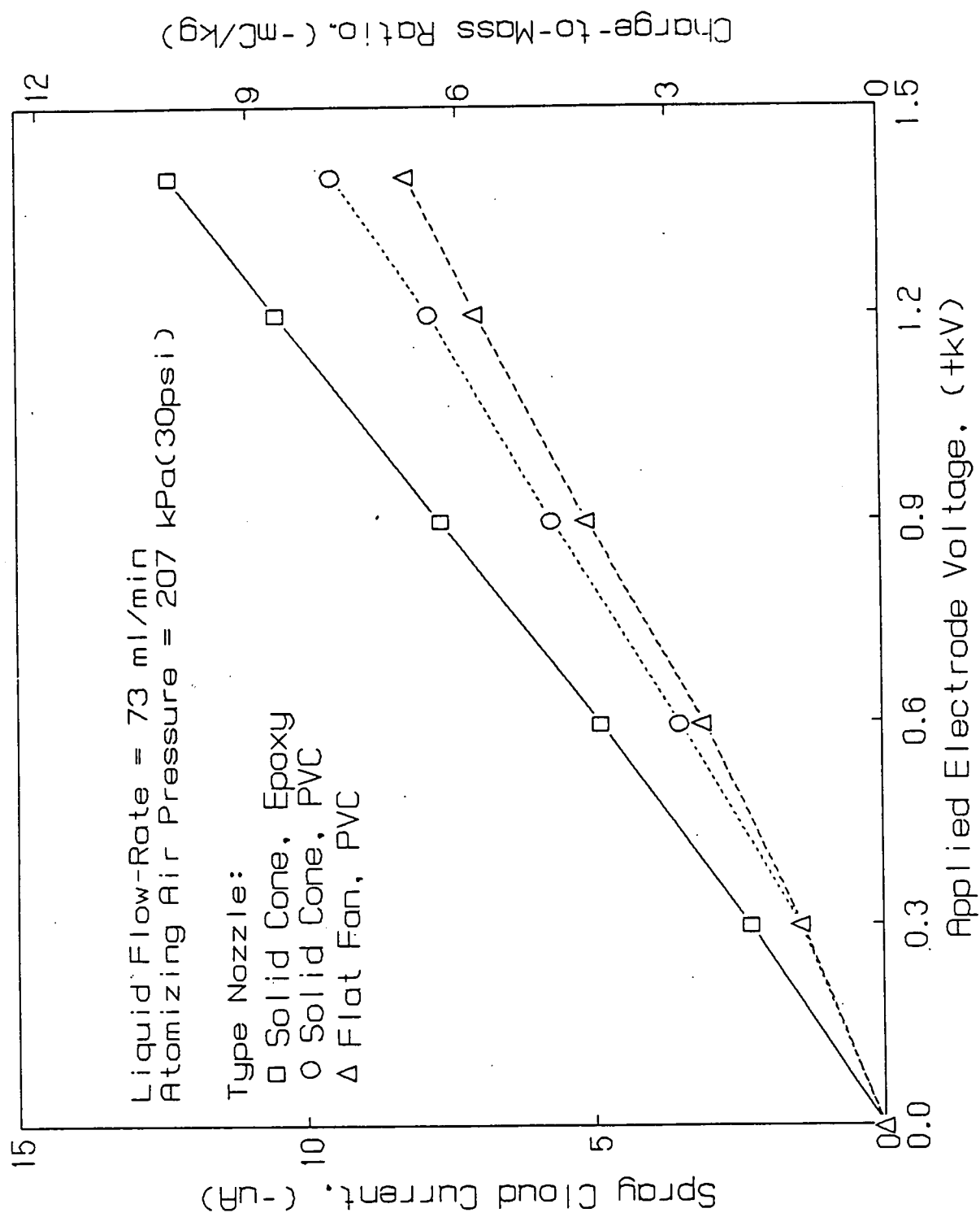


Figure A3. Spray charging characteristics of electrostatic-induction nozzles.



Figure A4. Backpack-type aerodynamic-electrostatic greenhouse sprayer.

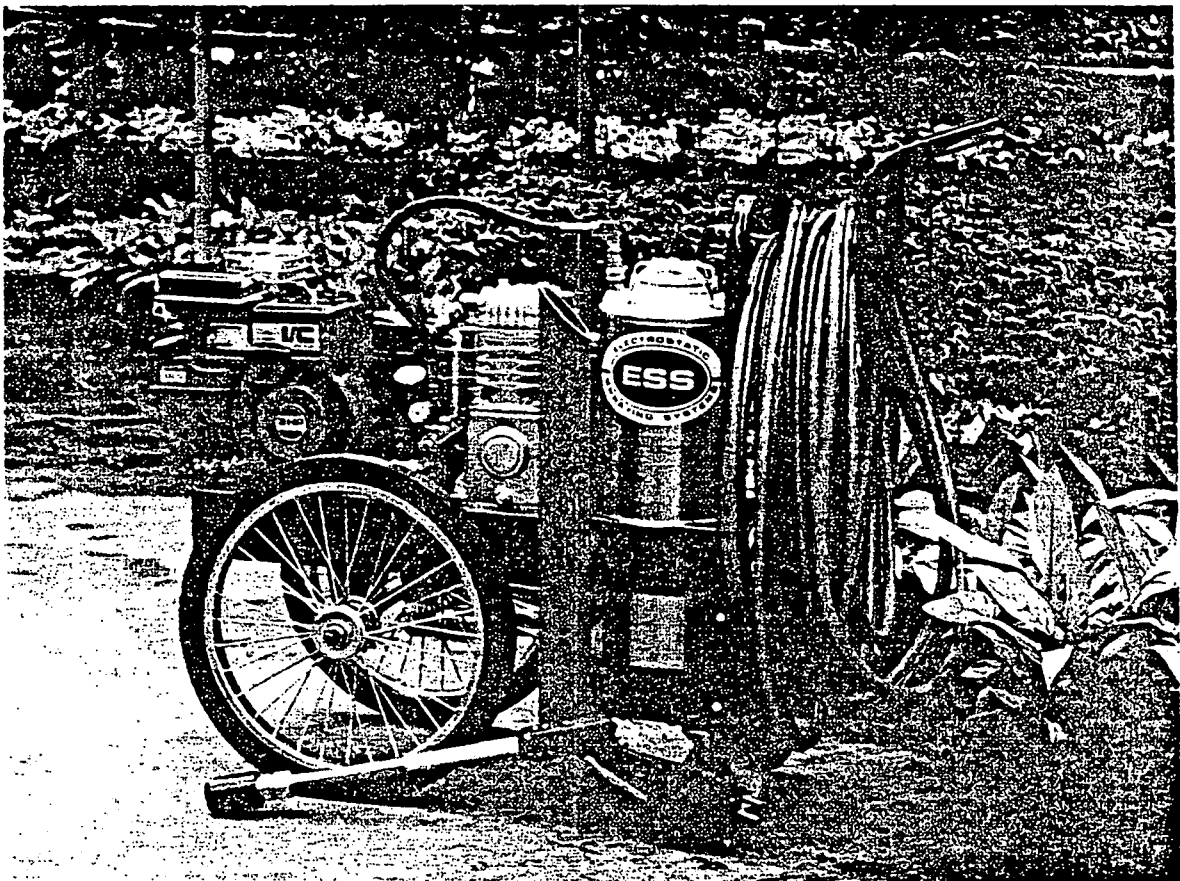


Figure A5. Self-contained pushcart-type aerodynamic-electrostatic greenhouse sprayer.

FLOW RATE: 200 mL/min.

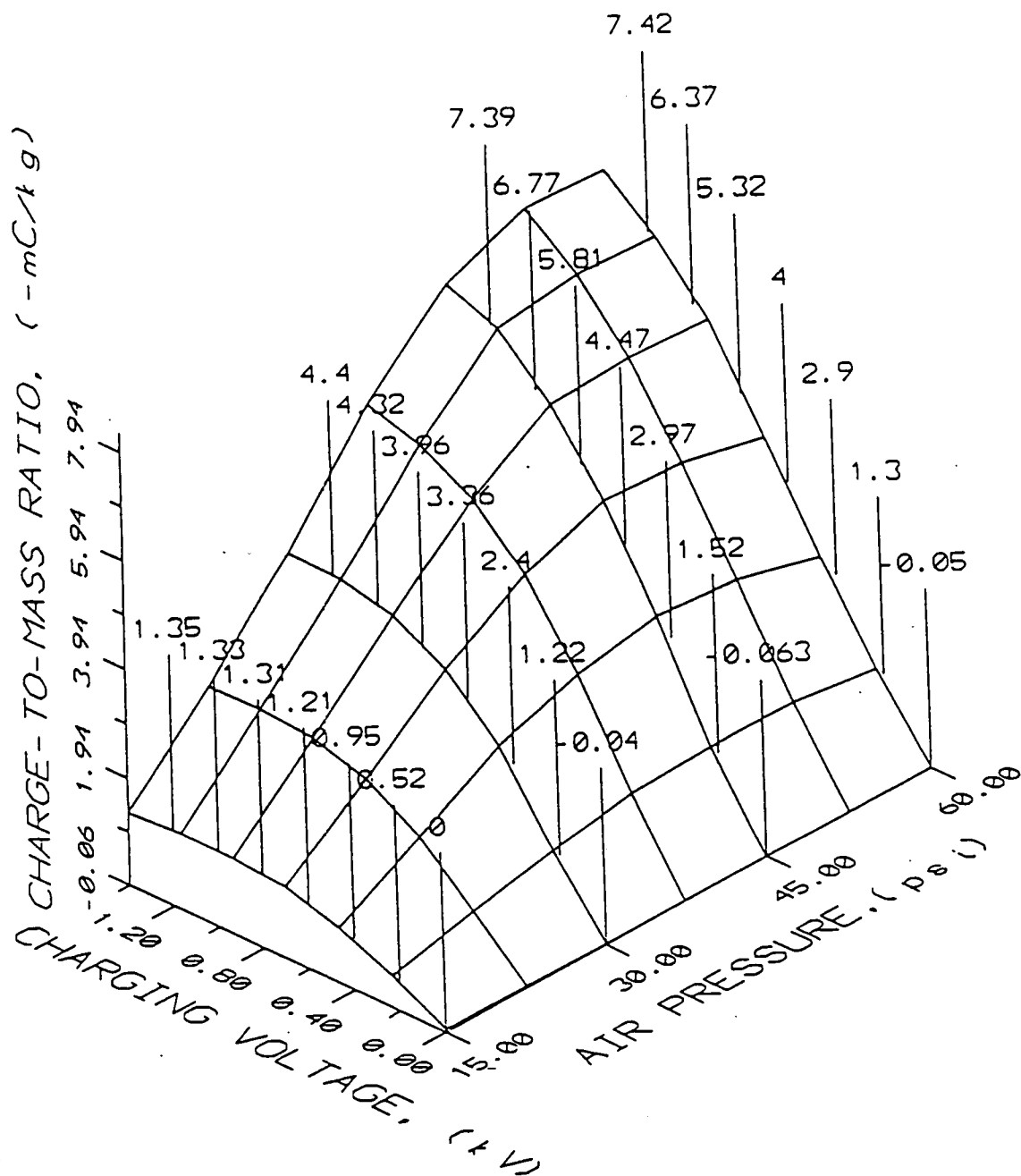


Figure A6. Spray-charging characteristics of dual-orifice nozzle for greenhouse aerodynamic-electrostatic applications.

**CHARGING VOLTAGE: +1400 volts.**

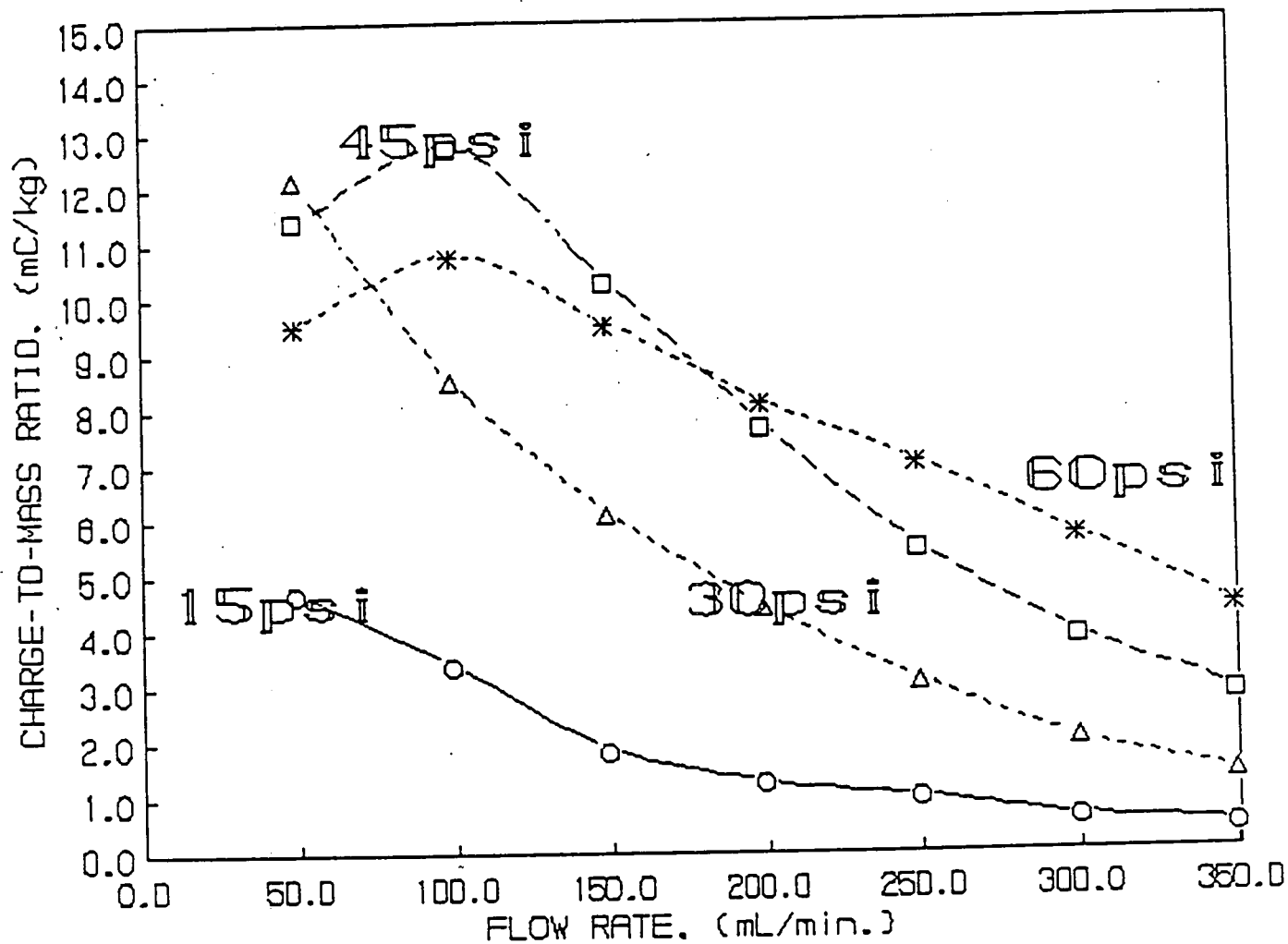


Figure A7. Spray-charging performance of dual-orifice induction nozzle as a function of liquid flow rate for various atomizing-air pressures.

## Charging Voltage: +1400 volts.

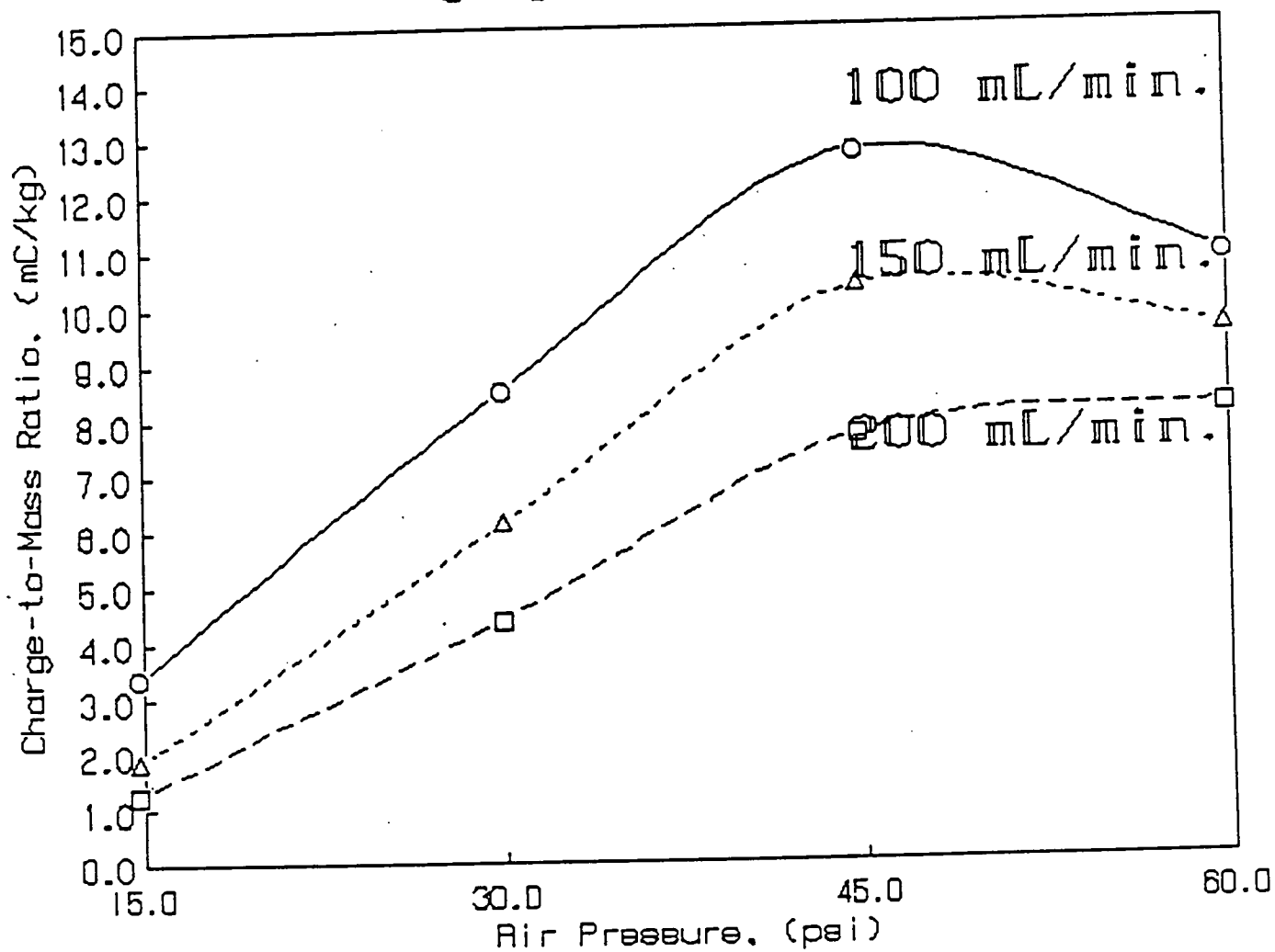


Figure A8. Spray-charging performance of dual-orifice induction nozzle as a function of atomizing-air pressure for various liquid flow rates.

Air pressure : 45 psi

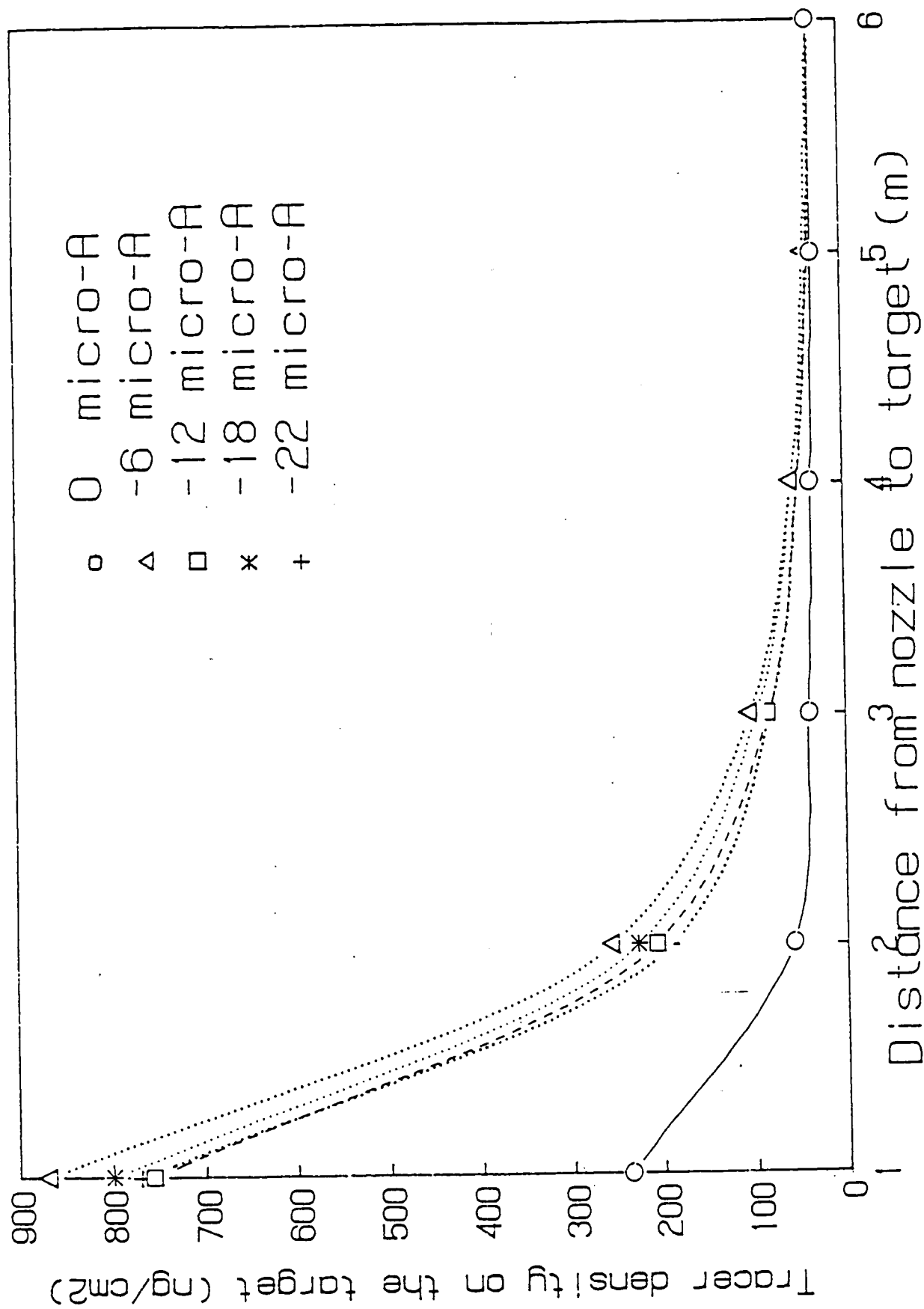


Figure A9. Spray deposition density achieved by dual-orifice aerodynamic-electrostatic nozzle as a function of nozzle-to-target distance for various  $\mu\text{A}$  intensities of spray-cloud current.



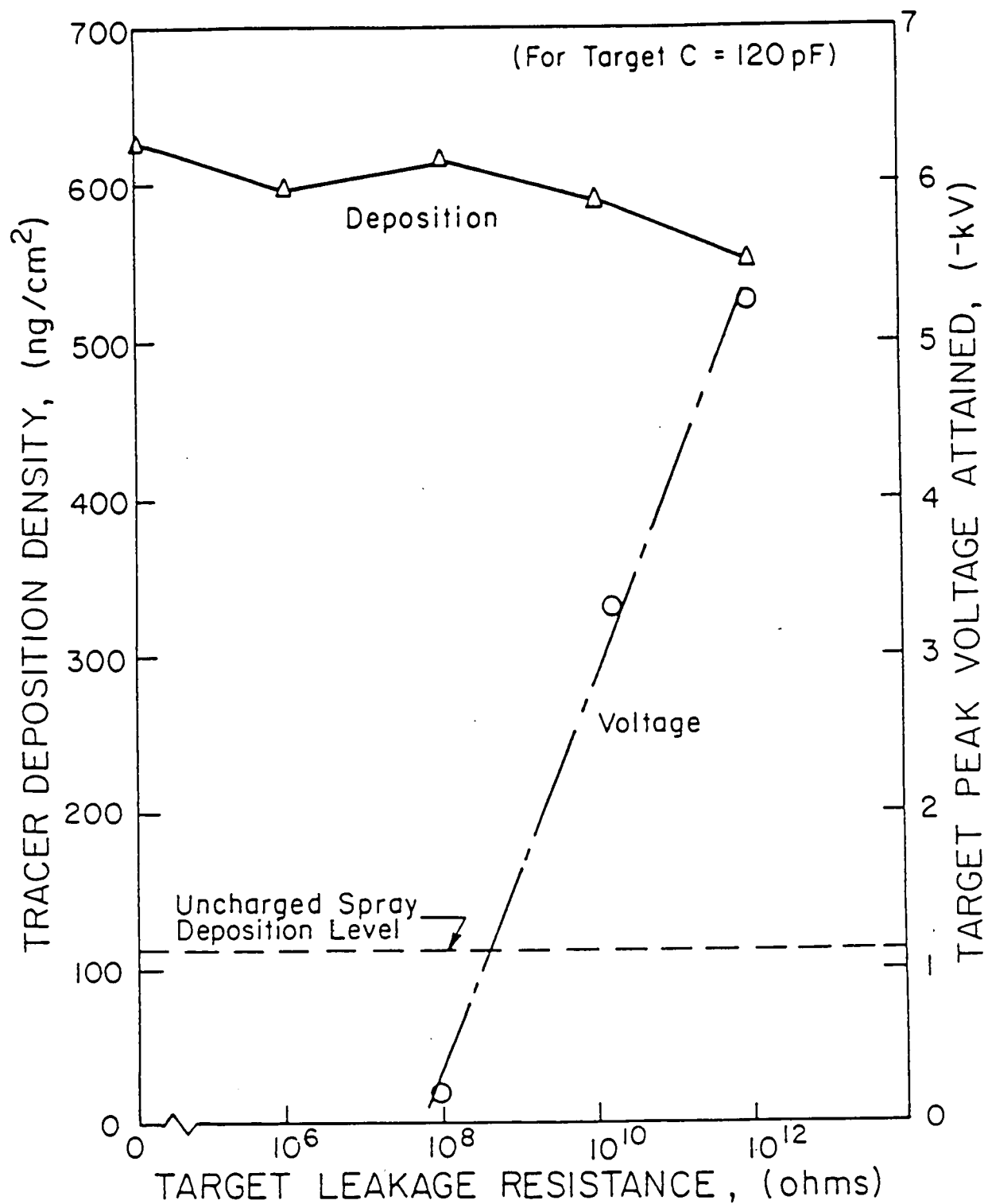


Figure A10. The effects which specified values of charge-leakage resistance to earth have upon peak target voltage attained and tracer deposition density achieved when spraying a 120 pF metal-sphere target with -4 mC/kg charged droplets.

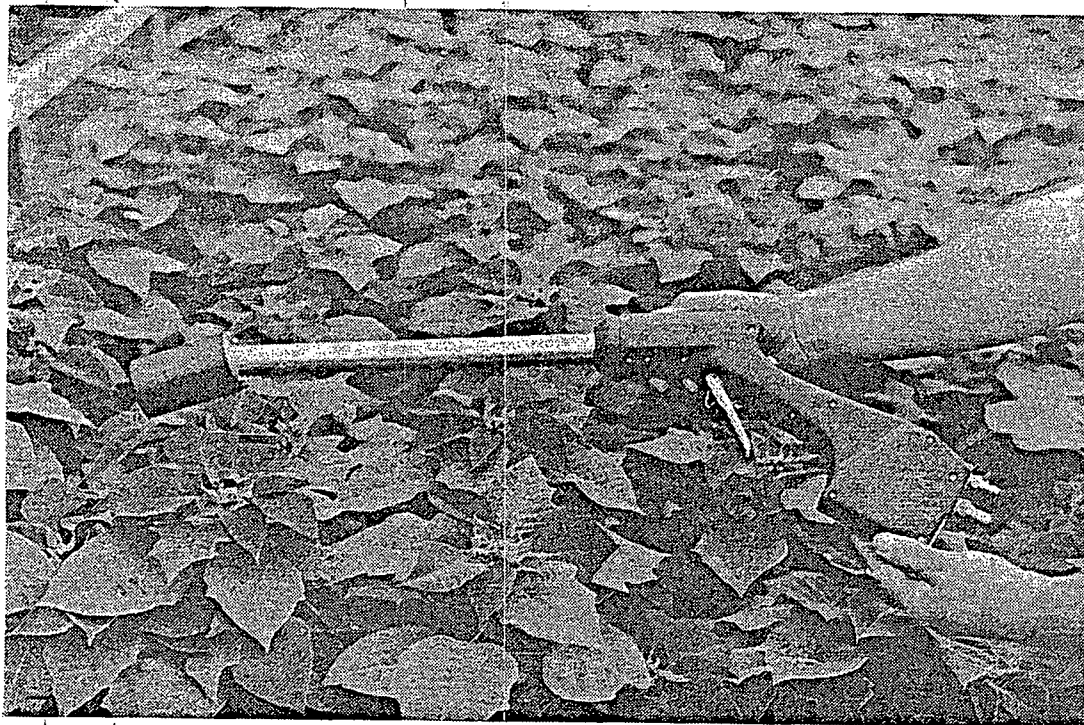


Figure A11. Electrostatic-sprayer handgun incorporating two embedded-electrode charging orifices. All electronics including battery are built into handle.



Figure A12. Electrostatic pushcart sprayer for greenhouse crops. Both gasoline and electric powered models as well as a backpack version have been developed.

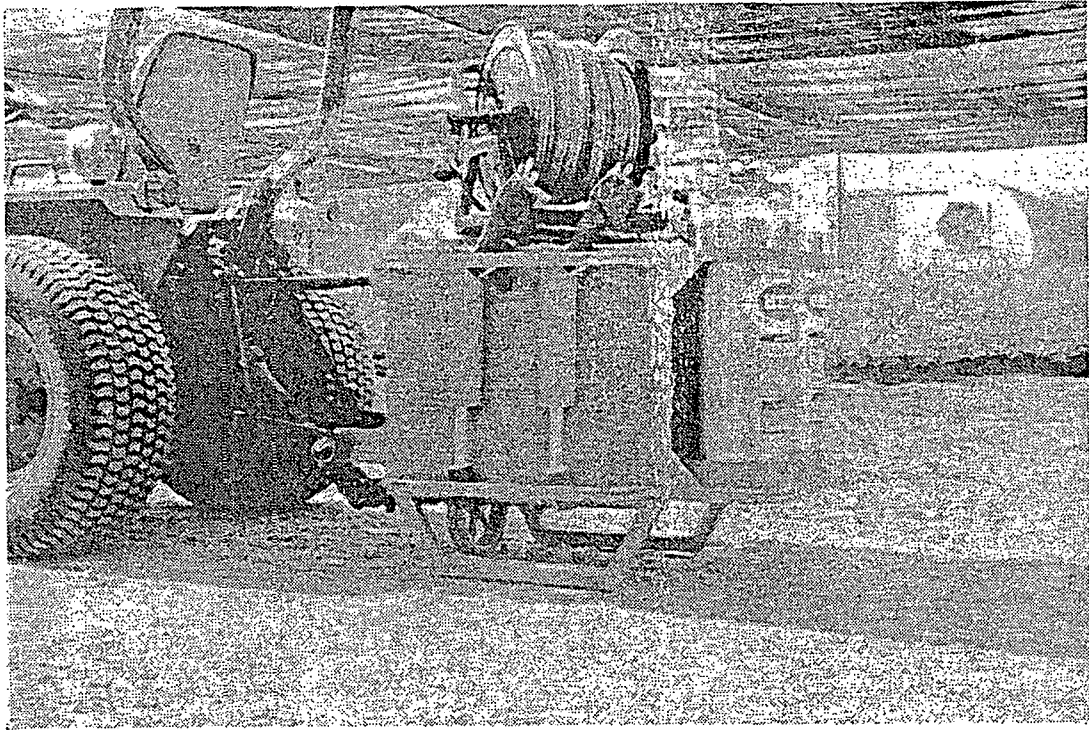


Figure A13. Three-point hitch mounted, pto-driven electrostatic sprayer for greenhouse and nursery applications. Unit can support two handguns.

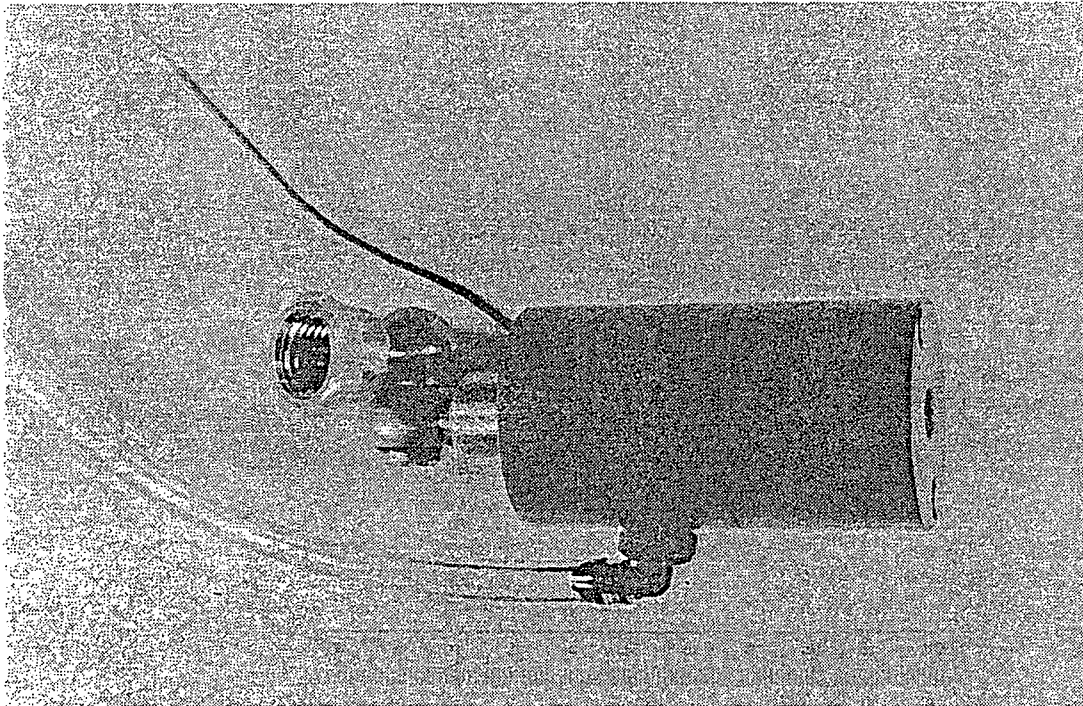


Figure A14. Embedded-electrode spray-charging nozzle adapted for boom-type swivel mounting.

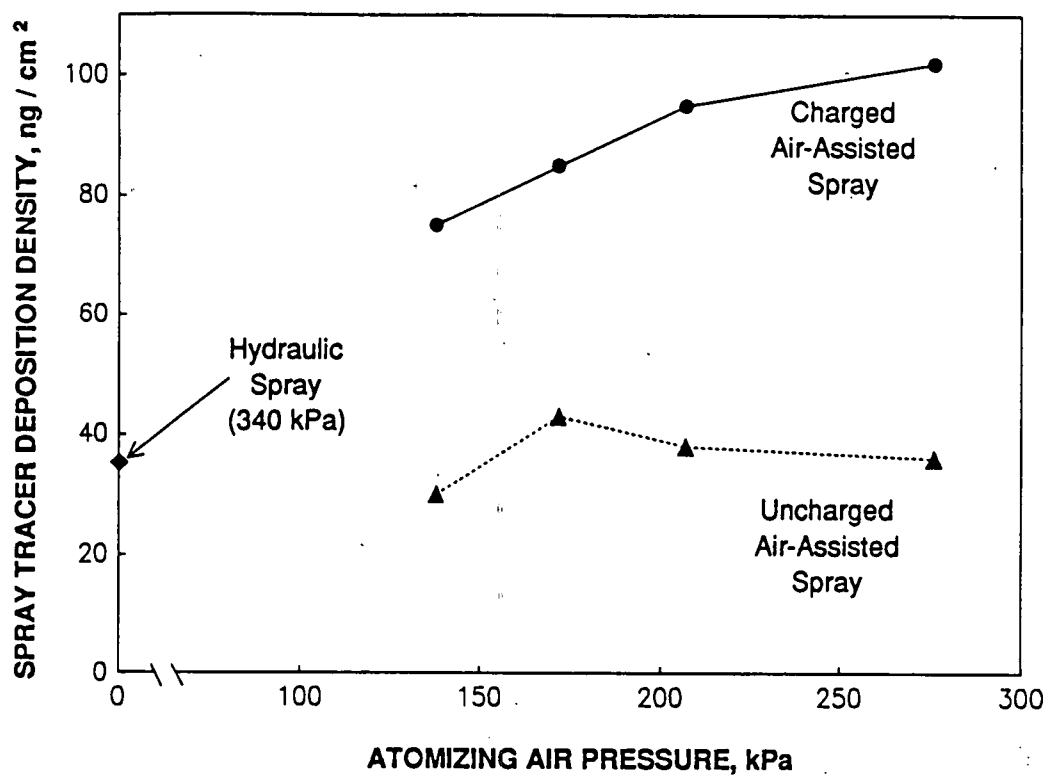


Figure A15. Effectiveness of three methods of spray application for depositing spray tracer onto undersides of leaf-targets placed within inner canopy region of cotton plants.

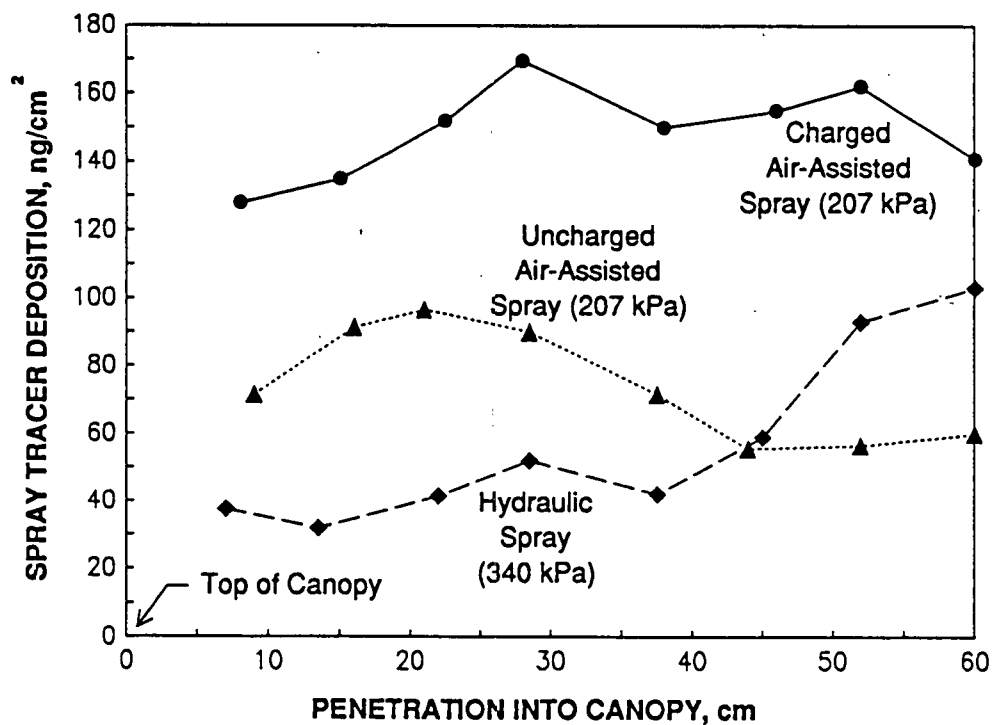
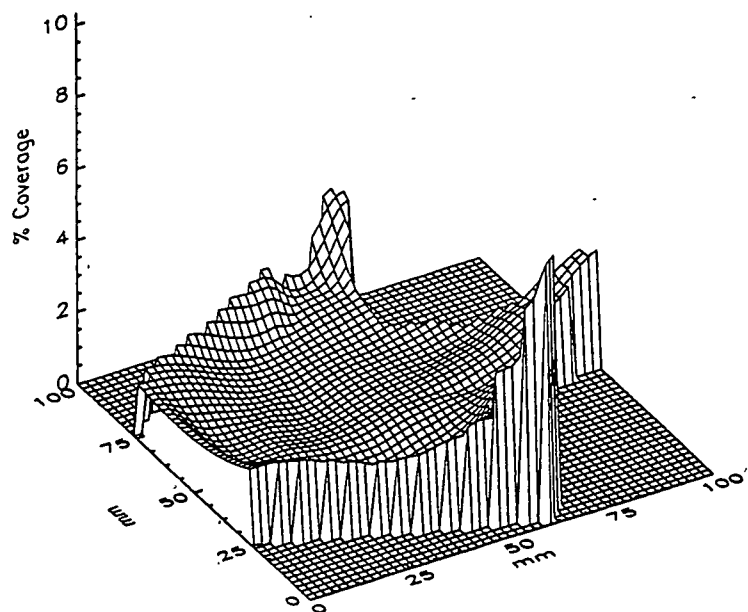
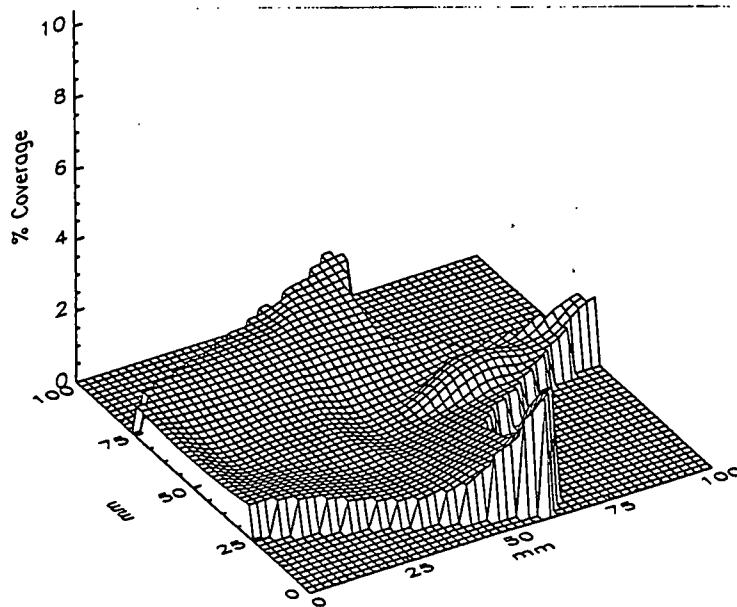


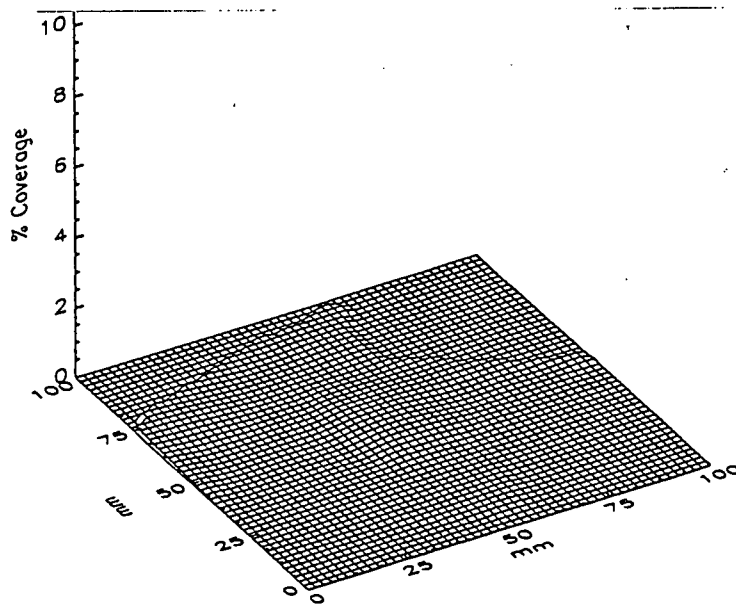
Figure A16. Effectiveness of three methods of spray application for depositing spray tracer onto vertical sides of target-cylinders placed near central stalk at indicated depths of penetration into cotton-plant canopy.



a) Charged  
air-assisted  
spray (207 kPa)



b) Uncharged  
air-assisted  
spray (207 kPa)



c) Hydraulic  
spray (340 kPa)

Figure A17. Spatial distribution of spray tracer deposited onto undersides of leaf-targets within cotton canopy as measured by machine-vision image analysis.

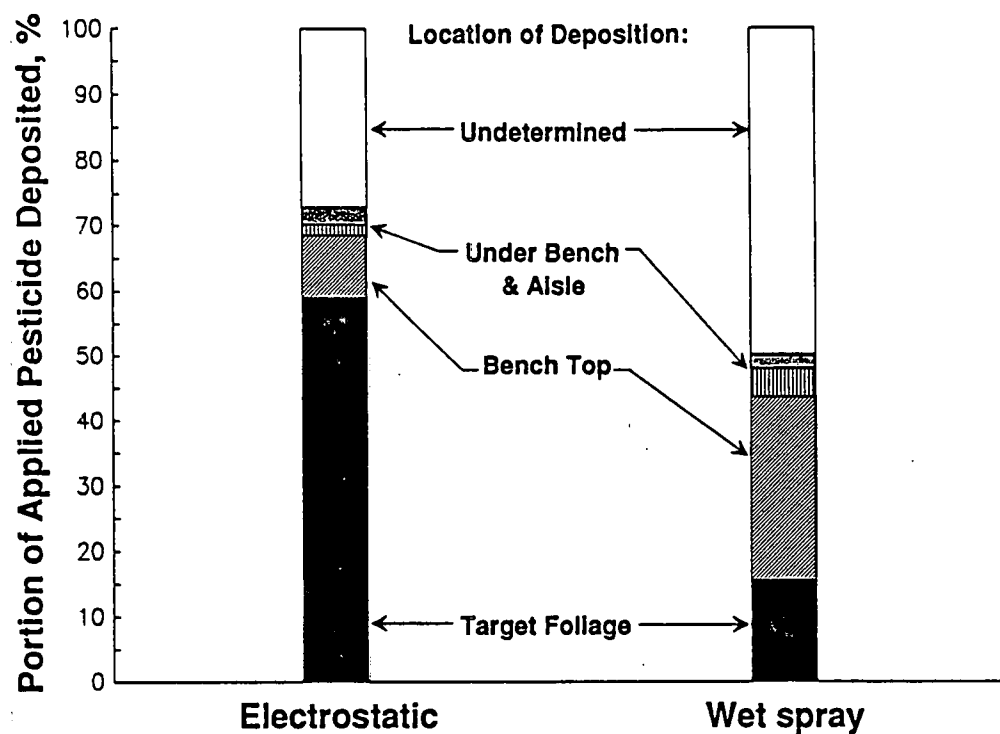


Figure A18. Accounting on a mass-basis for permethrin insecticide (Pounce™ 3.2 EC) dispensed in a greenhouse by two spray-application methods. (From Giles [6]).

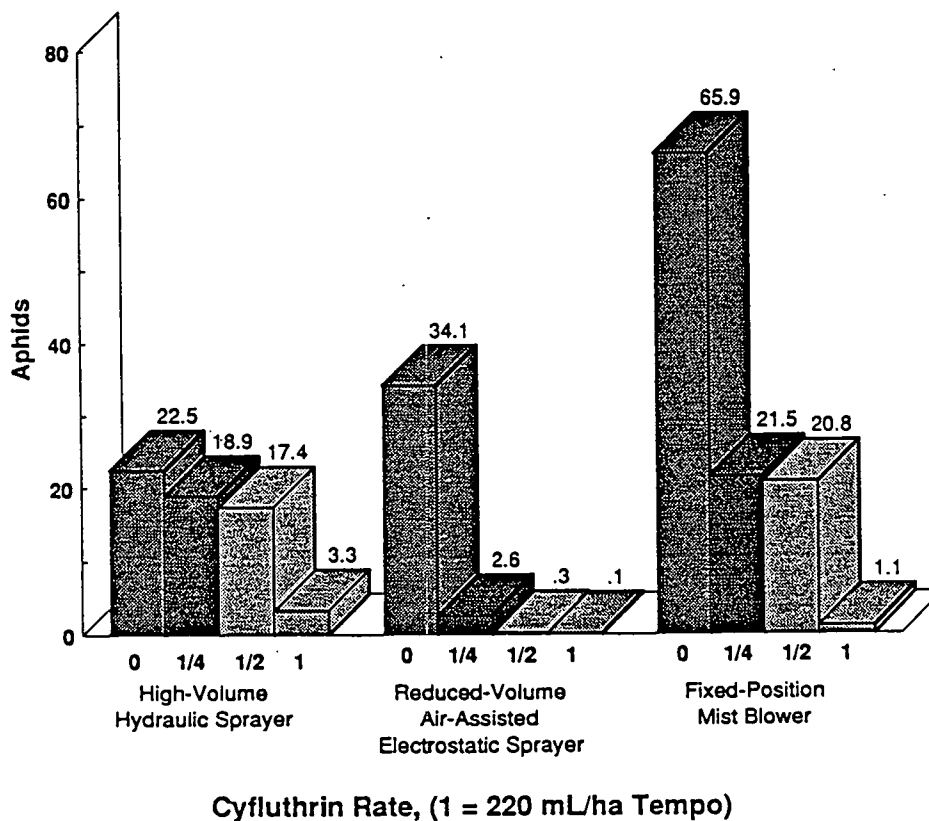


Figure A19. Effects of cyfluthrin (Tempo™ 2E) rate and spray-application method upon control of green peach aphids (*Myzus persicae*) on greenhouse marigold plants.

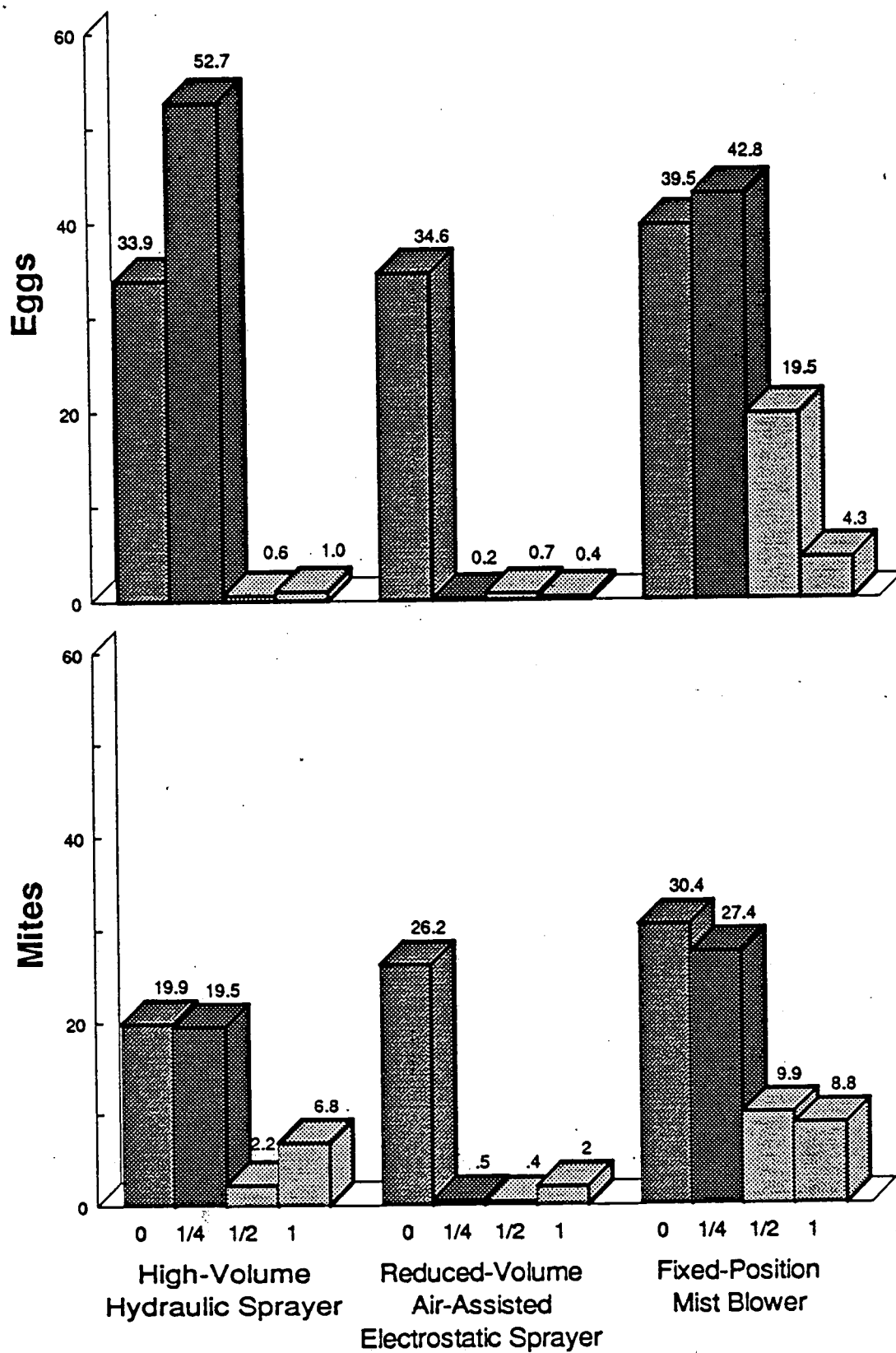


Figure A20. Effects of abamectin (Avid™ 2E) rate and spray-application method upon control of two-spotted spider mites (*Tetranychus urticae*) on greenhouse marigolds.

# **TABLES FOR SECTION IIIB**

**(R.D. Oetting)**



Table B1. Efficacy of acephate against aphids at different dilutions when applied as low volume application with the Electrostatic sprayer. Dilution equals the amount of water acephate is placed in for application on an area that would normally receive 100 gallons of spray applied at high volume.

<u>Dilution</u>	<u>Aphids per Leaf<sup>a</sup></u>		
	<u>PreCount</u>	<u>2 day</u>	<u>6 days</u>
5 gal.	260.0a	3.8a	0a
10 gal.	225.8a	0.7a	0a
20 gal.	197.8ab	0.9a	0.4a
50 gal.	179.1b	1.8a	0.2a
100 gal.	178.2b	1.3a	0a

a Means in columns followed by the same letter are not significantly different as determined by LSD ( $P \leq 0.05$ ).

Table B2. A comparison of the duration of application for a given area with low-volume electrostatic application and high-volume application with a standard hydraulic sprayer.

<u>Crop Treated</u>	<u>Mean Time in Seconds per Unit Area</u>	
	<u>Low Volume</u>	<u>High Volume</u>
<u>GA Stn/50 sq ft</u>		
Small Poinsettias	11.08	28.27
Small Poinsettias	11.31	28.25
Medium Poinsettias	18.20	66.00
Medium Poinsettias	15.50	56.40
<u>Commercial Greenhouse Bench</u>		
Small Poinsettias	30.50	166.75
Medium-Large Poinsettias	74.10	152.62

Table B3. List of bedding plants used in phytotoxicity tests with Sunspray 6E Plus oil using low volume and high volume spray equipment.

COMMON NAME	SCIENTIFIC NAME	
Aster	<u>Callistephus chinensis</u>	(Gem Mixed)
Begonia	<u>Begonia semperflorens</u>	(Rio White)
Celosia	<u>Celosia argentea plumosa</u>	(Kewpie Mix)
Egg Plant	<u>Solanum melongena</u>	(Black Beauty)
Marigold	<u>Tagetes patula</u>	(Yellow Boy)
Pepper, Bell	<u>Capsicum annuum</u>	(California Wonder)
Petunia	<u>Petunia hybrida</u>	(Light Salmon Pearls)
Pinks	<u>Dianthus chinensis</u>	(Double China)
Salvia	<u>Salvia splendens</u>	(Blaze of Fire)
Tomato	<u>Lycopersicon lycopersicum</u>	(Better Boy)

Table B4. Evaluation of phytotoxicity that could be associated with the application of Sunspray 6E Plus oil. Data were recorded as type and degree of damage following a series of 3 applications. The application rates were 1X=1%, 2X=2%, and 4X=4% of formulated oil.

Treatment: Sunspray 6E Plus High Volume

BEDDING PLANT	1X	2X	4X
Aster	I-1.0	I-2.0	D,I,T-1.0
Begonia	I,U-1.0	I,S-2.0	I,U-3.0
Celosia	M,P,T-3.0	T,U,L-4.0	D,L,U-4.0
Egg Plant	0	L,T-1.0	N,L,T-3.0
Marigold	D,C,T-3.0	D,P,B-4.0	D,L-4.0
Pepper, Bell	I-1.0	L,P-2.0	B,T,P,N-5.0
Petunia	F,X-1.0	F,N,X-2.0	F,N-3.0
Pinks	0	T-1.2	T-2.2
Salvia	P,L,F-3.0	F,I,P,L-4.0	B,F,I,L-4.0
Tomato	D,N,I-5.0	T,B,I-4.0	I,T,B-5.0

Damage Designations: B=marginal necrosis, C=marginal chlorosis, D=necrosis on leaves especially old leaves that results in leaf drop, F=flowering delayed, L=leathery leaf or blistery leaf, M=marginal chlorosis, N=twisting of new growth, P=cupping, S=leaf spotting or speckling, T=tip necrosis, U=stunting, W=wilting, X=accumulation of spray on leaf resulting in necrotic spot.

Damage Ratings: 0=no damage, 1-2=slight damage, 3-4=moderate damage, and 5-6=severe damage (death).

Table B5. Evaluation of phytotoxicity that could be associated with the application of Sunspray 6E Plus oil. Data were recorded as type and degree of damage following a series of three applications. The application rate was 1X=active ingredient equivalent of 1% high volume application, which equaled 20% LV. The 2X to 6X rates represent the number of repeat application made to that test group of plants to represent higher application rates or overdosage by grower spending excess time in applying material.

Treatment: Sunspray 6E Plus applied by Prototype electrostatic sprayer

BEDDING PLANT	Following Repeat Applications					
	1X	2X	3X	4X	5X	6X
Aster	0	0	0	0	0	0
Begonia	0	0	0	0	0	0
Celosia	T-0.8	T-1.2	T-2.0	T-3.0	T-3.2	T-3.0
Egg Plant	0	0	0	0	0	0
Marigold	0	0	0	0	0	0
Pepper, Bell	0	0	0	0	0	0
Petunia	0	0	0	0	0	0
Pinks	0	0	0	0	0	0
Salvia	0	0	0	B-3.0	F,B,I-4	F,B,I-4
Tomato	T-0.6	I-1.0	I,D,B-4	I,B,D-4	I,B-4	I,B-5

Damage Designations: B=marginal necrosis, C=marginal chlorosis, D=necrosis on leaves especially old leaves that results in leaf drop, E=leaf chlorosis, F=flowering delayed, I=interveinal chlorosis, L=leathery leaf or blistery leaf, M=marginal chlorosis, N=twisting of new growth, P=cupping, S=leaf spotting or speckling, T=tip necrosis, U=stunting, W=wilting, X=accumulation of spray on leaf resulting in necrotic spot.

Damage Ratings: 0=no damage, 1-2=slight damage, 3-4=moderate damage, and 5-6=severe damage (death).

Table B6. Abamectin efficacy against two-spotted spider mites on marigolds with high volume application (HV) and the prototype sprayer (LV) following a single application at two rates. The rate 2X equals 0.01 g/l of high volume spray equivalent and 1X equals 0.005 g equivalent. With LV 2X equals 0.01 g/50 ml and 1X equals 0.005 g/50 ml. The amount of active ingredient applied per unit area was the same for both application methods. Efficacy was determined by counting the number of eggs and mites (all stages) on the terminal seven leaflets of 2 leaves/plant and measuring the surface area of each terminal with a Li-Cor Model LI 3000 area meter. Data are reported as numbers per 10 cm<sup>2</sup>.

Two-Spotted Spider Mites/10 cm <sup>2</sup>						
Treatment (rate)	No. Eggs			No. Mites		
	3 days	7 days	28 days	3 days	7 days	28 days
HV (2X)	8.5	12.0	5.2	14.3	7.5	0.5
HV (1X)	18.3	16.8	4.6	16.9	9.3	0.4
LV (2X)	7.8	1.7	22.1	18.8	0.6	5.3
LV (1X)	1.0	22.8	17.8	10.4	12.7	3.0
Water HV	38.7	31.8	59.6	48.0	40.0	22.3

Table B7. Abamectin efficacy against western flower thrips on marigolds with high volume application (HV) and the prototype sprayer (LV) following a single application at two rates. The rate 2X equals 0.01 g/l of high volume spray equivalent and 1X equals 0.005 g equivalent. The amount of active ingredient applied per unit area was the same for both application methods. The following table summarizes two experiments, the first on flowering plants where efficacy against thrips was determined by removing 10 flowers from each treatment and placing them in a Berlese funnel to extract immature thrips. The second experiment was with non-flowering plants and efficacy was determined by sacrificing the plant and placing it in the Berlese funnel.

Western Flower Thrips/Flower or Plant

Treatment (rate)	<u>Immature Thrips/Flower</u>		<u>Thrips/Plant</u>	
	3 days	7 days	Immatures	Adults
HV (2X)	14.6 b	3.4 b	33.5 b	17.6 b
HV (1X)	16.5 b	4.8 b	32.4 b	16.4 b
LV (2X)	11.6 b	6.0 b	12.1 c	6.5 c
LV (1X)	17.3 b	6.4 b	12.5 c	9.6 c
Water HV	43.4 a	12.3 a	109.5 a	27.1 a

1 Means followed by the same letter are not significantly different, (LSD using PROC GLM -  $P \leq 0.05$ ).

Table B8. Abamectin efficacy against green peach aphids on chrysanthemums following three applications at two rates with high volume application (HV), the prototype sprayer (LV), and cold fog application from a fixed position (FP). The three applications were made at 7 day intervals. The rate 2X equals 0.01 g/l of high volume spray equivalent and 1X equals 0.005 g equivalent. Efficacy was determined by counting the number of aphids on the underside of 2 leaves per plant (4 reps.) 3 days after the initial application. A final population evaluation was made 28 days after the initial application by removing the terminal and placing it in a Berlese funnel for extration of aphids. Data are reported as numbers per leaf or terminal (stem).

Number of Green Peach Aphids<sup>a</sup>

Treatment (rate)	Aphids/Leaf 3 days	Aphids/stem 28 days
HV (2X)	58.3 a	15.3 ab
HV (1X)	107.5 b	51.8 b
LV (2X)	41.0 a	9.2 a
LV (1X)	191.0 c	4.6 a
PulseFog (2X)	127.3 b	209.7 c
Water HV	110.0 b	289.9 d

a Means in columns followed by the same letter are not significantly different (LSD using PROC GLM -  $p \leq 0.05$ ).

Table B9. Efficacy of cyfluthrin against green peach aphid on chrysanthemums with a single application using four rates: 0 active ingredient,  $\frac{1}{4}$  normal rate,  $\frac{1}{2}$  normal rate, and normal label rate. The rate given in the table was the volume of formulated insecticide needed to treat 10 m<sup>2</sup> of crop. Efficacy was determined by counting the aphids on two leaf terminals per plant before treatment and on day 4, 7, and 11 following application. Data are presented as mean aphids per terminal.

Cyfluthrin 2EC	aphids per terminal <sup>a</sup>			
	Pretreat	4 days	8 days	12 days
High Volume Hydraulic Sprayer				
0.0 ml	43.5 a	18.6 ab	18.9 a	46.5 a
0.06 ml	33.6 a	33.3 a	25.5 a	49.6 a
0.11 ml	50.5 a	17.1 ab	17.4 a	32.0 a
0.22 ml	28.6 a	3.9 b	3.3 b	7.0 b
Electrostatic Low Volume Sprayer				
0.0 ml	25.9 a	20.4 a	34.1 a	40.3 a
0.06 ml	68.8 b	0.8 b	2.6 b	0.6 b
0.11 ml	38.4 ab	0.5 b	0.3 b	0.3 b
0.22 ml	36.9 ab	1.1 b	0.1 b	0.1 b
Fixed Position Mist Blower				
0.0 ml	47.6 a	54.6 a	65.9 a	67.1 a
0.06 ml	59.9 a	10.5 b	21.5 b	19.1 b
0.11 ml	49.8 a	13.6 b	20.8 b	19.5 b
0.22 ml	51.3 a	0.3 c	1.1 c	2.3 c

a Means in columns for each spray technique followed by the same letter are not significantly different (LSD using PROC GLM -  $P \leq 0.10$ ).



Talbe B10. Efficacy of abamectin against two-spotted spider mite on marigolds with a single application using four rates: 0 active ingredient,  $\frac{1}{4}$  normal rate,  $\frac{1}{2}$  normal rate, and normal label rate. The rate given in the table was the volume of formulated insecticide needed to treat 10 m<sup>2</sup> of crop. Efficacy was determined by counting the number of mites and eggs on two leaf terminals of 7 leaflets on 6 plants per plot (5 reps). Data are presented as mean mites per leaf terminal.

abamectin 0.15EC	<u>pretreat</u>		mites/eggs per leaf <sup>a</sup>							
	mites eggs		<u>4 days</u>		<u>8 days</u>		<u>12 days</u>			
			mites	eggs	mites	eggs	mites	eggs	mites	eggs
High Volume Hydraulic Sprayer										
0.0 ml	47.0	73.8	73.8a	44.3a	19.5a	52.7a	31.6a	38.1a		
0.11 ml	34.3	63.9	20.7b	32.4a	19.9a	33.9b	47.6a	37.9a		
0.21 ml	25.5	34.9	4.0c	4.3b	2.2b	0.6c	2.4b	3.5b		
0.42 ml	30.2	67.7	2.0c	1.9b	6.8b	1.0c	5.3b	8.6b		
Electrostatic Low Volume Sprayer										
0.0 ml	28.8	101.1	28.1a	35.5a	26.2a	34.6a	28.6a	21.1a		
0.11 ml	39.9	77.1	5.3b	7.1b	0.5b	0.2b	0.7b	1.0b		
0.21 ml	42.5	90.2	0.6b	1.0b	0.4b	0.7b	0.2b	0.2b		
0.42 ml	27.4	57.4	0.3b	1.6b	2.0b	0.4b	1.0b	0.4b		

a Means in columns for each spray technique followed by the same letter are not significantly different (LSD using PROC GLM - P≤0.10)

Table B11. Efficacy of acephate and fenpropathrin against sweetpotato whitefly on poinsettias following 3 applications at 7 day intervals. Four rates were applied: 0 active ingredient (AI),  $\frac{1}{4}$  normal rate,  $\frac{1}{2}$  normal rate, and normal label rate. The rate given in the table is the volume of formulated insecticide needed to treat 10 m<sup>2</sup> of crop. Efficacy was determined by counting the number of whitefly immatures and eggs on the lower surface of leaves on day 14 following the final application and the data are presented as mean population per leaf.

acephate 75S + fenpropathrin 2.4EC	whiteflies/leaf <sup>a</sup>	
	eggs	immatures
High Volume Hydraulic Sprayer		
0.0 g + 0.0 ml	18.6 a	74.0 a
0.27 g + 0.2 ml	11.6 ab	37.2 b
0.54 g + 0.41 ml	0.2 b	0 c
1.09 g + 0.82 ml	4.6 b	4.6 c
Electrostatic Low Volume Sprayer		
0.0 g + 0.0 ml	23.4 a	51.6 a
0.27 g + 0.2 ml	26.0 a	16.4 b
0.54 g + 0.41 ml	11.6 b	6.4 b
1.09 g + 0.82 ml	8.0 b	8.6 b
fixed Position Mist Blower		
0.0 g + 0.0 ml	26.8 a	58.8 a
0.27 g + 0.2 ml	25.0 a	40.0 a
0.54 g + 0.41 ml	21.2 a	9.8 b
1.09 g + 0.82 ml	14.0 a	13.4 b

a Means in columns for each spray technique followed by the same letter are not significantly different (LSD using PROC GLM -  $P \leq 0.10$ ).

**FIGURES AND TABLES FOR SECTION IIIC**  
**(S. Gan-Mor)**

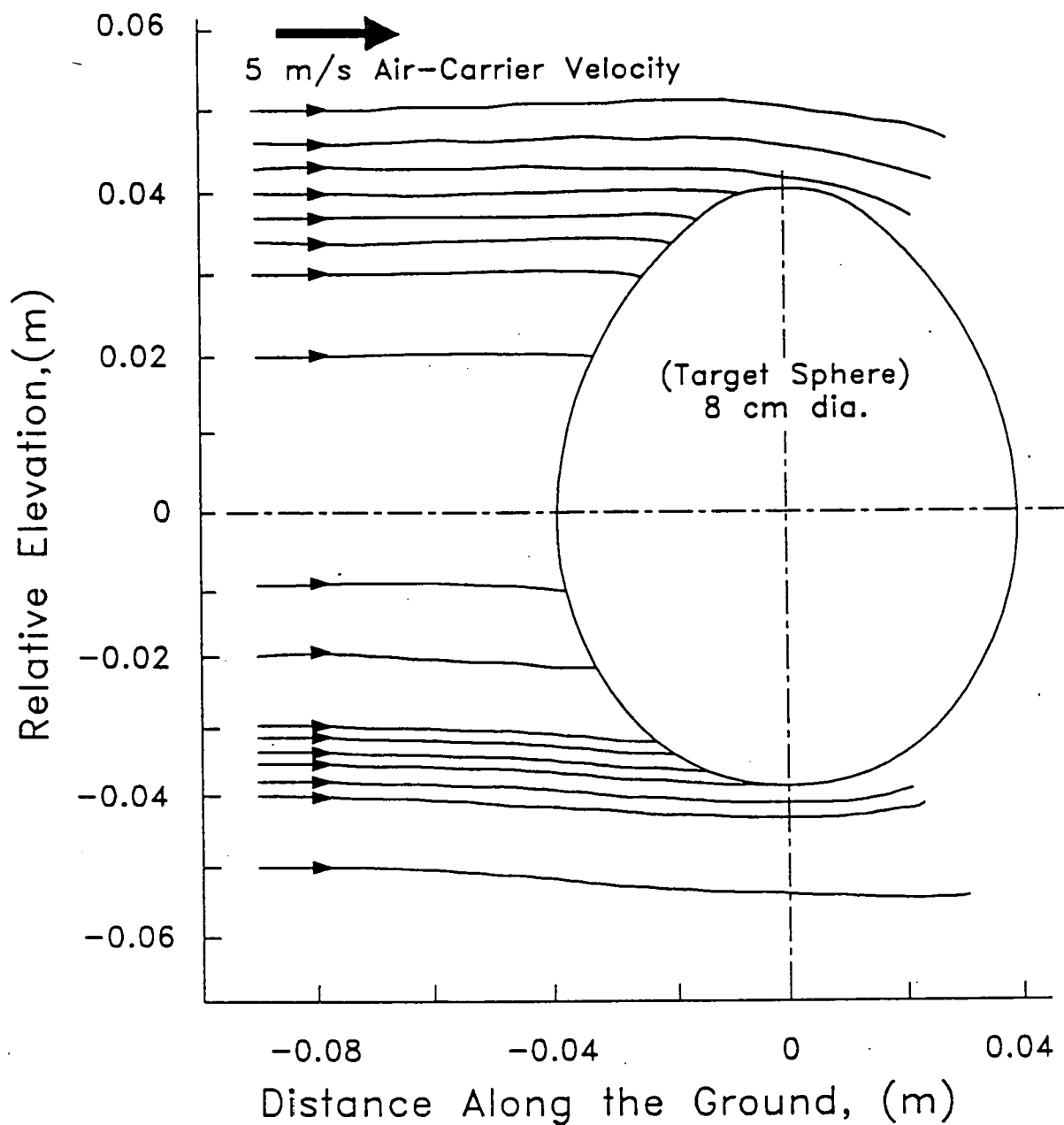


Figure C1. Simulated trajectories of charged  $130\text{ }\mu\text{m}$  particulates initiated at different heights relative to the horizontal central plane of a spherical target subjected to a uniform air-carrier stream. (Particulate charge-to-mass ratio= $1\text{ mC/kg}$ ; spray cloud space-charge density= $3.1\text{ }\mu\text{C/m}^3$ .)

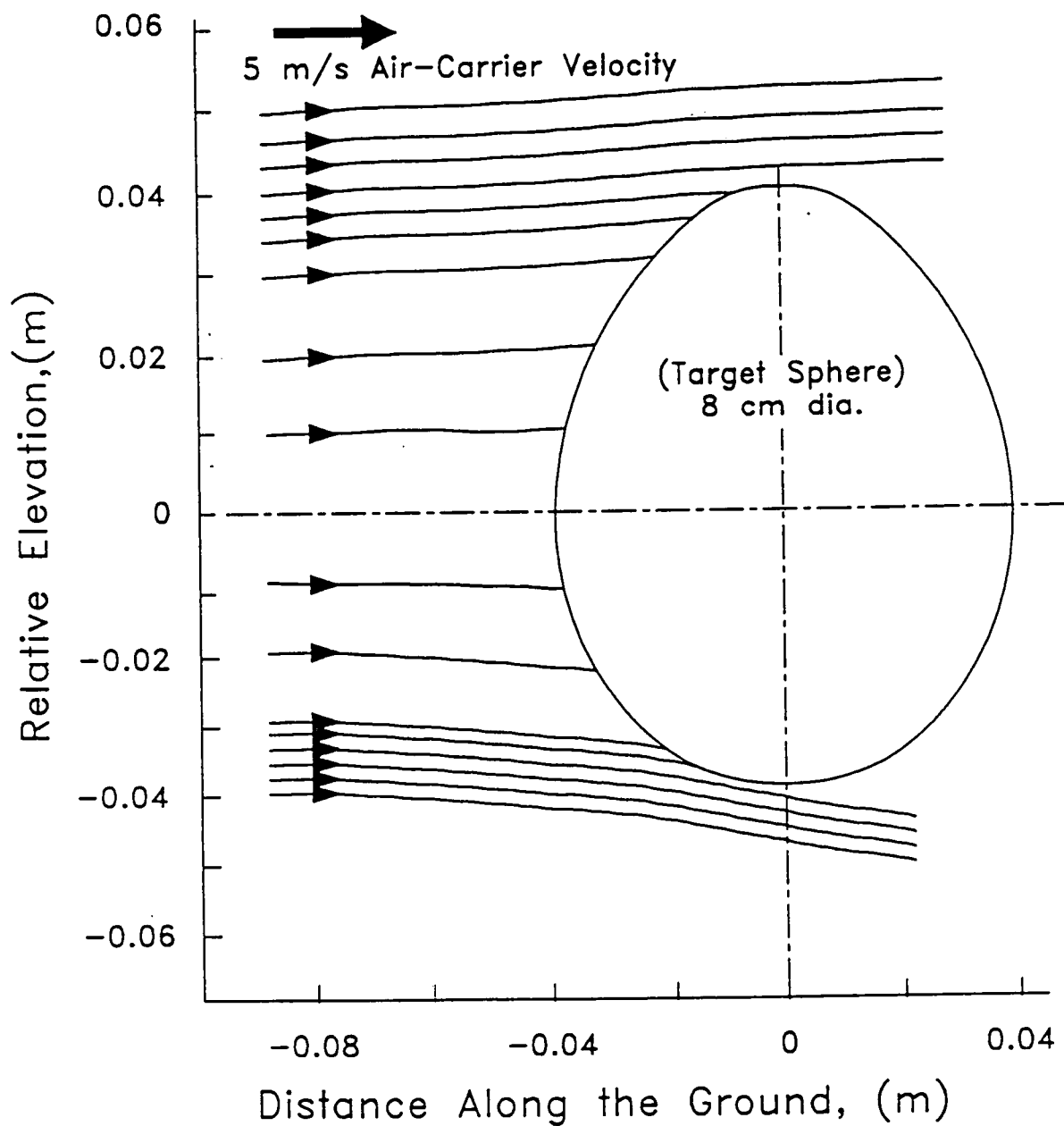


Figure C2. Simulated trajectories of uncharged  $130\ \mu\text{m}$  particulates initiated at different heights relative to the horizontal central plane of a spherical target subjected to a uniform air-carrier stream.

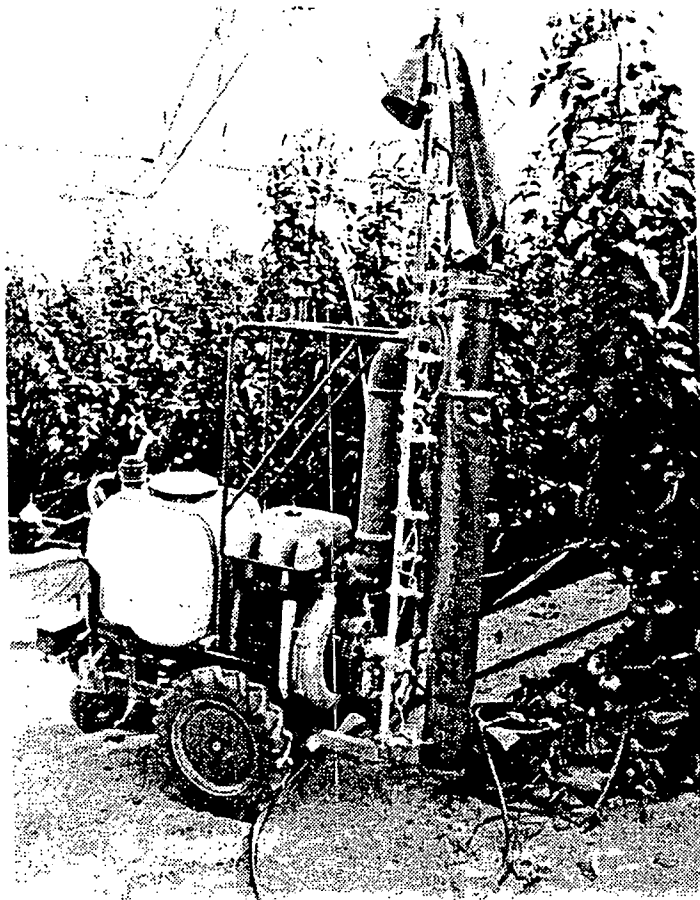


Fig. C3. The system for automatic guidance of greenhouse sprayer on a steel rail.

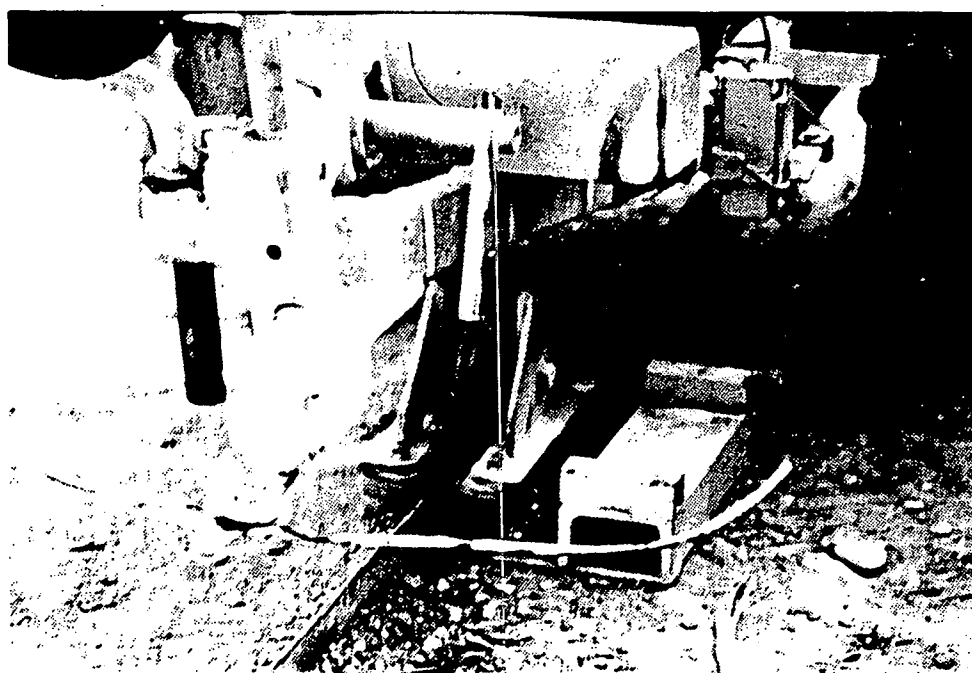


Fig. C4. Modification of outdoor commercial sprayer to operate in tomato greenhouse utilizing automatic guidance by steel rail.

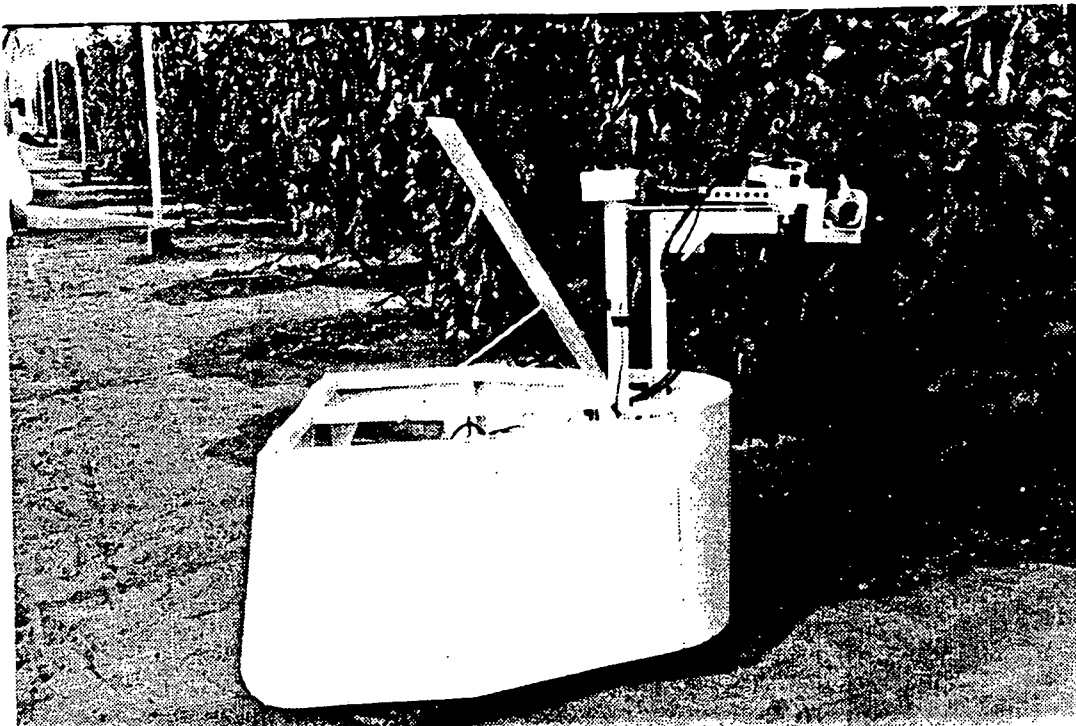


Fig. C5. Ultrasonic sensors mounted on each side of the test vehicle steering pole for measurement of the distance to the canopy.

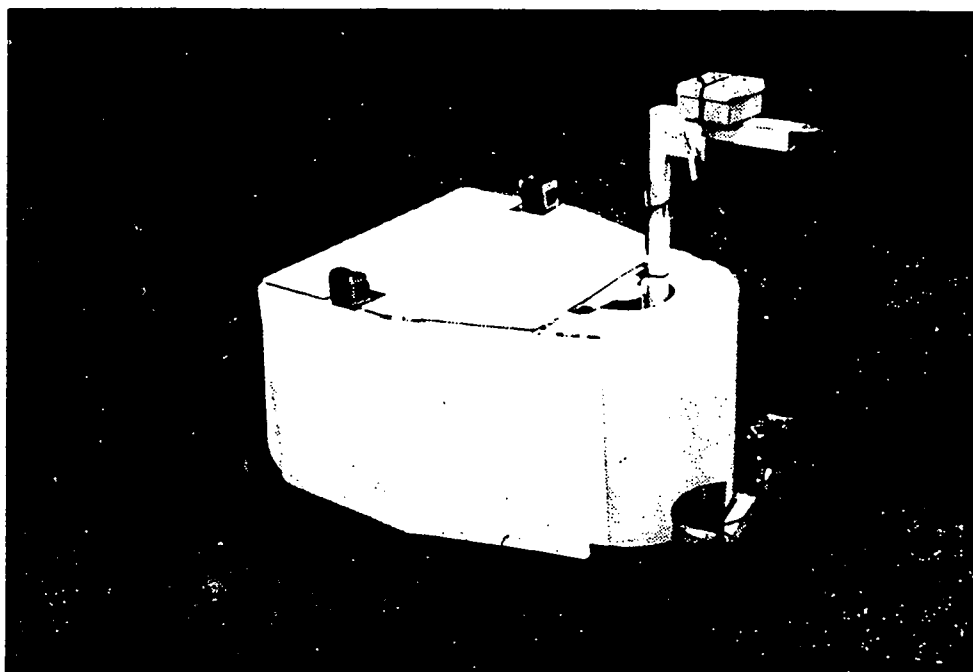


Fig. C6. Electromagnetic sensors mounted in front of the vehicle to measure the distance to the wires in the canopy bottom.

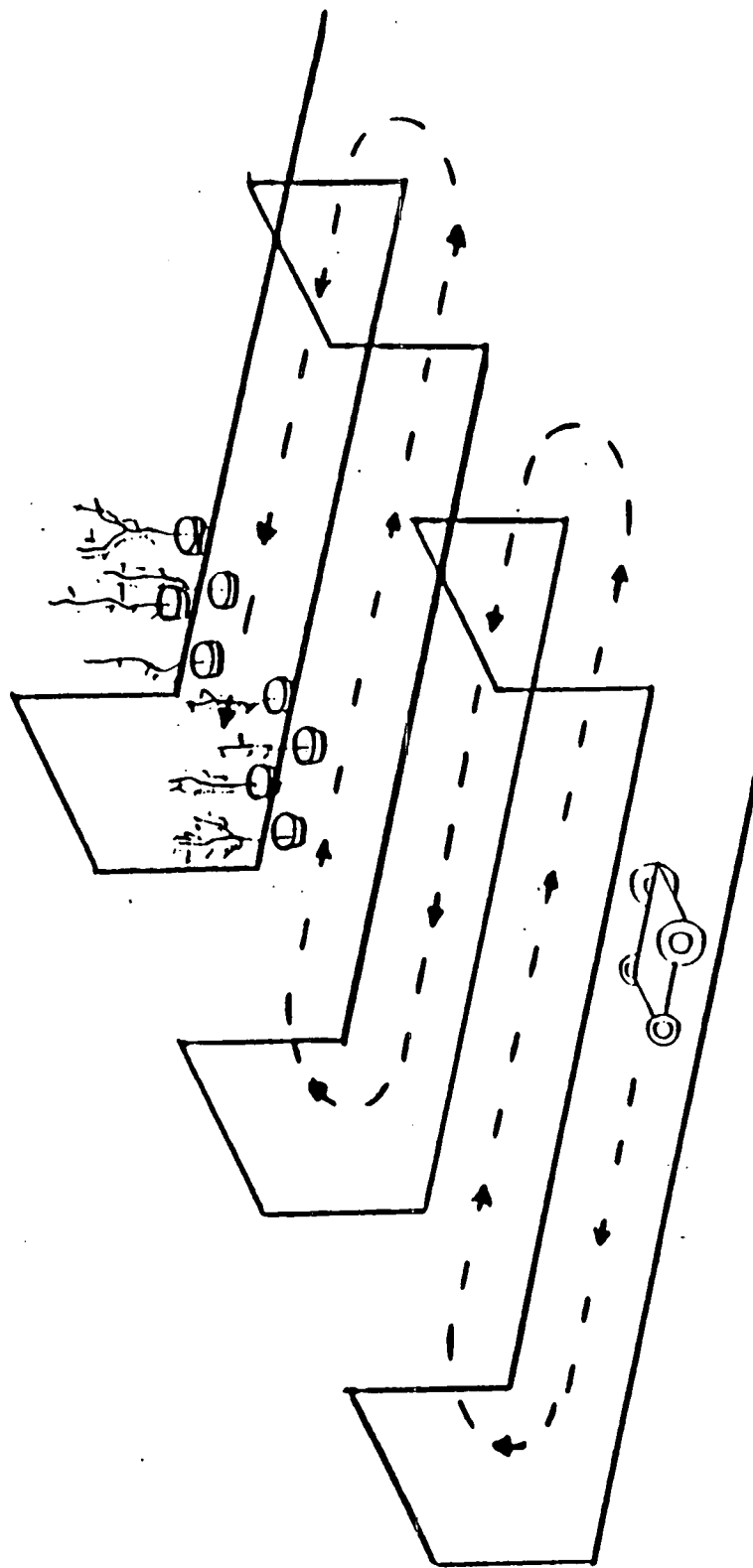


Fig. C7. Schematic description of the transmitting wires arrangement along the rows and at its end.



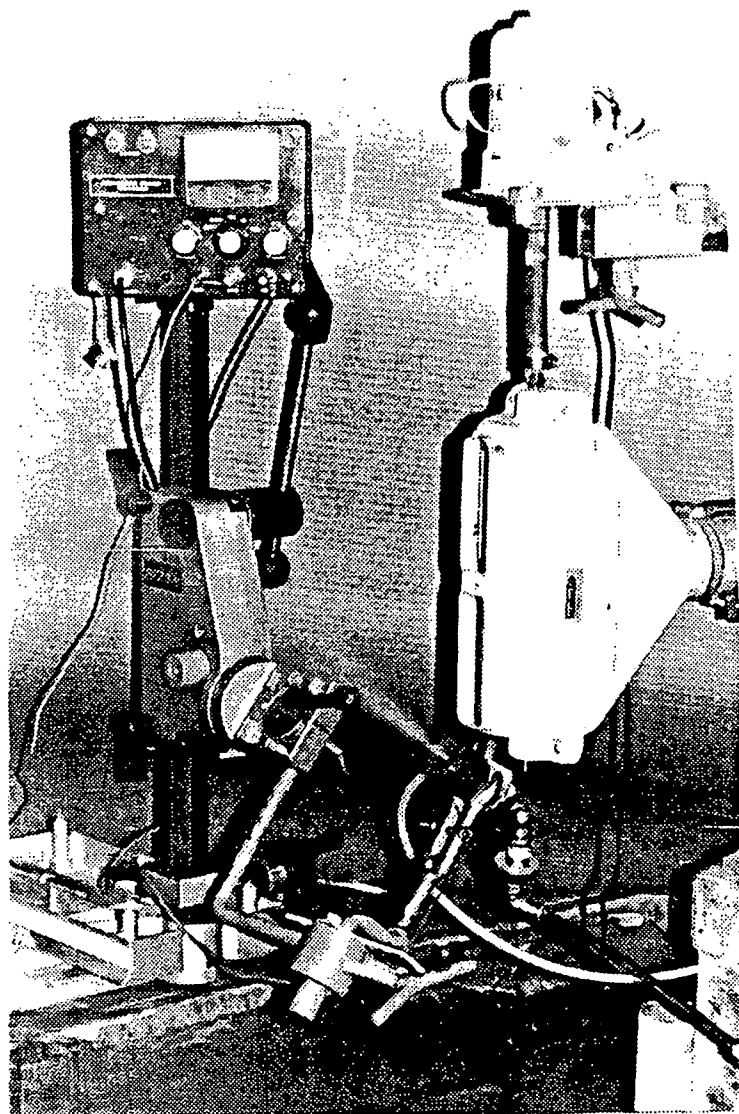


Fig. C8. The air pulsator, the electrostatic nozzle and the 5 degrees of freedom table for determining the nozzle location.

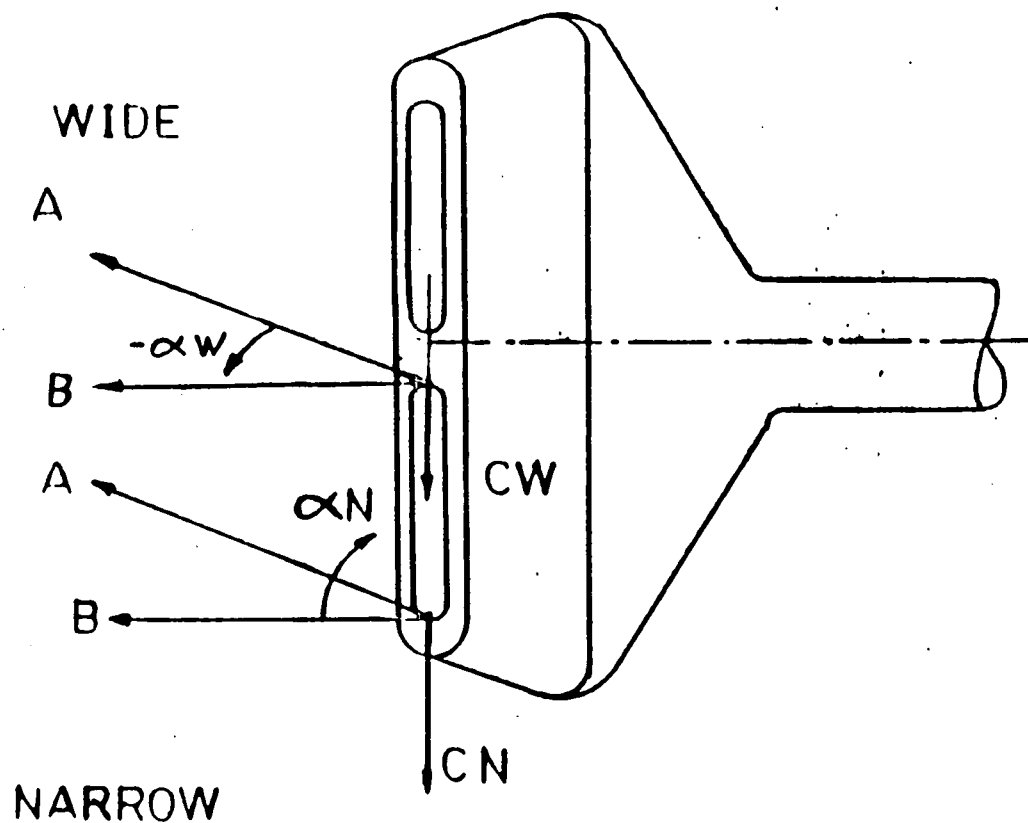


Fig. C 9. The directions of the scales of the parameters influencing the deposition densities shown in tables 1 and 2.

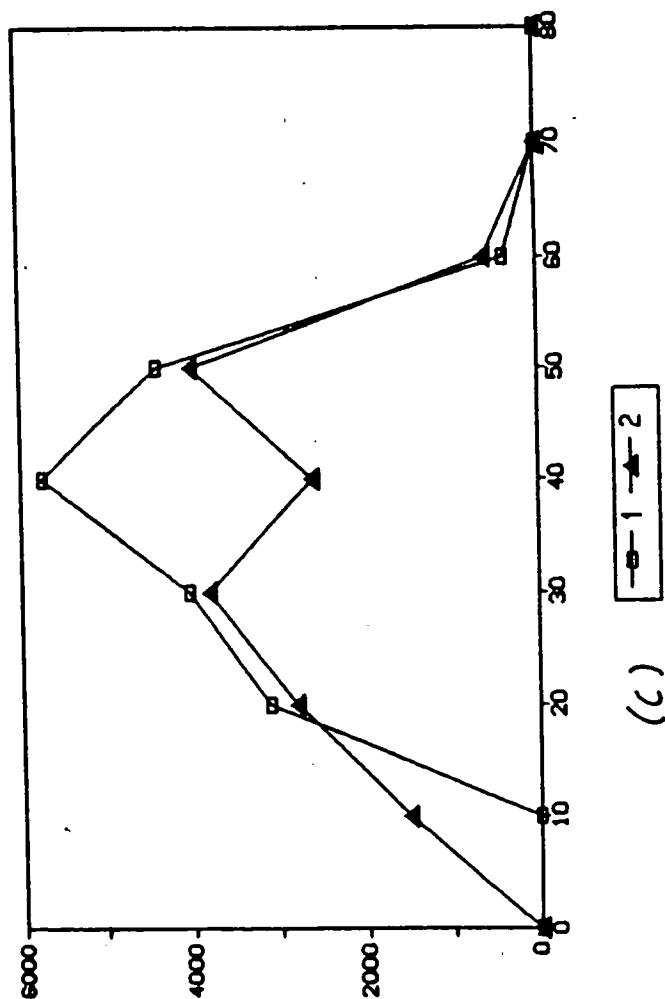
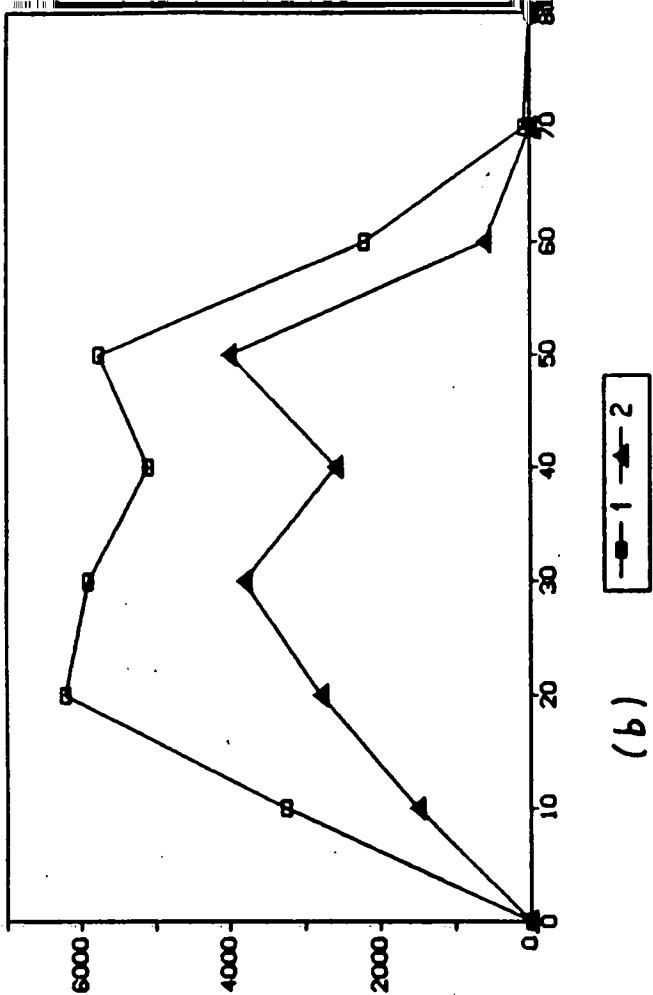
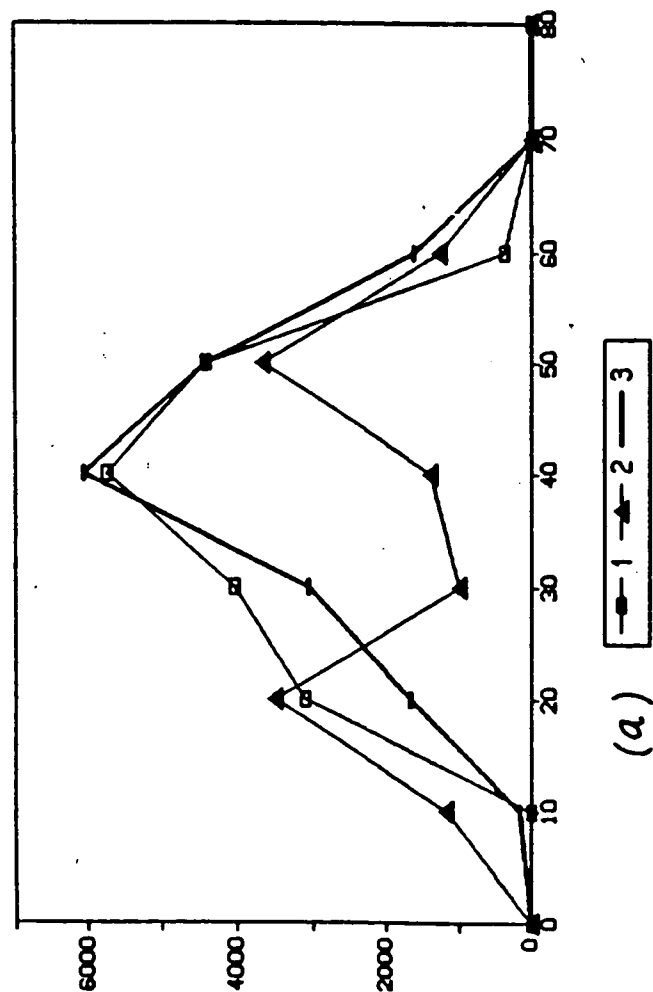


Fig. C10. Deposition density of the droplets as shown in table 2: (a) 1 - average for treatment # 111 and 112, 2 - average for treatment # 104 and 105, and 3 - average for treatment # 106 and 107, (b) 1 - average for treatment # 121 and 122, and 2 - average for treatment # 123 and 124, and (c) 1 - average for treatment # 106 and 107, and 2 - average for treatment # 123 and 124.

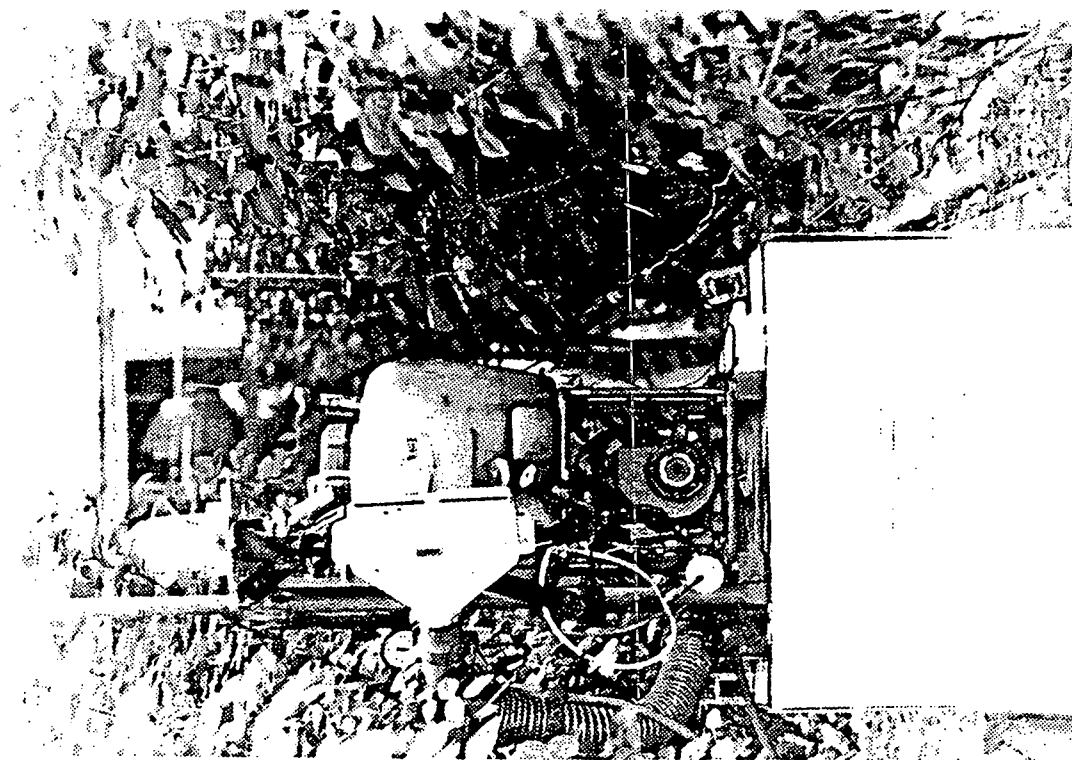
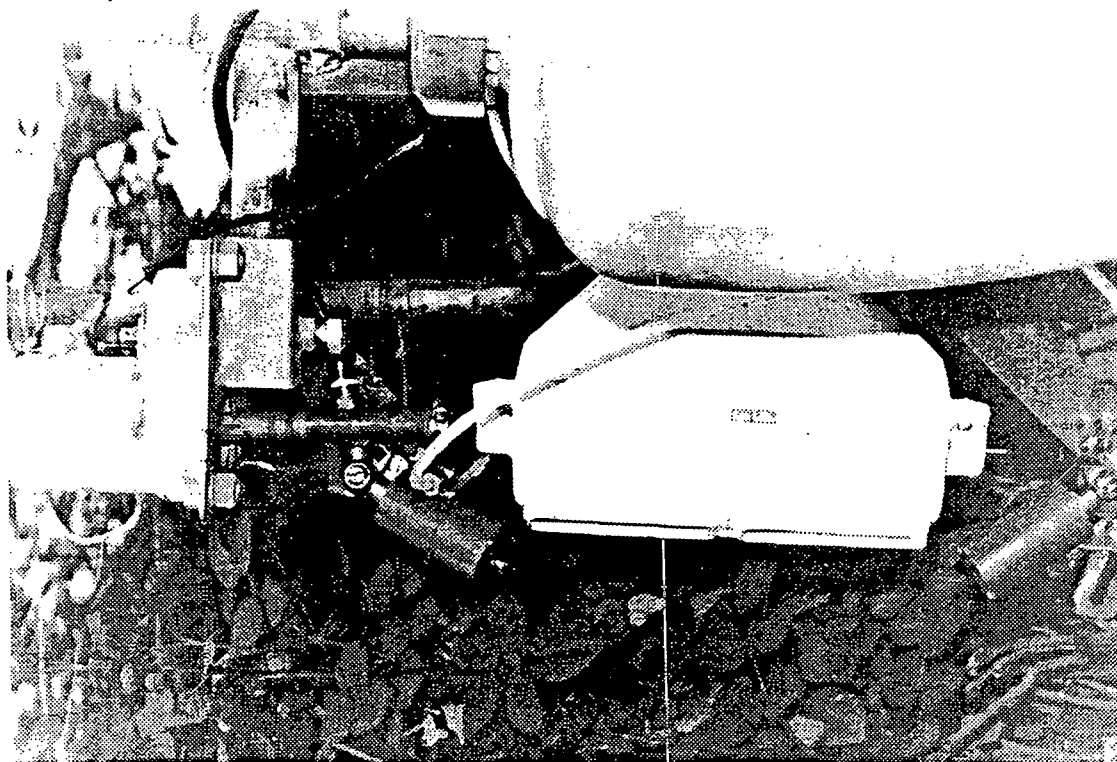


Fig. c11. The experimental system arrangement for the greenhouse tests.

Table D1. The parameters influencing the density of spray droplet deposition - Conjet x2 nozzle.

Test No.	Scale Coordinate		C	Pulse Freq. [R.P.M.]	Nozzle Location [Deg.]	Alfa	No. of Nozzles	Spray Deposit (along axis)		Density spray	[drops/sqr. cm]					
	A	B						10	20		30	40	50	60	70	80
1	0	15	30	420	narrow	40	1	30	120	500	7000	7000	900	270	30	0
2	0	15	30	420	narrow	40	1	40	160	270	7000	7000	7000	200	10	0
3	5	2	8	420	wide	40	1	0	70	300	7000	7000	7000	220	30	10
4	5	2	8	420	wide	40	1	0	220	300	500	7000	7000	530	50	0
5	5	2	10	420	wide	40	1	0	170	340	700	7000	7000	440	40	0
6	5	2	10	420	wide	40	1	0	70	200	500	7000	7000	600	60	0
7	5	2	6	420	wide	40	1	0	110	220	650	7000	640	120	30	0
8	5	2	6	420	wide	40	1	0	200	700	7000	7000	450	220	10	0
9	5	2	8	0	wide	40	1	0	40	40	500	7000	7000	660	50	0
10	5	2	8	0	wide	40	1	0	50	30	7000	7000	7000	600	60	0
11	5	2	8	200	wide	40	1	0	80	400	740	7000	500	280	40	0
12	5	2	8	800	wide	40	1	80	200	240	720	7000	7000	270	50	0
13	5	2	8	420	wide	40	2	7000	7000	1000	7000	7000	700	100	0	0
14	5	2	8	420	wide	40	2	7000	7000	900	1000	7000	800	200	0	0
15	5	2	6	420	wide	40	2	1000	7000	800	740	7000	700	200	0	0
16	5	15	6	420	wide	40	2	7000	7000	1000	1200	7000	700	500	0	0
17	0	15	30	420	narrow	35	2	1000	1200	1000	700	7000	800	120	0	0
18	0	15	30	420	narrow	35	2	580	1200	650	550	7000	650	60	0	0
19	0	15	30	420	narrow	35	2	1000	1200	1000	700	7000	800	120	0	0
20	0	15	30	420	narrow	35	2	580	1200	650	550	7000	650	60	0	0
21	0	15	30	420	narrow	60	2	500	600	450	400	720	700	60	0	0
22	0	15	30	420	narrow	60	2	800	900	500	420	650	420	60	0	0

Table D2.. The parameters influencing the density of spray droplet deposition - electrostatic nozzle.

Test No.	Scale	Coordinate	C	Pulse Freq. [R.P.M.]	Nozzle Location [Deg.]	Alfa	No. of Nozzles	Spray Deposit (along spray axis)	Density [drops/sqr. cm]	[cm]	40	50	60	70
101	5	2	8	420	wide	40	1	0	0	1200	7000	7000	7000	0
102	5	2	8	420	wide	40	1	0	0	0	2600	7000	7000	1200
103	5	2	8	420	wide	40	2	7000	7000	1800	7000	7000	1300	200
104	5	2	6	420	wide	40	2	350	2000	800	3200	3200	400	0
105	5	2	6	420	wide	40	2	2000	5000	1200	4100	4100	2100	0
106	5	2	4	420	wide	40	2	320	1100	3600	4400	4400	400	0
107	5	2	4	420	wide	40	2	0	2200	2500	7000	4400	2800	0
108	5	2	5	420	wide	40	2	1080	3900	1200	4800	4700	2000	0
109	5	2	5	420	wide	40	2	500	2800	3300	7000	7000	1840	0
110	5	0	5	420	wide	40	2	840	4300	2800	6000	7000	300	0
111	5	0	5	420	wide	40	2	500	2600	1960	3120	4500	1120	0
112	5	0	4	420	wide	40	2	0	3600	2500	3200	4500	300	0
113	5	0	4	420	wide	40	2	0	2800	5200	7000	6000	400	0
114	5	-1	4	420	wide	40	2	0	1040	2060	5700	5000	400	0
115	5	-1	4	420	wide	40	2	0	2640	3160	7000	3900	450	0
116	5	0	4	420	wide	40	2	0	2900	4400	7000	2700	400	0
117	0	15	30	420	narro	45	1	0	0	3200	7000	7000	3600	0
118	0	15	30	420	narro	45	1	0	0	1000	4400	7000	3000	0
119	0	15	30	420	narro	60	1	0	30	2300	7000	7000	4000	0
120	0	15	30	420	narro	60	1	0	700	2400	7000	7000	4000	0
121	0	15	30	420	narro	60	2	3300	7000	7000	7000	7000	2800	40
122	0	15	30	420	narro	60	2	3200	5400	4800	3200	4500	1600	130
123	0	15	30	420	narro	40	2	1200	2800	3600	2400	4000	300	0
124	0	15	30	420	narro	40	2	1800	2800	4000	2800	4000	890	0

Table D3. Spray droplet density in dense canopy of rose leaves - With Electrostatic Charging for two vehicle speeds.

Treatment	1(P)	a=upper side of the leaf	b=lower side of the leaf
Speed, km/h	1		
Applied vol., l/d	420		
Pulse, no/min	+		
Charge			

Area covered (%)						Droplets density (no/cm <sup>2</sup> )					
Middle a	Location 1		Location 2		Location 3	a	Location 1		Location 2		Locati
REPLI.	I	II	I	II	I II	REPL.	I	II	I	II	I II
Average	100.0	100.0	100.0	100.0	100.0	Average	3600.0	1680.0	396.0	268.0	140.0
SD	0.0	0.0	0.0	0.0	0.0	SD	0.0	960.0	128.0	156.8	0.0
CV (%)	0.0	0.0	0.0	0.0	0.0	CV (%)	0.0	57.1	32.3	58.5	0.0

Middle b	Location 1		Location 2		Location 3	b	Location 1		Location 2		Locati
REPLICAT	I	II	I	II	I II	REPLI.	I	II	I	II	I II
Average	100.0	100.0	90.0	95.0	55.0	Average	904.0	332.0	140.0	204.0	84.0
SD	0.0	0.0	12.2	10.0	10.0	SD	362.5	156.8	0.0	128.0	0.0
CV (%)	0.0	0.0	13.6	10.5	18.2	CV (%)	40.1	47.2	0.0	62.7	0.0

[illegible]

Table D4. Spray droplet density in dense canopy of rose leaves -  
With No Electrostatic Charging for two vehicle speeds.

Treatment 3 (O)  
Speed, km/h 1  
Applied vol., l/d 420  
Pulse, no/min -  
Charge -

Area covered (%)

Middle a	Location 1		Location 2		Location 3	
	I	II	I	II	I	II
REPLI.	100.0	100.0	100.0	100.0	90.0	100.0
Average	0.0	0.0	0.0	0.0	20.0	0.0
SD	0.0	0.0	0.0	0.0	22.2	0.0
CV (%)	0.0	0.0	0.0	0.0	22.2	0.0

Middle b	Location 1		Location 2		Location 3	
	I	II	I	II	I	II
REPLI.	100.0	100.0	95.0	75.0	30.0	55.0
Average	0.0	0.0	10.0	31.6	18.7	24.5
SD	0.0	0.0	10.5	42.2	62.4	44.5
CV (%)	0.0	0.0	10.5	42.2	62.4	44.5

Treatment 4 (N)  
Speed, km/h 2  
Applied vol., l/d 420  
Pulse, no/min -  
Charge -

Area covered (%)

Middle a	Location 1		Location 2		Location 3	
	I	II	I	II	I	II
REPLI.	100.0	100.0	95.0	100.0	90.0	100.0
Average	0.0	0.0	10.0	0.0	20.0	0.0
SD	0.0	0.0	10.5	0.0	22.2	0.0
CV (%)	0.0	0.0	10.5	0.0	22.2	0.0

Middle b	Location 1		Location 2		Location 3	
	I	II	I	II	I	II
REPLI.	100.0	95.0	80.0	95.0	35.0	30.0
Average	0.0	10.0	24.5	10.0	25.5	29.2
SD	0.0	10.5	30.6	10.5	72.8	97.2
CV (%)	0.0	10.5	30.6	10.5	72.8	97.2

Droplets density (no/cm<sup>2</sup>)

a	Location 1		Location 2		Location 3	
	I	II	I	II	I	II
REPLI.	3600.0	756.0	756.0	904.0	140.0	204.0
Average	0.0	362.5	362.5	362.5	0.0	128.0
SD	0.0	48.0	48.0	40.1	0.0	62.7
CV (%)	0.0	48.0	48.0	40.1	0.0	62.7

b	Location 1		Location 2		Location 3	
	I	II	I	II	I	II
REPLI.	904.0	396.0	416.0	204.0	112.0	84.0
Average	362.5	128.0	411.1	128.0	56.0	68.6
SD	40.1	32.3	98.8	62.7	50.0	81.6
CV (%)	40.1	32.3	98.8	62.7	50.0	81.6

Droplets density (no/cm<sup>2</sup>)

	Location 1		Location 2		Location 3	
	I	II	I	II	I	II
REPLI.	2640.0	3600.0	480.0	756.0	480.0	396.0
Average	1175.8	0.0	387.4	362.5	387.4	128.0
SD	44.5	0.0	80.7	48.0	80.7	32.3
CV (%)	44.5	0.0	80.7	48.0	80.7	32.3

b	Location 1		Location 2		Location 3	
	I	II	I	II	I	II
REPLI.	480.0	1200.0	268.0	204.0	140.0	140.0
Average	387.4	0.0	156.8	128.0	0.0	0.0
SD	80.7	0.0	58.5	62.7	0.0	0.0
CV (%)	80.7	0.0	58.5	62.7	0.0	0.0



**FIGURES AND TABLES FOR SECTION IIID**  
**(G. Manor)**

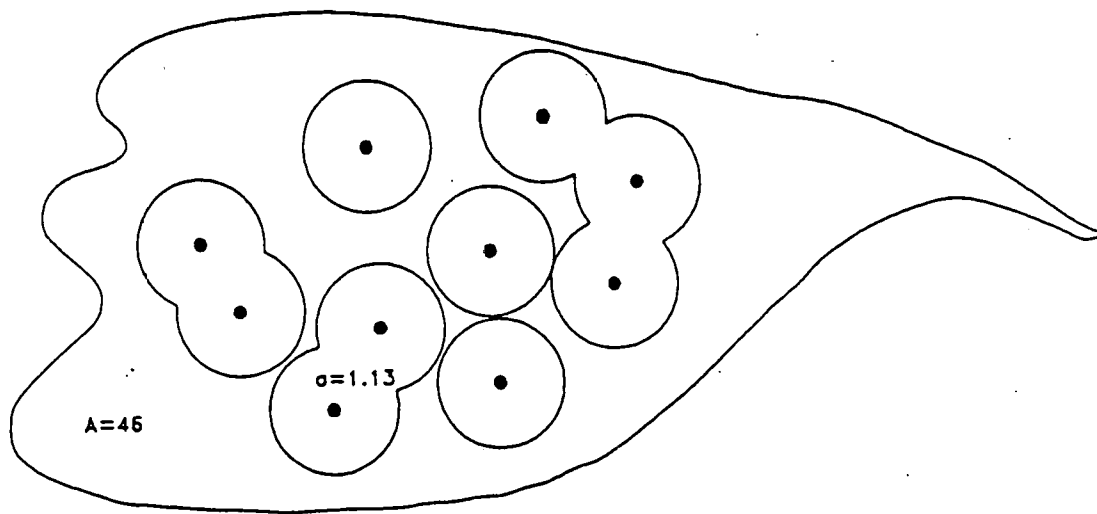


Figure D1. A leaf with deposited droplets and the area they effectively cover with their 22 mm diameter circles.

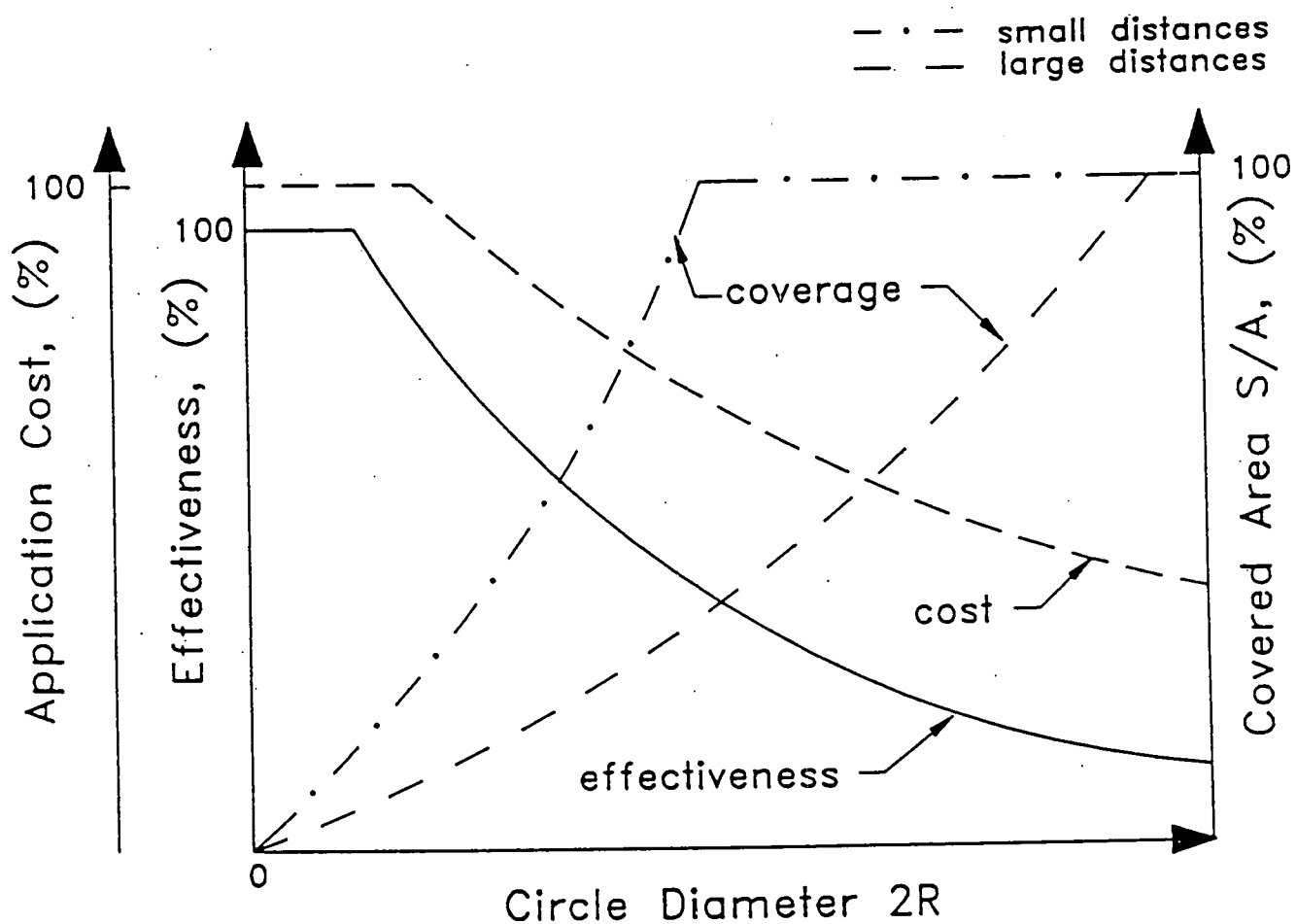


Figure D2. The relationship between the diameter of the control circles around the pesticide droplets, the area of the leaf covered by them, the effectiveness of the chemical applied, and the application cost.

# MAX. JET VELOCITY VS SPRAYER SPEED

distances are measured in diameters.

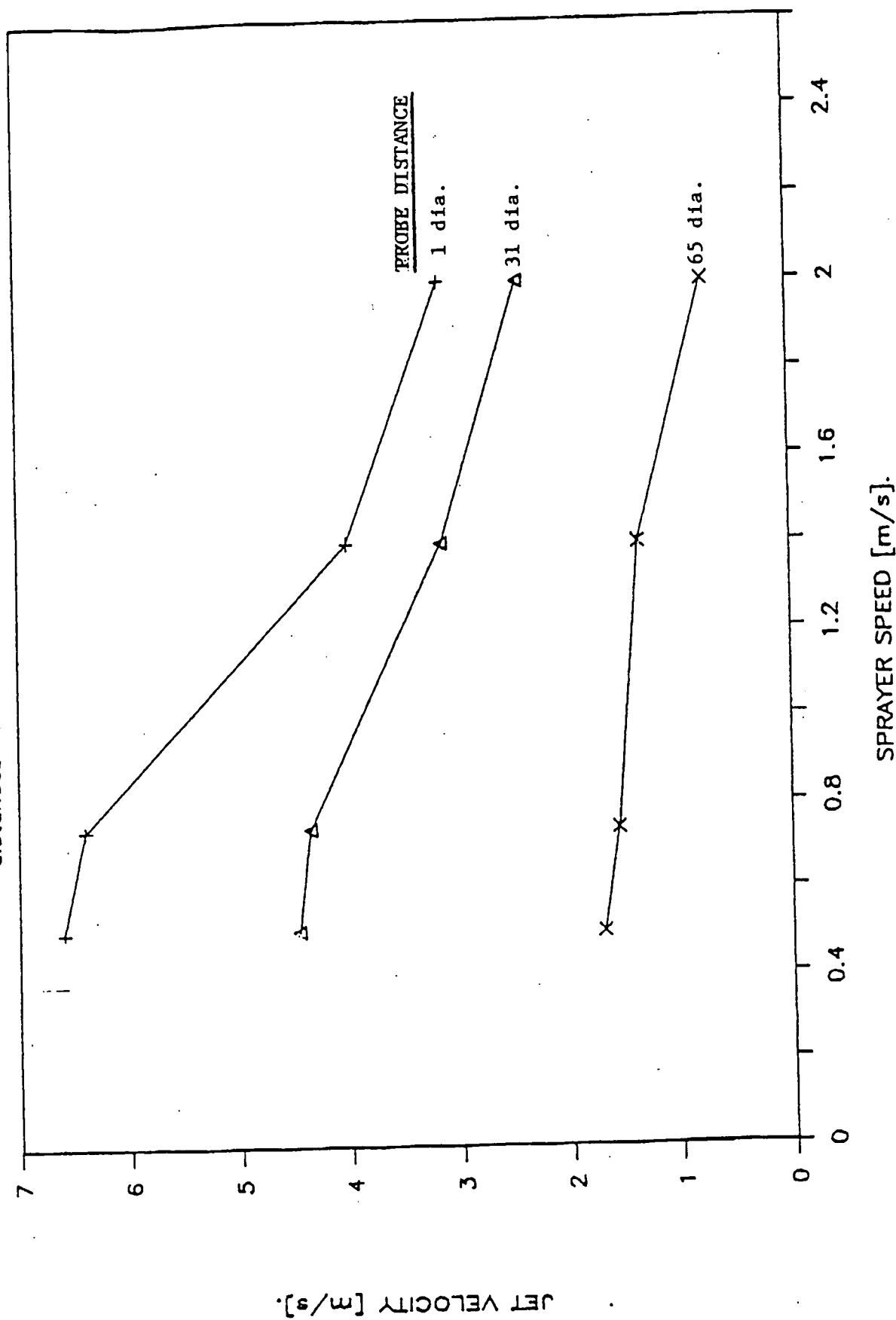


Figure D3. Air-jet velocity as a function of sprayer travel speed for three nozzle-to-probe distances.

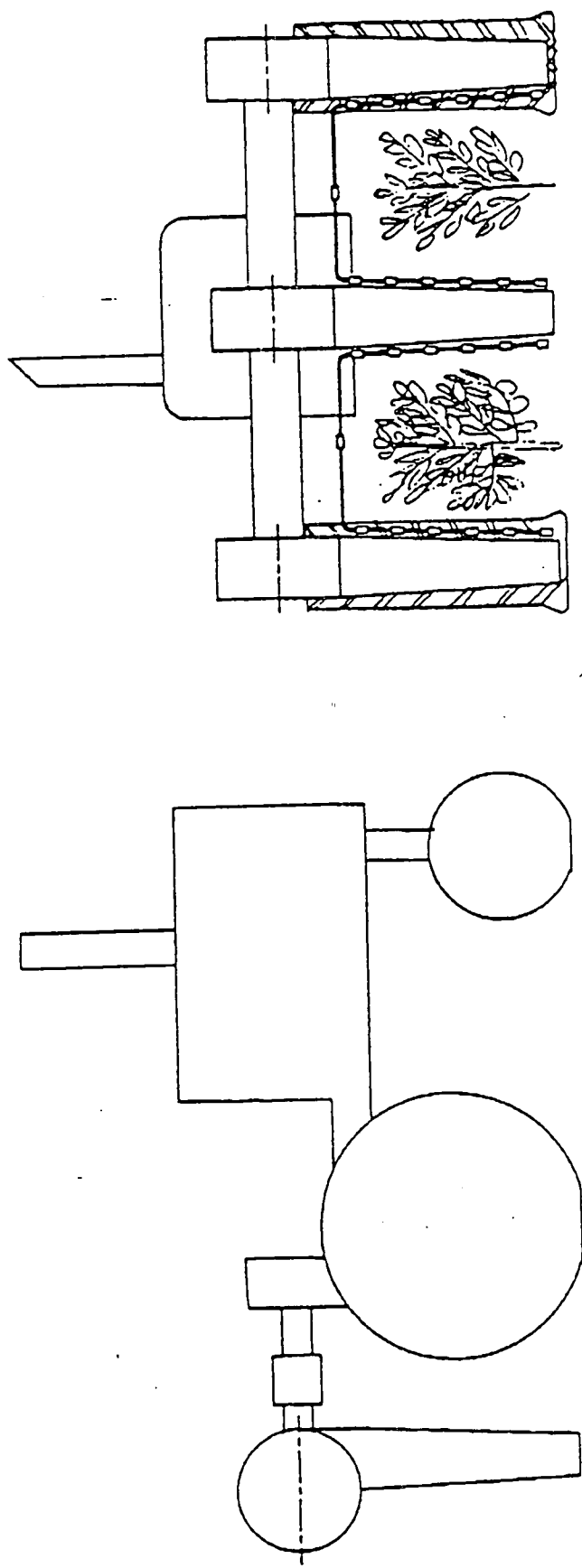


Figure D4. Experimental field sprayer for aerodynamic delivery of droplets.

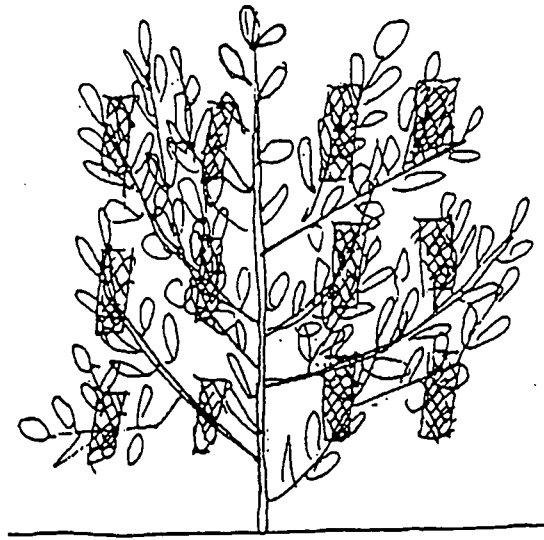


Figure D5. Sampling locations for spray deposited within plant canopies via aerodynamic delivery.

Figure D6. Spray direction compare with the row direction

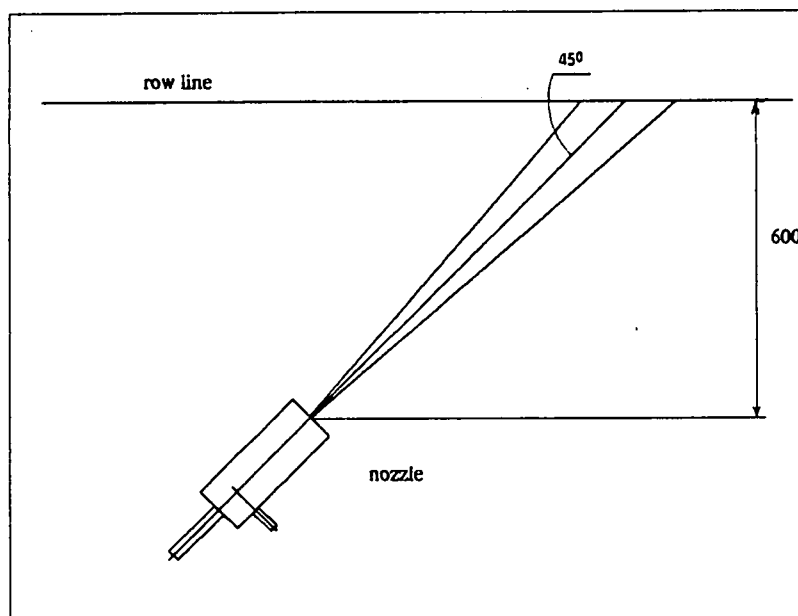


Figure D7. No. of droplets in  $\text{cm}^2$ .

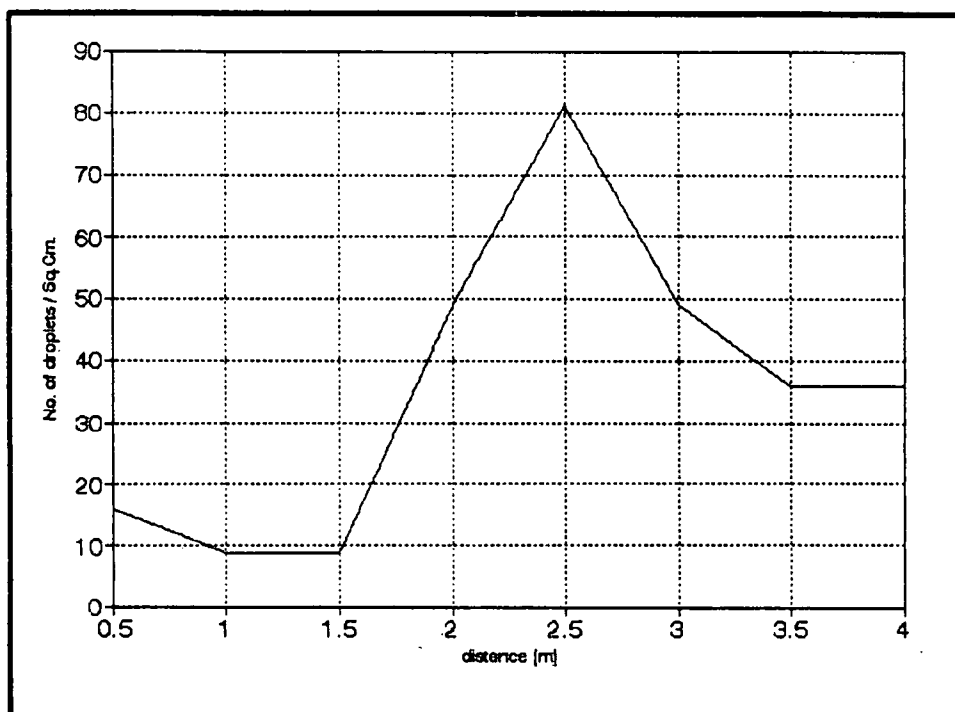


Fig.D8. Droplet mean diameter as a function of the distance from the nozzle.

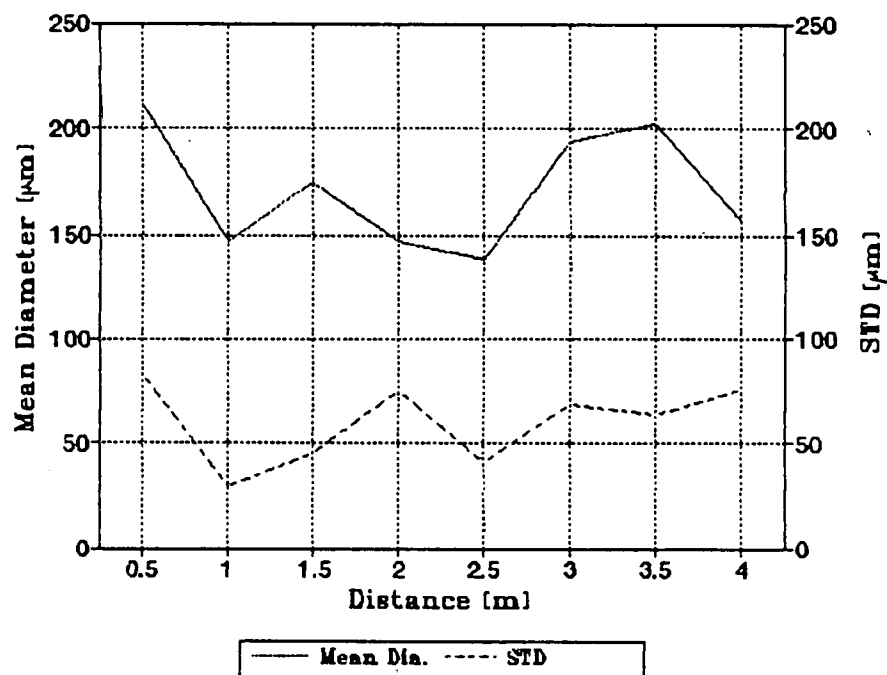


Table D1. number of droplets in cm<sup>2</sup> of the first nozzle.

Distance	0.25	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.00
DL, cm <sup>2</sup>	25	140	320	730	510	560	440	290	100

Table D2. percentage of covered area and coverage quality of the first nozzle.

mode	covered area	coverage quality
uncharged		
upper side	60%a	74%a
lower side	2%c	2%c
charged *		
upper side	77%a	74%a
lower side	10%b	17%b
charged		
upper side	80%a	88%a
lower side	37%d	10%b

\* pots were not grounded electrically.

Table D3. Droplets mean diameter, STD. and number of droplets in cm<sup>2</sup> as functions of the distance from the new nozzle.

Distance [m]	Mean Dia. [ $\mu$ m]	STD [ $\mu$ m]	Droplets No./cm <sup>2</sup>
0.5	212	82	16
1.0	147	29	9
1.5	175	45	9
2.0	147	75	49
2.5	138	41	51
3.0	194	69	49
3.5	203	64	26
4.0	157	76	36

Table D4. Coverage quality analysis.

	Covered Area [%]		Coverage Quality [%]		Volume Estimator	
	charged	uncharged	charged	uncharged	charged	uncharged
mean[%]	75.3	42.0	68.9	36.6	75.3	42.0
F value	10.69		12.13		13.18	

\*  $\alpha_{60}^1(0.1) = 7.08$