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Direct injection systems for agricultural chemical applicators

Kevin Dwayne Howard

To the Graduate Council:

I am submitting herewith a thesis written by Kevin Dwayne Howard entitled "Direct injection systems for agricultural chemical applicators." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biomedical Engineering.

Fred D. Tompkins, Major Professor

We have read this thesis and recommend its acceptance:

Luther R. Wilhelm, Robert S. Freeland, Gilbert N. Rhodes Jr

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Date 8/15/88

DIRECT INJECTION SYSTEMS
FOR
AGRICULTURAL CHEMICAL APPLICATORS

A Thesis

Presented for the

Master of Science

Degree

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Kevin Dwayne Howard

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DEDICATION

In memory of

ALICIA CORENE HOWARD
my Sister

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ABSTRACT

An experimental laboratory-model direct chemical injection system was designed, constructed, and evaluated at The University of Tennessee Department of Agricultural Engineering in Knoxville, Tennessee. Evaluations consisted of determining the transient period between initiation of chemical injection and achievement of full chemical concentration at the nozzle. The laboratory sprayer apparatus was also used to determine variation in chemical concentration in nozzle effluent both from nozzle to nozzle across the boom and with time. Performance using three injection points was evaluated for this system. Points included injection immediately upstream of the system pump, injection immediately downstream of the system pump, and injection at the individual nozzles. Tests were conducted at system operating pressures of 171, 275, and 378 kilopascals. Three injection pumps were also evaluated at the upstream injection point, and two pumps at each pressure-side injection site. The three pumps included one peristaltic pump and two piston pumps. The two piston pumps were used for pressure-side injection at both locations. A computer model for predicting transient times for low-pressure injection was also written and validated. Finally, flow characteristics within a conventional application system using a tank mix instead of direct injection were evaluated at the same three pressures to allow comparison with the different injection systems.

The sprayer was equipped with nine flat fan nozzles, and effluent samples were simultaneously taken from each nozzle. A potassium bromide

solution formulated at a concentration of 28.3 grams per liter was used as the simulated pesticide to be injected into the diluent stream. Conductivity of the effluent solution caught at the nozzles was measured and related to chemical concentration based upon a calibration of the conductivity meter performed prior to each test.

Results of laboratory studies indicated that performance of the direct injection system was very dependent upon component selection and system configuration. Direct injection systems when used for low-pressure injection with any of the three pumps produced chemical concentrations in the nozzle effluent equal in uniformity to those achieved through conventional tank mixing.

Injection on the high-pressure side of the system pump was effective in reducing the transient period in comparison to injection on the low-pressure side of the system pump. However, mixing of the diluent and the concentrated chemical was reduced. The reduced level of mixing was probably due to the fact that the chemical did not pass through the sprayer system pump, which was found to be effective in thoroughly mixing the two fluids.

When injecting at the individual nozzles, high system operating pressures produced increased variation in chemical concentration in the nozzle effluent. Further, location of diluent entrance to the boom became a critical issue. Flow to both sides of the boom must be equal to achieve uniform chemical concentration from nozzle to nozzle across the boom.

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CHAPTER I

INTRODUCTION

Background and Statement of Problem

According to Vidrine et al. (1975), the technology associated with agricultural field sprayers has remained essentially unchanged since the 1940's when use of such units became extensive. Since chemical application technology has changed little, problems associated with this technology have remained constant. There are primarily three problems associated with conventional or traditional chemical application technology. First, there is a problem with the calibration procedure in which the applicator calculates the rate of application for the sprayer and the amount of chemical to diluent ratio according to the rate of application. In 1979, a field survey of 152 private and commercial pesticide applicators was conducted in Nebraska and western Iowa. Results from the survey showed that only one out of every four operators was applying pesticides within 5 percent of their estimated application rate (Rider and Dickey, 1982). The survey also showed that incorrect calibration accounted for the greatest number of application errors. These errors ranged from 60 percent under-application to 90 percent over-application (Rider and Dickey, 1982). Once the calibration procedure is completed, the second problem with conventional chemical application appears, namely, exposure of the applicator to the concentrated chemical during spray solution mixing and sprayer loading.

Nationally, 8,241 workers were hospitalized from 1971 to 1973, an average of 2,747 per year, due to overexposure to pesticides (Akesson et al., 1978). These figures include industrial as well as agricultural workers. The third problem associated with conventional chemical application is disposal of excess spray mixture after the spraying operation is completed. Present day application methods favor applying any diluted spray as well as wash water from the sprayer back onto the crop (Akesson, 1987). Obviously, this approach will increase the applied dosage to that given area. If this application exceeds the labeled rate, then it is an illegal application. Not only is it illegal, it also can be potentially harmful to the crop and the environment.

In light of these problems, there is increased concern within society about agricultural chemicals and their impact on the environment. Efforts have been made to develop a versatile, highly-reliable chemical application system that will eliminate many of the problems characteristic of the conventional application method. Considerable amount of effort has been expended on developing a direct chemical injection system. This technology involves injecting the chemical concentrate directly into the diluent stream at some point before discharge from the sprayer nozzles. This approach eliminates the necessity of preparing a tank mix comprised of pesticide and diluent. In turn, both the applicator's exposure to the chemical concentrate during mixing and the need to dispose of excess mixture are eliminated. Like all new technology, this concept has some impediments. These impediments include lack of spray uniformity due to inadequate mixing and transient errors due to changing application speeds (Vidrine et al., 1975).

Objectives

Three objectives were defined for this project. The first objective was to evaluate and characterize the operational performance of an experimental direct injection system with the injection point located on the low-pressure side of the sprayer system pump. This evaluation was to include a measure of the transient time and an assessment of the mixing uniformity of the chemical concentrate and carrier both from nozzle to nozzle and with time. The second objective was to move the injection point to the high-pressure side of the sprayer system pump and again measure the transient time and the mixing uniformity of the chemical concentrate and carrier. The third objective was to construct and evaluate an experimental high-pressure direct injection system with the injection points at the individual nozzles. This evaluation was to include measurements of concentration uniformity both from nozzle to nozzle along the boom and with time.

CHAPTER II

REVIEW OF LITERATURE

Background of Pesticide Application

Pesticide Use

Agricultural chemicals have become an important element of successful crop production. Ksiazek (1985) states that chemicals were being used to control agricultural pests on 95 percent of all corn and soybeans in the United States. During 1972, more than 63.5 million kilograms of actual pesticides were used in California alone (Yates et al., 1974). In Illinois, farmers spend over $100,000,000 annually on pesticide applications (Butler and Bode, 1980). A United States Department of Agriculture (1987) survey predicted that 195 million kilograms of active pesticide ingredient will be used on major farm crops in 1987. The same report indicated that the use of pesticide is down from 1986 usage, which was 215 million kilograms of active ingredient. This reduction in usage of agricultural chemicals was due to the trend toward lower application rates using chemicals formulated with a higher concentration of active ingredient and to the decline in the number of hectares of major field crops planted. During 1987, 100 million hectares were planted, a decline from the 108 million planted in 1986 (United States Department of Agriculture Economic Research Service, 1987). The Agriculture Economic Research Service also reported that the

average cost of a kilogram of active ingredient in 1987 was $8.93, unchanged from 1986.

Traditional Spraying Systems

Calibration methods. Selling of agricultural pesticides is a large industry within the United States. About $12 billion are returned in increased crop yields for a $3 billion investment in pesticides (Pimentel and Levitan, 1986). For an applicator to receive the greatest return on the investment, the pesticide must be properly applied. To apply a given dosage of pesticide successfully with a conventional sprayer, the sprayer must be calibrated with respect to nozzle flow rate, chemical concentration in the tank, and the operating width and speed. Using these variables, the applicator should be able to calculate the application rate in volume per unit area.

There are several ways by which an operator can calibrate a conventional sprayer. Calibration methods used by operators include:

1. Known area,
2. Operator manual recommendation,
3. Collected output, and
4. All adjustments same as last year.

When using the known area method, the operator completely fills the sprayer tank and sprays a known area of land. Upon completion of this known area, the volume required to refill the tank is measured. The quantity of material to be applied and the application rate is thus calculated. This is a very popular method of calibration. In the survey conducted by Rider and Dickey (1982), including 152 applicators, 42.4 percent of the operators used the known area method of calibration. This method was also reported by Grisso et al. (1987) to be the most common method of calibration. Even though this is the most popular method of calibration, it may not be the most efficient. The operator only knows the volume of mix applied to a given area. The operator may not know if the rate across the boom is constant.

When using the operator's manual recommendation method, all application equipment is set according to the manufacturer's specifications. This method was used by 30.4 percent of the operators surveyed by Rider and Dickey (1982). This method may also result in uneven application rates since the data given in the operator's manual for a specific nozzle and pressure is not always absolutely constant from nozzle to nozzle and over time.

The caught output method is the sprayer calibration technique recommended in ASAE Standard EP367.1 (American Society of Agricultural Engineers, 1985). When using this method, the operator catches the effluent from each nozzle along the boom for a specified time and measures the travel speed of the sprayer. With these two variables and the boom width, the operator can calculate the application rate. By using this method of calibrating, the operator also knows the spray rate uniformity across the boom. This method is not frequently used by operators because it does require more time and calculations than other methods of calibration. The reluctance to use this technique was observed in the survey conducted by Rider and Dickey (1982) in that only 10 percent of the operators surveyed used the caught output method of calibration.

The final method of calibration, or lack of calibration, involves maintaining the same settings as last year and assuming that the rate of application remains constant. Less than 10 percent used this approach according to Rider and Dickey (1982). This method is the least desirable of the four. Sprayer parts become worn through use and need to be periodically recalibrated. The nozzle orifices become enlarged, and the pump tends to decrease in efficiency. Calibration will not remain constant from year to year.

Conventional application problems. Even though sprayer calibration seems a quick and easy task, farmers either are not calibrating as often as they should, or they do not use an appropriate method of calibration. In 1976, the National Agricultural Development and Advisory Service (ADAS) found that, of 91 sprayers surveyed in England and Wales, 46 percent had an application error of 10 percent or greater between the intended and the actual spray volume rates (Rutherford, 1976). Other surveys have been conducted, and the results were consistent. For example, in 1980 Hoehne and Brumett (1982) surveyed northeast Missouri and found that 14 percent of the operators reported incorrect application rates. In 1983, Hofman and Hauck (1983) surveyed 60 North Dakota farmers and 60 percent were found to be misapplying by more than 10 percent from the predicted amount. And in 1986 Grisso et al. (1987) surveyed 140 operators from central and eastern Nebraska and found 60 percent of the applicators had a calibration or mixing error in excess of 5 percent, and over 10 percent had both calibration and mixing errors. In the same survey conducted by Grisso et al. (1987), 55 percent of the application errors were due to incorrect calibration and 19 percent were due to tank mix errors.

When calibration is incorrect, application rate can also be expected to be incorrect. The result is either over- or under-application. Errors in application rate are costly to the operator and potentially harmful to the environment. The social and environmental costs of damage from pesticides have been estimated to be at least $1 billion annually (Pimentel and Levitan, 1986). Pimentel and Levitan also reported that less than 0.1 percent of pesticides applied to crops reaches the targeted pests. To look at the cost from an applicator's standpoint, a 10 percent over-application of chemicals costing $37 per hectare would add $4,500 to the cost of spraying 122 hectares (Grisso et al., 1987). An under-application rate can cost the operator in yield reduction and in added expense for reapplication of the chemical.

After the operator has calibrated the sprayer, a tedious volumetric measurement of the concentrated chemical takes place in preparation for forming the spray mixture. During this process, the operator is exposed to the concentrated chemical. Studies in the 1970's showed that ground pesticide equipment operators such as mixers, loaders and applicators have the highest potential for injury (Dewey et al., 1984). It was also reported that ground rig applicators had by far the greatest illness incidence with 33 percent of the 757 reported pesticide related illnesses in 1976 and 30.5 percent of the 774 reported pesticide related illnesses in 1977. Allen et al. (1986) cited a study conducted by Richard Fenske in which a skin-binding fluorescent tracer was added to the chemicals. Fenske found that the greatest level of contamination occurred when the operator mixed the chemical, loaded the sprayer, and cleaned the sprayer. The long-term effects of exposure to most agricultural chemicals are not know, but Barthel (1981) reported that of 1,658 men who worked with pesticides for more than five years, 169 (approximately 10 percent) were diagnosed to have malignant tumors. Doherty (1986) stated that Kansas farmers who applied herbicides more than 20 days per year had six times greater risk of non-Hodgkin's limphomas than non-farmers.

Even if the operator does calibrate the sprayer correctly, variations in travel speed may cause an incorrect application of the pesticide. Reichard and Ladd (1983) stated that sprayers apply the proper rate of pesticide only when precisely operated at the speed of calibration. He noted that operators frequently do not maintain the correct travel speed while spraying. In the survey conducted in North Dakota, inaccurate travel speed was the reason that 32 percent of the 36 operators had calibration errors (Hofman and Hauck, 1983).

When the operator has finished spraying the field, disposal of the excess spray mixture becomes an environmental problem. Previously reported questionable disposal methods include washing the excess spray and rinse water into drains and sewers or allowing pesticides to run off into adjacent drainage ways (Brown, 1986). These methods allow the excess pesticide to move from the initial disposal site into surface or underground water supplies. In Illinois, 400 farmers were surveyed on their pesticide use and disposal. Of the 400 farmers, 71 percent held excess pesticides in containers until the time came to apply on an appropriate crop. Four percent used an approved landfill, and 32 percent used an evaporation pit or other methods (Anonymous, 1985). These other methods frequently consisted of letting the excess drain out along the side of the road or applying the excess over the previous sprayed area.

California's Closed System Law

Introduction

In 1949, California began monitoring farm worker pesticide illnesses by requiring all physicians to report any illness or injury appearing to be pesticide related (Brazelton and Akesson, 1987). These reports by the California Physicians Reporting Service indicated that from 1949 to 1959 an average of 10 to 25 workers per year were being treated for pesticide illnesses (Akesson et al., 1978). This report also indicated that in 1970 the number of illnesses jumped to 55 workers per year. Brazelton et al. (1981) indicated that the increased number of pesticide-related illnesses were due a number of the hydrocarbons that were banned and the subsequent use of organophosphates and N-methyl carbamates, both highly toxic in their concentrated form, became very popular. With the intensified acute illnesses that have resulted from operator exposure during pesticide handling, the State of California sought safer methods to handle highly toxic pesticides. Akesson et al. (1978) reported that there are two basic ways of protecting workers who handle, mix, and apply agricultural chemicals. One is by placing the worker in a protective capsule comprised of suit, gloves, shoes, helmets, and respirators. The other is to isolate the contaminant by enclosing it in a closed transfer, mixing, and loading system. In spite of considerable advances in fabrics for protective clothing, the basic problem of using the capsule method of protecting the worker is having to wear this protective clothing in the hot summer climate (Brazelton and Akesson, 1987). Further, a test conducted by Maddy et al. (1983) found that even among workers who wore waterproof gloves still experienced hand exposure which represented 40.9 percent of their total dermal exposure.

Definition of Closed Systems

Since convincing operators to wear protective clothing is difficult, the State of California in 1973 required by law the use of closed system mixing for class one toxic pesticides (Brazelton and Akesson, 1987). The definition of a closed system is:

> a procedure for removing a pesticide from its container, rinsing the emptied container, and transferring the pesticide and rinse solution through connecting hoses, pipes, and couplings that are sufficiently tight to prevent exposure of any person to the pesticide or rinse solution (California Department of Food and Agriculture, 1985).

Due to the lack of acceptable available closed systems, enforcement of this law was delayed until January 1, 1978 (Brazelton and Akesson, 1987).

Regulations of Closed Systems

Several requirements must be met in order to conform to the provisions of the closed system law. A closed system must be capable of:

1. Removing pesticides from their shipping containers,
2. Rinsing the container,
3. Transferring the pesticide and the rinsate into mixing tanks and/or application equipment, and
4. Measuring the amount of pesticide removed from or remaining in the container (Jacobs, 1987).

A full listing of the California closed system criteria is included in Appendix A.

Advantages of Closed Systems

The primary advantage of a closed mixing system is that the operator is protected from exposure to the concentrated chemical. One study found that a closed mixing system could reduce the daily exposure of a mixer/loader by as much as 99 percent as compared to hand pouring (Dewey et al., 1984). The California Department of Food and Agriculture (1985) reported that proper use of a closed system reduced the potential for human exposure between 10 and 100 times. By establishing the closed mixing system and protecting the operator, other benefits were obtained. These include:

1. Significant reduction in the number of human illnesses,
2. Reduction in the need and expenditure for protective clothing and equipment, and
3. Reduction in medical expenses and insurance costs associated with illnesses and disabilities caused by exposure to pesticides (Brazelton et al., 1981).

Moreover, if a closed mixing system has the capability of rinsing the containers, this system has many other benefits. They include:

1. Making container handling safer,
2. Making container disposal easier and safer,
3. Avoiding wastage of any pesticide remaining in unrinsed containers,
4. Reducing the time and effort required for mixing and rinsing,
5. Reducing or eliminating field-site contamination, and
6. Reducing the possibility of water source contamination (Dewey et al., 1984).

Impediments to Using Closed Systems

A closed mixing system will only protect the operator when the system is properly operating, clean, and well-maintained (California Department of Food and Agriculture, 1985), and when the operator is well trained in the proper use of the closed system (Brazelton et al., 1981). In tests conducted by Brazelton et al. (1980) and Maddy and Barish (1979), use of a closed system did not decrease exposure of the operator to the concentrated chemical as expected, primarily because the operator was not well educated about proper use of the system.

There are four additional problems associated with closed mixing systems. The first and most critical is the variation in the sizes and types of pesticide packages (Rutz, 1987). The container openings range in size from 19 to 51 millimeters in diameter, and the capacity varies from 4 to 19 liters with 57, 114 and 208-liter drums also available (Brazelton et al., 1987). Thus, a single method to open all types of plastic and metal containers without causing leaks in the system is very difficult.

The second problem with closed systems is keeping the earlier models operational (Rutz, 1987). Third is the regulatory requirement for accurate measurement of the volume of concentrated chemical left in the container or the quantity that has been used (Rutz, 1987). Reichenberger (1986) reported on the accuracy of bulk meters on farms across the corn belt. Results indicated that measurement errors in excess of 10 percent frequently existed in some systems.

Finally, selling the concept of closed mixing system technology to users was difficult (Jacobs, 1987). The publics perception of the closed mixing system was unfavorable due to: 1) the initial cost of the system, 2) the lack of efficiency, 3) the lack of versatility in handling different containers and dry materials, 4) the equipment problems, 5) the operational complexity, and 6) whether the system effectively reduce exposure (Jacobs, 1987).

Methods for Controlling Application Rates

The increasing use and cost of agricultural pesticides in crop production requires the use of spray application monitors and controllers in order to reduce distribution errors (Hughes and Frost, 1985). Once the chemical is mixed with the diluent and the mix is placed in the sprayer without contaminating the operator, the application rate must remain constant as the sprayer travels across the field. One of the problems mentioned earlier was the fact that if the sprayer speed was not maintained at the same level as used in calibration, an error in the application rate would occur. There are two ways to have a constant application rate while allowing the travel speed to vary. The first involves varying the nozzle flow rate while keeping the concentration of the active ingredient constant (Hughes and Frost, 1985). Varying the nozzle flow rate may be accomplished by using a by-pass nozzle. The by-pass nozzle provides the capability of adjusting the pesticide application rate or maintaining a constant application rate over a range of travel speeds by means of a single control valve (Ahmad et al., 1981). In theory, a by-pass nozzle allows variable amounts of the nozzle flow to be returned to the supply tank through a separate line without appreciably affecting the atomization quality over a range of flow rates (Bode et al., 1979). Tests conducted with the by-pass nozzle showed that the spray discharge angle varied from 86 to 80 degrees over a 6 to 1 turndown ratio. The combined nozzle spray distribution pattern was only slightly affected (Ahmad et al., 1981).

The rate of chemical applied for a pre emergent or pre plant applied pesticide depends upon the organic matter of the soil. As the organic matter increases, so should the application rate, sometimes by as much as a factor of six (Han et al., 1985). Han et al. (1985) developed a microprocessor-based sprayer control system to regulate chemical application rate according to the soil organic matter content and the sprayer ground speed by using the by-pass nozzle. Another application of the by-pass nozzle involved using a digitizing camera, and a computer to identify or classify a weed within the scene. Once the weed is known the proper chemical and rate of chemical to control the weed can be applied (Guyer et al., 1985). Results from tests reported by Guyer et al. (1985) showed that spatial features are sufficient for identifying weeds and that vision systems could provide necessary sensory information for spot spraying weeds. However, there are problems associated with distinguishing between closely related objects.

The second method of maintaining a constant application rate while allowing ground speed variations is to kept the nozzle flow rate constant while varying the concentration of active ingredient (Hughes and Frost, 1985). This method requires that the concentrated chemical and the diluent be keep in separate tanks. The two substances must then be mixed in proper proportion at some point before discharge from the nozzle. This method eliminates excess spray mixture while keeping the application rate constant. This cannot be accomplished with the by-pass nozzle since the contaminated spray is returned to the tank.

Direct Injection System

Definition of Direct Injection

A direct chemical injection system involves introducing the chemical concentrate directly into the carrier volume at some point before discharge from the sprayer nozzle. With this system, the diluent and the concentrated chemical are maintained in separate sprayer tanks. On the basis of 1) desired chemical application rate, 2) sprayer nozzle flow, and 3) machine operating speed, the concentrated chemical is metered and injected into the sprayer fluid transport system. It then becomes mixed with the carrier before passing through the nozzle. The ground speed is measured with a speed sensing device. The speed sensor is connected to the metering device which injects the concentrated chemical into the conduit of the sprayer.

Advantages of Direct Injection

Personal safety. There are several advantages associated with the direct injection system. One advantage is the operator's safety. Since the concentrated chemical and the diluent are kept in separate tanks, there is no hand measuring or mixing required. If the system has the capability of pumping the concentrated chemical from the manufacturer's package into the sprayer holding tank, there is absolutely no physical contact between personnel and concentrated chemical. Barthel (1981) noted that occupational exposure to pesticide was associated with an increased risk of lung cancer.

Environmental protection. Another advantage of the direct injection system is the protection of the environmental by eliminating excess spray mixture. There is also no over- nor under-application of chemical since the concentrated chemical is injected into the pipeline of the sprayer based upon the forward travel speed of the machine.

Cost efficiency. Finally, the direct injection system is cost efficient for the operator. According to the survey conducted by Rider et al. (1980), one-third of the corn crop received a 25 percent over-application of pesticide when a conventional sprayer was used. If the pesticide costs $39.50 per hectare, the annual cost due to over-application would be over $9 million dollars based upon 227,900 hectares of corn (Rider et al., 1980). In contrast, if an operator under-applies a pesticide, the result could be yield reduction and possibly the need for a second application. Ksiazek (1985) reported that if misapplication causes a loss in yield of 1 percent in corn, this could amount to a 25 to 38 kilograms per hectare loss in a typical field. At a market price of about $0.10 per kilogram, this would mean a $2.50 to $3.80 loss per hectare. On a typical farm producing 200 hectares of corn, this could result in a loss of $510 to $765 in yield per year (Ksiazek, 1985). These estimates do not include possible extra chemical expense. Also, direct injection saves the operator money since the formation of excess spray mixture is eliminated. According to Spurrier (1987), reduction of rinsates and waste is more cost effective than waste disposal.

Impediments to Direct Injection

There are several inherent problems associated with the direct injection system concept. Hughes and Frost (1985) cited three aspects of the direct injection sprayer which are not technologically sound.

Transient time. The first problem area is associated with transient time errors due to changing ground speeds. Peck and Roth (1975) defined transient time as the elapsed time from the instant of speed change to the instant the application rate reaches a value of 95 percent of the equilibrium rate. Koo et al. (1987) conducted tests to determine the transient time errors for a direct injection system. The results indicated that the transient time error was very significant. Delay times reaching 20 seconds were measured for the fluid to travel to 4 nozzles spaced at 0.51 meter intervals. The injection point was located on the high-pressure side of the sprayer system pump, and a mixer was used to obtain proper mixing. Koo et al. (1987) concluded that, to eliminate the delays completely, the concentrated chemical needs to be injected directly into each nozzle body. Larson et al. (1982) designed and tested a direct injection system in which the injection point was located at each nozzle. The results were encouraging, but more data were needed before definite conclusions could be made. However, Larson et al., (1982) indicated the system plumbing would have to be carefully planned in order to obtain equal or uniform chemical distribution to each nozzles.

Uniformity of distribution. The second problem associated with direct chemical injection is the inadequate mixing of concentrated chemicals and carrier (Hughes and Frost, 1985). After the concentrated chemical has been metered at the proper rate and the transient error has been resolved, the problem of mixing the concentrated chemical with the carrier must be considered. Several techniques have been tested for effectiveness in mixing the two fluids together. One technique involved mixing the carrier and the concentrated chemical in a mixing chamber by mechanical agitation before discharge into the nozzle (Peck and Roth, 1975). Another technique involves feeding the two fluids into a centrifugal pump where they are agitated and discharged toward the nozzles (Yates and Ashton, 1960). Some systems inject the concentrated chemical directly into the carrier on the pressure side of the sprayer system pump, and the two fluids are mixed by turbulence and diffusion (Vidrine et al., 1975).

The transient time was extended when using either a mixing chamber or the centrifugal pump, although these devices perform well in mixing wettable powders or emulsifiable liquid concentrates. The chemical concentrate and diluent fluids can be inadequately mixed when using the turbulence and diffusion method for injection close to the nozzles. However, the farther the point of confluence of the two fluids is located upstream from the nozzle, the greater the transient error becomes. Most of the commercial companies producing direct injection systems are using the mixing chambers and the centrifugal pump to agitate the two fluids because producers would prefer transient error over inadequate mixing.

Metering of concentrated chemical. The third problem with direct chemical injection is associated with the accurate metering of small flows. According to Gebhardt et al. (1984), direct injection systems hold promise if the flow rate can be measured and controlled. Basically there are two methods of metering concentrated pesticides. One involves using a positive driven metering pump in an open-loop system (Gebhardt et al., 1984). An open-loop system is one in which there is no positive feedback from the system. The output of the meter is assumed to be a function of the pump speed (Gebhardt et al., 1984). Any component wear or change in the system will cause an error in the flow rate of the metering pump.

The second method of metering concentrated pesticides involves the use of flowmeters or sensors as part of a closed-loop control system (Gebhardt et al., 1984). A closed-loop system is capable of sensing both ground speed and the concentrated chemical flow rate. As a result, the flowmeter can adjust the flow rate so that the chosen application rate is maintained (Ksiazek, 1985). Flowmeter selection for concentrated chemicals is limited because the flow rate range is extremely low, the flowmeter has to be resistant to corrosion and abrasion, the power requirement for the flowmeter has to be compatible with the electrical systems on farm machinery, and the cost must be moderate (Gebhardt et al., 1984).

Research has been conducted on different types of flowmeters. Gebhardt et al. (1984) evaluated a drag-body type flowmeter and found that the meter must be calibrated for each pesticide used and that the temperature of the pesticide would have to be closely controlled. Most of the pumps used on direct injection systems are positive driven pumps. The most common is the piston type. This pump is expensive but can be accurate to +/- 0.5 percent (Hughes and Frost, 1985).

Direct Injection Equipment Development

Research Equipment

Several universities as well as research and development organizations have built successful direct chemical injection systems. Hare et al. (1969) designed and constructed an experimental pesticide metering unit for application of wettable powders. The unit was operated to satisfactorily apply pesticide at rates ranging from 0.15 to 9.0 kilograms per hectare. Tests showed that the delivery system was dependent upon drive speed, density, and physical characteristics of the wettable powders.

Nelson and Roth (1973) built and tested a system that allowed wettable powders to be continuously metered, mixed, and induced into the boom supply line. A jet pump was used to draw a wettable powder slurry or an emulsifiable liquid concentrate from a mixing chamber, and then mix the pesticide with the diluent. The laboratory tests showed no significant effect on the characteristics of the suspension due to level of turbulence in the mixing zone of the jet pump or to powder metering ratio within the practical operating ranges. They indicated that the suspension from this system was not as well dispersed as that which can be produced with a conventional sprayer.

Harrell et al. (1973) designed and built an injection sprayer that mixed insoluble dry pesticides with water concurrent with spraying. The injection point on this system was located on the low-pressure side of the sprayer system pump. An in-line mixer was also used. Results from the laboratory and field studies indicated that this sprayer could be used instead of conventional sprayers. There was no significant performance difference between this and conventional equipment when tested for controlling corn earworm [*Heliothis zea* (Boddie)] on sweet corn.

Peck and Roth (1975) built a sprayer that used either a ground-driven powder metering unit or a peristaltic pump to inject pesticides into the conduit of the sprayer. The two fluids mixed within a chamber before being discharged through the nozzle. The spray mixture was delivered from the chamber with a jet pump into a manifold distribution system. An analytical model of this system was used to test system performance. Results showed that the mixing volume and jet pump suction rate, rather than the pesticide metering rate, influenced the lag time when the operating speed was changed. When the model prediction was compared to the actual system, results showed a similar relationship with time.

Vidrine et al. (1975) constructed a model that used a positive displacement pump to inject the concentrated chemical into the conduit of the sprayer. The injection point was located on the pressure side of the sprayer system pump. Test results showed that the uniformity of deposition of the nozzle effluent was inferior to application by conventional tank methods.

Reichard and Ladd (1983) designed and built an experimental direct injection and transfer system. The sprayer metered pesticides at the proper rates into the conduit of the sprayer regardless of travel speed. The operator could also transfer the pesticide from the shipping container to the pesticide tank on the sprayer and flush the container. The injection point was located on the pressure side of the sprayer system pump, and piston pumps were used to meter the concentrated chemical. The sprayer was field tested for the control of Colorado potato beetle [Leptinotarsa decimlineate (Say)]. The results showed that spraying with the injection system controlled the potato beetle as well as application with a conventional sprayer.

Cho et al. (1985) conducted experiments on a spraying system which metered two chemicals simultaneously. They conducted tests which revealed that the concentration with respect to nozzle location and sampling time was not completely uniform, but was as good as conventional spraying systems.

Commercial Equipment

There are several complete chemical injection sprayers available on the commercial market. Several modification kits that convert conventional sprayers into chemical injection sprayers are also available. The manufacturing companies producing direct injection systems and the features of the systems are listed in Table 1.

A primary drawback of the chemical injection sprayer is price. The price for a complete chemical injection sprayer ranges from $1200 to $3000 depending upon the model and company from which the sprayer is purchased. The price for comparable conventional sprayer ranges from $295 to $875.

The number and size of tanks available on the several models varies. The number of tanks determines how many different chemicals can be injected simultaneously with variable rates. Extra tanks allow the operator to carry more than one chemical at a time and spray only the chemical or mix of chemicals that is needed. The tank size determines the amount of chemical that can be applied before the applicator must be stopped to refill. All of the available sprayers have a diluent tank capacity of 760-liter or greater.

Piston and diaphragm pumps are used in the injection system because they both can produce high operating pressures. Both are positive displacement pumps. This means they positively engage a given amount of fluid with each cycle of operation. Both pumps can be operated by an electric motor that can be controlled in response to a ground speed indicator.

Table 1. Companies marketing complete direct injection sprayers.

Manufacturer	Price Range ($)	Number and Size of Tanks	Type of Pump	Radar or Ground Driven Control	Type of Mixing Device
Ag Systems Weed Buster[1]	1500-3000	1-190 L 2-95 L	Piston	Ground Driven	In-Line
John Blue Co. Chem-N-Jector[2]	1400-2100	1-57 L	Piston	Ground Driven	Chamber
Sprayrite S.I.S.[3]	1400-3800	2-208 L	Diaphragm	Both	In-Line
Pleasure Products[4]	1200-2000	1-95 L	Diaphragm	Ground Driven	In-Line
Walsh Mfg. CCI-2000[5]	1500-3000	1-76 L 1-57 L 1-19 L	Diaphragm	Both	In-Line

[1]Gergen, Bill. 1985B. Mix-on-the-go sprayers: two new sprayers eliminate errors and waste of tank mixing. Farm Industry News, March. pp. 98-99.

[2]John Blue Company. 1985. Chem-N-Jector. Huntsville, Al 35805.

[3]Gergen, Bill. 1985A. Direct inject: new way to spray chemicals. Farm Industry News, December. pp. 22-24.

[4]Gergen, Bill. 1985A. Direct inject: new way to spray chemicals. Farm Industry News, December. pp. 22-24.

[5]Cedar Valley Products, Inc. 1986. Walsh CCI-2000 chemical injection system for field sprayers. Walsh Sprayer Division, Charles City, IA 50616.

Either a ground driven wheel or a radar gun can be used to control the metering pump as a function of the sprayer travel speed. The radar controller is more accurate in measuring the ground speed than is the ground-contacting wheel (Tompkins et al., 1987). The sprayer monitor enables the operator to adjust the rate of application or to change from one chemical tank to another while still on the move.

The concentrated chemical and the carrier volume are either mixed in-line or in a chamber. Most of the commercial sprayers use in-line mixing (Table 1). The in-line mixer takes advantage of the kinetic energy of the flowing fluid to mix the two fluids together. The Chem-N-Jector is equipped with a mixing chamber which allows the chemical and the carrier volume to be mixed before entering the nozzles.

The direct injection modification kits have about the same basic features as the complete direct injection sprayers. The companies which sell the kits and the features that differentiate the units are listed in Table 2.

Prices are somewhat lower for the modification kits than for the complete sprayers. Anyone who is proficient in the use of hand tools and small power equipment can acquire the parts and assemble an injection system. Elimination of assembly labor at the factory is one reason the retrofit units cost less. Another reason is that the kits do not come with as many accessories or options. They all have one chemical tank, a diaphragm pump, and in-line mixing. The average size of the tank is 95-liters. Only the kit made by Agrobotics comes equipped with the radar controller.

Table 2. Companies marketing injection sprayer modification or retrofit kits.

Manufacturer	Price Range ($)	Radar or Ground Driven Control
Agrobotics	1200-3500	Radar
Junge Control	1000-1600	Ground Driven
Pleasure Products	900-1500	Ground Driven

Source: Gergen, Bill. 1985A. Direct inject: new way to spray chemicals. Farm Industry News, December. pp. 22-24.

CHAPTER III

PROCEDURES AND EXPERIMENTAL METHODS

Introduction

An experimental direct injection system was designed and built to allow measurements of the transient time and concentration consistency of an injection system installed at three different injection points. A computer model was developed to characterize theoretical transient time of a direct injection system with the injection point located on the upstream side of the sprayer system pump. Sprayer performance studies were then conducted using the experimental direct injection system in the laboratory. These evaluation studies included collection of data to facilitate checking the validity of the computer model and for determining the variation in chemical concentration in the nozzle effluent, both from nozzle to nozzle across the boom and with time. After tests with injection upstream of the sprayer system pump, the injection point was then moved to the downstream side of the sprayer system pump, and the same test procedure was followed to determine the variation in chemical concentration at the nozzles. The transient time was also measured for this system in simulated responses to changes in indicated ground speed. Finally, the chemical injection points were moved to the individual nozzles. Transient time with this system configuration was negligible since each nozzle had its own injection line and all the lines were the same length. Tests were then conducted to evaluate the uniformity of chemical concentration among the several nozzles on the boom.

Experimental Sprayer Design

An experimental direct injection system was designed to operate over a pressure range of 140 to 690 kilopascals and to maintain a fluid velocity in the pump outlet conduit between 1.5 and 1.8 meters per second. The boom was equipped with 9 flat fan nozzles ranging from 8001 to 8004, spaced 0.51 meter apart (Spraying Systems Co., 1987). The sprayer was also equipped with a 95-liter capacity tank.

The desired diameter of hose connecting the individual nozzles on the boom was calculated using the continuity equation. The continuity equation as follows:

$$Q = V * A * 60{,}000 \qquad \text{Eqn [1]}$$

where:

Q = flow rate of the sprayer, L/min,
V = velocity of the fluid in the hose, m/sec, and
A = cross sectional area of the hose, m^2.

By knowing that the velocity of the fluid is to be maintained between 1.5 and 1.8 meters per second and the flow rate listed in the manufacturer's catalog for the largest capacity nozzle used (8004), the diameter of the hose connecting the individual nozzles on the boom can be calculated. To insure that fluid velocity is maintained within the recommended range, both maximum and minimum velocity limits were used to calculate the hose diameter. The average of the two calculated diameters was used for actual hose selection.

Average hose diameter for use with the 8004 nozzles based upon the flow rate at a pressure of 690 kilopascals, and the flow velocity constraints, was 17 millimeters. This is somewhat larger than the 13-millimeter hose diameter actually used for the laboratory sprayer. This means that a velocity somewhat greater than 1.8 meters per second will be maintained for the 8004 nozzles operated at high pressures.

The leader hose, or the hose connecting the pump with the boom, is made up of two different sizes. The suction hose, selected to match the size of the inlet port on the pump was 19 millimeters. This same size hose was also used to connect the discharge or outlet port of the pump to the pressure regulator. The 13-millimeter diameter hose was used to connect the pressure regulator to the boom section.

The sprayer system pump was chosen based upon calculations involving the pump equation. This equation is expressed as follows:

$$PC = (AG + Q)*1.2 \qquad \text{Eqn. [2]}$$

where:

PC = pump capacity, L/min,
AG = required agitation rate, L/min, and
Q = total flow of all sprayer nozzles, L/min.

Since no agitation is required for a direct injection system, the equation was reduced to:

$$PC = Q * 1.2 \qquad \text{Eqn. [3]}$$

The system operating conditions requiring the greatest pump capacity were used to calculate pump size. Using a flat fan 8004 nozzle at 690 kilopascals, the required pump capacity was 25.8 liters per minute. For this requirement, a Hypro roller pump (Model number N6310) was selected.

This pump was operated by an electric motor. The power requirement was determined by:

$$Hp = (Q * P * 0.00001667) / Eff \qquad \text{Eqn. [4]}$$

where:

Hp = required power, kW,
Q = maximum flow rate of the pump, L/min,
P = maximum pump pressure, kPa, and
Eff = assumed efficiency of the motor = 0.5.

The power required to operate the pump was determined to be 0.6 kilowatt. A 0.75-kilowatt motor to be operated at 1725 rpm was selected to power the pump.

Other equipment needed to complete construction of the experimental direct injection sprayer included:

1. Two check valves to keep contaminated chemical and water from flowing back into their respective tanks,
2. A 19-millimeter nylon strainer with a pressure rating of 760 kilopascals and a flow rate capacity of 87 liters per minute,
3. A 19-millimeter pressure relief valve with a maximum pressure capability of 2,000 kilopascals,
4. A liquid-filled pressure gage with a range of 0 to 1,400 kilopascals, and
5. Spraying Systems (1987) QJ-100 series nozzle bodies equipped with the recommended strainers.

A pressure transducer, rated at 1,400 kilopascals, was installed at the boom. The transducer was monitored by an IBM PC Data Acquisition and Control Adapter which was connected to an IBM personal computer.

There are two distinct differences between a chemical injection sprayer and a conventional sprayer. The direct injection unit has an injection pump and more conduit fittings for connecting the injection pump into the fluid circuit of the sprayer. Another major difference is that the pressure relief return line on the direct injection system is not directed back into the diluent tank as it typically is for a conventional sprayer (see Figure 1). On the direct injection sprayer the return line is directed back to a point just upstream of the system pump, as shown in Figure 2. The reason for this is that, once the fluid has gone through the pump, it is contaminated with chemical and cannot be returned to the diluent tank.

Injection Pumps

To insure that an accurately metered quantity of chemical is being delivered at a constant rate, a positive displacement pump was needed as the injection device. Criteria considered in selecting the injection pump included 1) chemical formulation, 2) ground speed of the sprayer, 3) number of nozzles, 4) nozzle spacing, and 5) desired application rate. The typical range of chemical formulation rates and machine operating speeds of a sprayer were used for this experiment. The accommodated application rate range was from 0.60 to 9.4 liters of chemical concentrate per hectare, and the speed of the sprayer ranged from 4.8 to 11.3 kilometers per hour. As indicated previously, the boom was equipped with nine nozzles spaced 0.51 meter apart. The volumetric flow rate of chemical formulation injected into the conduit of the sprayer was determined by calculating the rate of chemical to be applied

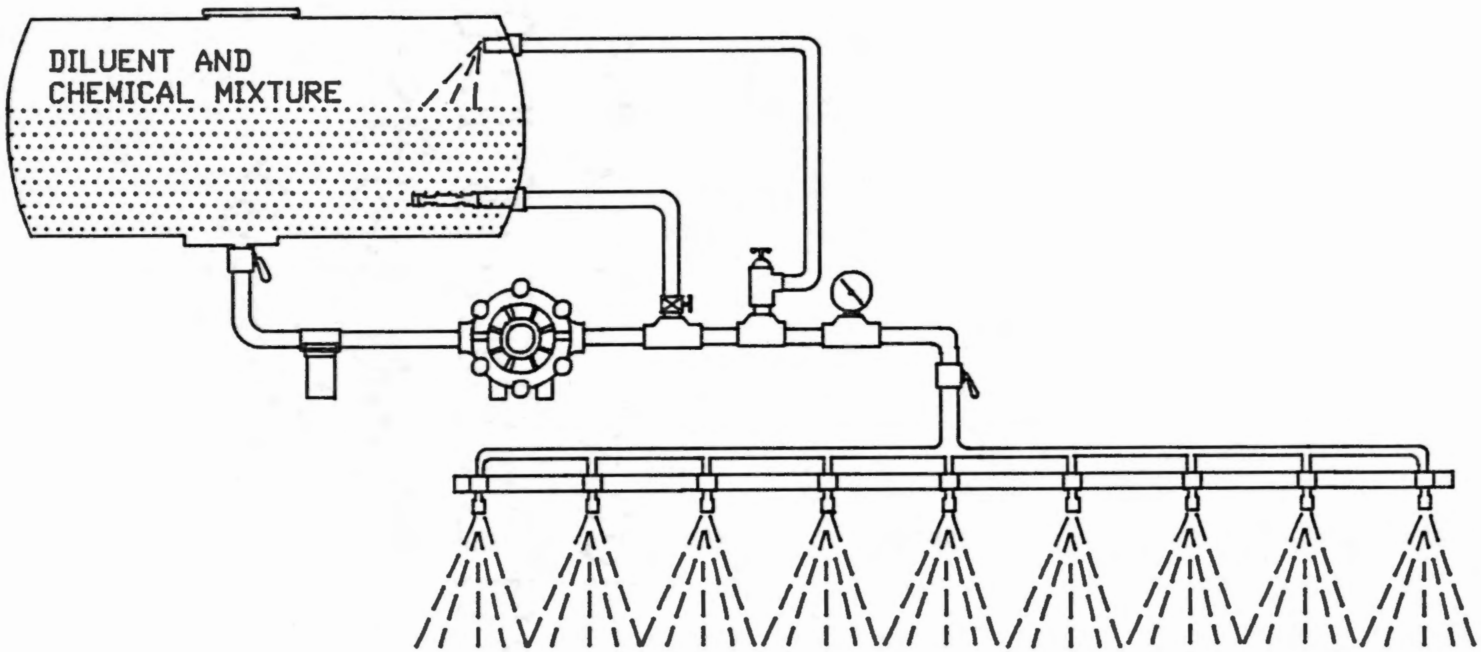

Figure 1. Layout of the fluid handling and transport components on a typical conventional hydraulic sprayer.

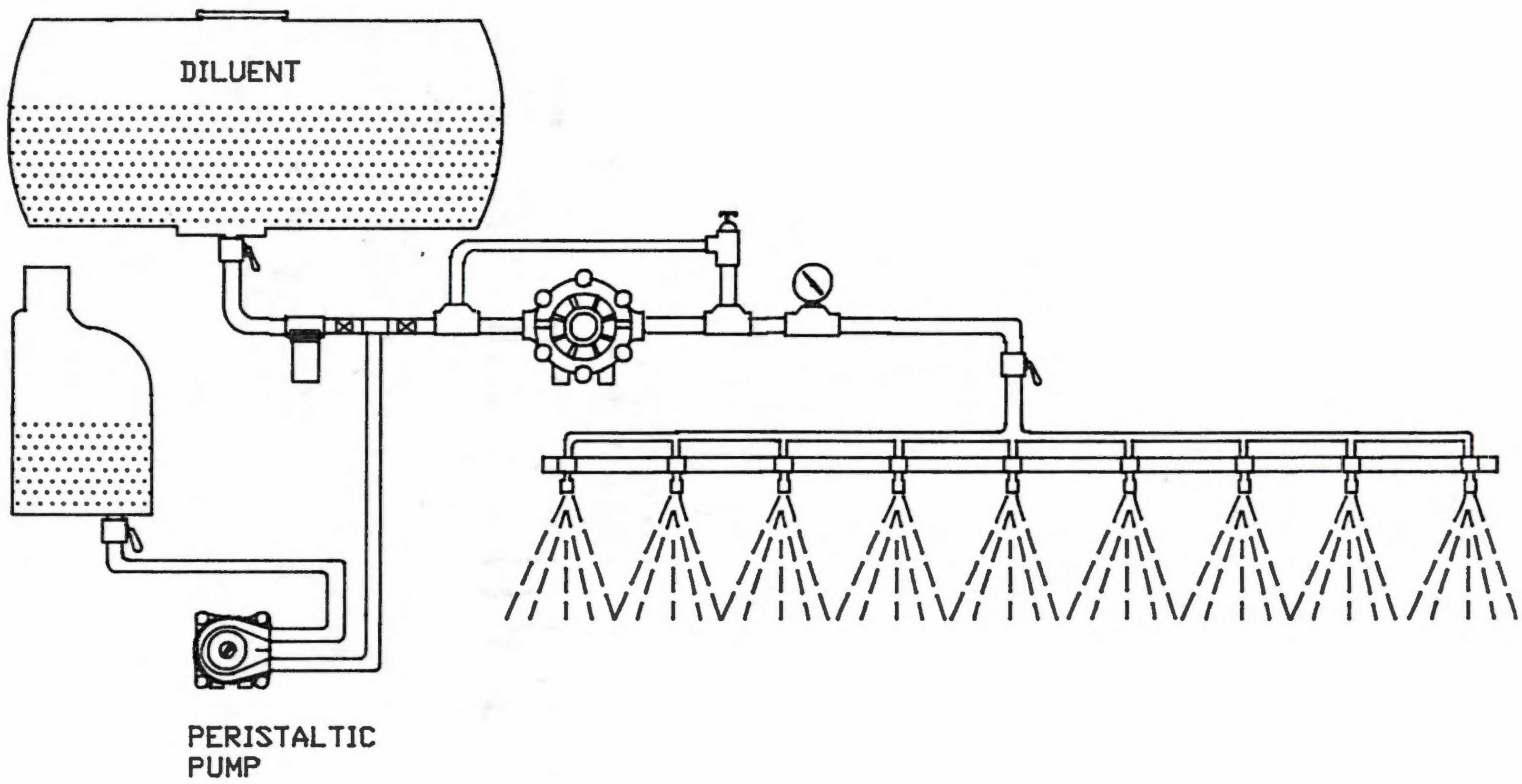

Figure 2. Layout of the fluid handling and transport system components on an experimental hydraulic sprayer employing direct chemical injection at a point immediately upstream of the sprayer system pump.

per unit area. The equation used in calculating this injection rate was expressed as follows:

$$Q = F * W * S * N * 1.67 \qquad \text{Eqn. [5]}$$

where:

Q = Flow rate of injected chemical concentrate, ml/min,
F = Chemical concentrate application rate, L/ha,
W = Nozzle spacing, m,
S = Speed of the sprayer, km/hr, and
N = Number of nozzles.

An application rate of 0.6 liter per hectare at a speed of 4.8 kilometers per hour was determined to require a flow rate of 22 milliliters per minute. For 9.4 liters of chemical concentrate per hectare at a speed of 11.3 kilometers per hour, the required flow rate was 814 milliliters per minute.

Peristaltic Pump

A Master Flex™ peristaltic pump model number J-7015-20 (Figure 3), manufactured by Cole-Parmer Instrument Company, was used for chemical injection on the upstream side of the sprayer system pump. This pump has a flow capacity of 10 to 1000 milliliters per minute when using a 6 to 600 revolutions per minute motor. The pump was driven by a stepper motor rated at 200 steps per revolution. The motor was powered through a transformer, and the speed was controlled by a frequency generator. The motor drive circuit was monitored and controlled by an IBM PC Data Acquisition and Control Adapter. The system was operated by a BASIC language program designed to control the stepper motor. This pump could only be used during the low-pressure injection studies since

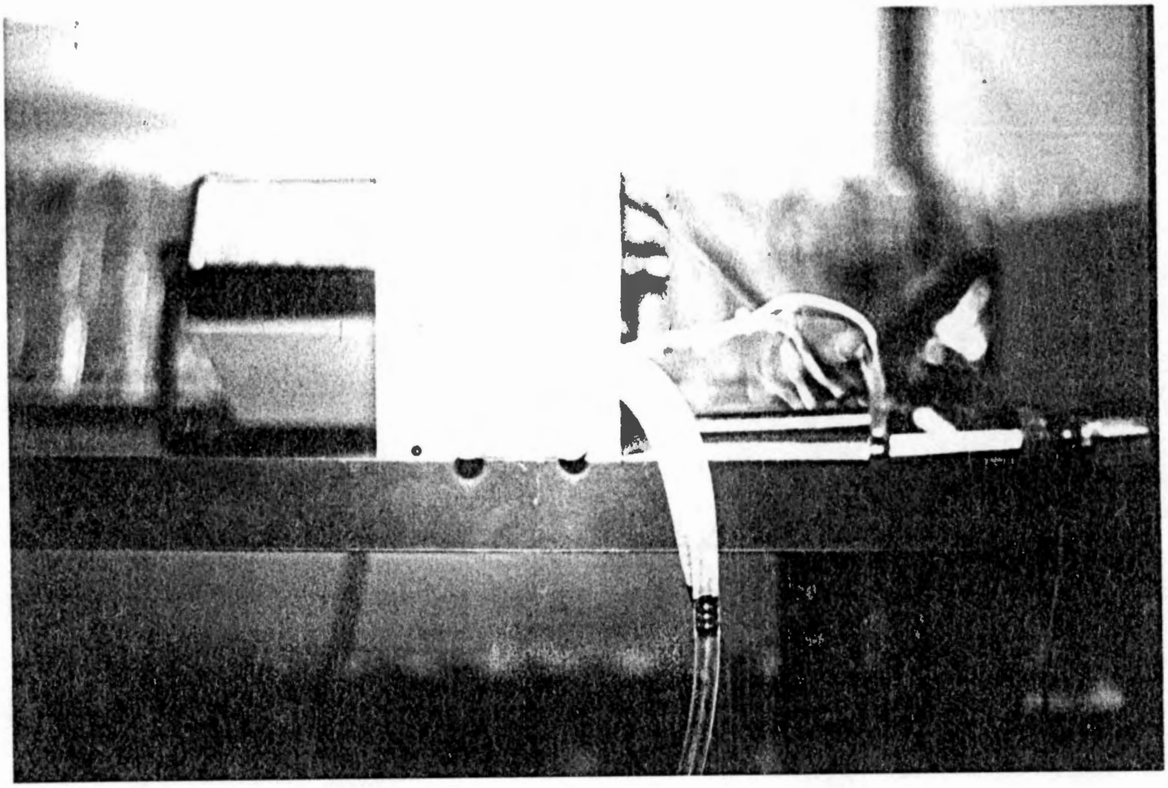

Figure 3. Master Flex^{TM} peristaltic pump, manufactured by Cole-Parmer Instrument Company, used for direct chemical injection on the low-pressure side of the sprayer system pump.

its pressure capability was inadequate for injecting on the downstream side of the sprayer system pump.

Scienco Experimental Piston Pump

An experimental pump designed and manufactured by Scienco Inc. specifically for high-pressure direct injection systems was obtained for performance and evaluation studies with the laboratory direct injection system. This pumping unit consisted of a piston pump built inside a fluid holding tank, a calibration cylinder located on top of the fluid holding tank, and a piston stroke length adjustment for setting pump discharge rate. Each pump unit accommodates one concentrated chemical. The pump is calibrated for that chemical and is subsequently used only with that chemical. The tank for each unit will hold 18 liters of fluid.

A calibration stand was built by the manufacturer for use by the applicator to calibrate the piston pump to the appropriate application rate. This calibration stand had an electric motor with couplings to connect the piston pump to the stand. A counter on the stand indicated the number of revolutions of the piston pump. To calibrate this piston pump, the operator connected the unit to the calibration stand and pulled the handle on top of the calibration cylinder, allowing pump flow to move into the calibration container. The operator must know the number of revolutions the sprayer drive wheel makes to cover a given area. The pump itself makes one revolution for each revolution of the drive wheel. When the calibration process is started, the fluid that is discharged from the pump goes directly into the calibration cylinder.

The operator stops the fluid flow when the pump has discharged enough chemical to cover the designated area. The fluid collected in the cylinder is the quantity that will be sprayed for the specified travel distance. If necessary, the operator can then adjust the stroke of the pump to obtain the appropriate application rate. After each calibration check, the operator again pushes down the handle located on top of the calibration cylinder so that the fluid in the calibration cylinder is returned to the holding tank. This means the operator can calibrate the injection pump and without coming into physical contact with the chemical concentrate.

The calibration stand was used to operate the pump in the laboratory. This Scienco piston pump was used for testing at all three points of injection considered in the laboratory study. The unit is illustrated in Figure 4.

Fluid Metering Piston Pump

A piston pump manufactured by Fluid Metering Inc. (FMI) was obtained from Ciba-Geigy Corporation for use in evaluating the various direct injection systems and to compare with the Scienco pump. This pump can be connected directly into the electrical system of a typical agricultural tractor, but was operated by a 12-volt power supply in the laboratory. The capacity range of this pump is from 0 to 750 milliliters per minute. This pump was also used for chemical injection at all three designated points on the laboratory sprayer. The FMI pump is illustrated in Figure 5.

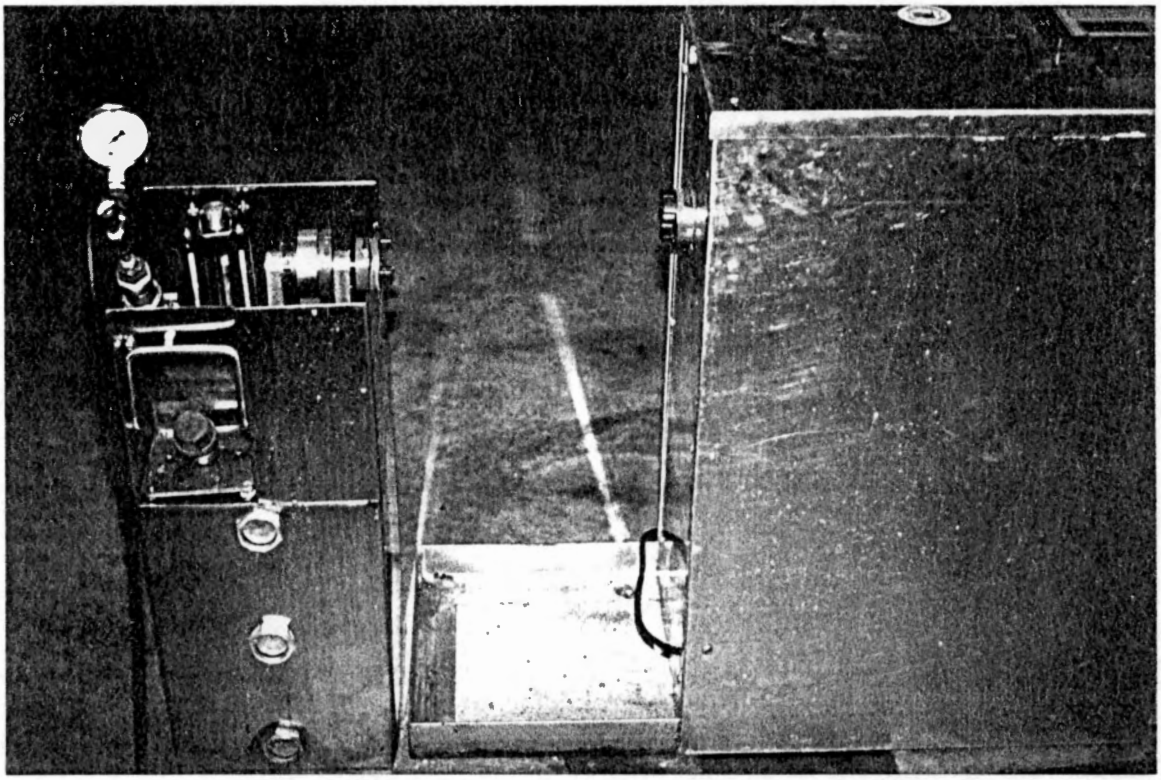

Figure 4. Scienco Inc. piston pump and calibration stand used for direct chemical injection at both low-pressure and high-pressure sides of the sprayer system pump.

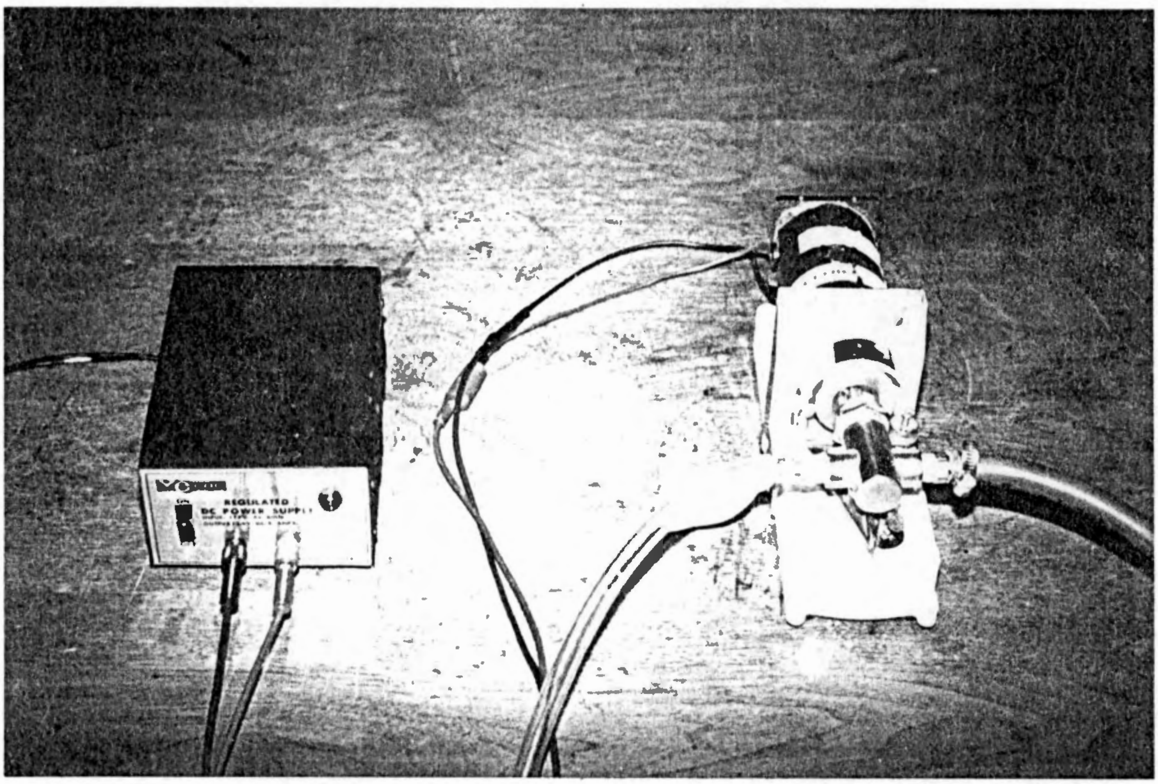

Figure 5. Fluid Metering Inc. piston pump and power supply used for chemical direct injection at both low-pressure and high-pressure sides of the sprayer system pump.

Method for Measuring Chemical Concentration

Several methods have been used by various researchers to measure the concentration of chemical in the mix produced by the direct injection procedure. Cho et al. (1985) injected a salt solution and then dried the samples that were collected from the effluent from each nozzle. Dried samples were then weighed, and weights of the samples were related to the chemical concentration in the spray; the heavier the residue sample, the higher the concentration. This method of measuring the chemical concentration in effluent samples took more than a day to complete due to the drying process.

Larson et al. (1982) used a Spectronic 20 colorimeter to measure chemical concentration. The colorimeter measured the color intensity of the solution, and readings were made at the wavelength of the most strongly absorbed radiation (Pesez and Bartos, 1974). The intensity of the color increased with increasing concentration of the colored species. The absorption of a particular wavelength was then related to concentration by using a calibration curve prepared based upon known amounts of the compound under the same conditions.

A more sensitive method for measuring absorption involves use of a fluorimeter. Koo et al. (1987) injected a fluorescent dye (Rhodamine B) and connected a fluorimeter to the boom. The fluorimeter measured the intensity of the emitted light from the effluent (Pesez and Bartos, 1974). Intensity increased as concentration increased. The fluorimeter reading was related to concentration through use of a calibration curve similar to that used in colorimetric measurement. Vidrine et al. (1975) also used a fluorimeter.

In selecting a method for measuring chemical concentration, one requiring less time to complete than the salt solution technique described by Cho et al. (1985) was sought. Further, a technique which eliminated the extensive system cleaning required following use of a fluorescent dye was considered very desirable. A potassium bromide solution was selected to represent the simulated pesticide concentrate to be injected into the sprayer conduit. The selection of potassium bromide was based upon a study conducted by Bruce et al. (1985). In this study bromide was applied to the surface of soil for the purpose of assigning solute transport characteristics. Potassium bromide is a white granular material with a specific gravity of 2.75. One gram will readily dissolve in 1.5 milliliters of water. The aqueous solution is pH neutral. Large doses of potassium bromide will cause central nervous system depression, and prolonged intake may cause mental deterioration and acne-torn skin eruptions. The material is used in the manufacturing of photographic papers and plates and in process engraving. Therapeutic applications of potassium bromide include uses as a sedative and an anticonvulsant (Windholz et al. 1983).

A solution of 28.3 grams of potassium bromide per liter of distilled water was injected into the conduit of the sprayer. The effluent of each nozzle was simultaneously sampled. The sampling was accomplished by building a frame that held 9 rows of 12 cans each, evenly spaced across so the effluent from each nozzle would be discharged into a can for some time interval (Figure 6). The boom was

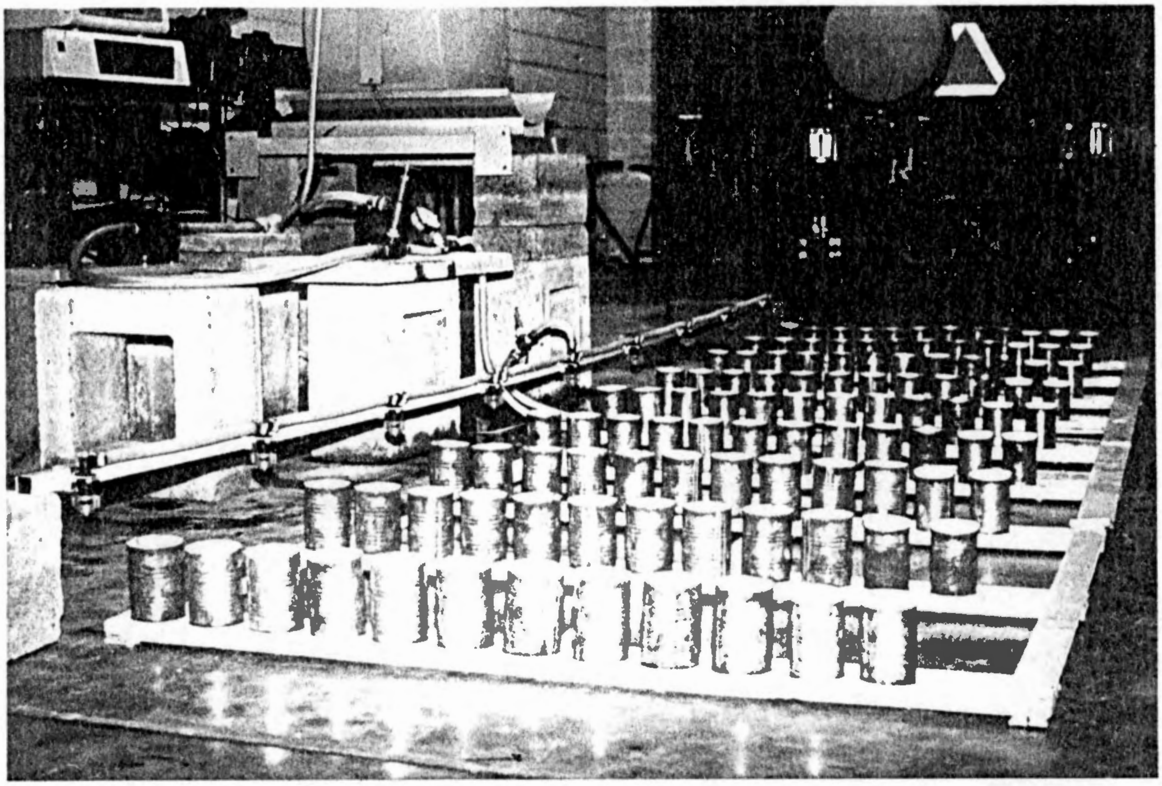

Figure 6. Laboratory setup including the experimental direct injection sprayer and sampling system.

manually moved so that the total discharge of each nozzle could be caught in individual cans. The potassium bromide concentration in each sample was measured with a conductivity meter. The instrument selected was a field conductivity meter manufactured by Cole-Parmer Instrument Company (Figure 7). Its range was 0 to 20,000 micromhos per centimeter in five ranges, with an accuracy of 2.0 percent of full scale. Measured conductivity of the solution was then converted to chemical concentration by using an empirical equation that was derived based upon a calibration procedure conducted on the meter before each test run. Each sample takes only approximately 30 seconds to process. Since the meter was calibrated for each test run, all of the equations are not shown. However, each equation had a coefficient of determination (R^2) value of nearly 1.00. A graph of conductivity meter readings versus chemical concentrations for a typical calibration is illustrated in Figure 8.

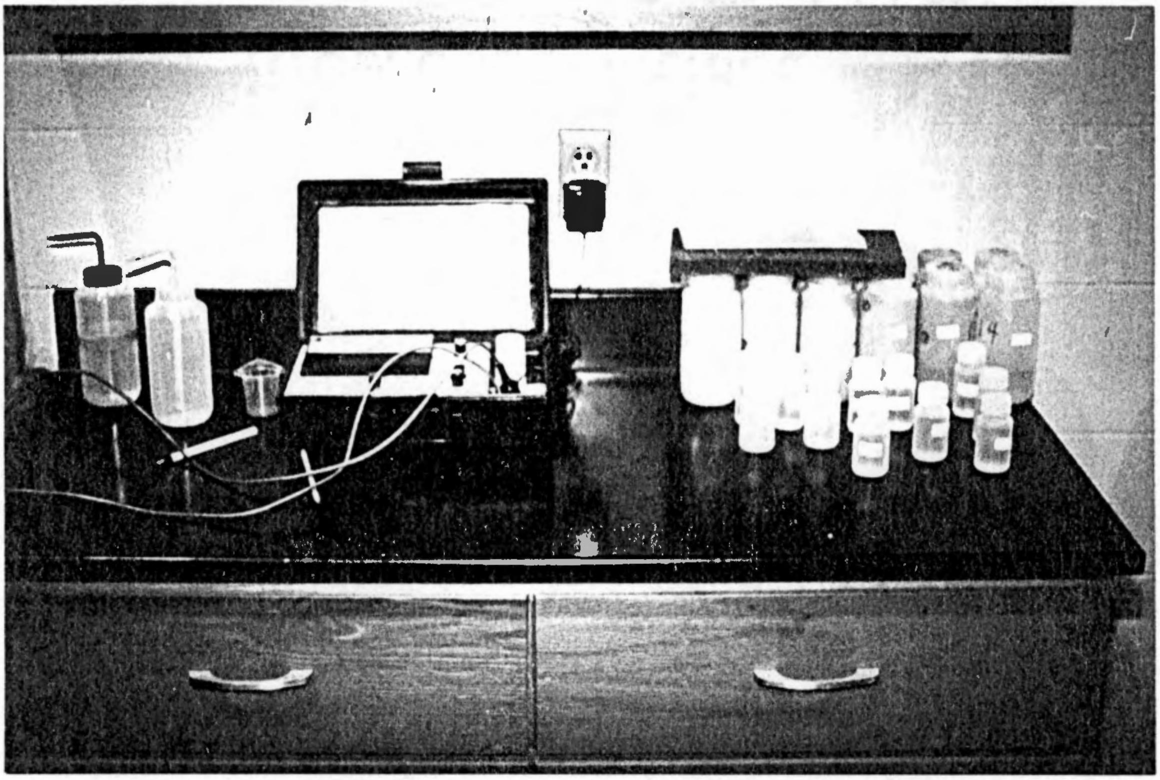

Figure 7. Field conductivity meter for measuring chemical concentration in the nozzle effluent.

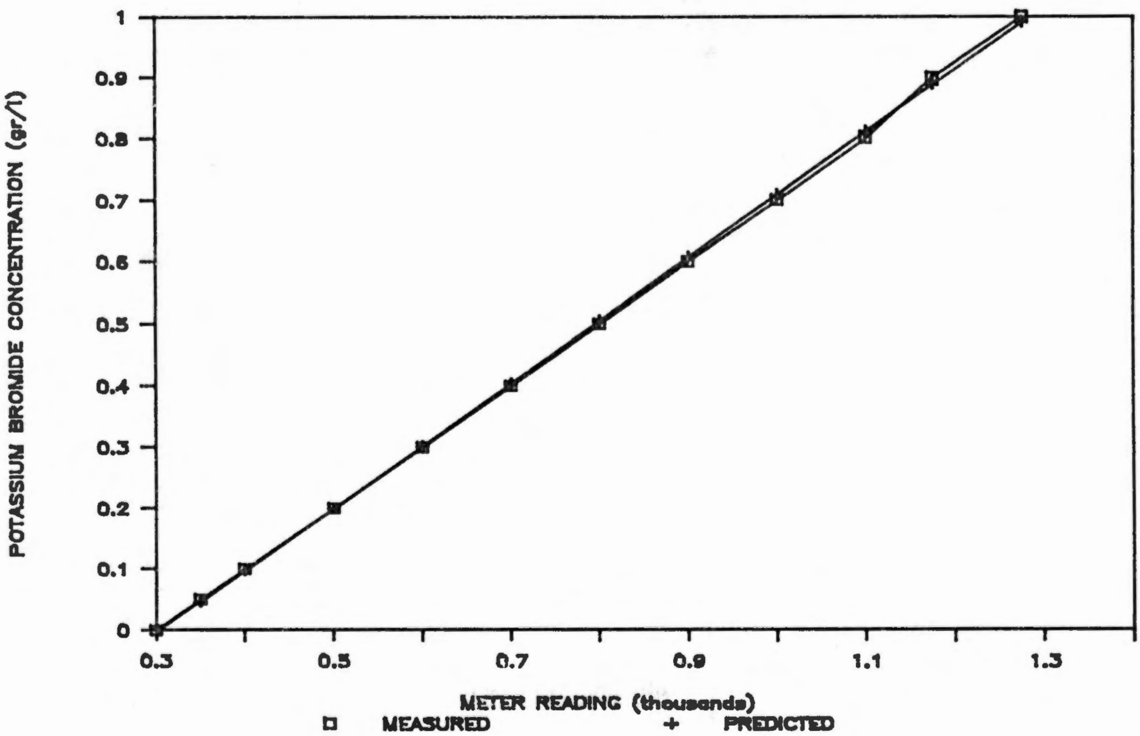

Figure 8. Comparison of actual potassium bromide concentrations and predicted concentrations based upon conductivity meter readings. Comparison is typical of all calibrations performed.

CHAPTER IV

RESULTS AND DISCUSSION

Computer Model

A computer model to simulate fluid flow characteristics in a direct injection boom-type sprayer was developed. The model calculated predicted transient time of chemical-laden fluid travel from instant of injection to arrival at each nozzle. The model also determined the forward distance traveled by the sprayer during the fluid transient period. This model is applicable to any injection sprayer having the injection point on the low-pressure side of the sprayer system pump and for any quantity and capacity of Spraying Systems Co. (1987) TeeJet flat fan nozzles.

Algorithm

The interactive model first required the user to input the following parameters:

1. Manufacturer's nozzle number designation,
2. Machine ground speed (m/sec),
3. System operating pressure (kPa),
4. Diameter of the hose feeding individual nozzles (mm),
5. Nozzle spacing along the boom (m),
6. Number of nozzles along the boom,
7. Diameter of the leader hose supplying the boom (mm), and
8. Length of the leader hose supplying the boom (m).

The manufacturer's nozzle designation nomenclature is such that a flow rate for a 275-kilopascal operating pressure is clearly indicated by the number on the nozzle. The nozzle orifice coefficient can be calculated based upon this flow rate and the 275-kilopascal designated pressure. The nozzle orifice coefficient is a proportionality constant relating flow rate and pressure for a given orifice. The nozzle coefficient is typically expressed as follows:

$$K = Q / P^{1/2} \quad \text{Eqn [6]}$$

where:

K = nozzle coefficient, $L/(min\text{-}(kPa)^{1/2})$,
Q = flow rate of the nozzle, L/min, and
P = pressure drop across the orifice, kPa

The nozzle coefficient computed using this expression was then used in subsequent calculations to determine flow rates at other operating pressures.

Flow velocity within the leader hose was then calculated using the continuity equation (Eqn. 1, page 29). Since the leader hose was in two sections with different cross-sectional dimensions and lengths, parameters used in the model included the diameters and lengths of both the leader hose extending from the injection point to the pressure regulator and the leader hose connecting the pressure regulator to the entrance of the boom.

When the velocity of the fluid in the leader hose has been calculated by the model, the user may select among the following options: 1) graphs to be plotted, 2) input new parameters, or 3) end the program. The graph selection options are:

1. A plot of the nozzle designation by position on the boom versus the travel time (transient period) of the fluid from instant of injection to arrival at the specified nozzle,
2. A plot of the nozzle designation by position on the boom versus the travel time of the fluid from the time of fluid entrance into the boom to arrival at specified nozzle,

3. A plot of the nozzle designation by position on the boom versus the distance traveled by the sprayer when travel time is measured from the initiation of chemical injection into the system until arrival of chemical at the specified nozzle, and
4. A plot of the nozzle designation by position on the boom versus the distance traveled by the sprayer when travel time is measured from the time of fluid entrance into the boom until arrival at the specified nozzle.

When the desired graph is chosen by the user, the program proceeds to the proper subroutine and performs the necessary calculations. After the time interval required for the fluid to travel to each nozzle and the distance traveled by the sprayer are calculated, the program then proceeds to the graphics routine which will present the calculated values in graphical form. Once the graph is completed, the user can choose to obtain a hard copy by sending the results to the printer.

Two assumptions were made in developing this model. First, the velocity of the fluid in the boom was calculated using the continuity equation. In this equation, the volumetric flow rate (Q) is the product of the number of nozzles on the boom and the flow rate through a single nozzle. In this model, the assumption was made that the velocity along the boom will decrease after each nozzle has been passed because the number of escape paths for the fluid has decreased. Secondly, the point at which the fluid is introduced into the boom was assumed to be at the middle nozzle for an odd number of nozzles and between the middle two nozzles for an even number of nozzles. A complete listing of the program algorithm is included in Appendix B.

Model Validation

Tests were conducted to validate or verify the computer model describing flow in the direct injection system illustrated in Figure 2 (page 34). First, the computer model was used to calculate the predicted transient time based upon the input parameters listed in Table 3. Next, five tests were conducted in the laboratory. Samples were taken each second from the time the potassium bromide tracer was initially injected into the conduit of the sprayer until it was detected at each nozzle. The injection rate of potassium bromide solution was 4.53 milliliters per second, and the nozzle pressure was maintained constant at 275 kilopascals. The arithmetic average of transient times was calculated for each nozzle. Results are presented in Table 4 along with the values predicted by the computer model. A graph of the nozzle designation by position on the boom versus both the measured and the predicted transient times is shown in Figure 9. The error between the measured and the predicted transient times was calculated for each nozzle using the equation:

$$E = \frac{Fm - Fp}{Fp} * 100 \qquad \text{Eqn [7]}$$

where:

E = Error, percentage,
Fm = Measured transient time, (sec), and
Fp = Predicted transient time, (sec)

The largest error between the measured and the predicted transient time values occurred at either end nozzle and was calculated to be 17.9 percent. This error could be due, in part, to the fact that each sample was not taken for exactly the one-second sampling interval. However, the fact that the margin between the two curves is symmetrical about the center nozzle suggests that the error is more systematic in nature.

Table 3. Input parameters for validation of the computer model developed to predict the transient time of fluid travel for a direct injection boom-type sprayer with the injection point located on the upstream side of the sprayer system pump.

Manufacturer's nozzle number	=	8004
Machine ground speed	=	1.65 m/sec
System operating pressure	=	275 kPa
Diameter of hose supplying nozzles on the boom section	=	13 mm
Nozzle spacing along the boom	=	0.51 m
Number of nozzles along the boom	=	9
Diameter of leader hose from injector to regulator	=	19 mm
Length of leader hose from injector to regulator	=	1.57 m
Diameter of leader hose from regulator to boom	=	13 mm
Length of leader hose from regulator to boom	=	1.98 m

Table 4. Measured and predicted transient times for fluid travel in a direct injection boom-type sprayer with the injection point on the upstream side of the sprayer system pump and the operating pressure maintained at 275 kPa.

Position on the Boom	Measured Transient Time (sec)	Predicted Transient Time (sec)
1	7.00	5.94
2	4.80	4.62
3	4.00	3.95
4	3.40	3.51
5	2.80	3.18
6	3.40	3.51
7	4.00	3.95
8	4.80	4.62
9	7.00	5.94

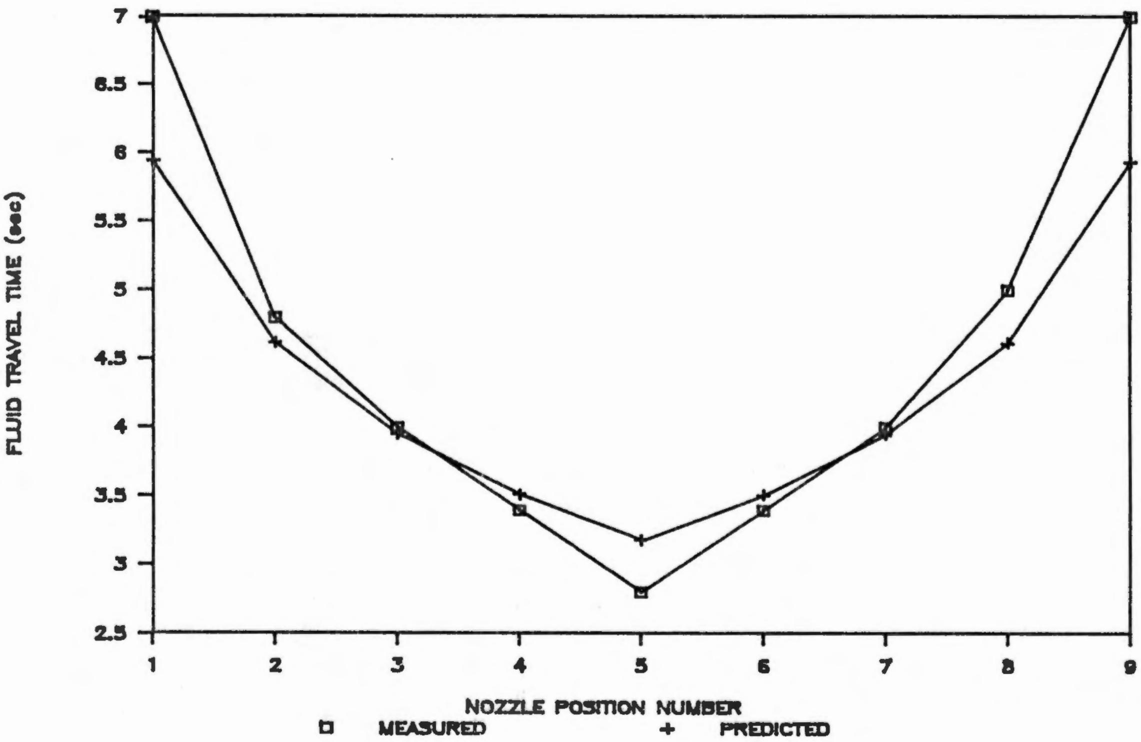

Figure 9. Measured and predicted transient times for fluid travel in a direct injection boom-type sprayer with the injection point at the upstream side of the sprayer system pump and the operating pressure maintained at 275 kPa.

The validity of the nozzle coefficient equation was questioned. In particular, the pressure term raised to the one-half power is apparently not always valid for flat fan nozzles. In an extensive calibration check of this system, nozzle flow rates at pressures ranging from 138 to 414 kilopascals were measured. Results from the calibration check were tabulated, and the least squares method for power curve fitting was used to determine the nozzle coefficient and the power term for the pressure. The nozzle coefficient was calculated to be 0.114 $L/(min\text{-}(kPa)^{1/2})$, and the power term for pressure was calculated to be 0.4539. These results differ from the nozzle coefficient value of 0.0913 $L/(min\text{-}(kPa)^{1/2})$ calculated using Equation 6 (page 48), which presumes an exponent of 0.5 for the pressure term. When the new, empirically-determined equation was used for predicting the transient times, the shape of the prediction curve did not change when compared to that resulting from the use of Equation 6 (page 48). However, the prediction curve was moved upward.

Another potential source of error in the model is associated with the conduits used in the sprayer system. These hoses were not rigid and may have expanded under pressure. Such expansion would have changed the cross sectional area, resulting in erroneous values from the continuity equation. Inputting different conduit sizes to the model does in fact change the shape of the prediction curve resulting in better fits. However, no attempt was made to quantify the actual change in conduit diameter.

Low-Pressure Injection Upstream of System Pump

Transient Time

Tests were conducted to determine the time interval from initiation of injection to attainment of full chemical concentration in the effluent at each nozzle along the boom. The sprayer system layout for these initial tests was identical to that used in tests associated with validation of the model (see Figure 2, page 34). In subsequent tests with the Scienco and the FMI piston pumps, the same layout was retained with the exception that the appropriate pump was substituted for the peristaltic unit. System pressure monitored just downstream of the pressure regulator was maintained constant at 275 kilopascals. Nozzle designation by location along the boom is illustrated in Figure 10. Figures 11 and 12 show that the nozzle effluent from the system equipped with the peristaltic pump reached full concentration at the outermost nozzle positions in 29 seconds. Injection rate was 4.53 milliliters of potassium bromide solution per second. Figure 11 shows the transient times for nozzles 1 through 5, and Figure 12 shows the transient times for nozzles 5 through 9. Nozzle 5 was the middle nozzle and the point of fluid entrance to the boom.

Transient times for the peristaltic pump were markedly greater than those resulting from the use of either the Scienco or the FMI piston pumps. Injection rates were 4.81 and 4.79 milliliters per second, respectively, for the two piston pumps. Figures 13 and 14 show that the Scienco pump produced full chemical concentration in the nozzle effluent in 24 seconds, and Figures 15 and 16 show that the FMI pump

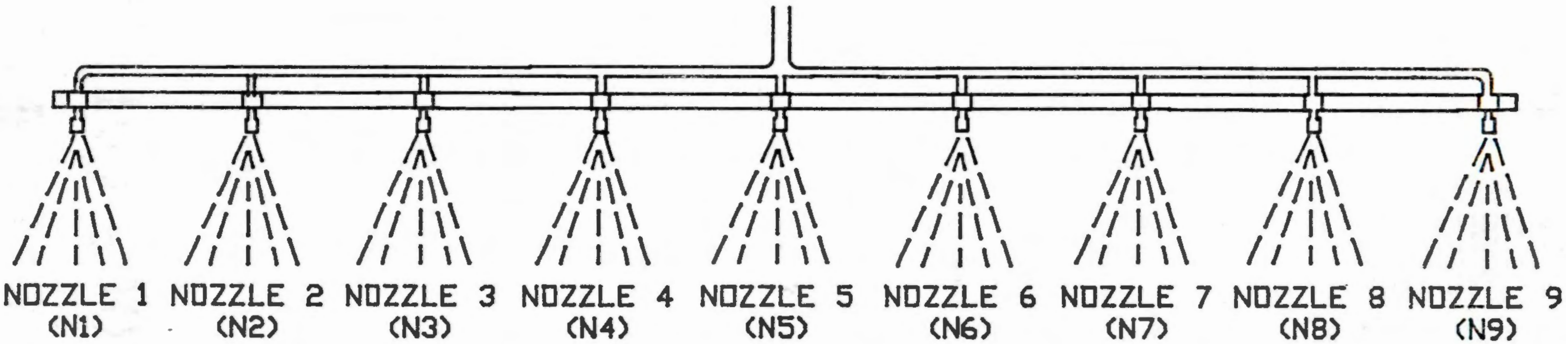

Figure 10. Nozzle designation by location along the sprayer boom.

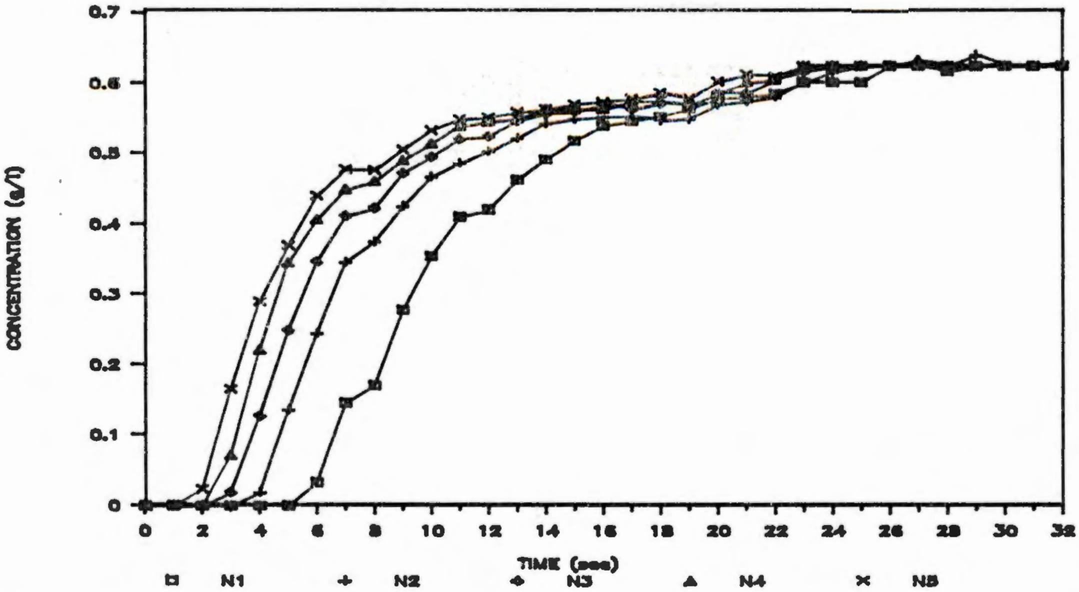

Figure 11. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the peristaltic pump was immediately upstream of the system pump. Injection began at time = 0, and system pressure was 275 kPa.

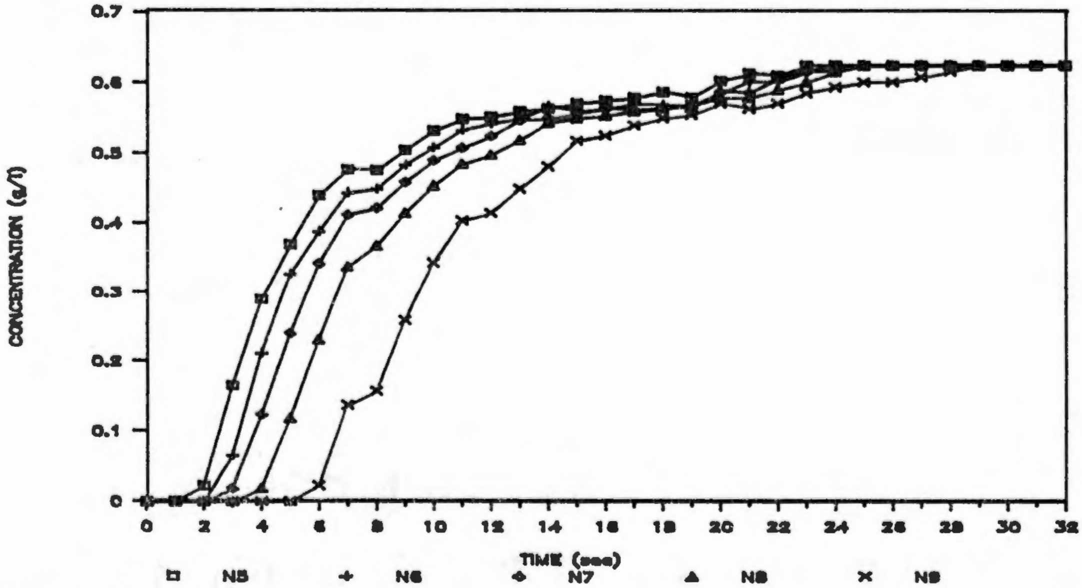

Figure 12. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the peristaltic pump was immediately upstream of the system pump. Injection began at time = 0, and system pressure was 275 kPa.

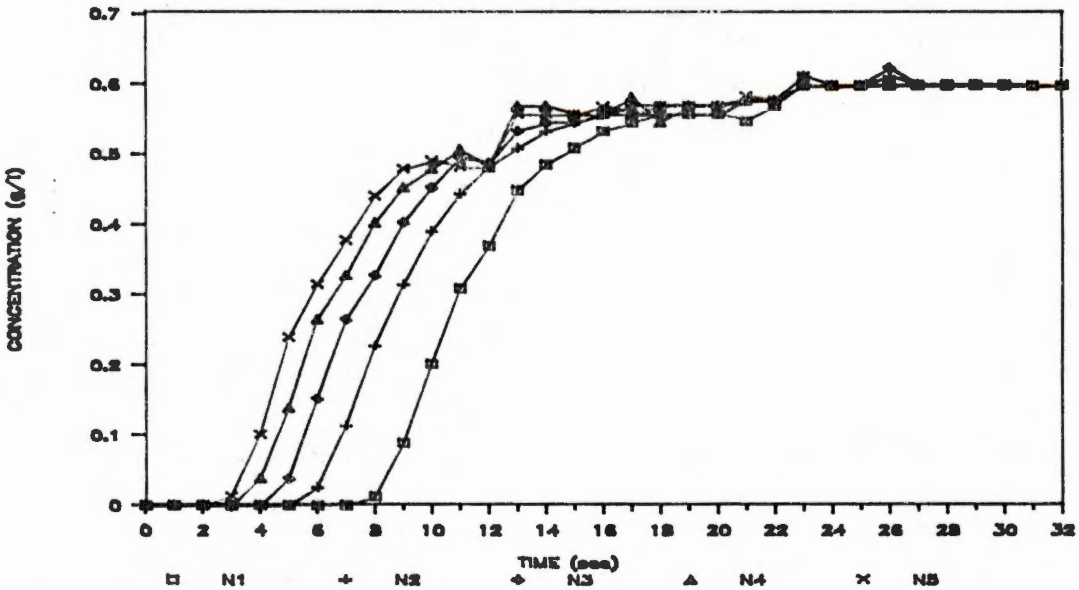

Figure 13. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the Scienco pump was immediately upstream of the system pump. Injection began at time = 0, and system pressure was 275 kPa.

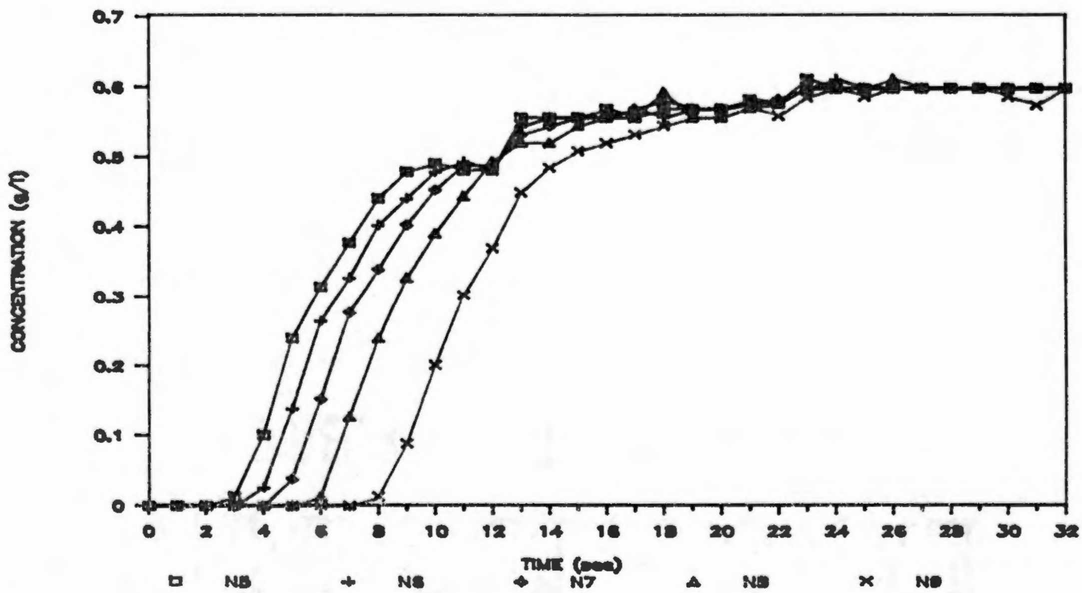

Figure 14. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the Scienco pump was immediately upstream of the system pump. Injection began at time = 0, and system pressure was 275 kPa.

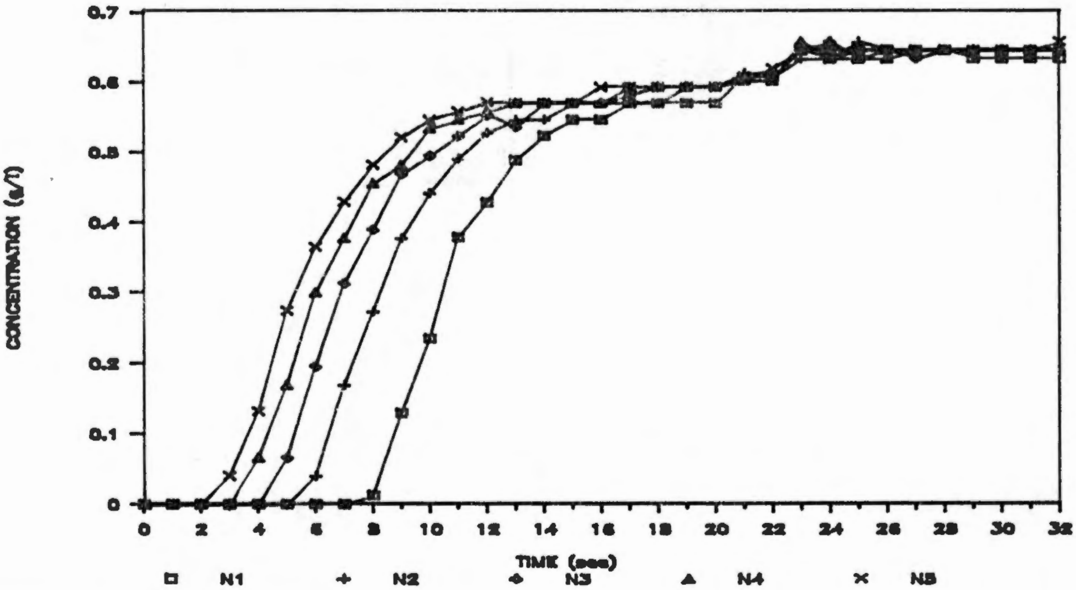

Figure 15. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the FMI pump was immediately upstream of the system pump. Injection began at time = 0, and system pressure was 275 kPa.

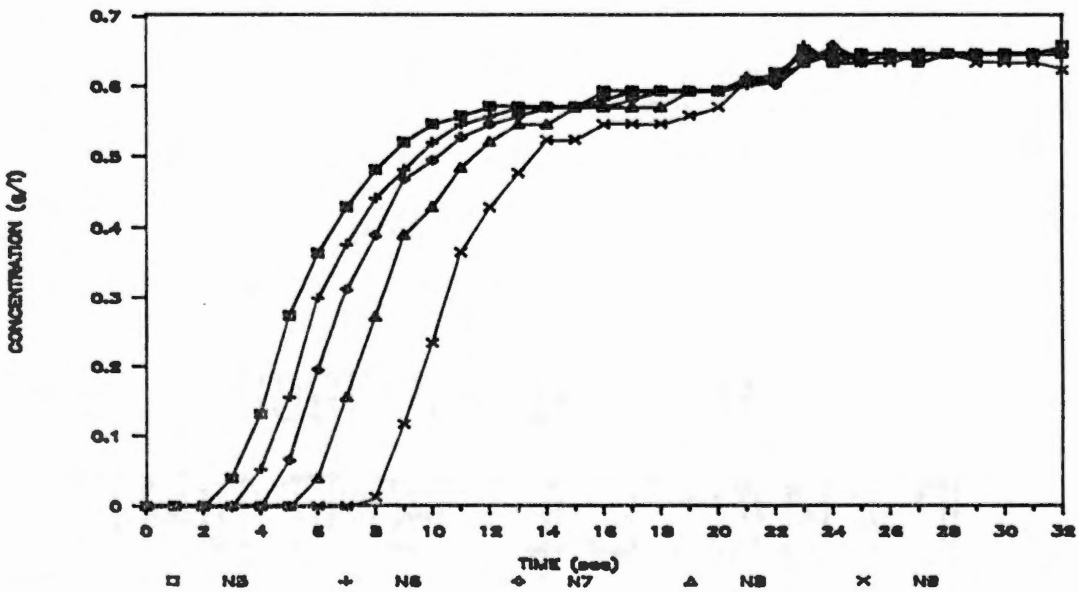

Figure 16. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the FMI pump was immediately upstream of the system pump. Injection began at time = 0, and system pressure was 275 kPa.

produced similar results in 23 seconds. The speed of the FMI pump, 2185 revolutions per minute, produced chemical injection flow which appeared to be a smooth stream, absent of obvious pulses. On the other hand, fluid pulses in the output of the Scienco pump, which operated at 285 revolutions per minute, were clearly visible by observation. Similarly, the peristaltic pump also produced pulsed output flow at its selected operating speed of 150 revolutions per minute. Even though the two piston pumps had shorter transient periods, the peristaltic pump produced a consistent output once full concentration was obtained (see Figures 11 and 12).

Concentration Uniformity

When evaluating the uniformity of chemical concentration in the effluent both from nozzle to nozzle and with time, the system was operated with the same chemical injection rates for the various pumps as was listed in the previous section and with the fluid pressure maintained constant at 275 kilopascals. Nozzle effluent samples collected for a duration of five seconds each were taken at one-minute intervals.

Results presented in Figures 17 and 18 show that the system with the peristaltic pump had a maximum variation of 0.013 grams per liter, or 2.3 percent of the average concentration. Furthermore, the concentration tended to be more consistent with time than from nozzle to nozzle. Figures 19 and 20 show the results produced with the Scienco pump. The variation in concentration was somewhat larger than with the peristaltic pump. The maximum difference in chemical concentration was

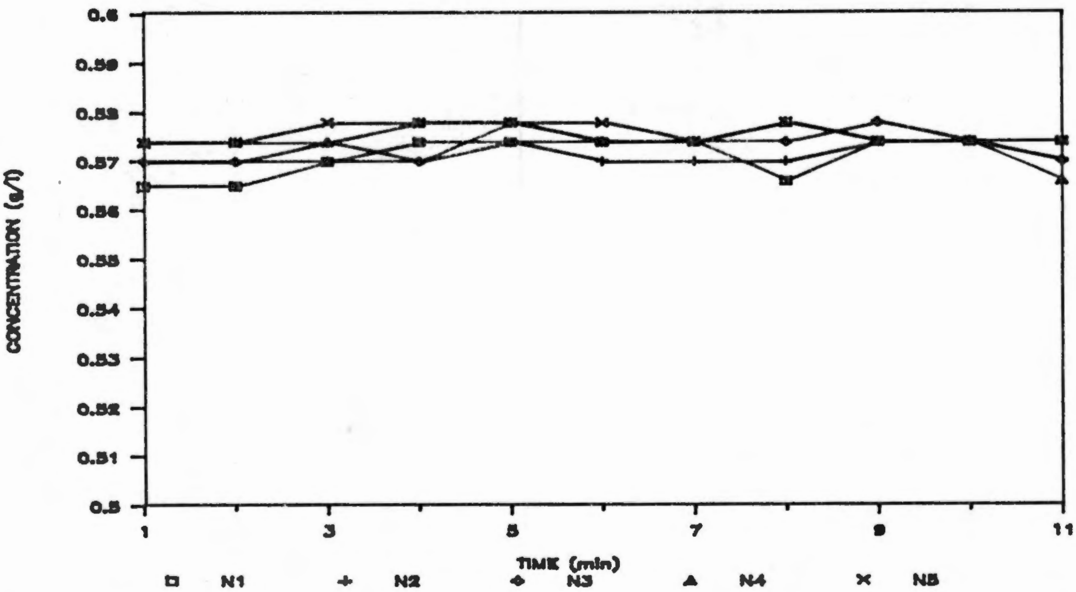

Figure 17. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the peristaltic pump was immediately upstream of the system pump. Sampling began at time = 1 min, and system pressure was 275 kPa.

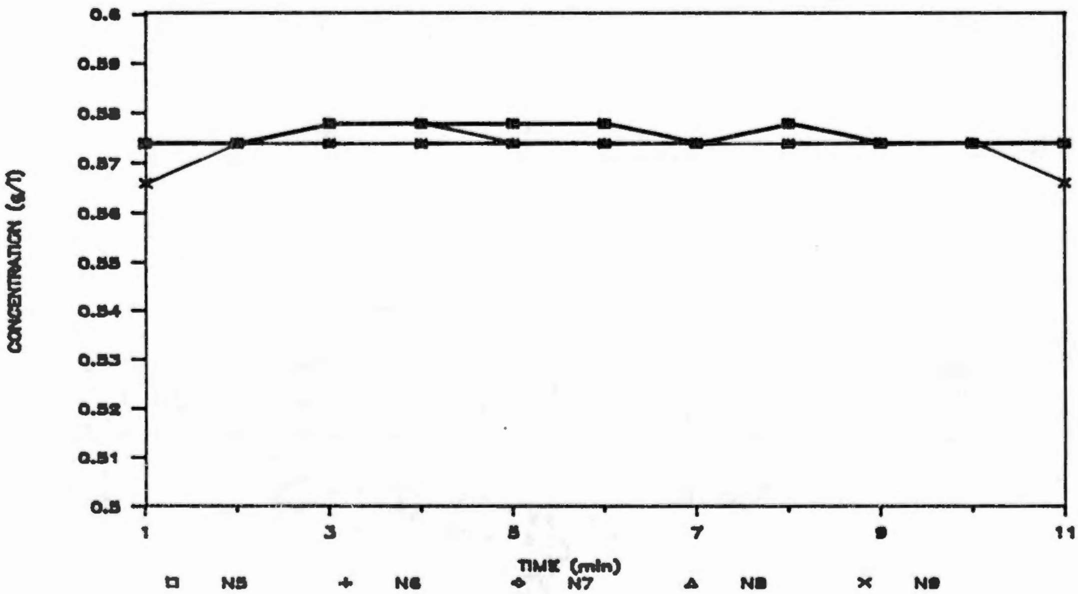

Figure 18. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the peristaltic pump was immediately upstream of the system pump. Sampling began at time = 1 min, and system pressure was 275 kPa.

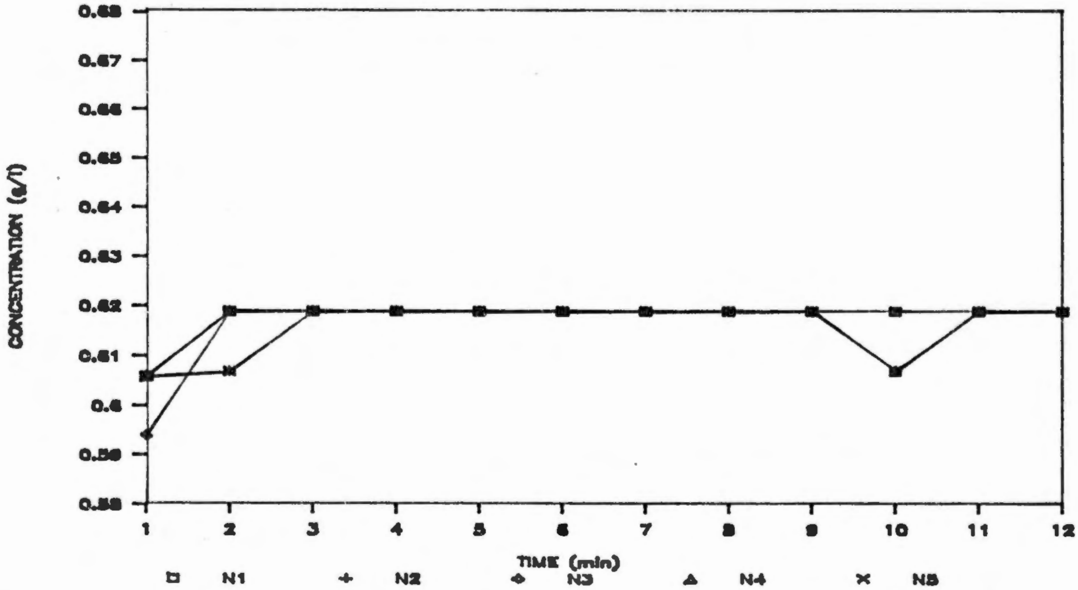

Figure 19. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the Scienco pump was immediately upstream of the system pump. Sampling began at time = 1 min, and system pressure was 275 kPa.

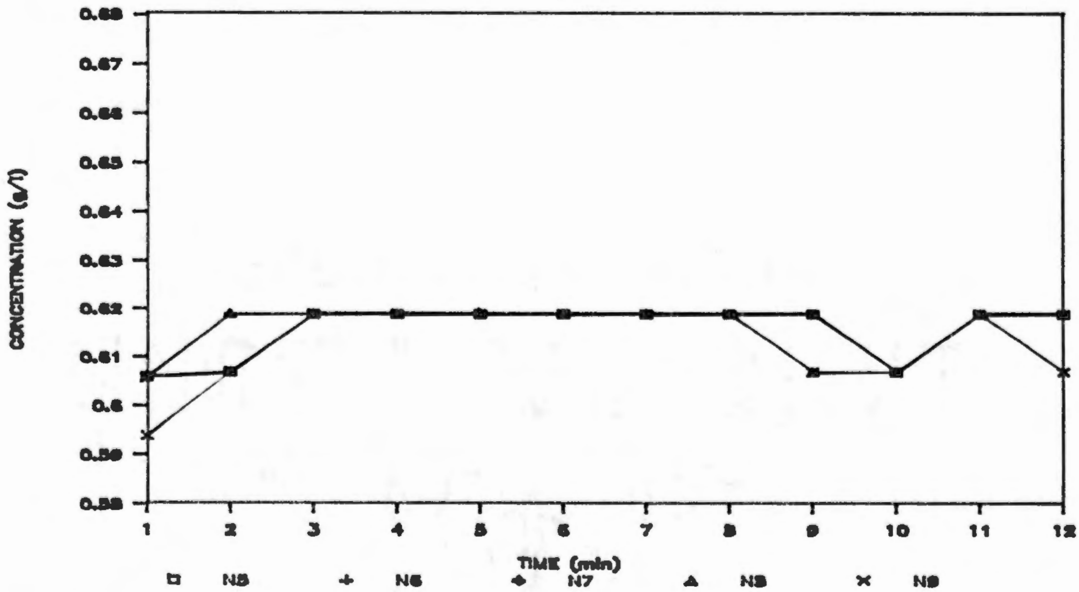

Figure 20. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the Scienco pump was immediately upstream of the system pump. Sampling began at time = 1 min, and system pressure was 275 kPa.

0.025 grams per liter, or 4.0 percent of the average sustained concentration. Note that for several minutes, the concentration variation among individual nozzles and with time was too small to be detected with the concentration measuring techniques used in this study. Figures 21 and 22 indicate that the maximum variation in concentration was 0.023 grams per liter, or about 3.4 percent of the average chemical concentration for the FMI pump. The concentration among nozzles and with time was very uniform. Perhaps this uniformity in concentration over time can be attributed, at least in part, to the fact that the output of the pump was a smooth flow without visible pulses.

The fact that the variation, both from nozzle to nozzle across the boom and with time, was quite small with all three injection units suggests the sprayer system pump was quite effective in thoroughly mixing the chemical and diluent. Additional mixing probably also occurred in the leader hose supplying the boom section. The results given in Figures 17 to 22 suggest that the mixing was adequate to effectively negate any differences in the injection characteristics of the three injection pumps.

High-Pressure Injection Immediately Downstream of System Pump

Transient Time

Laboratory tests employing high-pressure injection immediately downstream of the system pump were conducted to determine the characteristics of the transient period extending from the instant of injection initiation to the time when the chemical concentration in the

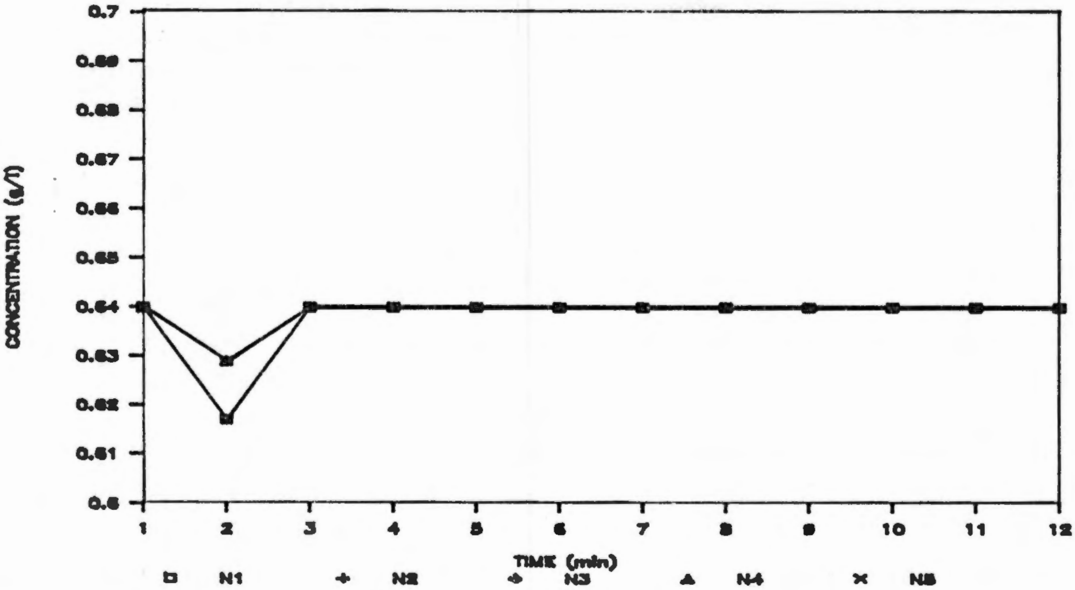

Figure 21. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the FMI pump was immediately upstream of the system pump. Sampling began at time = 1 min, and system pressure was 275 kPa.

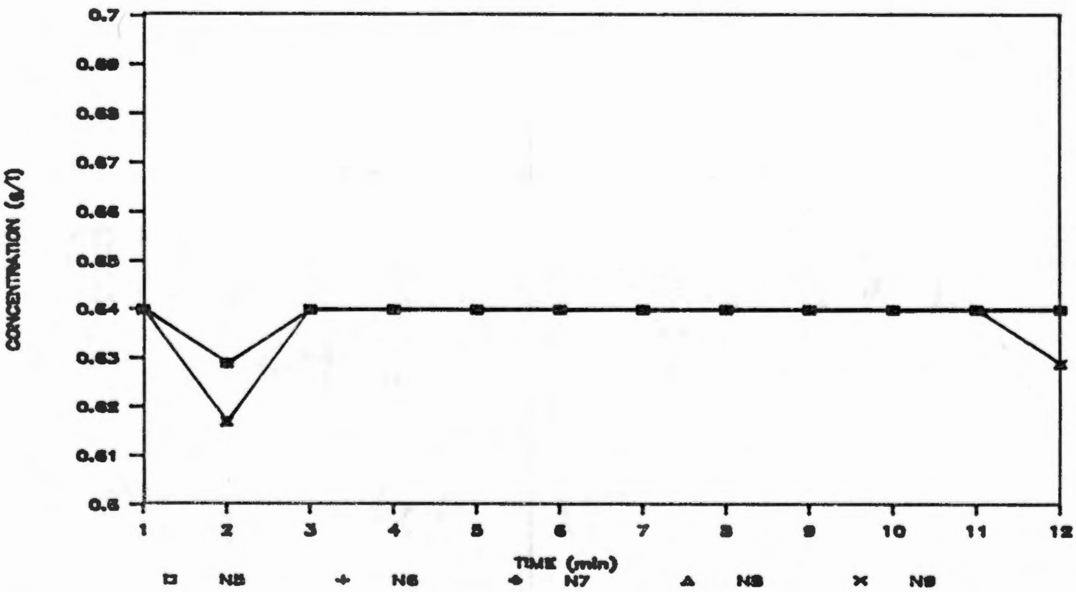

Figure 22. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the FMI pump was immediately upstream of the system pump. Sampling began at time = 1 min, and system pressure was 275 kPa.

nozzle effluent became uniform. The two piston-type pumps, Scienco and FMI, were used in a system layout similar to that illustrated in Figure 23. The operating pressure of the sprayer system was maintained at 275 kilopascals. Chemical injection rates for the Scienco and the FMI pumps were 3.50 and 3.64 milliliters per second, respectively. These rates were selected somewhat arbitrarily but were set to be approximately the same level. Figures 24 to 27 indicate that the system equipped with either the FMI or the Scienco pump took about 42 seconds to establish a fairly uniform chemical concentration in the nozzle effluent. As the chemical concentration reached its maximum value, the curves characterizing the FMI pump were much smoother than those describing the Scienco pump. This suggests that mixing in the FMI-equipped system was superior to that in the system including the Scienco pump. Perhaps the high-speed operation of the FMI pump, the characteristic which effectively eliminated the formation of pulses in the injected fluid, was important in this result. In previous testing which included injection upstream of the system pump, mixing as the chemical concentrate and diluent passed through the pump had negated the smooth flow advantage associated with the high-speed pump.

Since injection on the high-pressure side of the pump involved introduction of the chemical at a site closer to the points of discharge at the individual nozzles, the transient time was logically expected to be shorter than that observed when injection was farther upstream. One contributor to the unexpectedly long transient times observed with the downstream injection system was apparently the 19-millimeter ball check valve that was used to insure that the diluted chemical was not forced

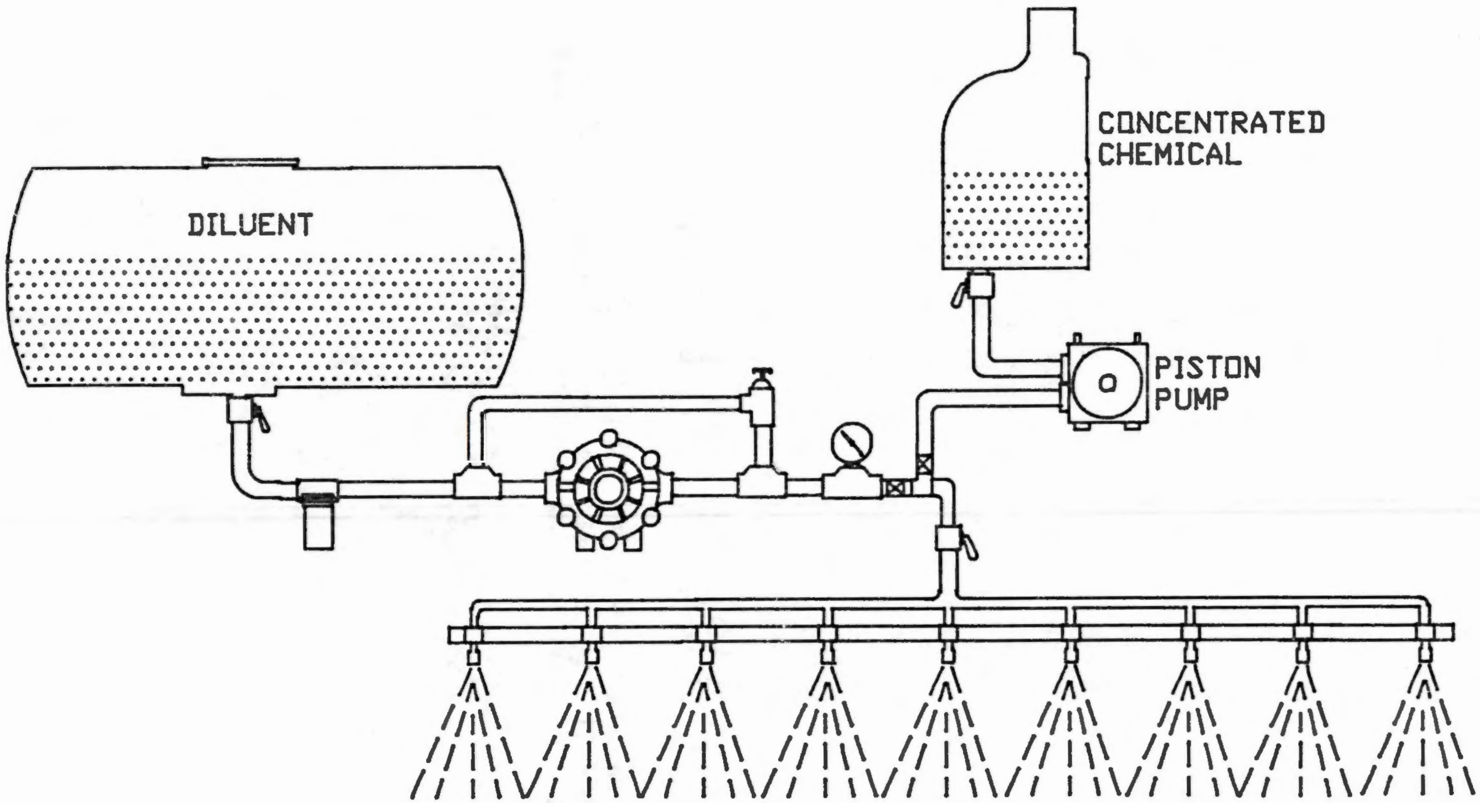

Figure 23. Layout of the fluid handling and transport system components on an experimental hydraulic sprayer employing direct chemical injection at a point immediately downstream of the sprayer system pump.

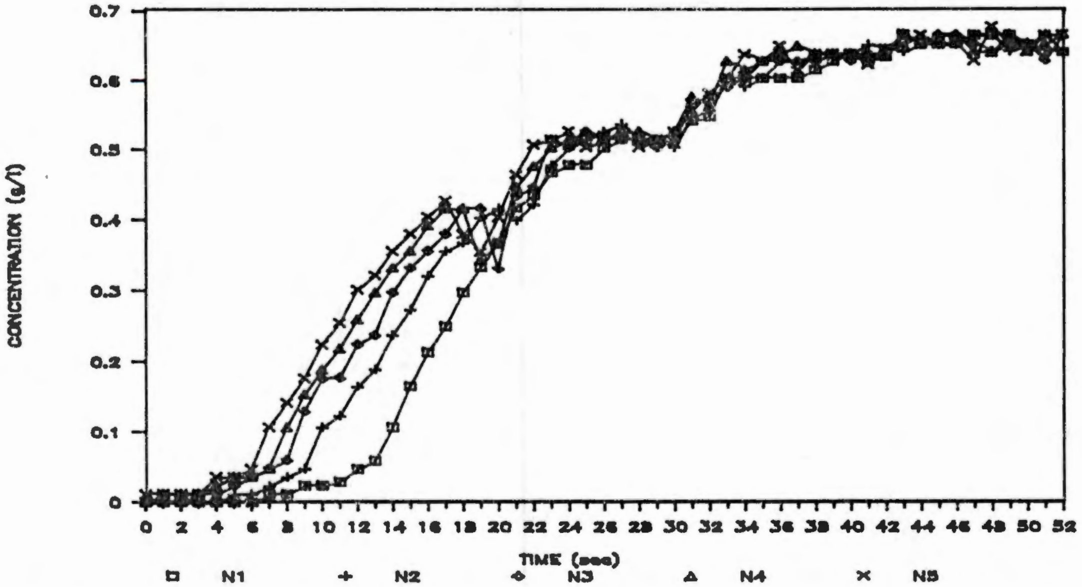

Figure 24. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the FMI pump was immediately downstream of the system pump. Injection began at time = 0, and system pressure was 275 kPa.

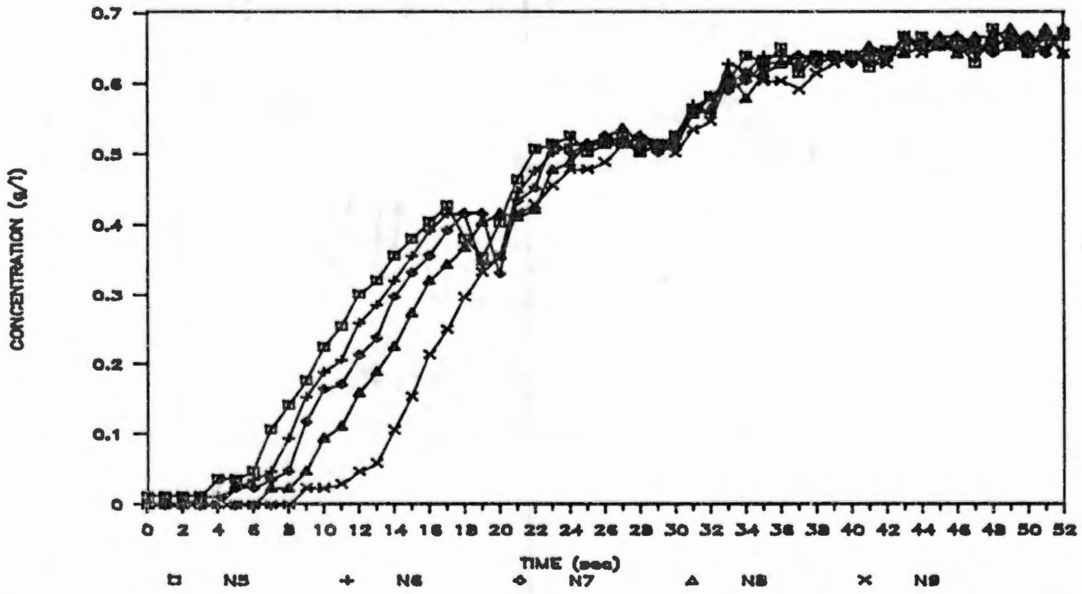

Figure 25. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the FMI pump was immediately downstream of the system pump. Injection began at time = 0, and system pressure was 275 kPa.

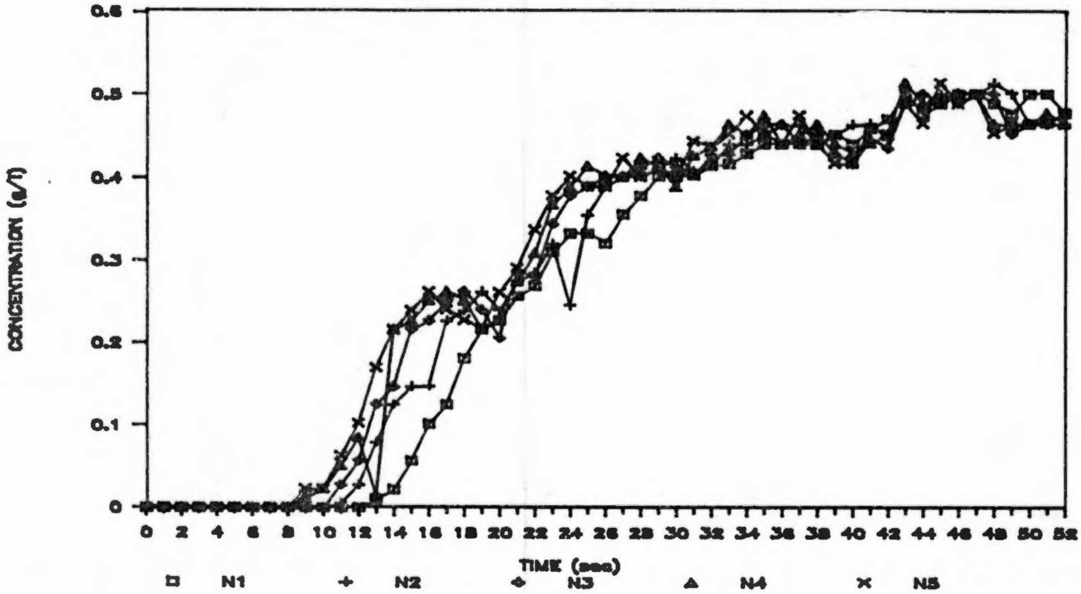

Figure 26. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the Scienco pump was immediately downstream of the system pump. Injection began at time = 0, and system pressure was 275 kPa.

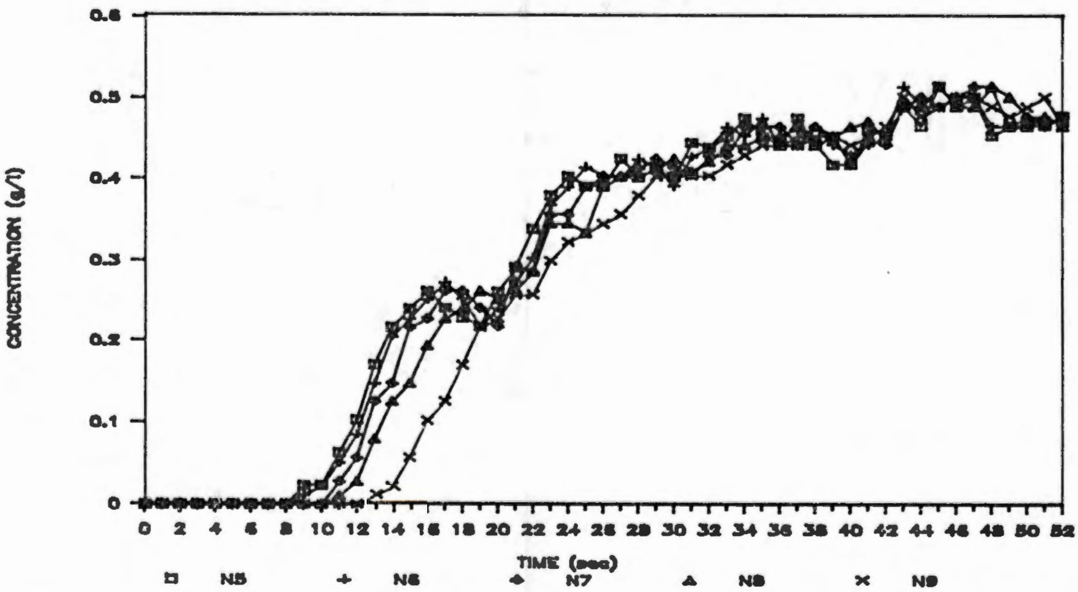

Figure 27. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the Scienco pump was immediately downstream of the system pump. Injection began at time = 0, and system pressure was 275 kPa.

back into the concentrated chemical tank. This large check valve apparently provided some storage and did not allow the chemical concentrate to be smoothly fed into the sprayer conduit. This check valve was subsequently replaced by a smaller 6.4-millimeter check valve. Tests were repeated at a pressure of 275 kilopascals using only the Scienco pump. Results are illustrated in Figures 28 and 29. These should be directly compared with the results shown in Figures 26 and 27. The only difference in the two test setups was the size of the check valve in the conduit connecting the injection pump with the sprayer boom feeder hose. The smaller check valve resulted in the transient period being reduced from about 42 seconds to 15 seconds. When this same Scienco pump had been used upstream of the sprayer system pump, the transient period had a duration of approximately 24 seconds.

Concentration Uniformity

Further laboratory tests were conducted to evaluate the uniformity of chemical concentration in the sprayer effluent both from nozzle to nozzle and with time. Sprayer setup remained in the configuration illustrated in Figure 23. The system was operated at pressures of 171, 275, and 378 kilopascals, and the larger check valve was used. Nozzle effluent samples were collected using the same procedures employed with the tests involving low-pressure injection. While the pump setting remained constant, injection rates of the potassium bromide solution varied in response to the static pressure encountered during injection. At a pressure of 275 kilopascals, the injection rates were the same as in previous tests reported above. Results with the FMI pump and a

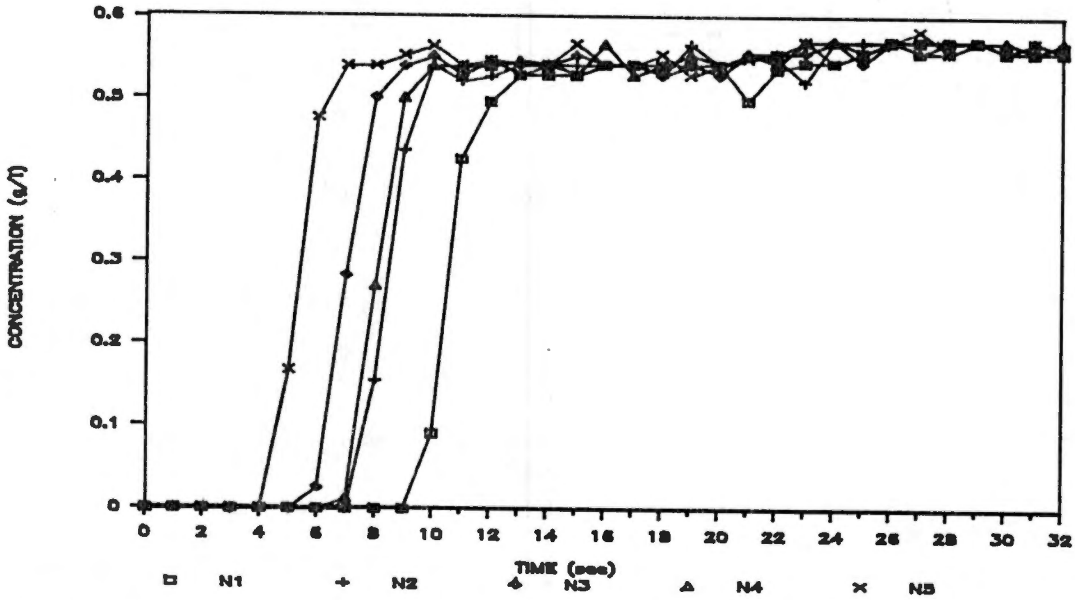

Figure 28. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the Scienco pump was immediately downstream of the system pump. A smaller check valve was included. Injection began at time = 0, and system pressure was 275 kPa.

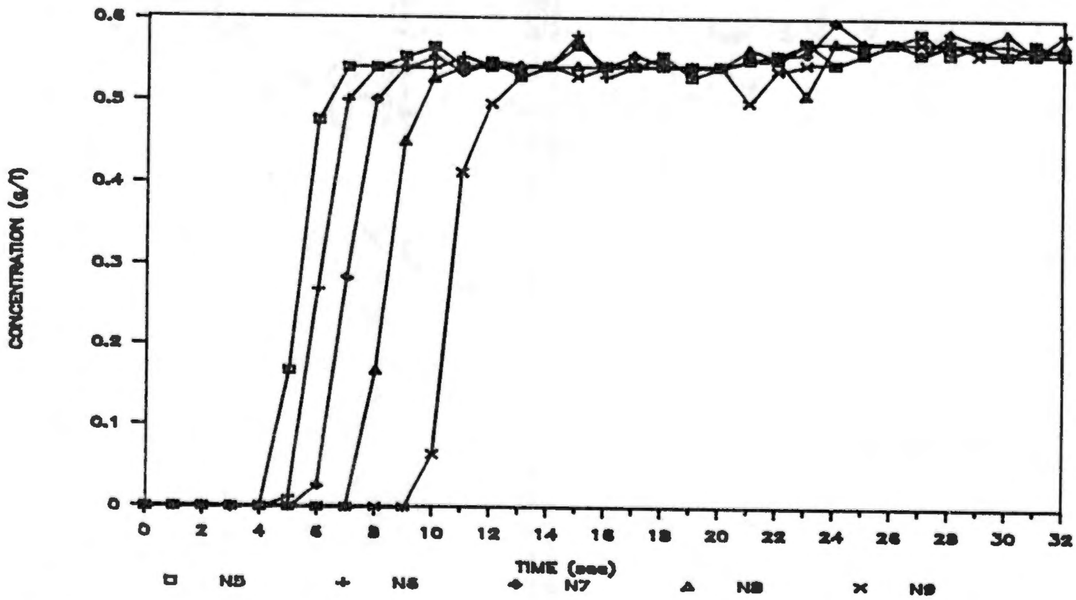

Figure 29. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the Scienco pump was immediately downstream of the system pump. A smaller check valve was included. Injection began at time = 0, and system pressure was 275 kPa.

system pressure of 275 kilopascals are shown in Figures 30 and 31. Maximum variation in nozzle effluent concentration over the series of 12-minute tests was 0.031 grams per liter, or 4.9 percent of the average concentration. Results for the Scienco pump operated at the same pressure are presented in Figures 32 and 33. Maximum variation in concentration was 0.055 grams per liter or 11 percent of the average concentration. Thus, the FMI pump tended to result in less variation in chemical concentration both from nozzle to nozzle and with time. This may be partially attributable to pulsations in the output of the Scienco pump. The trend toward increasing concentration with time (Figures 32 and 33) indicates that the Scienco pump required an extended period to reach an equilibrium concentration.

When the pumps were operated against a system pressure of 171 kilopascals, the chemical solution injection rates for the FMI pump and the Scienco pump were 4.18 and 4.06 milliliters per second, respectively. Figures 34 and 35 show the results with the FMI pump, and Figures 36 and 37 show the results of tests using the Scienco pump. Variation in chemical concentration with the FMI unit was 0.060 grams per liter, or 8.2 percent of the average concentration. Similarly, concentration variation with the Scienco pump was 0.067 grams per liter, or 10.7 percent of the average concentration. Thus, there is again more variation both from nozzle to nozzle and with time evident with the Scienco pump than with the FMI pump.

When operated against a system pressure of 378 kilopascals, the injection rate for each pump decreased. The injection rate for the FMI pump was 4.08 milliliters per second and that for the Scienco pump was

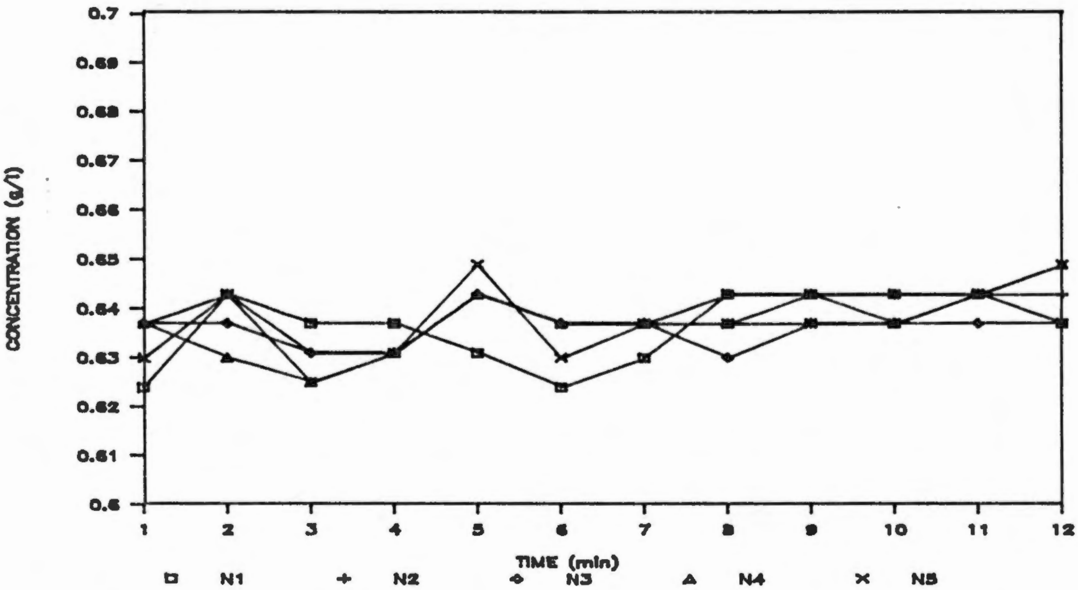

Figure 30. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the FMI pump was immediately downstream of the system pump. Sampling began at time = 1 min, and system pressure was 275 kPa.

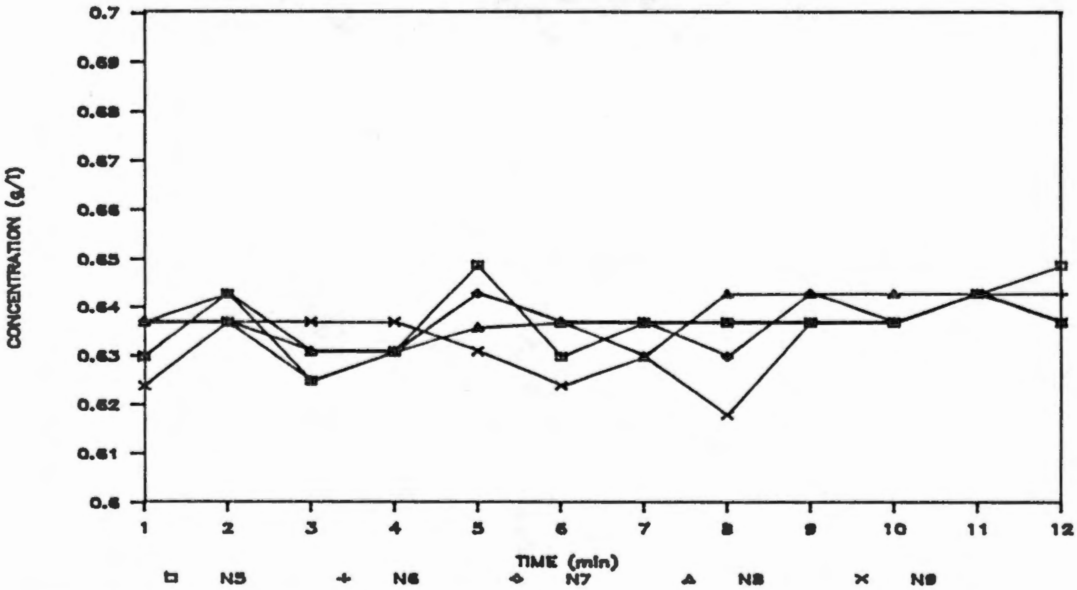

Figure 31. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the FMI pump was immediately downstream of the system pump. Sampling began at time = 1 min, and system pressure was 275 kPa.

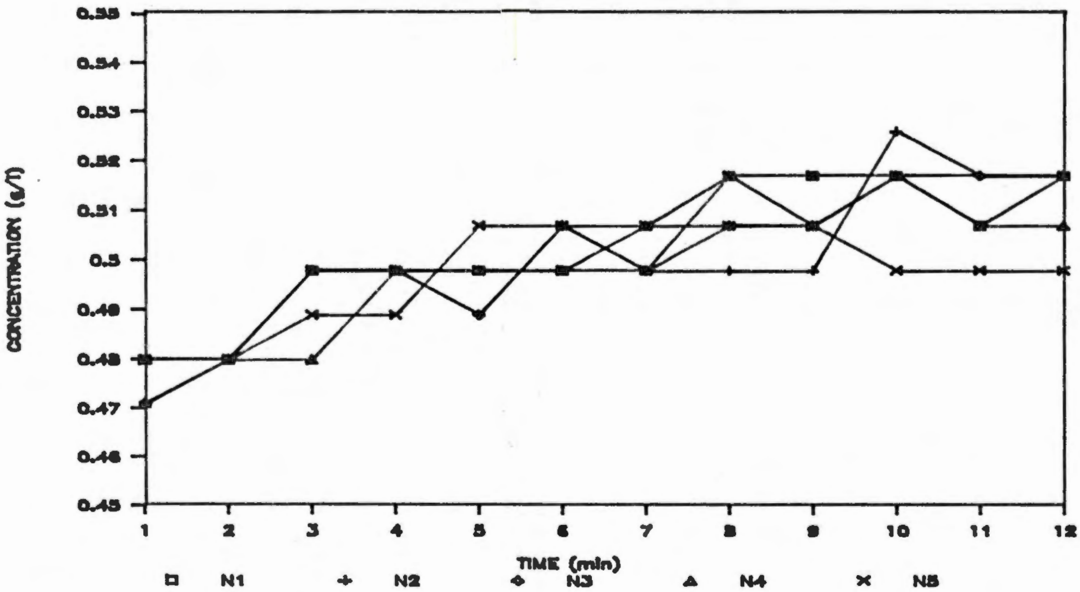

Figure 32. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the Scienco pump was immediately downstream of the system pump. Sampling began at time = 1 min, and system pressure was 275 kPa.

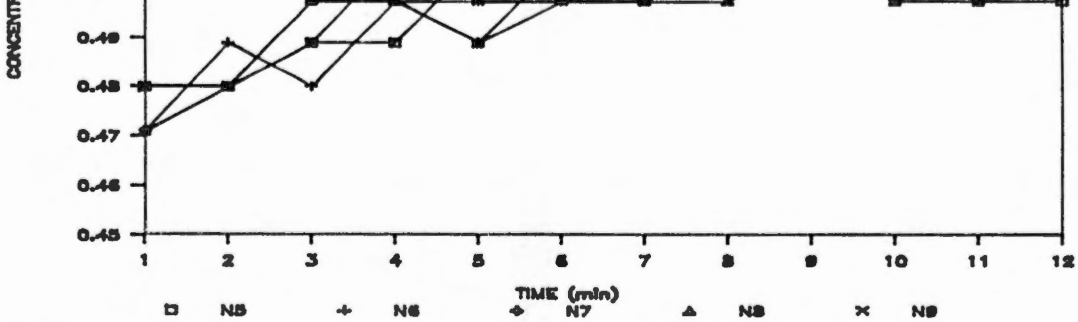

Figure 33. Variation in chemical concentration of the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the Scienco pump was immediately downstream of the system pump. Sampling began at time = 1 min, and system pressure was 275 kPa.

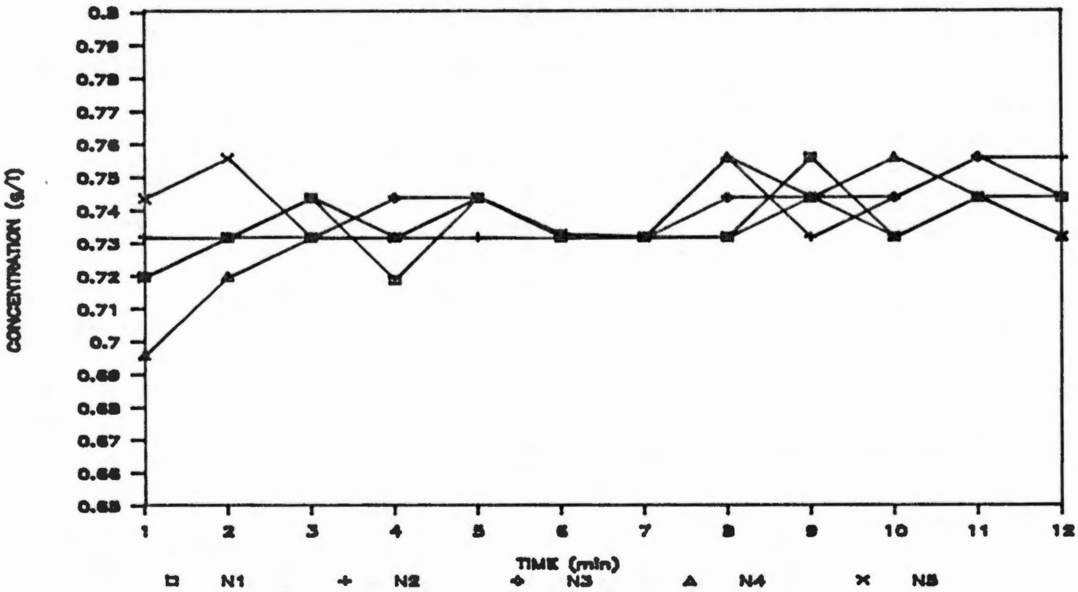

Figure 34. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the FMI pump was immediately downstream of the system pump. Sampling began at time = 1 min, and system pressure was 171 kPa.

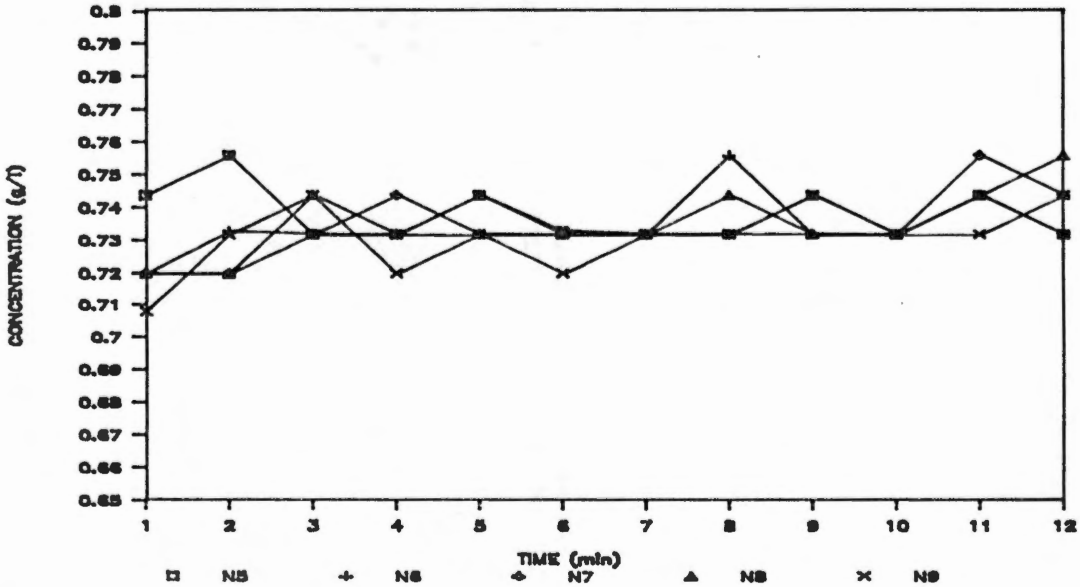

Figure 35. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the FMI pump was immediately downstream of the system pump. Sampling began at time = 1 min, and system pressure was 171 kPa.

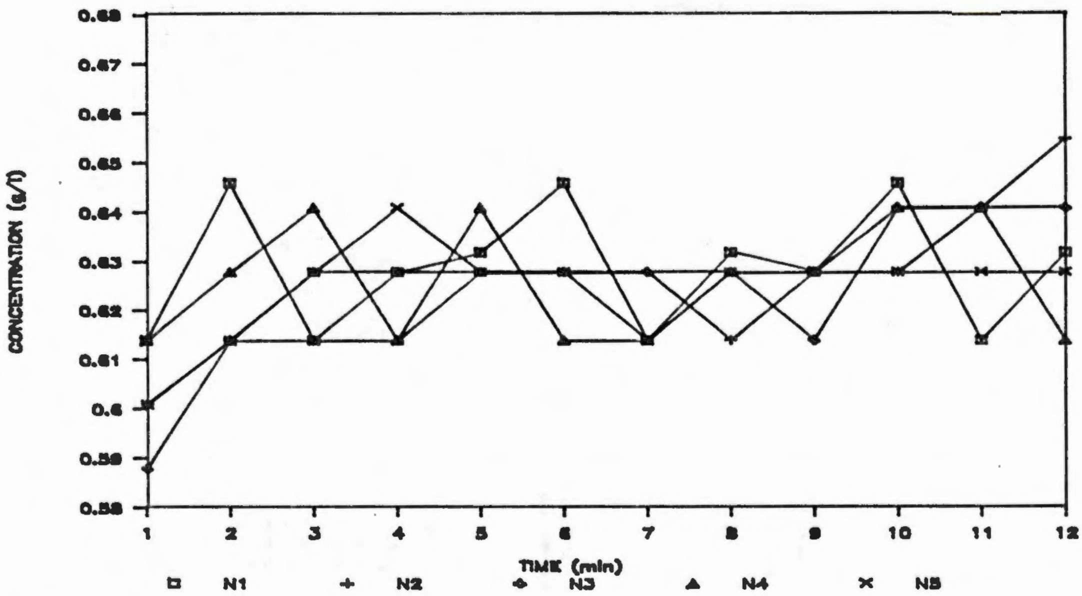

Figure 36. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the Scienco pump was immediately downstream of the system pump. Sampling began at time = 1 min, and system pressure was 171 kPa.

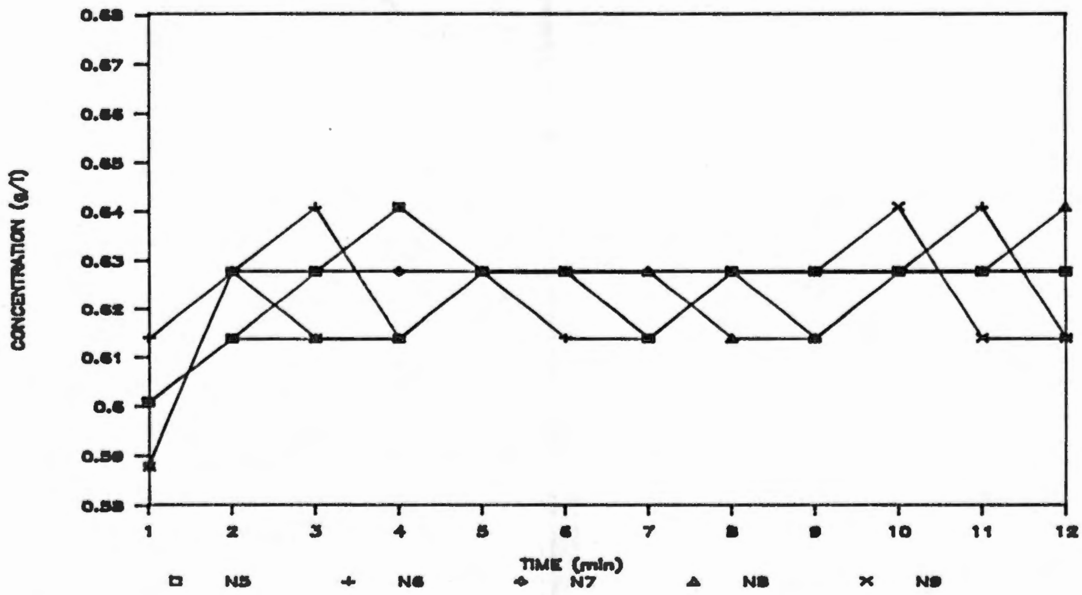

Figure 37. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the Scienco pump was immediately downstream of the system pump. Sampling began at Time = 1 min, and system pressure was 171 kPa.

3.3 milliliters per second. The variation in concentration for the FMI pump (Figures 38 and 39) was again lower at 0.035 grams per liter, or 7.4 percent of average concentration, when compared to the Scienco pump (Figures 40 and 41). The Scienco unit resulted in a variation in concentration of 0.05 grams per liter, or 11.1 percent of average. By inspection, the uniformity of concentration from nozzle to nozzle and with time was similar for the two systems.

In general, the degree of mixing achieved when the chemical concentrate was injected downstream of the system pump was less than that obtained with injection upstream of the pump. The obvious conclusion is that the system pump is an effective mixing device.

Injection at the Individual Nozzles

The injection point was moved to each individual nozzle for a third series of injection tests. A hole to accommodate a microtube was drilled and tapped into the wall of each nozzle body just above the quick-lock cap (Figure 42). A cylindrical manifold with 10 discharge ports was designed and constructed by the Scienco Inc. to use for direct injection experiments at the nozzle (Figure 43). One discharge port in the manifold was plugged since the boom was equipped with 9 nozzles. Equal lengths of microtubing were used to connect the individual manifold ports with the individual nozzle bodies on the boom. The injection pump was connected to the manifold to supply the potassium bromide solution to the individual nozzles (Figure 44). Tests were conducted at a system static pressure of 275 kilopascals using the

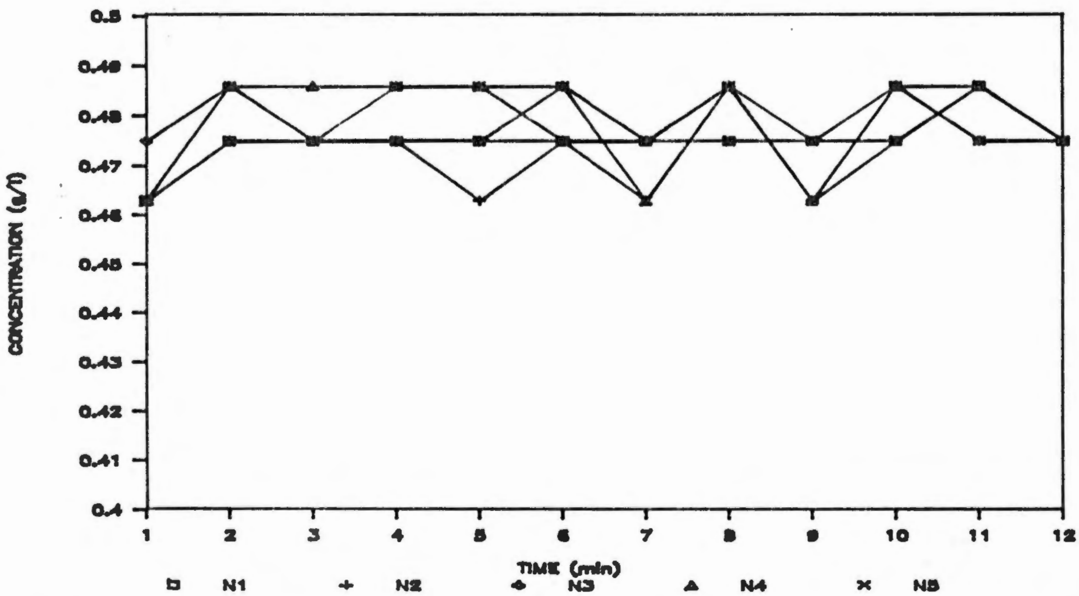

Figure 38. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the FMI pump was immediately downstream of the system pump. Sampling began at time = 1 min, and system pressure was 378 kPa.

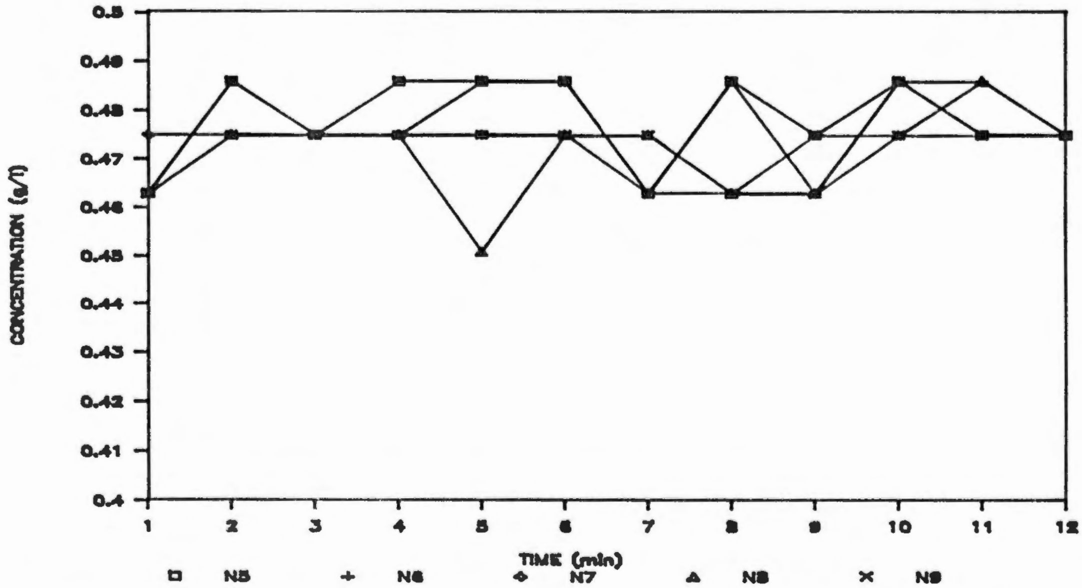

Figure 39. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the FMI pump was immediately downstream of the system pump. Sampling began at time = 1 min, and system pressure was 378 kPa.

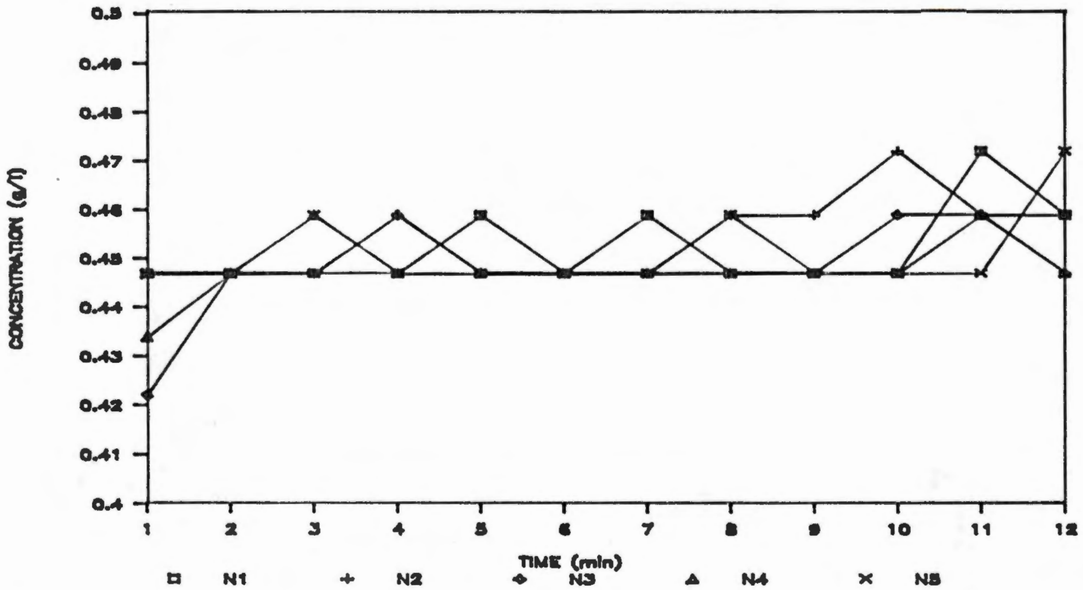

Figure 40. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the Scienco pump was immediately downstream of the system pump. Sampling began at time = 1 min, and system pressure was 378 kPa.

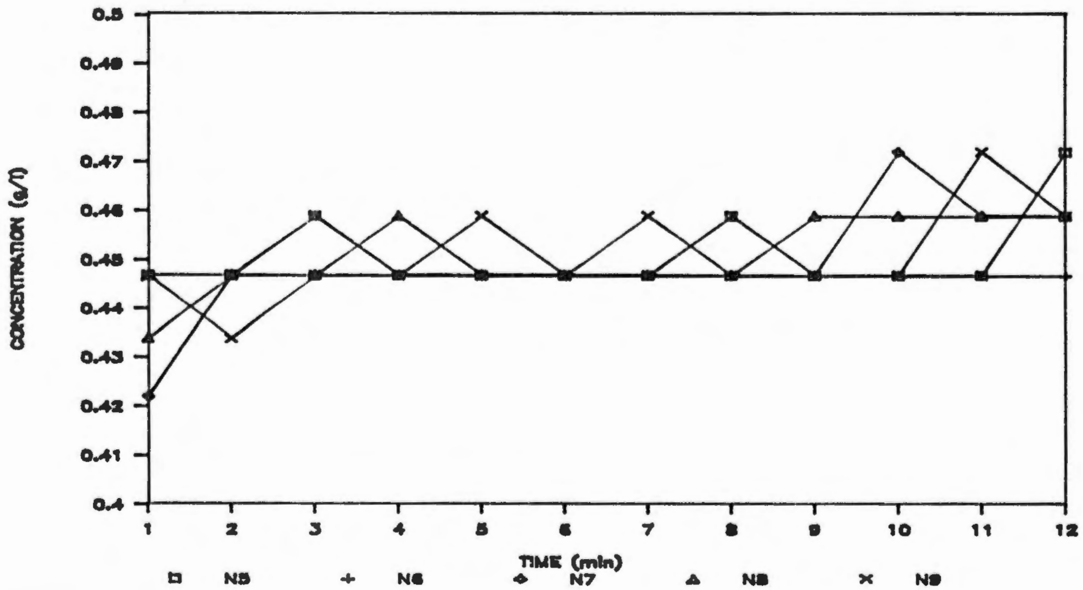

Figure 41. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the Scienco pump was immediately downstream of the system pump. Sampling began at time = 1 min, and system pressure was 378 kPa.

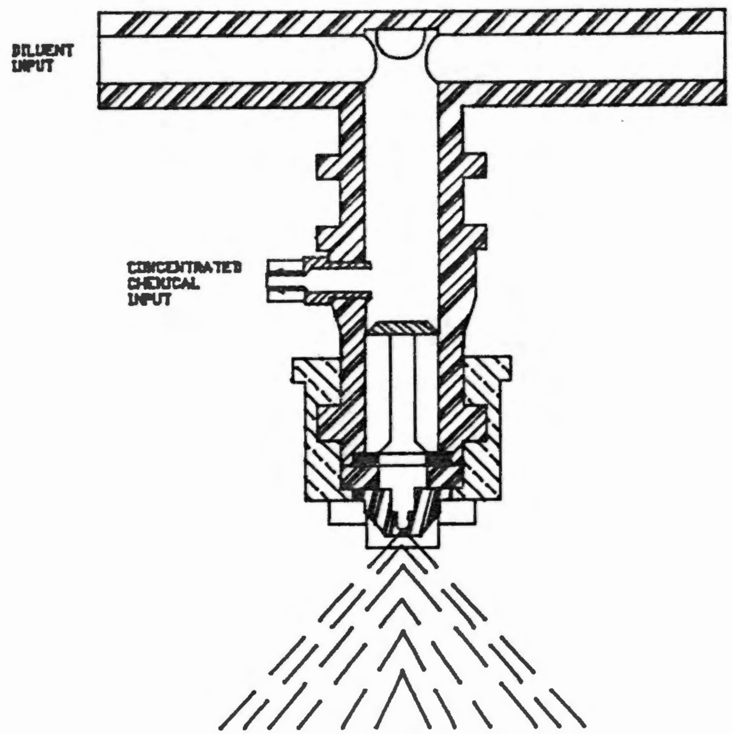

Figure 42. Cross-section of a nozzle body with the microtube insertion port.

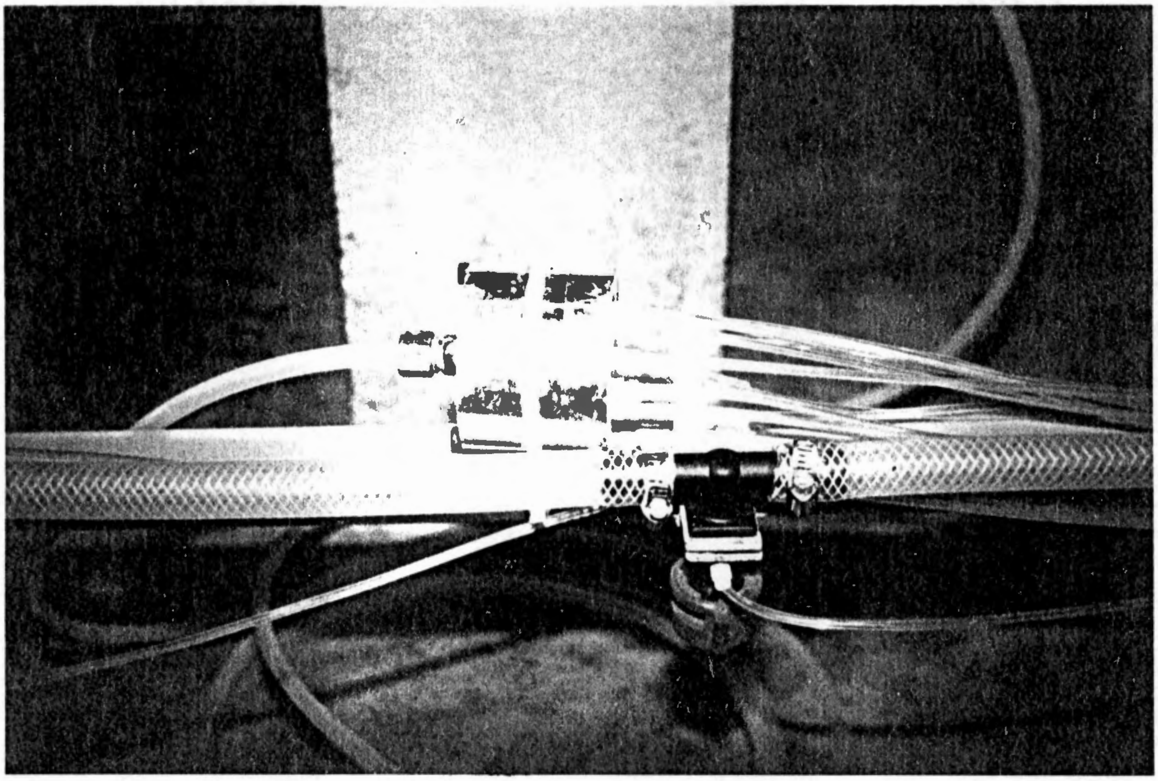

Figure 43. Cylindrical manifold used to distribute concentrated chemical to the individual nozzles.

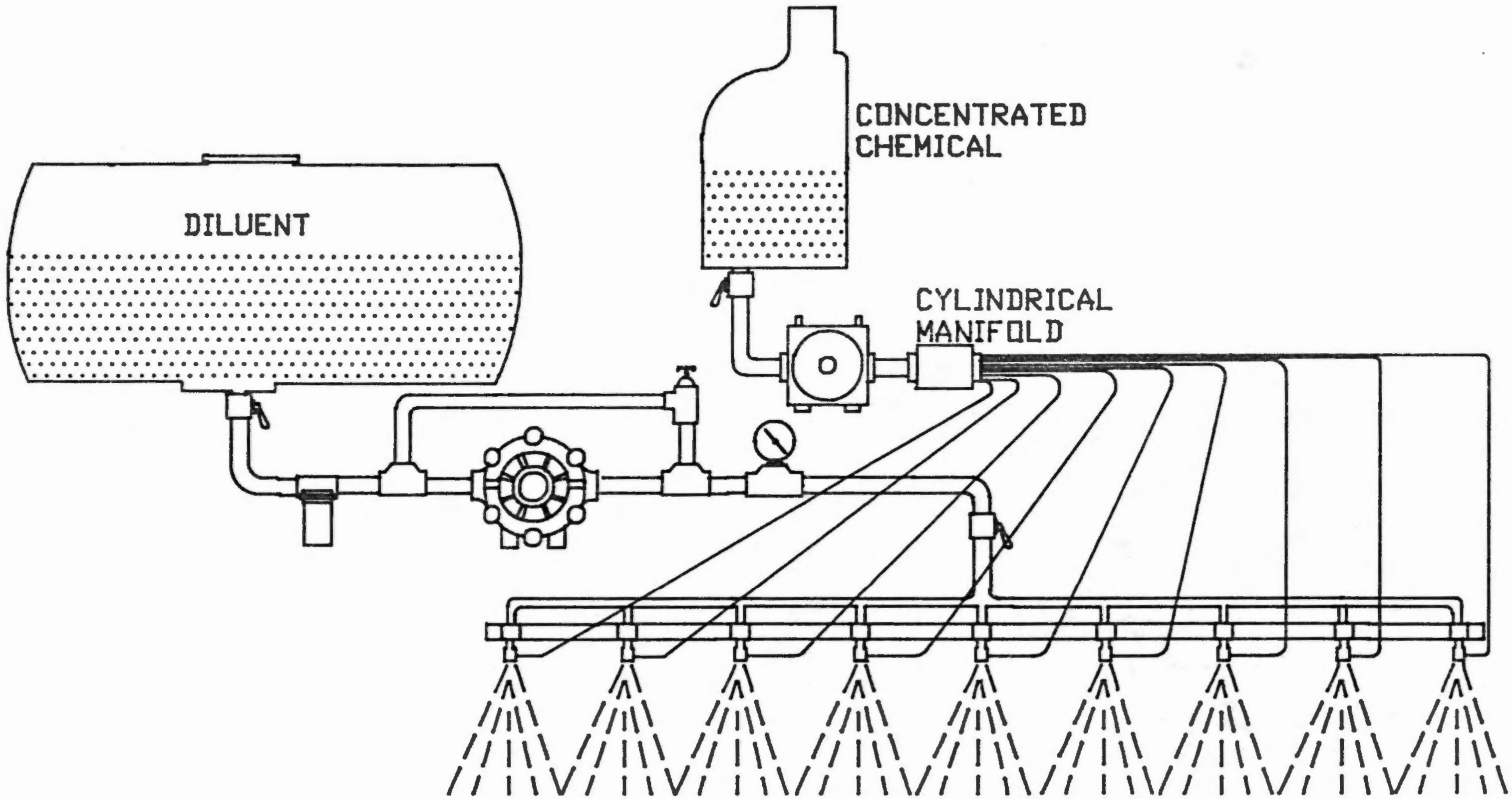

Figure 44. Layout of the fluid handling and transport system components on an experimental hydraulic sprayer employing direct chemical injection at the individual nozzles.

equipment configuration shown in Figure 44. The Scienco pump with a chemical injection rate of 3.5 milliliters per second was used as the injection unit. Results of measurements of chemical concentration uniformity in the nozzle effluent are shown in Figures 45 and 46. Nozzle 5 received little or none of the bromide solution. This nozzle was located in the center of the boom and was the point at which the diluent entered the boom section. The action associated with the fluid entering at this point may have created a localized pressure greater than the pressure at the other nozzles. Thus, very little of the chemical-bearing fluid distributed by the manifold was delivered to that nozzle. With the exception of the phenomenon which occurred at the center nozzle (number 5), Figures 45 and 46 show the chemical concentration both among the several other nozzles and with time was uniform. Chemical concentration in the nozzle effluent tended to be greater toward the center of the boom and decreased slightly toward either outboard end.

The point of fluid entrance to the boom was then moved slightly to the side of nozzle 5 as shown in Figure 47. Tests were first conducted at a system pressure of 275 kilopascals using the Scienco pump with the injection rate maintained at the same level as above. Test results are shown in Figures 48 and 49. The maximum variation in nozzle effluent chemical concentration was 0.19 grams per liter, or 37.4 percent of the average concentration. Variation with time was considerable less than the variation among the nozzles. Similar tests were then performed with the FMI pump using a solution injection rate of 3.64 milliliters per second. Results are shown in Figures 50 and 51. Maximum variation in

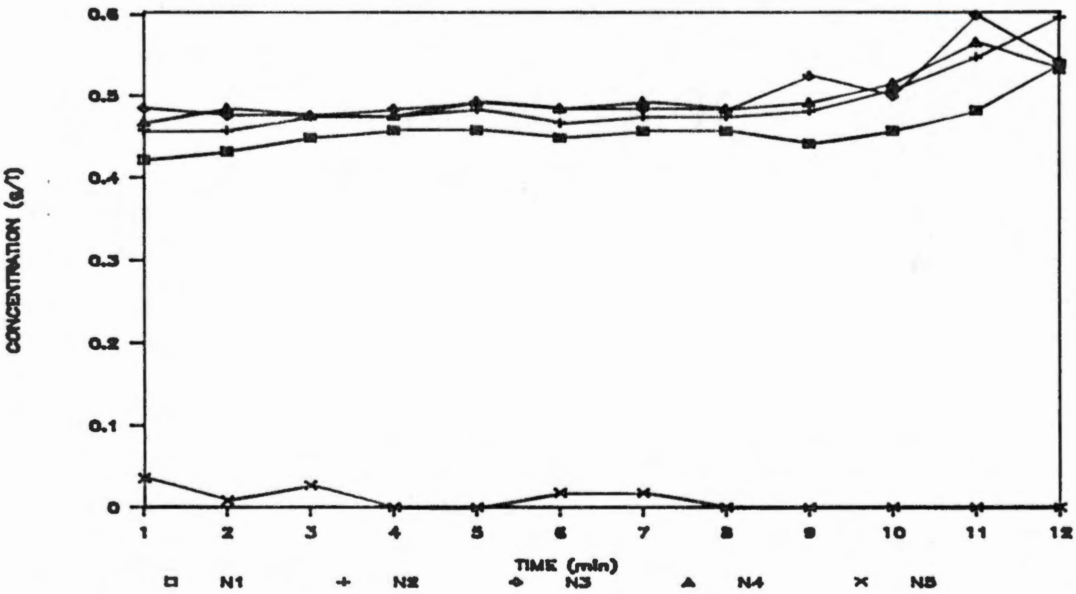

Figure 45. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the Scienco pump was at the individual nozzles. Sampling began at time = 1 min, and system pressure was 275 kPa.

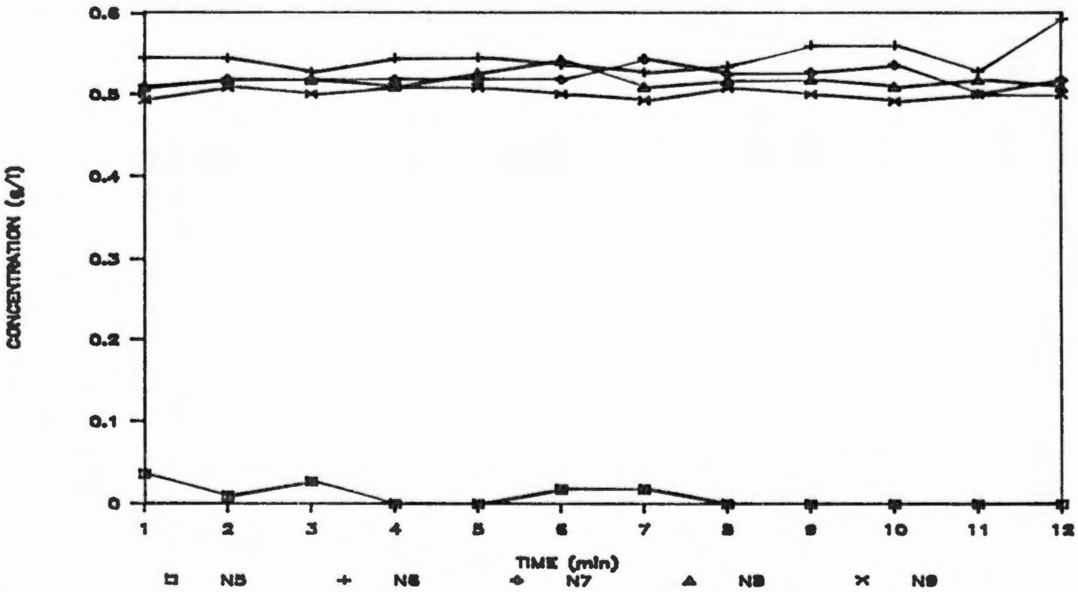

Figure 46. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the Scienco pump was at the individual nozzles. Sampling began at time = 1 min, and system pressure was 275 kPa.

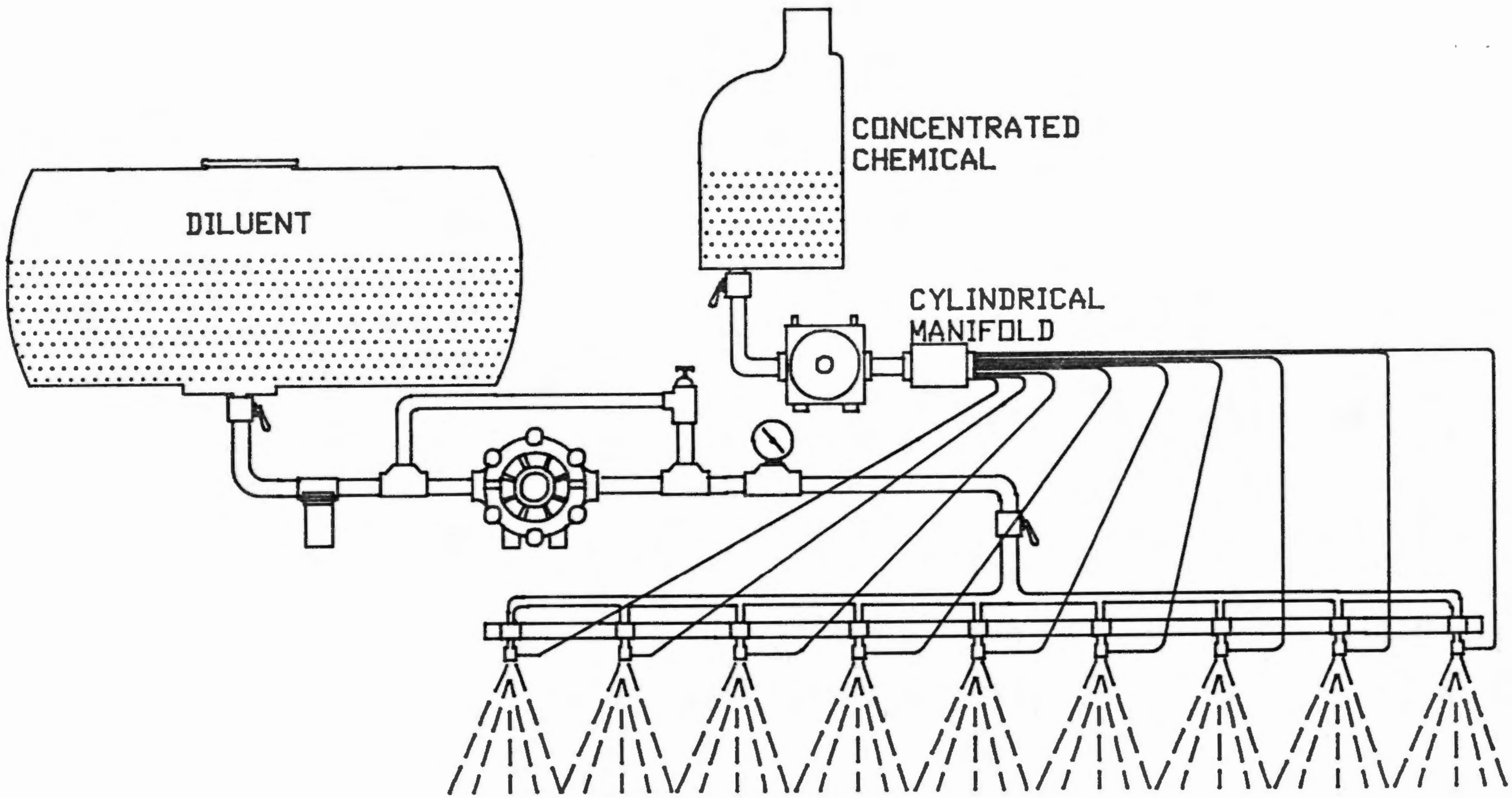

Figure 47. Layout of the fluid handling and transport system components on an experimental hydraulic sprayer employing direct chemical injection at the individual nozzles. Fluid entrance to the boom was slightly to the side of nozzle 5.

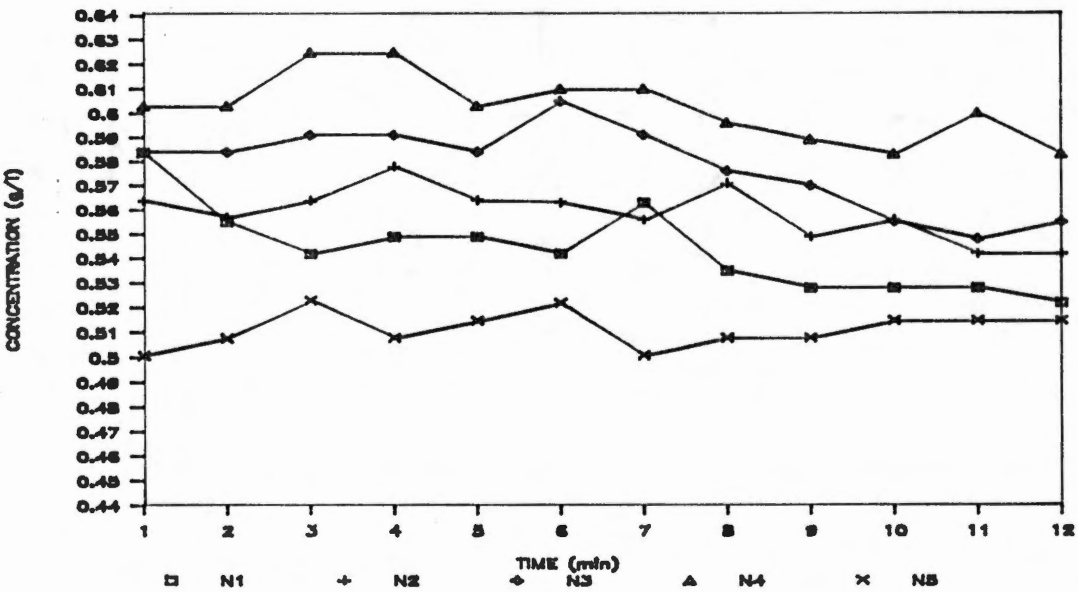

Figure 48. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the Scienco pump was at the individual nozzles, and fluid entrance to the boom was slightly to the side of nozzle 5. Sampling began at time = 1 min, and system pressure was 275 kPa.

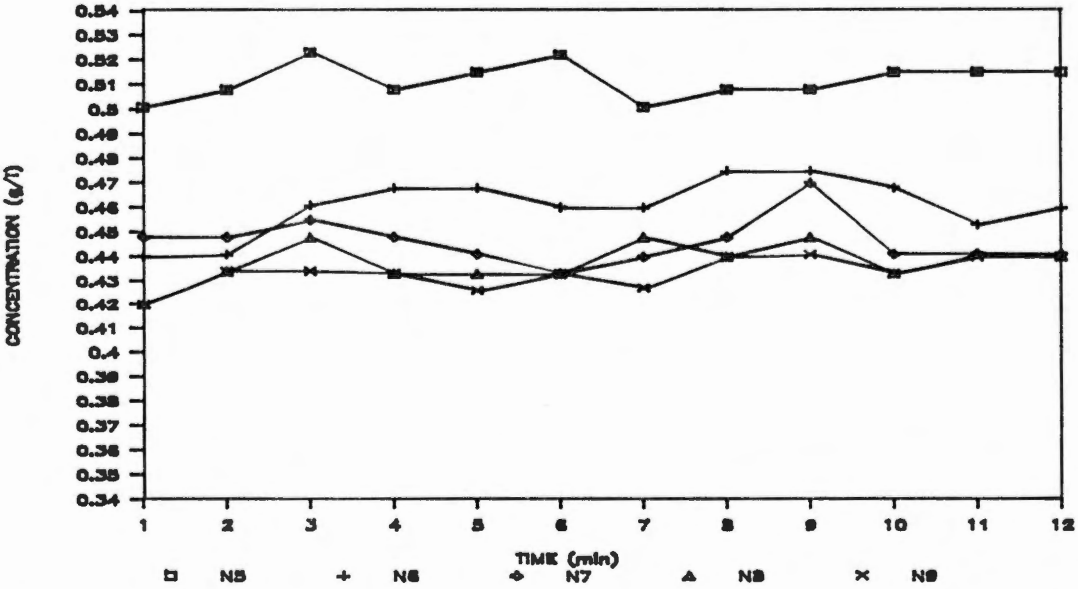

Figure 49. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the Scienco pump was at the individual nozzles, and fluid entrance to the boom was slightly to the side of nozzle 5. Sampling began at time = 1 min, and system pressure was 275 kPa.

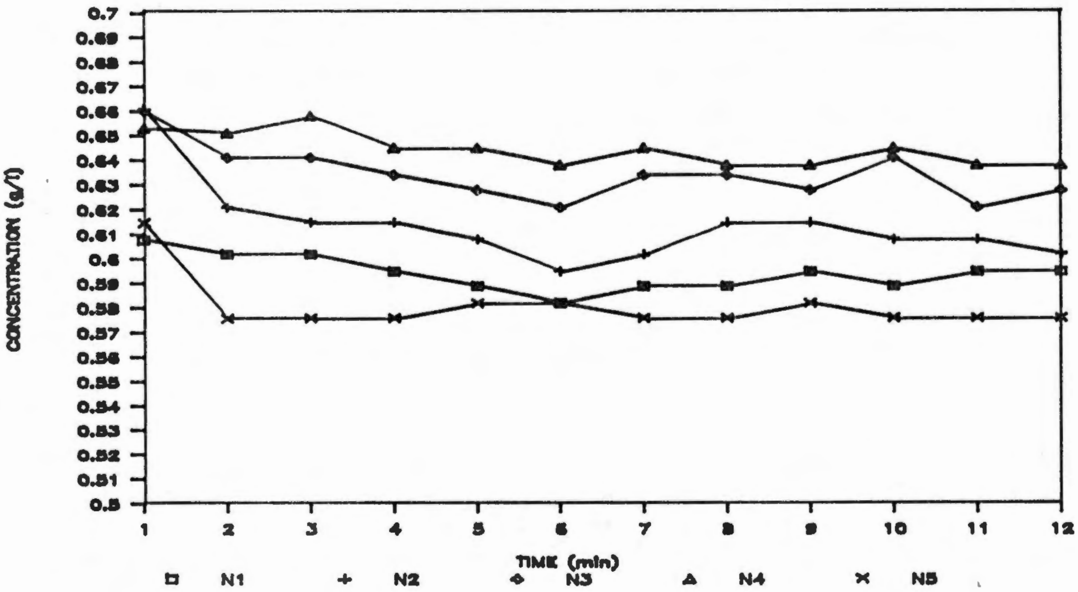

Figure 50. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the FMI pump was at the individual nozzles, and fluid entrance to the boom was slightly to the side of nozzle 5. Sampling began at time = 1 min, and system pressure was 275 kPa.

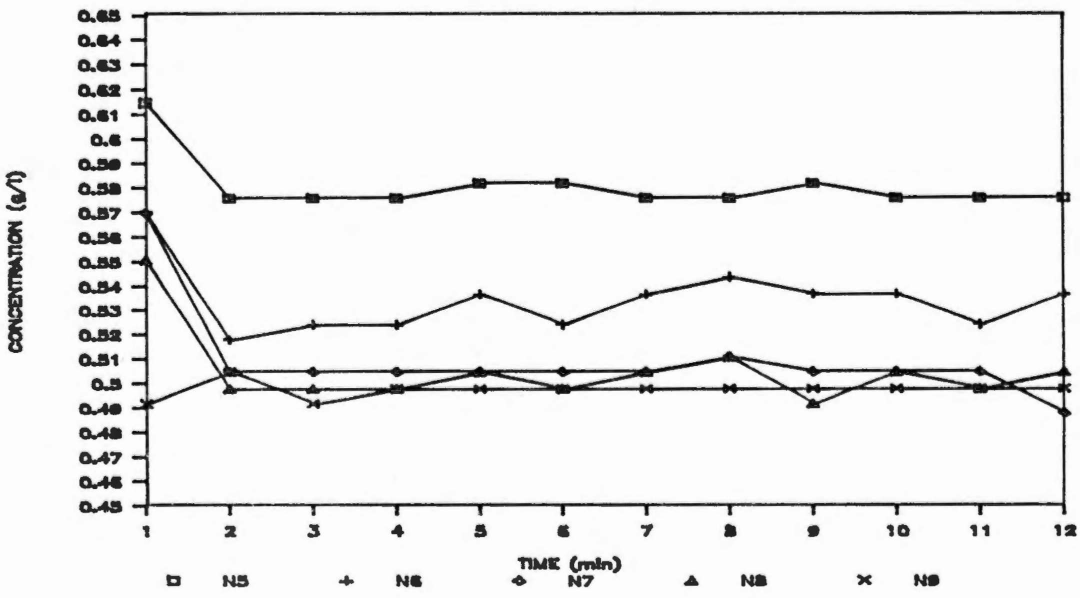

Figure 51. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the FMI pump was at the individual nozzles, and fluid entrance to the boom was slightly to the side of nozzle 5. Sampling began at time = 1 min, and system pressure was 275 kPa.

effluent concentration among the nozzles was 0.173 grams per liter, or 30.5 percent of the average concentration. Concentration of chemical in the output of any nozzle was quite uniform over time. Effluent concentrations on the left side of the boom were markedly greater than those on the right side. During one series of test, two microtubes were switched to determine if the tubing had a significant effect on the results. No appreciable difference in performance was detected.

Further tests at system pressures of 171 and 378 kilopascals were conducted using the same injection systems and boom design as is shown in Figure 47. At 171 kilopascals, the injection rates for the Scienco and FMI pumps were again 4.06 and 4.18 milliliters per second, respectively. Figures 52 and 53 show the results of the tests with the Scienco pump. Maximum variation in concentration among nozzles was 0.140 grams per liter or 22.7 percent of the average concentration. Concentration variation over time for a given individual nozzle was quite small. Note that the chemical concentration in the effluent of nozzle 5 was absolutely constant over the 12-minute test period. Results of tests using the FMI pump at 171 kilopascals are given in Figures 54 and 55. Maximum variation in chemical concentration among nozzles was 0.119 grams per liter or 17.5 percent of the average concentration. Variation among individual nozzles tended to be substantially greater than the variation with time for a given nozzle. For both pumps at 171 kilopascals, the chemical concentration on one side of the symmetric boom was greater than on the other. However, the overall variation in chemical concentration in the nozzle effluent was

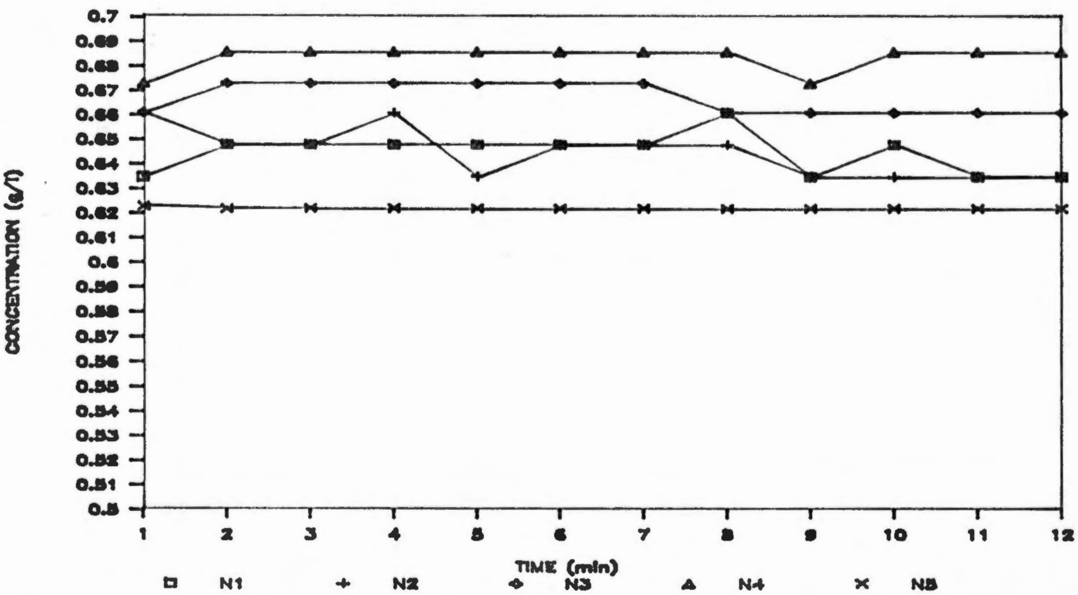

Figure 52. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the Scienco pump was at the individual nozzles, and fluid entrance to the boom was slightly to the side of nozzle 5. Sampling began at time = 1 min, and system pressure was 171 kPa.

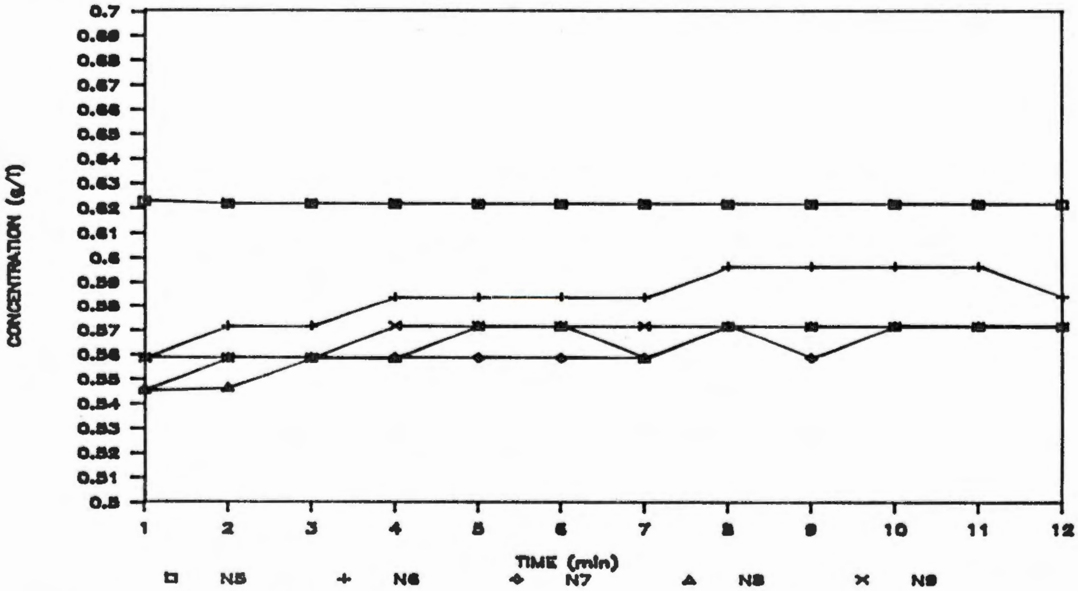

Figure 53. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the Scienco pump was at the individual nozzles, and fluid entrance to the boom was slightly to the side of nozzle 5. Sampling began at time = 1 min, and system pressure was 171 kPa.

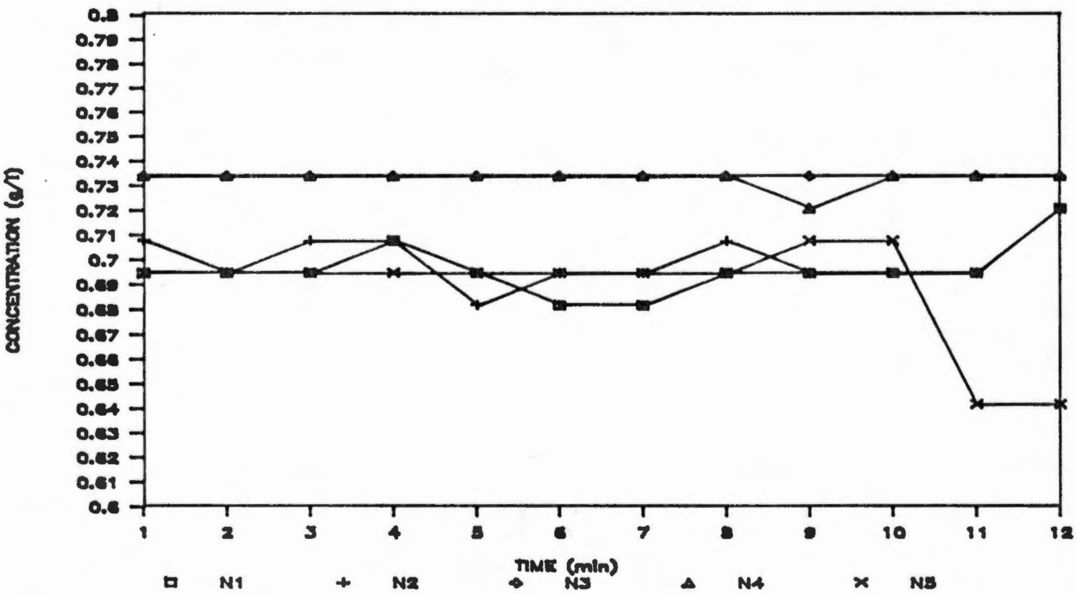

Figure 54. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the FMI pump was at the individual nozzles, and fluid entrance to the boom was slightly to the side of nozzle 5. Sampling began at time = 1 min, and system pressure was 171 kPa.

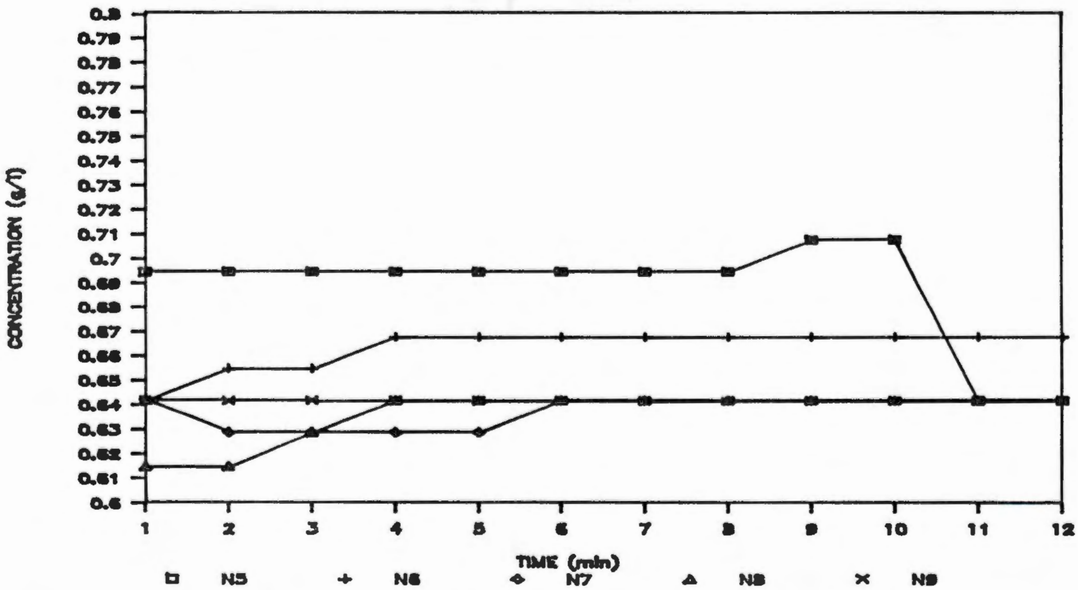

Figure 55. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the FMI pump was at the individual nozzles, and fluid entrance to the boom was slightly to the side of nozzle 5. Sampling began at time = 1 min, and system pressure was 171 kPa.

generally lower for operation at a system pressure of 171 kilopascals than for operation at 275 kilopascals.

Figures 56 and 57 show results of tests conducted with the Scienco pump operating against a system pressure of 378 kilopascals and at a chemical injection rate of 3.3 milliliters per second. At this pressure the Scienco pump system produced a concentration variation among nozzles of 0.216 grams per liter or 44.4 percent of the average concentration. However, the concentration variation with time for a given nozzle was generally small. The large concentration variation among nozzles was also apparent in tests involving the FMI pump operating against a system pressure of 378 kilopascals and injecting at a rate of 4.08 milliliters per second (see Figures 58 and 59). This variation in concentration was 0.256 grams per liter or 44.2 percent of the average concentration. In comparing Figures 58 and 59 with Figures 56 and 57, the concentration variation over time is clearly less for the Scienco pump. This is probably attributable the Scienco pump having greater pressure capability than the FMI unit. Again, one side of the boom had chemical concentrations in the nozzle effluent which were markedly higher than those on the other side.

In general, as the system operating pressure was increased, the variation in chemical concentration among the nozzles tended to increase. The variation in concentration with time tended to increase with system pressure for the FMI pump. However, the uniformity in effluent concentration over time actually appeared to improve with increasing pressure for the Scienco pump, which is designed for high-pressure operation. Recalling that the Scienco pump delivered pulses of

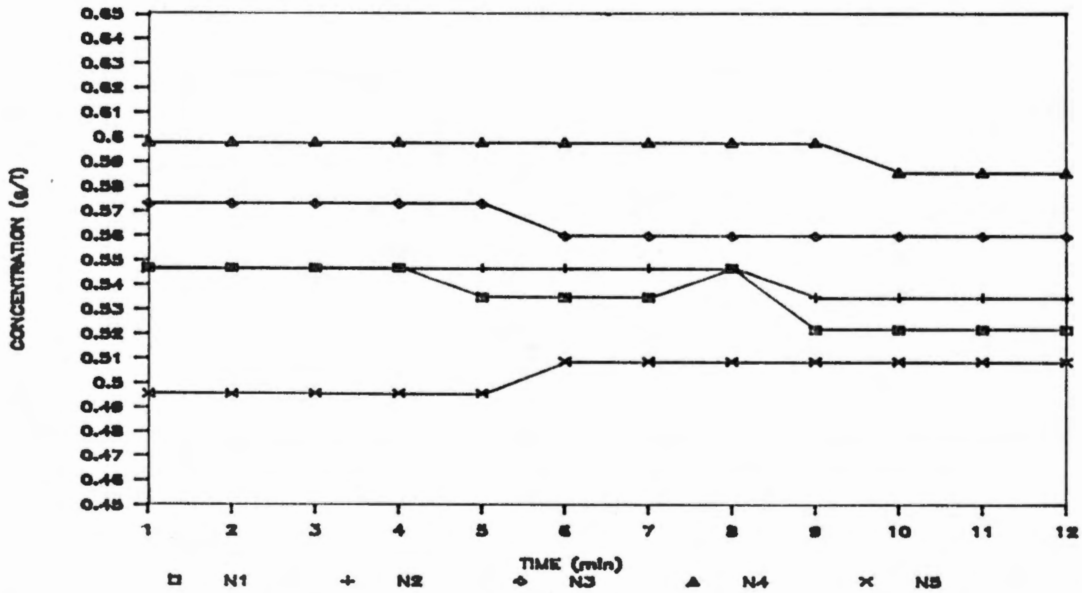

Figure 56. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the Scienco pump was at the individual nozzles, and fluid entrance to the boom was slightly to the side of nozzle 5. Sampling began at time = 1 min, and system pressure was 378 kPa.

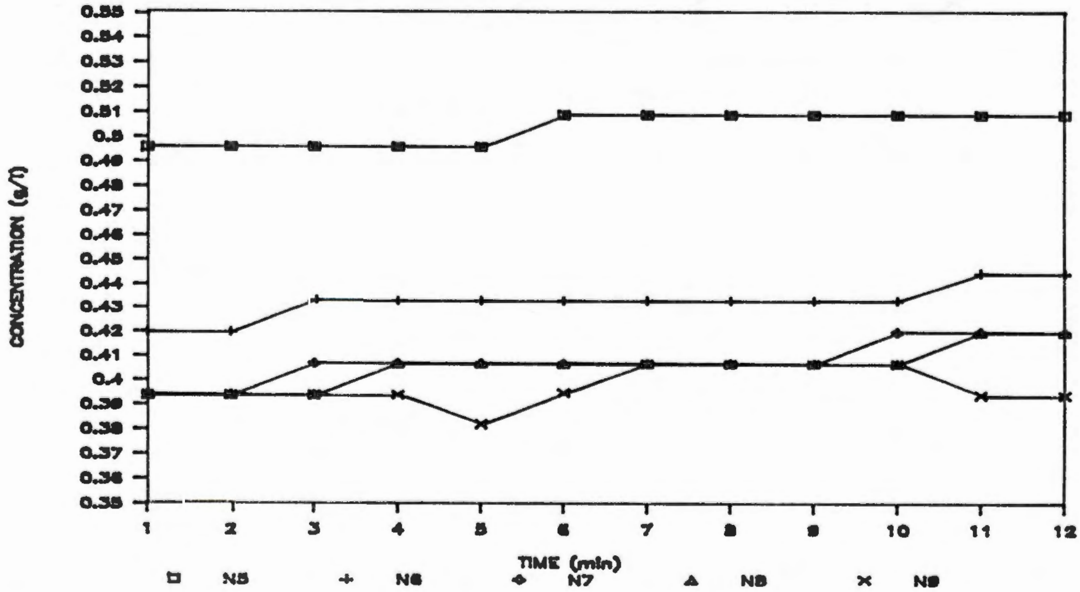

Figure 57. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the Scienco pump was at the individual nozzles, and fluid entrance to the boom was slightly to the side of nozzle 5. Sampling began at time = 1 min, and system pressure was 378 kPa.

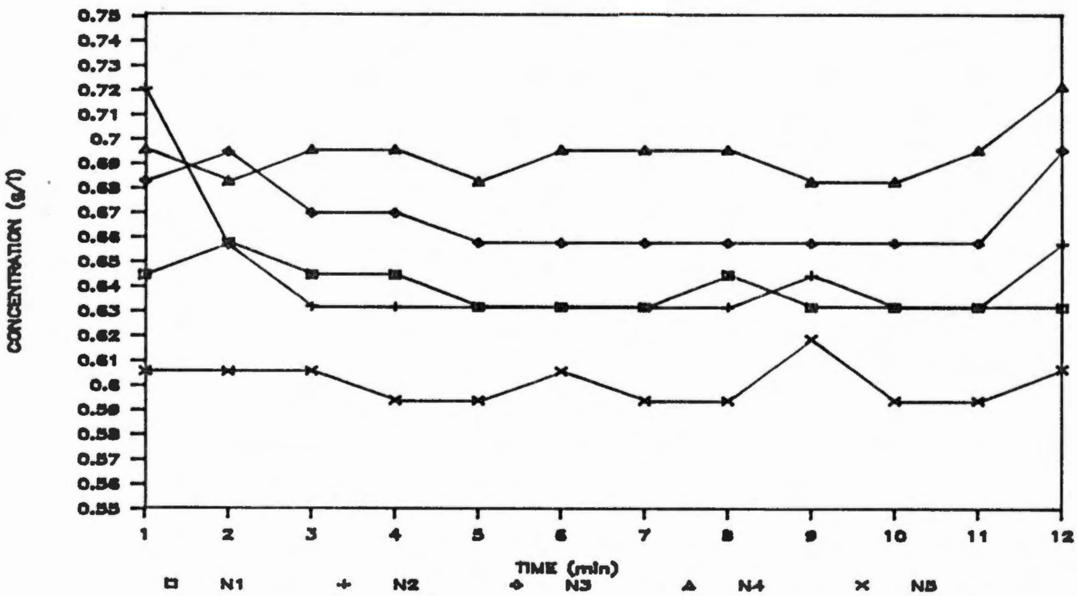

Figure 58. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the FMI pump was at the individual nozzles, and fluid entrance to the boom was slightly to the side of nozzle 5. Sampling began at time = 1 min, and system pressure was 378 kPa.

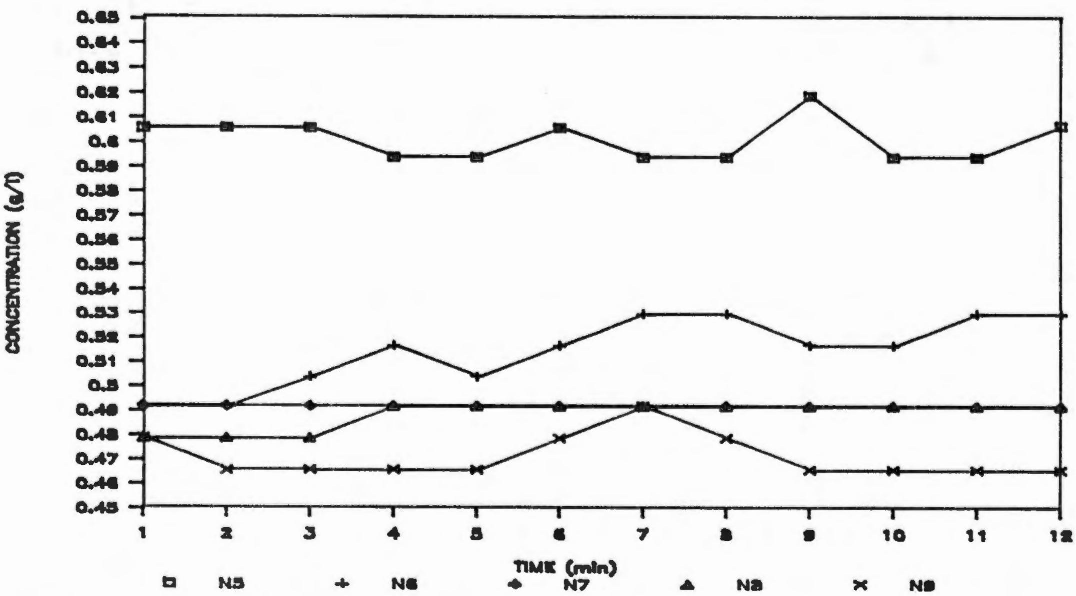

Figure 59. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the FMI pump was at the individual nozzles, and fluid entrance to the boom was slightly to the side of nozzle 5. Sampling began at time = 1 min, and system pressure was 378 kPa.

output fluid in previous tests involving upstream injection, a pulsation dampener was designed and implemented for this system. However, the presence of the dampener did not appreciably affect the system performance at the low flows characteristic of these tests.

System performance appeared to be sensitive to boom configuration. Thus, a symmetric boom equipped with 8 nozzles was constructed with the fluid entrance to the boom located midway between the fourth and fifth nozzles (Figure 60). Tests were then conducted using only the Scienco pump at 275 kilopascals with an injection rate of 3.5 milliliters per second. Figures 61 and 62 show a maximum concentration variation among nozzles of 0.10 grams per liter or 19.5 percent of the average concentration. This is the smallest variation of concentration among nozzles on the boom observed for any test conducted using injection directly at the nozzle. Most of this variation resulted from measurements of the first sample taken at the one-minute point. If this sample was omitted, the concentration variation is reduced to 0.087 grams per liter or 15 percent of the average concentration. The concentration in the nozzle effluent is also more nearly equal on the two ends of the boom.

Conventional Tank-Mix Application

Tests were conducted with a conventional sprayer (refer to Figure 1, page 33) to insure the accuracy of the conductivity meter and to allow comparison of conventional application to the results obtained with the three different direct injection systems. These tests only

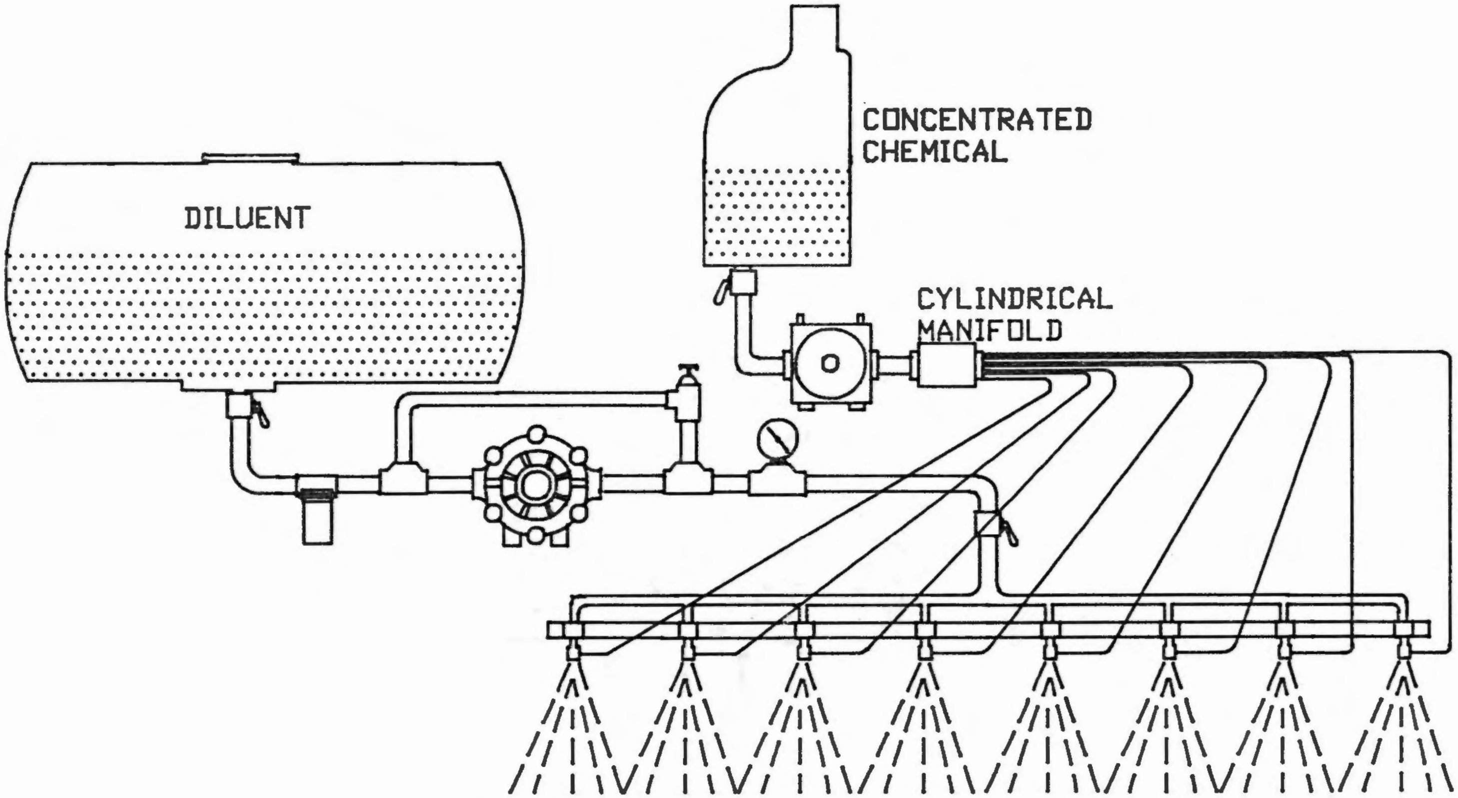

Figure 60. Layout of the fluid handling and transport system components on an experimental hydraulic sprayer employing direct chemical injection at the individual nozzles for an eight-nozzle boom.

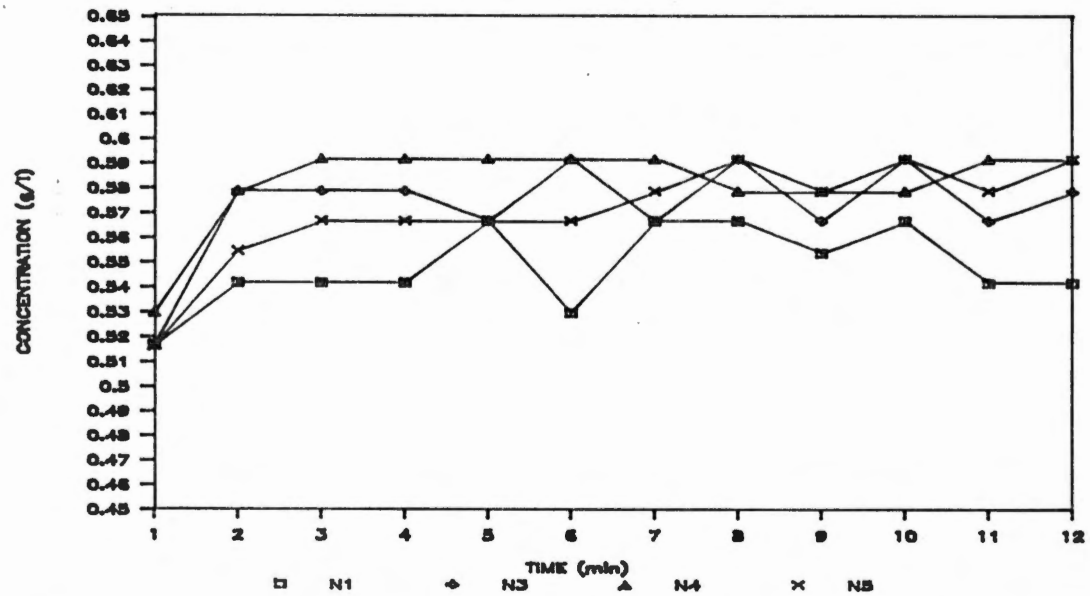

Figure 61. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time. Chemical injection with the Scienco pump was at the individual nozzles for an eight-nozzle boom. Sampling began at time = 1 min, and system pressure was 275 kPa.

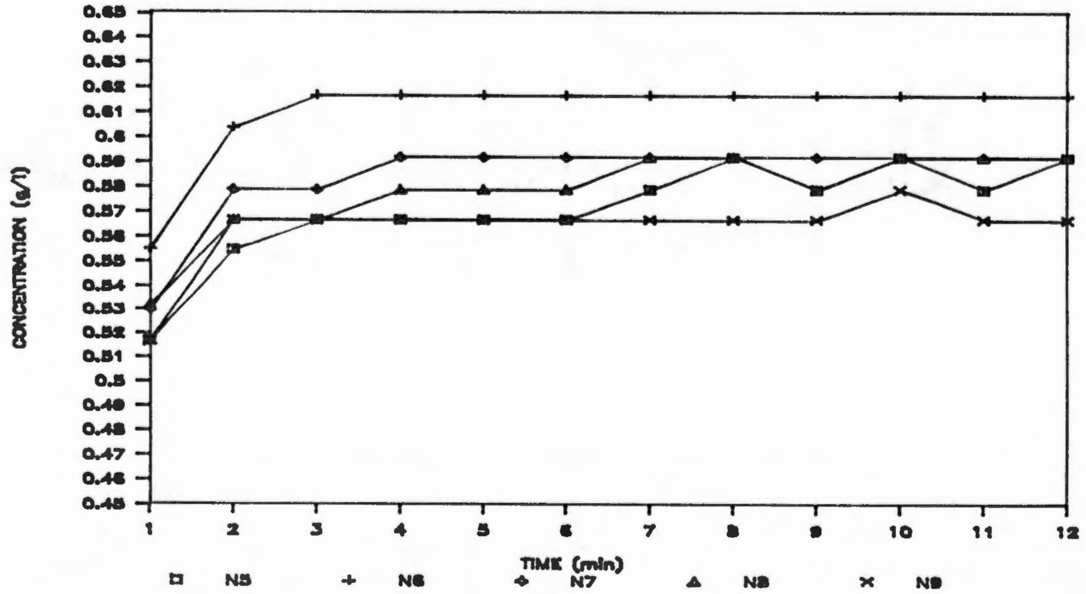

Figure 62. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time. Chemical injection with the Scienco pump was at the individual nozzles for an eight-nozzle boom. Sampling began at time = 1 min, and system pressure was 275 kPa.

included measurements of chemical concentration consistency in the nozzle effluent at system operating pressures of 171, 275, and 378 kilopascals. The tank mix was a combination of water and a potassium bromide solution.

Figures 63 and 64 show that the conventional sprayer operating at 275 kilopascals produced a maximum chemical concentration variation of 0.014 grams per liter or 2.0 percent of the average potassium bromide concentration. This level of variation is comparable to that observed using direct injection with the peristaltic pump positioned just upstream of the system pump. Results of tests at 171 kilopascals are shown in Figures 65 and 66, and performance at 378 kilopascals are depicted in Figures 67 and 68. Maximum variation in the chemical concentration in the nozzle effluent for the two tests were 3.7 and 3.1 percent of the average concentration, respectively. If the assumption can be made that the effluent discharged from the individual nozzles in a system using a conventional mix has an absolutely uniform chemical concentration, then the measuring system used to establish concentration has been shown capable of measuring concentration to within less than 4 percent of the average concentration. This is necessarily true, of course, only over the small range of chemical concentrations used in these tests. Based upon this reasoning, direct injection on the low-pressure side of the system pump has been shown to produce an output of uniform chemical concentration.

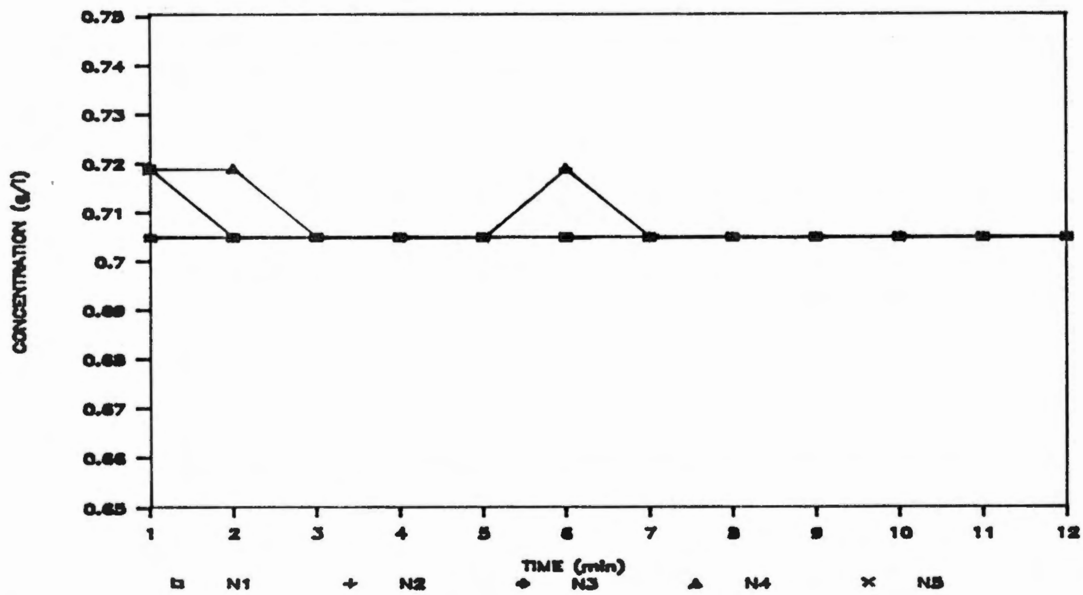

Figure 63. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time with a conventional application system at a pressure of 275 kPa. Sampling began at 1 min.

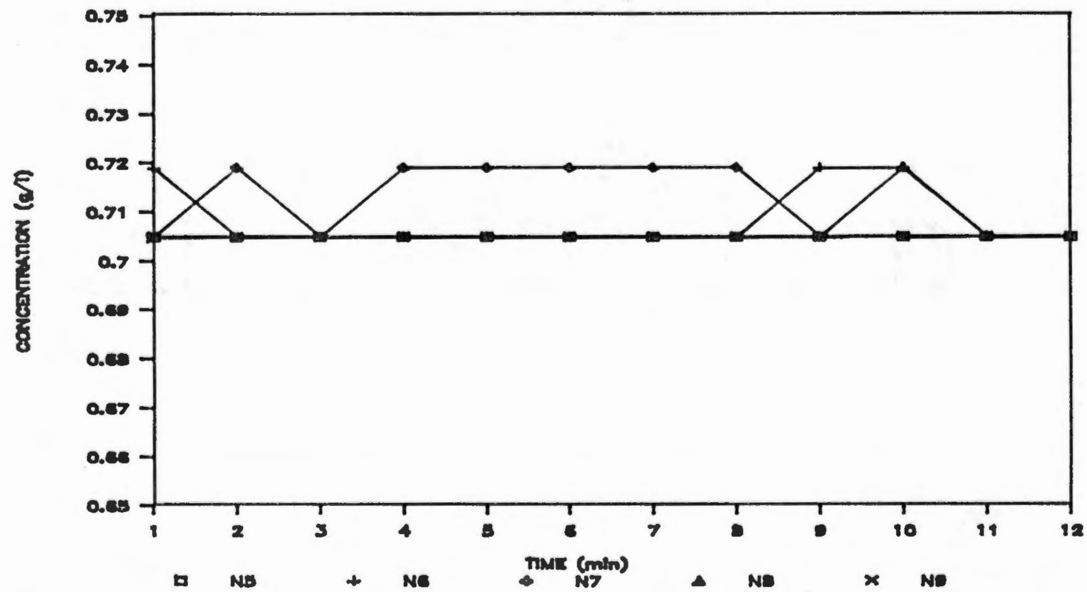

Figure 64. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time with a conventional application system at a pressure of 275 kPa. Sampling began at 1 min.

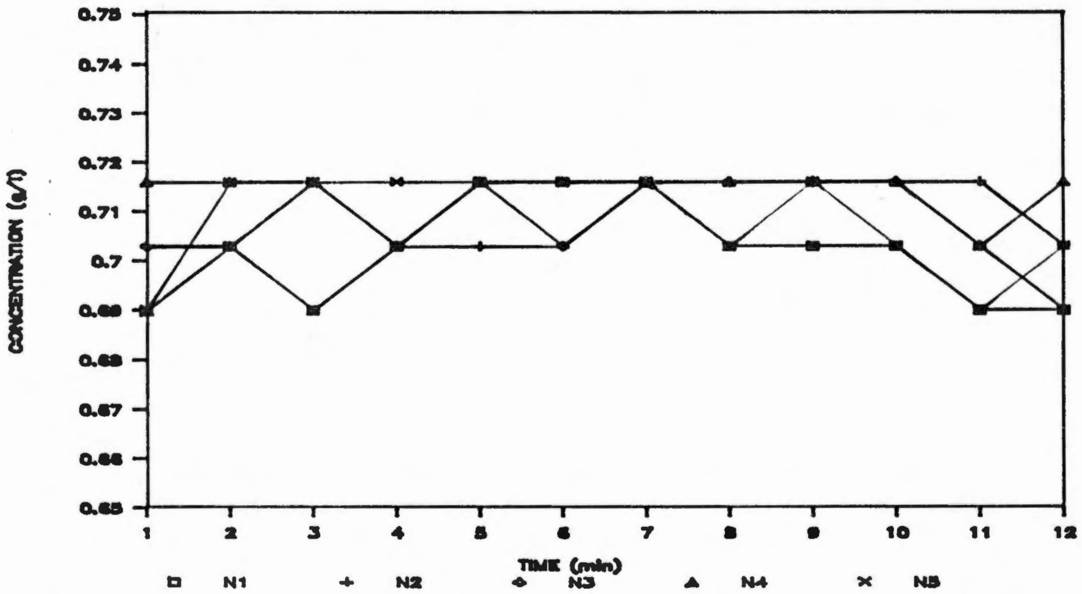

Figure 65. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time with a conventional application system at a pressure of 171 kPa. Sampling began at 1 min.

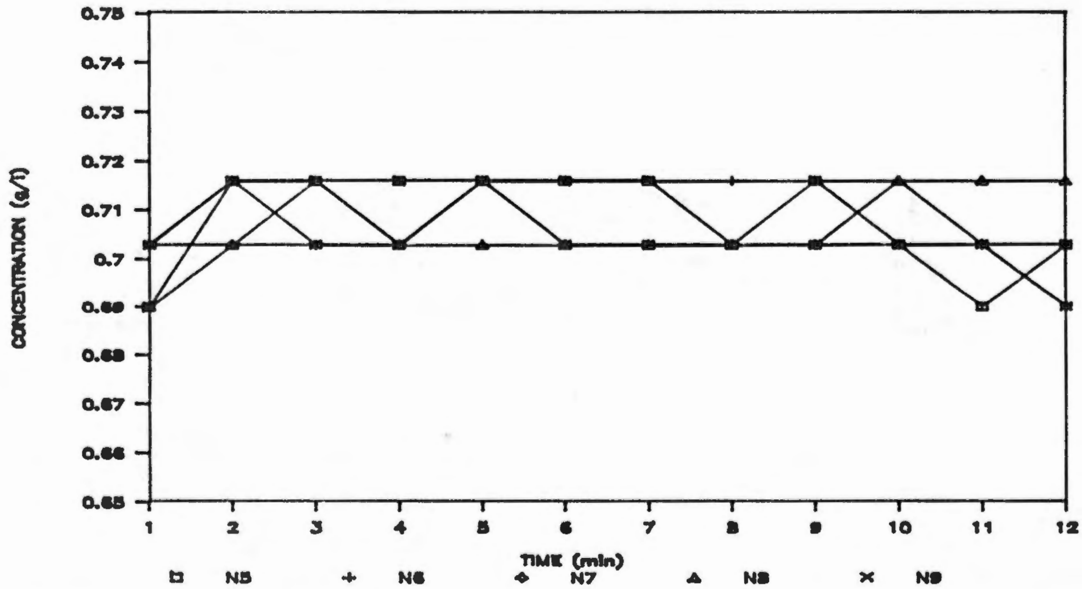

Figure 66. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time with a conventional application system at a pressure of 171 kPa. Sampling began at 1 min.

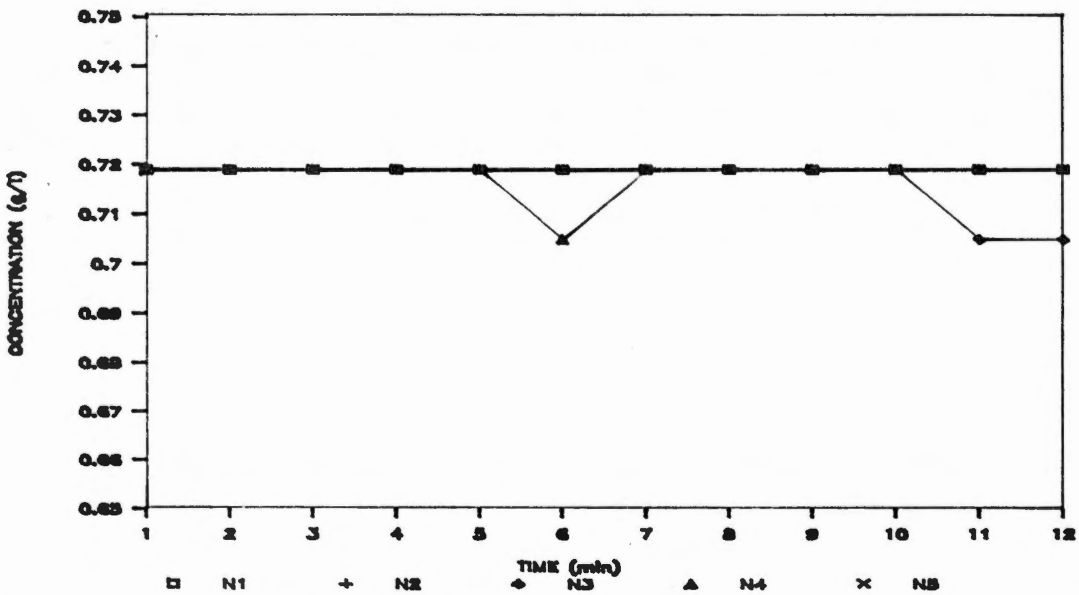

Figure 67. Variation in chemical concentration in the effluent of nozzles 1 through 5 as a function of time with a conventional application system at a pressure of 378 kPa. Sampling began at 1 min.

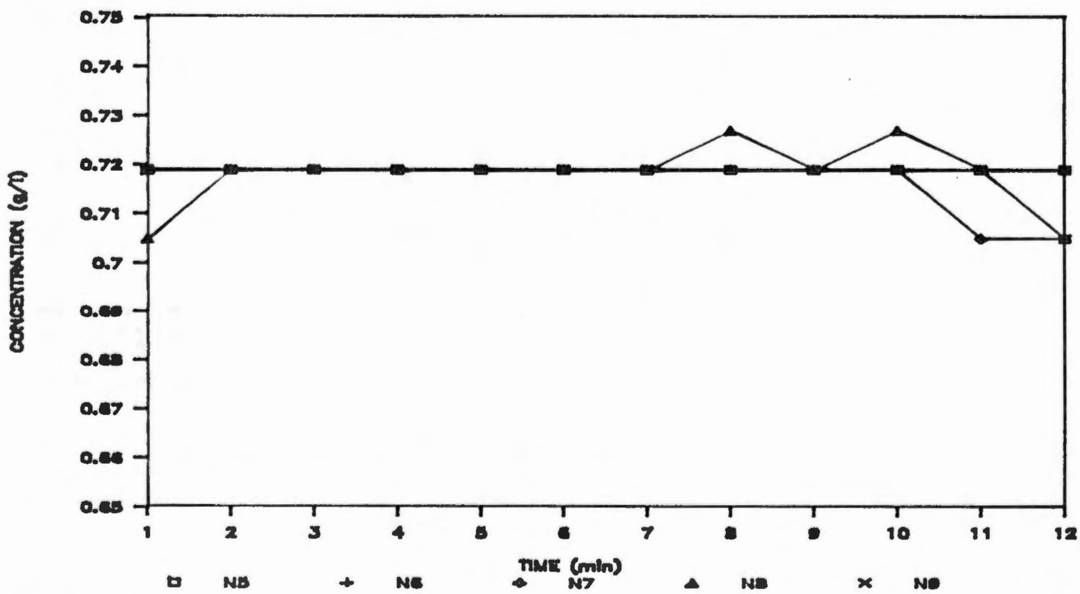

Figure 68. Variation in chemical concentration in the effluent of nozzles 5 through 9 as a function of time with a conventional application system at a pressure of 378 kPa. Sampling began at 1 min.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

Injection of chemical concentrate directly into the spray diluent has several potential advantages. These advantages include less exposure for the applicator, less potential environmental contamination due to application errors and disposal of excess tank mix, and cost effectiveness. However, disadvantages or problems related to the transient time in achieving appropriate concentration of chemical in the nozzle effluent, inadequate mixing of chemical and diluent, and precise metering of small flows of chemical concentrate for injection have been hindrances to the acceptance and adoption of this technological concept.

An experimental laboratory-model direct injection system was designed, constructed, and used to measure the transient period between initiation of chemical injection and achievement of full chemical concentration at the nozzle. The apparatus was also used to determine the variation in chemical concentration in the nozzle effluent both from nozzle to nozzle across the boom and with time. Chemical concentrate was introduced directly into the diluent stream at three points. The points were injection immediately upstream of the system pump, injection immediately downstream of the system pump, and injection at the individual nozzles on the boom. Tests were conducted at system operating pressures of 171, 275, and 378 kilopascals. Three pumps were also tested at the upstream injection point and two pumps at each pressure-side injection point. The three pumps were a peristaltic pump, an experimental piston pump manufactured by Scienco Inc., and a piston pump manufactured by Fluid Metering Inc. The latter two units were used for pressure-side injection at both locations. A computer model for predicting transient times for low-pressure injection was also written and validated.

A potassium bromide solution formulated at a concentration of 28.3 grams per liter was used as the simulated pesticide to be injected into the diluent stream. The conductivity of the effluent solution caught at the nozzles was measured. This conductivity was correlated to chemical concentration in the effluent to determine magnitude and uniformity of concentration.

Conclusions

Evaluation of the data acquired during the development and operation of a laboratory model direct injection chemical application system resulted in the following conclusions:

1. A computer model for determining transient time or interval from initiation of chemical injection to the instant that chemical is detected in the nozzle effluent may be useful in predicting performance of various component options on a direct injection sprayer system. However, the flow rate through the orifice of a flat fan nozzle may not be accurately predicted if considered directly proportional to the square root of static pressure across the orifice. Further, careful

attention may be required in determining the effective conduit cross sectional area, given that the diameter of flexible tubing may change under influence of the fluid pressure.

2. Measuring the electrical conductivity of the chemical-diluent mix formed by injecting a solution containing a known concentration of potassium bromide was an effective method of determining the concentration of chemical in the nozzle effluent. The conductivity was highly correlated with chemical concentration. Results of the measurements were repeatable.

3. Performance of a chemical applicator equipped with direct injection is very dependent upon component selection and system configuration. Changes in component size and placement markedly affected the system response time and uniformity of chemical delivery to the nozzles.

4. Direct injection on the low-pressure side of the system pump using each of three different injection pumps produced chemical concentrations in the nozzle effluent equal to that achieved through conventional tank mixing. Variations in chemical concentrations in the nozzle effluent with both time and from nozzle to nozzle across the boom were similar for conventional tank mixing and low-pressure direct injection.

5. The sprayer system pump is effective in thoroughly mixing injected chemical with the diluent. In comparing direct injection immediately upstream of the system pump to injection immediately downstream, chemical concentration variations at the nozzle were usually greater with downstream injection.

6. Injection downstream of the sprayer system pump is effective in reducing the transient period in comparison to injection on the low-pressure side of the pump. The transient period ranged from 23 to 29 seconds with upstream injection, and was reduced to a little as 15 seconds in some tests involving injection immediately downstream of the system pump. The transient period was effectively eliminated by injecting the chemical concentrate directly into the individual nozzles.

7. An injection pump designed for high-speed operation to produce a rather constant chemical flow is particularly desirable when injecting downstream of the sprayer system pump. Since this injection site disallows use of the system pump for chemical-diluent mixing, pulsed input of the chemical can result in substantial variation in chemical concentrations at the sprayer nozzles.

8. Higher system operating pressures produce increased variation in the nozzle effluent chemical concentrations when chemical is being injected directly into the individual nozzle bodies.

9. When directly injecting chemical into the individual nozzles, the chemical concentration in the effluent of a given nozzle varied relatively little with time. However, achieving a uniform concentration from nozzle to nozzle across the boom was very difficult and not consistently accomplished.

10. Further testing and more extensive studies need to be conducted in an effort to determine the flow characteristics inside the conduit system of the sprayer. Such information is needed to serve as the basis for designing an effective direct injection system.

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APPENDIXES

APPENDIX A

CALIFORNIA'S CLOSED SYSTEM CRITERIA

adapted from:
California Department of Food And Agriculture

available from:
California Department of Food And Agriculture
Division of Pest Management, Environmental
Protection and Worker Safety
Worker Health and Safety Branch
1220 N Street, Sacramento, California 95814

CALIFORNIA'S CLOSED SYSTEM CRITERIA

1. The liquid pesticide shall be removed from its original shipping container and transferred through connecting hoses, pipes and/or couplings that are sufficiently tight to prevent exposure of any person to the pesticide concentration, use dilution, or rinse solution.

2. All hoses, piping, tanks and connections used in conjunction with a closed liquid pesticide system shall be of a type appropriate for the pesticide being used and the pressure and vacuum to be encountered.

3. All sight gauges shall be protected against breakage. External sight gauges shall be equipped with valves so that the pipes to the sight gauge can be shut off in case of breakage or leakage.

4. The closed system shall adequately measure the pesticide being used. Measuring devices shall be accurately calibrated to the smallest unit in which the material is being weighted or measured. Consideration must be given to any pesticide remaining in the transfer lines as to the effect on accuracy of measurement

5. The movement of a pesticide concentrate, beyond a pump by positive pressure, shall not exceed 25 pounds per square inch of pressure.

6. A probe shall not be removed from a container except when:

    a. The container is emptied and the inside of the container and the probe have been rinsed in accordance with Item 8.

    b. The Department of Food and Agricultural has evaluated the probe and determined that, by the nature of its construction or design, it eliminated significant hazard of worker exposure to the pesticide when withdrawn from a partial container.

    c. The pesticide is used without dilution and the container has been emptied.

7. Shut-off device shall be installed on the exit end of all hoses and at all disconnect points to prevent leakage of the pesticide when the transfer is stopped and the hose is removed or disconnected.

    a. If the hose carried pesticide concentrate and has not been rinsed in accordance with Item 8, a dry coupler that will minimize pesticide drippage to not more than 2 milliliters per disconnect shall be installed at the disconnect point.

b. If the hose carried a pesticide use dilution or rinse solution, a reversing action pump or a similar system that will empty the hose and eliminate dripping of liquid from the end of the hose may be used as an alternative to a shut-off device.

8. When the pesticide is to be diluted for use, the closed system shall provide for adequate rinsing of containers that have held less than 60 gallons of a liquid pesticide. Rinsing shall be done with a medium that contains no pesticide, such as water.

a. The rinsing system shall be capable of spray-rinsing the inner surfaces of the container, and the rinse solution shall go into the pesticide mix tank or applicator vehicle via the closed system. The system shall be capable of adequately rinsing the probe (if used) and all hoses, measuring devices, etc.

b. A minimum of 15 pounds pressure per square inch shall be used for rinsing.

c. The rinsing shall be continued until a minimum of 10 gallons or one-half of the container volume, whichever is less, of rinse medium has been used.

d. The rinse solution shall be removed from the pesticide container concurrent with introduction of the rinse medium.

e. Pesticide containers shall be protected against excessive pressure during the container rinse operation. The maximum container pressure shall not exceed 5 pounds pressure per square inch.

9. Each commercially produced closed system or component to be used with a closed system shall be sold with a complete set of instructions consisting of a functional operating manual and a decal covering the basic operation; the decal shall be placed in a prominent location on the system.

The instructions shall include specific directions for cleaning and maintenance of the system in a scheduled basis. The instructions shall also describe any restrictions or limitations relating to the system, such as pesticides that are incompatible with materials used in the construction of the system, types (or sizes) of containers or closures that cannot be handled by the system, any limits on ability to correct for over measurement of a pesticide, or special procedures of limitations on the ability of the system to deal with partial containers.

A list of closed systems found to meet these criteria is available from the California Department of Food Agriculture.

APPENDIX B

COMPUTER MODEL

COMPUTER MODEL

```
10 CLS:KEY OFF
20 '*****INJECTION POINT AT LOW PRESSURE SIDE OF PUMP**********
30 '
40 '   VARIABLE DEFINITION:
50 '
60 '        NOZ          = MANUFACTURER'S NOZZLE NUMBER
70 '        GS           = GROUND SPEED OF THE SPRAYER (FT/SEC)
80 '        PRESS        = OPERATING PRESSURE (PSI)
90 '        HD           = DIAMETER OF THE HOSE (IN)
100 '        NS           = SPACING OF THE NOZZLES ON THE SPRAY BOOM (IN)
110 '        NN           = NUMBER OF NOZZLES ON THE SPRAYER BOOM
120 '        NOZZ         = DISCHARGE RATE OF THE NOZZLE (GPM)
130 '        K            = NOZZLE COEFFICIENT
140 '        GPM          = DISCHARGE RATE OF THE NOZZLE AT GIVEN PRESSURE
                             (GPM)
150 '        FV           = VELOCITY OF THE FLUID IN THE HOSE (FT/SEC)
160 '        TI           = TIME FROM INJECTION POINT TO BOOM (SEC)
170 '        NUMNO        = NUMBER OF NOZZLES ON EACH SIDE OF INJECTION
                             POINT
180 '        FLTM(RED)    = TIME FROM INJECTION POINT TO EACH NOZZLE (SEC)
190 '        HDIA         = DIAMETER OF HOSE FROM THE INJECTION POINT TO
                             REGULATOR (IN)
200 '        HL           = LENGTH OF HOSE FROM INJECTION POINT TO
                             REGULATOR (IN)
210 '        HDIAM        = DIAMETER OF HOSE FROM REGULATOR TO BOOM (IN)
220 '        HLT          = LENGTH OF HOSE FROM REGULATOR TO BOOM (IN)
230 '        FVRTB        = VELOCITY OF THE FLUID FROM REGULATOR TO
                             ENTRANCE OF BOOM (FT/SEC)
240 '        TIRTB        = TIME OF FLUID TRAVEL FROM REGULATOR TO
                             ENTRANCE OF BOOM (SEC)
250 '        FVITR        = VELOCITY OF THE FLUID FROM INJECTION POINT TO
                             REGULATOR (FT/SEC)
260 '        TIITR        = TIME OF FLUID TRAVEL FROM INJECTION POINT TO
                             REGULATOR (SEC)
270 '        N            = THE NUMBER WHICH IS SELECTED FOR THE
                             APPROPRIATE GRAPH
280 '        STRT         = THE POSITION AT WHICH THE GRAPH STARTS
290 '        COUNT,CNT    = THE X POSITION ON THE GRAPH
300 '        XMAX,XMIN = THE MAXIMUM AND MINIMUM X AXIS VALUES
310 '        YMAX,YMIN    = THE MAXIMUM AND MINIMUM Y AXIS VALUES
320 '        TIT$,TITL$   = THE HEADINGS FOR EACH GRAPH
330 '        DIST(GREEN) = THE DISTANCE TRAVELED BY THE SPRAYER WHEN
                             ACCORDING TO FLUID TRAVEL TIME(FT)
340 '        RED,NUN,CT,C,GREEN,BLUE,BLACK = ARE USED FOR COUNTERS OF
                             LOOP
350 '
360 '*****************************************************************
370 '
```

```
380 ' THIS SECTION ALLOWS THE USER TO INPUT THE NEEDED PARAMETERS.
390 '
400 LOCATE 4,15:INPUT "MANUFACTURER'S NOZZLE NUMBER DESIGNATION
                         (######)";NOZ
410 LOCATE 6,26:INPUT "MACHINE GROUND SPEED (FT/SEC)";GS
420 LOCATE 8,25:INPUT "SYSTEM OPERATING PRESSURE (PSI)";PRESS
430 LOCATE 10,14:INPUT "DIAMETER OF THE HOSE FEEDING INDIVIDUAL NOZZLES
                         (IN)";HD
440 LOCATE 12,24:INPUT "NOZZLE SPACING ALONG THE BOOM (IN)";NS
450 LOCATE 14,25:INPUT "NUMBER OF NOZZLES ALONG THE BOOM";NN
460 LOCATE 16,14:INPUT "DIAMETER OF THE HOSE FROM INJECTOR TO REGULATOR
                         (IN)";HDIA
470 LOCATE 18,15:INPUT "LENGTH OF THE HOSE FROM INJECTOR TO REGULATOR
                         (IN)";HL
480 LOCATE 20,16:INPUT "DIAMETER OF THE HOSE FROM REGULATOR TO BOOM
                         (IN)";HDIAM
490 LOCATE 22,17:INPUT "LENGTH OF THE HOSE FROM REGULATOR TO BOOM
                         (IN)";HLT
500 '
510 ' THIS SECTION USES THE NOZZLE NUMBER TO OBTAIN THE FLOW RATE FOR
520 ' THE NOZZLE AT A PRESSURE OF 40 PSI.
530 '
540 NOZ$ = STR$(NOZ)
550 Q = INT(LOG(NOZ))
560 ON (Q-2) GOTO 570,600,630
570 NOZZ$ = RIGHT$(NOZ$,1)
580 NOZZ = VAL(NOZZ$)/10
590 GOTO 650
600 NOZZ$ = RIGHT$(NOZ$,2)
610 NOZZ = VAL(NOZZ$)/100
620 GOTO 650
630 NOZZ$ = RIGHT$(NOZ$,3)
640 NOZZ = VAL(NOZZ$)/1000
650 '
660 ' THIS SECTION CALCULATES THE NOZZLE COEFFICIENT, THE GALLONS PER
670 ' ACRE, AND THE FLUID VELOCITY OF THE BOOM AT THE SELECTED PRESSURE.
680 '
690 K = NOZZ/SQR(40)
700 GPM = K*SQR(PRESS)
710 FV = (GPM*NN/449)/((HD^2*3.1416/4)/144)
720 '
730 ' THIS SECTION CALCULATES THE FLUID VELOCITY AND THE FLUID TRAVEL
740 ' TIME FOR THE LEADER HOSE (HOSE FROM INJECTION POINT TO THE
750 ' REGULATOR AND THE HOSE FROM THE REGULATOR TO THE BOOM).
760 '
770 FVRTB = (GPM*NN/449)/((HDIAM^2*3.1416/4)/144)
780 TIRTB = HLT/(FVRTB*12)
790 FVITR = (GPM*NN/449)/((HDIA^2*3.1416/4)/144)
800 TIITR = HL/(FVITR*12)
810 TI = TIRTB + TIITR
820 NUMNO = INT(NN/2)
830 '
```

```
840 CLS
850 SCREEN 0,0,0
860 '
870 ' THIS SECTION ALLOWS THE USER TO SELECT WHICH GRAPH IS TO BE DRAWN,
880 ' INPUT NEW PARAMETERS, OR END THE PROGRAM.
890 '
900 LOCATE 1,18:PRINT"WHICH FUNCTION WOULD YOU LIKE TO PERFORM"
910 LOCATE 3,7:PRINT "1. A PLOT OF NOZZLE DESIGNATION BY POSITION ON
                         THE BOOM VERSUS THE
920 LOCATE 4,7:PRINT "   TRAVEL TIME OF THE FLUID FROM INSTANT OF
                         INJECTION TO ARRIVAL AT"
930 LOCATE 5,7:PRINT "   THE SPECIFIED NOZZLE"
940 LOCATE 7,7:PRINT "2. A PLOT OF NOZZLE DESIGNATION BY POSITION ON THE
                         BOOM VERSUS THE"
950 LOCATE 8,7:PRINT "   TRAVEL TIME OF THE FLUID FROM INSTANT OF FLUID
                         ENTRANCE INTO THE"
960 LOCATE 9,7:PRINT "   BOOM TO ARRIVAL AT SPECIFIED NOZZLE"
970 LOCATE 11,7:PRINT "3. A PLOT OF NOZZLE DESIGNATION BY POSITION ON
                          THE BOOM VERSUS THE"
980 LOCATE 12,7:PRINT "   DISTANCE TRAVELED BY THE SPRAYER WHEN TRAVEL
                          TIME IS MEASURED"
990 LOCATE 13,7:PRINT "   FROM THE INITIATION OF CHEMICAL INJECTION INTO
                          THE SYSTEM UNTIL"
1000 LOCATE 14,7:PRINT "   ARRIVAL OF CHEMICAL AT THE SPECIFIED NOZZLE"
1010 LOCATE 16,7:PRINT "4. A PLOT OF NOZZLE DESIGNATION BY POSITION ON
                           THE BOOM VERSUS THE"
1020 LOCATE 17,7:PRINT "   DISTANCE TRAVELED BY THE SPRAYER WHEN TRAVEL
                           TIME IS MEASURED"
1030 LOCATE 18,7:PRINT "   FROM THE TIME OF FLUID ENTRANCE INTO THE BOOM
                           UNTIL ARRIVAL"
1040 LOCATE 19,7:PRINT "   AT THE SPECIFIED NOZZLE"
1050 LOCATE 21,7:PRINT "5. INPUT NEW PARAMETERS"
1060 LOCATE 23,7:PRINT "6. END PROGRAM"
1070 LOCATE 25,7:INPUT "INPUT NUMBER OF SELECTION";N
1080 IF N = 1 GOTO 1240
1090 IF N = 2 GOTO 2230
1100 IF N = 3 GOTO 1240
1110 IF N = 4 GOTO 2230
1120 IF N = 5 GOTO 10
1130 IF N = 6 GOTO 3140
1140 '
1150 '************ FROM INJECTION POINT TO EACH NOZZLE ***********
1160 '
1170 ' THIS SECTION DETERMINES IF THE BOOM IS EQUIPPED WITH AN EVEN OR
1180 ' ODD NUMBER OF NOZZLES ON THE BOOM.  IF THERE IS AN ODD NUMBER OF
1190 ' NOZZLES THEN THIS SECTION CALCULATES THE FLUID VELOCITY TO EACH
1200 ' NOZZLE AND THE TIME OF FLUID TRAVEL TO EACH NOZZLE.  THIS SECTION
1210 ' ALSO CHECKS TO SEE WHICH GRAPH THE USER SELECTED AND SETS THE
1220 ' APPROPRIATE PARAMETERS FOR THE GRAPH.
1230 '
1240 IF NUMNO = (NN/2) THEN GOTO 1530
1250 NUN = NN - 1
```

```
1260 FLTM(1) = TI
1270 FOR RED = 2 TO NUMNO + 1
1280    FV = (GPM*NUN/449)/((HD^2*3.1416/4)/144)
1290    FLTM(RED) = NS/(FV*12) + FLTM(RED-1)
1300    NUN = NUN - 2
1310 NEXT RED
1320 '
1330 ' THIS SECTION CALCULATES THE DISTANCE TRAVELED BY THE SPRAYER FOR
1340 ' A BOOM EQUIPPED WITH AN ODD NUMBER OF NOZZLES AND WHEN TIME IS
1350 ' MEASURED FROM INITIATION OF CHEMICAL INJECTION INTO THE SYSTEM
1360 ' UNTIL ARRIVAL OF CHEMICAL AT THE SPECIFIED NOZZLE.
1370 '
1380 FOR GREEN = 1 TO NUMNO + 1
1390   DIST(GREEN) = FLTM(GREEN) * GS
1400 NEXT GREEN
1410 IF N = 3 THEN GOTO 1900
1420 STRT = NUMNO + 1
1430 COUNT = RED - 1:CNT = RED - 1
1440 CT = 1
1450 GOTO 1780
1460 '
1470 ' THIS SECTION CALCULATES THE FLUID VELOCITY TO EACH NOZZLE FOR A
1480 ' BOOM WITH AN EVEN NUMBER OF NOZZLES AND THE TIME OF
1490 ' FLUID TRAVEL TO EACH NOZZLE.  THIS SECTION ALSO CHECKS TO SEE
1500 ' WHICH GRAPH THE USER SELECTED AND SETS THE APPROPRIATE PARAMETERS
1510 ' FOR THE GRAPH.
1520 '
1530 FLTM(0) = TI
1540 FLTM(1) = (NS/2)/(FV*12) + TI
1550 NUN = NN - 2
1560 FOR RED = 2 TO NUMNO
1570    FV = (GPM*NUN/449)/((HD^2*3.1416/4)/144)
1580    FLTM(RED) = NS/(FV*12) + FLTM(RED-1)
1590    NUN = NUN - 2
1600 NEXT RED
1610 '
1620 ' THIS SECTION CALCULATES THE DISTANCE TRAVELED BY THE SPRAYER FOR
1630 ' A BOOM EQUIPPED WITH AN EVEN NUMBER OF NOZZLES AND WHEN TIME IS
1640 ' MEASURED FROM INITIATION OF CHEMICAL INJECTION INTO THE SYSTEM
1650 ' UNTIL ARRIVAL OF CHEMICAL AT THE SPECIFIED NOZZLE.
1660 DIST(0) = FLTM(0) * GS
1670 FOR GREEN = 1 TO NUMNO
1680   DIST(GREEN) = FLTM(GREEN) * GS
1690 NEXT GREEN
1700 IF N = 3 THEN GOTO 1990
1710 STRT = NUMNO + .5
1720 COUNT = RED - 1:CNT = RED
1730 CT = 0
1740 '
1750 ' THIS SECTION SETS THE MAXIMUM AND MINIMUM VALUES FOR THE X AND Y
1760 ' AXIS AND THE HEADINGS OF THE GRAPH.
1770 '
```

```
1780 XMAX = NN: XMIN = 1
1790 YMAX = FLTM(RED-1): YMIN = 0
1800 C = RED - 1
1810 TIT$ = "NOZZLES POSITION VERSUS TIME OF FLUID TRAVEL FROM"
1820 TITL$ = "    INJECTION POINT TO EACH NOZZLE (SEC)"
1830 GOSUB 3170
1840 GOTO 690
1850 '
1860 ' THIS SECTION SETS THE PARAMETERS FOR THE GRAPH OF NOZZLE POSITION
1870 ' VERSUS THE DISTANCE TRAVELED BY THE SPRAYER FOR AN ODD NUMBER OF
1880 ' NOZZLES.
1890 '
1900 STRT = NUMNO + 1
1910 COUNT = GREEN - 1:CNT = GREEN - 1
1920 CT = 1
1930 GOTO 2060
1940 '
1950 ' THIS SECTION SETS THE PARAMETERS FOR THE GRAPH OF NOZZLE POSITION
1960 ' VERSUS THE DISTANCE TRAVELED BY THE SPRAYER FOR AN EVEN NUMBER OF
1970 ' NOZZLES.
1980 '
1990 STRT = NUMNO + .5
2000 COUNT = GREEN - 1:CNT = GREEN
2010 CT = 0
2020 '
2030 ' THIS SECTION SETS THE MAXIMUM AND MINIMUM VALUES FOR THE X AND Y
2040 ' AXIS AND THE HEADINGS OF THE GRAPH.
2050 '
2060 XMAX = NN: XMIN = 1
2070 YMAX = DIST(GREEN-1): YMIN = 0
2080 C = GREEN - 1
2090 TIT$ = "    NOZZLE POSITION VERSUS DISTANCE TRAVELED (FT)"
2100 TITL$ = "WHEN TIME STARTS FROM INJECTION POINT TO EACH NOZZLE"
2110 GOSUB 3170
2120 GOTO 690
2130 '
2140 '*********** FROM ENTRANCE OF BOOM TO EACH NOZZLE ***********
2150 '
2160 ' THIS SECTION DETERMINES IF THE BOOM IS EQUIPPED WITH AN EVEN OR
2170 ' ODD NUMBER OF NOZZLES ON THE BOOM.  IF THERE IS AN ODD NUMBER OF
2180 ' NOZZLES THEN THIS SECTION CALCULATES THE FLUID VELOCITY TO EACH
2190 ' NOZZLE AND THE TIME OF FLUID TRAVEL TO EACH NOZZLE.  THIS SECTION
2200 ' ALSO CHECKS TO SEE WHICH GRAPH THE USER SELECTED AND SETS THE
2210 ' APPROPRIATE PARAMETERS FOR THE GRAPH.
2220 '
2230 IF NUMNO = (NN/2) THEN GOTO 2510
2240 NUN = NN - 1
2250 FLTM(1) = 0
2260 FOR BLUE = 2 TO NUMNO + 1
2270    FV = (GPM*NUN/449)/((HD^2*3.1416/4)/144)
2280    FLTM(BLUE) = NS/(FV*12) + FLTM(BLUE-1)
2290    NUN = NUN - 2
```

```
2300 NEXT BLUE
2310 '
2320 ' THIS SECTION CALCULATES THE DISTANCE TRAVELED BY THE SPRAYER FOR
2330 ' A BOOM EQUIPPED WITH AN ODD NUMBER OF NOZZLES AND WHEN TIME IS
2340 ' MEASURED FROM INITIATION OF CHEMICAL INJECTION INTO THE SYSTEM
2350 ' UNTIL ARRIVAL OF CHEMICAL AT THE SPECIFIED NOZZLE.
2360 '
2370 FOR BLACK = 1 TO NUMNO + 1
2380   DIST(BLACK) = FLTM(BLACK) * GS
2390 NEXT BLACK
2400 IF N = 4 GOTO 2900
2410 STRT = NUMNO + 1
2420 COUNT = BLUE - 1:CNT = BLUE - 1
2430 CT = 1
2440 GOTO 2780
2450 '
2460 ' THIS SECTION CALCULATES THE FLUID VELOCITY TO EACH NOZZLE FOR A
2470 ' BOOM WITH AN EVEN NUMBER OF NOZZLES AND THE TIME OF FLUID TRAVEL
2480 ' TO EACH NOZZLE.  THIS SECTION ALSO CHECKS TO SEE WHICH GRAPH THE
2490 ' USER SELECTED AND SETS THE APPROPRIATE PARAMETERS FOR THE GRAPH.
2500 '
2510 FLTM(0) = 0
2520 FLTM(1) = (NS/2)/(FV*12)
2530 NUN = NN - 2
2540 FOR BLUE = 2 TO NUMNO
2550    FV = (GPM*NUN/449)/((HD^2*3.1416/4)/144)
2560    FLTM(BLUE) = NS/(FV*12) + FLTM(BLUE-1)
2570    NUN = NUN - 2
2580 NEXT BLUE
2590 '
2600 ' THIS SECTION CALCULATES THE DISTANCE TRAVELED BY THE SPRAYER FOR
2610 ' A BOOM EQUIPPED WITH AN EVEN NUMBER OF NOZZLES AND WHEN TIME IS
2620 ' MEASURED FROM INITIATION OF CHEMICAL INJECTION INTO THE SYSTEM
2630 ' UNTIL ARRIVAL OF CHEMICAL AT THE SPECIFIED NOZZLE.
2640 '
2650 '
2660 DIST(0) = 0
2670 FOR BLACK = 1 TO NUMNO
2680   DIST(BLACK) = FLTM(BLACK) * GS
2690 NEXT BLACK
2700 IF N = 4 GOTO 2990
2710 STRT = NUMNO + .5
2720 COUNT = BLUE - 1:CNT = BLUE
2730 CT = 0
2740 '
2750 ' THIS SECTION SETS THE MAXIMUM AND MINIMUM VALUES FOR THE X AND Y
2760 ' AXIS AND THE HEADINGS FOR THE GRAPH.
2770 '
2780 XMAX = NN: XMIN = 1
2790 YMAX = FLTM(BLUE-1): YMIN = 0
2800 C = BLUE - 1
2810 TIT$ = "NOZZLE POSITION VERSUS THE TIME OF FLUID TRAVEL FROM"
```

```
2820 TITL$ = "     ENTRANCE OF BOOM TO EACH NOZZLE (SEC)"
2830 GOSUB 3170
2840 GOTO 690
2850 '
2860 ' THIS SECTION SETS THE PARAMETERS FOR THE GRAPH OF NOZZLE POSITION
2870 ' VERSUS THE DISTANCE TRAVELED BY THE SPRAYER FOR AN ODD NUMBER OF
2880 ' NOZZLES.
2890 '
2900 STRT = NUMNO + 1
2910 COUNT = BLACK - 1:CNT = BLACK - 1
2920 CT = 1
2930 GOTO 3060
2940 '
2950 ' THIS SECTION SETS THE PARAMETERS FOR THE GRAPH OF NOZZLE POSITION
2960 ' VERSUS THE DISTANCE TRAVELED BY THE SPRAYER FOR AN EVEN NUMBER OF
2970 ' NOZZLES.
2980 '
2990 STRT = NUMNO + .5
3000 COUNT = BLACK - 1:CNT = BLACK
3010 CT = 0
3020 '
3030 ' THIS SECTION SETS THE MAXIMUM AND MINIMUM VALUES FOR THE X AND Y
3040 ' AXIS AND THE HEADINGS FOR THE GRAPH.
3050 '
3060 XMAX = NN: XMIN = 1
3070 YMAX = DIST(BLACK-1): YMIN = 0
3080 C = BLACK - 1
3090 TIT$ = "   NOZZLES POSITION VERSUS DISTANCE TRAVELED (FT)"
3100 TITL$ = "WHEN TIME STARTS FROM ENTRANCE OF BOOM TO EACH NOZZLE"
3110 GOSUB 3170
3120 GOTO 690
3130 '
3140 CLS
3150 END
3160 '
3170 '************************* GRAPHICS ******************************
3180 '
3190 CLS
3200 LOCATE 10,20:PRINT "IF YOU WANT A HARD COPY OF THE GRAPH JUST HIT"
3210 LOCATE 11,20:PRINT "THE SHIFT KEY AND THE PRINT SCREEN KEY AT THE"
3220 LOCATE 13,20:PRINT "SAME TIME.  IF YOU DO NOT WANT A HARD COPY OF"
3230 LOCATE 14,20:PRINT "THE GRAPH JUST HIT THE RETURN KEY."
3240 LOCATE 16,20:PRINT "HIT ANY KEY TO CONTINUE"
3250 K$ = INKEY$:IF K$ = "" THEN 3250
3260 '
3270 CLS
3280 SCREEN 2,2
3290 '
3300 ' THIS SECTION SETS THE VALUES FOR THE BOUNDARIES FOR THE GRAPH.
3310 '
3320 UPPER=XMAX:LOW=XMIN
3330 YL=.3*(YMAX-YMIN)
```

```
3340 YU=1.5*YL
3350 XL=.3*(UPPER-LOW)
3360 WINDOW(LOW-XL,YMIN-YL)-(UPPER+XL,YMAX+YU)
3370 '
3380 ' THIS LOOP DRAWS THE TIC MARKS ON THE X AXIS.
3390 '
3400 FOR X=LOW TO 1.001*UPPER STEP 1
3410     LINE(X,YMIN)-(X,YMIN-.03*(YMAX-YMIN))
3420 NEXT X
3430 '
3440 ' THIS LOOP DRAWS THE TIC MARKS ON THE Y AXIS.
3450 '
3460 FOR Y=YMIN TO YMAX STEP (YMAX-YMIN)/10
3470     LINE(LOW,Y)-(LOW+.01*UPPER,Y)
3480 NEXT Y
3490 '
3500 ' THIS SECTION DRAWS THE BOX FOR THE GRAPH AND THE HEADINGS FOR THE
       GRAPH.
3510 '
3520 LINE(LOW,YMIN)-(UPPER,YMAX),,B
3530 LOCATE 4,16 :PRINT TIT$
3540 LOCATE 5,15 :PRINT TITL$
3550 '
3560 ' THIS LOOP PRINTS THE X VARIABLES ON THE GRAPH.
3570 '
3580 FOR X=LOW TO 1.001*UPPER STEP 1
3590     SPOT=13+(X-LOW)*50/(UPPER-LOW)
3600     LOCATE 23,SPOT:PRINT USING"####";X
3610 NEXT X
3620 '
3630 ' THIS LOOP PRINTS THE Y VARIABLES ON THE GRAPH.
3640 '
3650 FOR Y=YMIN TO YMAX STEP (YMAX-YMIN)/10
3660     LOY=CINT(6+((Y-YMIN)/(YMAX-YMIN))*(16))
3670     LOCATE LOY,8:PRINT USING"###.#";(YMAX-Y)+YMIN
3680 NEXT Y
3690 '
3700 '  THIS SECTION DETERMINES WHICH GRAPH WAS SELECTED TO BE DRAWN AND
3710 '  GRAPHS THE CURVE OF THE NOZZLE POSITION VERSUS THE TIME OF
3720 '  FLUID TRAVEL TO EACH NOZZLE.
3730 '
3740 IF N > 2 GOTO 3910
3750 X=STRT:Y=FLTM(CT):LINE(X,Y)-(X,Y)
3760 FOR J = 1 TO C
3770    X=COUNT:Y=FLTM(J)
3780    LINE-(X,Y)
3790    COUNT = COUNT - 1
3800 NEXT J
3810 X=STRT:Y=FLTM(CT):LINE(X,Y)-(X,Y)
3820 FOR K = 1 TO C
3830    X=CNT:Y=FLTM(K)
3840    LINE-(X,Y)
```

```
3850    CNT = CNT + 1
3860 NEXT K
3870 GOTO 4090
3880 '
3890 ' THIS SECTION GRAPHS THE CURVE OF THE NOZZLE POSITION VERSUS THE
3900 ' SPRAYER TRAVEL DISTANCE IN FEET.
3910 '
3920 X=STRT:Y=DIST(CT):LINE(X,Y)-(X,Y)
3930 FOR J = 1 TO C
3940    X=COUNT:Y=DIST(J)
3950    LINE-(X,Y)
3960    COUNT = COUNT - 1
3970 NEXT J
3980 X=STRT:Y=DIST(CT):LINE(X,Y)-(X,Y)
3990 FOR K = 1 TO C
4000    X=CNT:Y=DIST(K)
4010    LINE-(X,Y)
4020    CNT = CNT + 1
4030 NEXT K
4040 '
4050 ' THIS SECTION ALLOWS THE USER TO GET A HARD COPY OF THE GRAPH AND
4060 ' RETURN BACK TO THE MAIN MENU TO SELECT OTHER GRAPHS OR INPUT NEW
4070 ' PARAMETERS.
4080 '
4090 K$ = INKEY$:IF K$ = "" THEN 4090
4100 IF ASC(K$)< > 13 THEN 3990
4110 RETURN
```

APPENDIX C

TEST DATA

TEST DATA

Transient time data for low-pressure injection with the peristaltic pump at a system pressure of 275 kPa.

T sec	N1	N2	N3	N4	N5	N6	N7	N8	N9
					grams/liter				
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.023	0.000	0.000	0.000	0.000
3	0.000	0.000	0.019	0.071	0.165	0.066	0.019	0.000	0.000
4	0.000	0.019	0.127	0.221	0.290	0.212	0.123	0.019	0.000
5	0.000	0.136	0.249	0.346	0.370	0.328	0.240	0.118	0.000
6	0.033	0.245	0.347	0.407	0.440	0.389	0.342	0.231	0.023
7	0.146	0.347	0.412	0.449	0.477	0.444	0.412	0.338	0.137
8	0.171	0.376	0.423	0.461	0.476	0.450	0.422	0.368	0.157
9	0.278	0.426	0.472	0.490	0.505	0.484	0.459	0.415	0.259
10	0.355	0.467	0.495	0.514	0.533	0.509	0.490	0.454	0.344
11	0.411	0.487	0.521	0.539	0.549	0.534	0.508	0.485	0.404
12	0.421	0.504	0.525	0.546	0.552	0.543	0.525	0.498	0.415
13	0.463	0.523	0.547	0.550	0.560	0.550	0.547	0.519	0.449
14	0.492	0.544	0.557	0.564	0.564	0.567	0.550	0.544	0.481
15	0.519	0.550	0.560	0.564	0.571	0.560	0.557	0.550	0.518
16	0.540	0.553	0.571	0.564	0.575	0.564	0.564	0.554	0.526
17	0.547	0.554	0.564	0.575	0.579	0.571	0.561	0.560	0.540
18	0.554	0.548	0.572	0.576	0.587	0.569	0.565	0.564	0.550
19	0.565	0.550	0.569	0.569	0.579	0.569	0.565	0.569	0.555
20	0.579	0.571	0.587	0.587	0.603	0.587	0.587	0.579	0.571
21	0.582	0.575	0.586	0.602	0.613	0.602	0.586	0.579	0.563
22	0.586	0.582	0.606	0.606	0.610	0.602	0.606	0.590	0.571
23	0.601	0.601	0.616	0.624	0.624	0.616	0.616	0.601	0.586
24	0.601	0.616	0.624	0.624	0.624	0.624	0.616	0.616	0.594
25	0.601	0.624	0.624	0.624	0.624	0.624	0.624	0.624	0.601
26	0.624	0.624	0.624	0.624	0.624	0.624	0.624	0.624	0.601
27	0.624	0.624	0.624	0.632	0.624	0.624	0.624	0.624	0.608
28	0.616	0.624	0.624	0.624	0.624	0.624	0.624	0.624	0.616
29	0.624	0.640	0.624	0.624	0.624	0.624	0.624	0.624	0.624
30	0.624	0.624	0.624	0.624	0.624	0.624	0.624	0.624	0.624
31	0.624	0.624	0.624	0.624	0.624	0.624	0.624	0.624	0.624
32	0.624	0.630	0.624	0.624	0.624	0.624	0.624	0.624	0.624

Transient time data for low-pressure injection with the Scienco pump at a system pressure of 275 kPa.

T sec	N1	N2	N3	N4	N5	N6	N7	N8	N9
					grams/liter				
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.013	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.038	0.101	0.026	0.000	0.000	0.000
5	0.000	0.000	0.038	0.139	0.240	0.139	0.038	0.000	0.000
6	0.000	0.026	0.152	0.265	0.315	0.265	0.152	0.013	0.000
7	0.000	0.114	0.265	0.328	0.378	0.328	0.277	0.127	0.000
8	0.013	0.228	0.328	0.403	0.441	0.403	0.340	0.240	0.013
9	0.089	0.315	0.403	0.453	0.479	0.441	0.403	0.328	0.089
10	0.202	0.391	0.453	0.479	0.491	0.479	0.453	0.391	0.202
11	0.309	0.444	0.494	0.506	0.481	0.494	0.488	0.444	0.303
12	0.370	0.482	0.487	0.481	0.481	0.481	0.487	0.494	0.370
13	0.449	0.509	0.533	0.569	0.557	0.545	0.533	0.521	0.449
14	0.485	0.533	0.545	0.569	0.557	0.557	0.545	0.521	0.485
15	0.509	0.545	0.545	0.557	0.557	0.557	0.557	0.545	0.509
16	0.533	0.557	0.557	0.557	0.569	0.557	0.557	0.557	0.521
17	0.545	0.557	0.569	0.581	0.557	0.569	0.569	0.557	0.533
18	0.557	0.557	0.569	0.545	0.569	0.557	0.581	0.593	0.545
19	0.557	0.557	0.569	0.569	0.569	0.569	0.569	0.557	0.557
20	0.557	0.557	0.569	0.569	0.569	0.569	0.569	0.557	0.557
21	0.547	0.577	0.577	0.577	0.583	0.577	0.577	0.571	0.571
22	0.571	0.577	0.577	0.577	0.577	0.577	0.583	0.577	0.559
23	0.598	0.598	0.611	0.598	0.611	0.598	0.598	0.598	0.586
24	0.598	0.598	0.598	0.598	0.598	0.611	0.598	0.598	0.598
25	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.586
26	0.598	0.611	0.623	0.598	0.598	0.598	0.598	0.611	0.598
27	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598
28	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598
29	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598
30	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.586
31	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.574
32	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598	0.598

Transient time data for low-pressure injection with the FMI pump at a system pressure of 275 kPa.

T sec	N1	N2	N3	N4	N5	N6	N7	N8	N9
	grams/liter								
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.040	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.066	0.132	0.053	0.000	0.000	0.000
5	0.000	0.000	0.066	0.170	0.274	0.157	0.066	0.000	0.000
6	0.000	0.040	0.196	0.300	0.365	0.300	0.196	0.040	0.000
7	0.000	0.170	0.313	0.378	0.430	0.378	0.313	0.157	0.000
8	0.013	0.273	0.390	0.456	0.482	0.442	0.390	0.273	0.013
9	0.130	0.378	0.469	0.482	0.521	0.482	0.469	0.391	0.117
10	0.235	0.442	0.495	0.534	0.547	0.521	0.495	0.430	0.235
11	0.379	0.491	0.523	0.547	0.559	0.547	0.528	0.485	0.366
12	0.429	0.528	0.553	0.559	0.572	0.559	0.547	0.522	0.429
13	0.489	0.547	0.536	0.571	0.571	0.571	0.559	0.547	0.477
14	0.524	0.547	0.571	0.571	0.571	0.571	0.571	0.547	0.524
15	0.547	0.571	0.571	0.571	0.571	0.571	0.571	0.571	0.524
16	0.547	0.571	0.571	0.571	0.594	0.583	0.571	0.571	0.547
17	0.571	0.571	0.583	0.594	0.594	0.594	0.583	0.571	0.547
18	0.571	0.571	0.594	0.594	0.594	0.594	0.594	0.571	0.547
19	0.571	0.594	0.594	0.594	0.594	0.594	0.594	0.594	0.559
20	0.571	0.594	0.594	0.594	0.594	0.594	0.594	0.594	0.571
21	0.608	0.614	0.608	0.603	0.608	0.602	0.608	0.614	0.608
22	0.608	0.608	0.608	0.602	0.620	0.608	0.603	0.614	0.608
23	0.646	0.634	0.646	0.658	0.646	0.658	0.634	0.634	0.646
24	0.646	0.634	0.658	0.634	0.634	0.634	0.658	0.646	0.646
25	0.646	0.658	0.634	0.634	0.646	0.634	0.634	0.646	0.634
26	0.646	0.646	0.646	0.634	0.646	0.646	0.646	0.646	0.634
27	0.646	0.634	0.634	0.646	0.646	0.646	0.634	0.634	0.646
28	0.646	0.646	0.646	0.646	0.646	0.646	0.646	0.646	0.646
29	0.634	0.646	0.646	0.646	0.646	0.646	0.646	0.646	0.634
30	0.634	0.646	0.646	0.646	0.646	0.646	0.646	0.646	0.634
31	0.634	0.646	0.646	0.646	0.646	0.646	0.646	0.646	0.634
32	0.634	0.646	0.646	0.646	0.658	0.646	0.646	0.646	0.623

Concentration consistency data for low-pressure injection with the peristaltic pump at a system pressure of 275 kPa.

T min	N1	N2	N3	N4	N5 grams/liter	N6	N7	N8	N9
1	0.565	0.570	0.570	0.574	0.574	0.574	0.574	0.574	0.566
2	0.565	0.570	0.570	0.574	0.574	0.574	0.574	0.574	0.574
3	0.570	0.574	0.570	0.574	0.578	0.578	0.578	0.574	0.574
4	0.574	0.570	0.570	0.578	0.578	0.578	0.578	0.574	0.574
5	0.574	0.574	0.578	0.578	0.578	0.578	0.574	0.574	0.574
6	0.574	0.570	0.574	0.574	0.578	0.578	0.574	0.574	0.574
7	0.574	0.570	0.574	0.574	0.574	0.574	0.574	0.574	0.574
8	0.566	0.570	0.574	0.578	0.578	0.578	0.578	0.574	0.574
9	0.574	0.574	0.578	0.574	0.574	0.574	0.574	0.574	0.574
10	0.574	0.574	0.574	0.574	0.574	0.574	0.574	0.574	0.574
11	0.574	0.570	0.570	0.566	0.574	0.574	0.574	0.574	0.566

Concentration consistency data for low-pressure injection with the Scienco pump at a system pressure of 275 kPa.

T min	N1	N2	N3	N4	N5 grams/liter	N6	N7	N8	N9
1	0.606	0.606	0.594	0.606	0.606	0.606	0.606	0.606	0.594
2	0.619	0.607	0.619	0.619	0.607	0.619	0.607	0.619	0.607
3	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619
4	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619
5	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619
6	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619
7	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619
8	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619
9	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.607	0.607
10	0.619	0.607	0.607	0.607	0.607	0.607	0.607	0.607	0.607
11	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619
12	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.607

Concentration consistency data for low-pressure injection with the FMI pump at a system pressure of 275 kPa.

T min	N1	N2	N3	N4	N5	N6	N7	N8	N9
					grams/liter				
1	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640
2	0.617	0.617	0.629	0.629	0.629	0.629	0.629	0.617	0.617
3	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640
4	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640
5	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640
6	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640
7	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640
8	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640
9	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640
10	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640
11	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.640
12	0.640	0.640	0.640	0.640	0.640	0.640	0.640	0.629	0.629

Transient time data for high-pressure injection with the FMI pump at a system pressure of 275 kPa.

T sec	N1	N2	N3	N4	N5	N6	N7	N8	N9
					grams/liter				
0	0.000	0.000	0.000	0.000	0.012	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.012	0.012	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.012	0.012	0.000	0.000	0.000	0.000
3	0.000	0.000	0.012	0.012	0.012	0.012	0.000	0.000	0.000
4	0.000	0.000	0.012	0.024	0.036	0.012	0.000	0.000	0.000
5	0.000	0.012	0.024	0.036	0.036	0.024	0.024	0.000	0.000
6	0.000	0.012	0.036	0.036	0.048	0.036	0.024	0.000	0.000
7	0.012	0.024	0.048	0.048	0.107	0.048	0.036	0.024	0.000
8	0.012	0.036	0.060	0.107	0.142	0.095	0.048	0.024	0.000
9	0.024	0.048	0.130	0.154	0.177	0.154	0.118	0.048	0.024
10	0.024	0.107	0.177	0.189	0.225	0.189	0.165	0.095	0.024
11	0.029	0.124	0.178	0.219	0.255	0.207	0.172	0.112	0.029
12	0.047	0.166	0.225	0.260	0.302	0.260	0.213	0.160	0.047
13	0.059	0.190	0.238	0.298	0.322	0.286	0.238	0.190	0.059
14	0.107	0.238	0.298	0.333	0.357	0.322	0.298	0.226	0.107
15	0.166	0.274	0.333	0.357	0.381	0.357	0.333	0.274	0.154
16	0.214	0.322	0.357	0.393	0.405	0.393	0.357	0.322	0.214
17	0.250	0.357	0.381	0.417	0.428	0.417	0.393	0.345	0.250
18	0.298	0.369	0.417	0.417	0.381	0.417	0.417	0.369	0.298
19	0.334	0.405	0.417	0.344	0.355	0.344	0.417	0.405	0.334
20	0.369	0.417	0.332	0.367	0.404	0.356	0.332	0.417	0.357
21	0.418	0.400	0.435	0.448	0.465	0.448	0.435	0.412	0.418
22	0.436	0.423	0.448	0.477	0.508	0.477	0.453	0.423	0.430
23	0.468	0.479	0.515	0.503	0.515	0.503	0.515	0.479	0.456
24	0.479	0.503	0.503	0.515	0.527	0.515	0.503	0.490	0.479
25	0.479	0.515	0.526	0.526	0.503	0.515	0.515	0.515	0.479

26	0.503	0.526	0.515	0.515	0.515	0.515	0.526	0.526	0.490
27	0.515	0.538	0.515	0.526	0.527	0.515	0.515	0.538	0.515
28	0.515	0.515	0.515	0.527	0.503	0.527	0.526	0.515	0.503
29	0.515	0.515	0.503	0.515	0.515	0.515	0.503	0.515	0.515
30	0.515	0.503	0.515	0.527	0.527	0.527	0.515	0.515	0.503
31	0.542	0.547	0.565	0.577	0.558	0.571	0.565	0.559	0.536
32	0.548	0.559	0.577	0.564	0.582	0.558	0.583	0.565	0.548
33	0.604	0.604	0.591	0.629	0.605	0.629	0.591	0.616	0.604
34	0.604	0.591	0.605	0.617	0.640	0.617	0.605	0.580	0.616
35	0.604	0.605	0.629	0.629	0.629	0.640	0.629	0.616	0.604
36	0.604	0.629	0.629	0.640	0.651	0.640	0.629	0.629	0.604
37	0.604	0.629	0.629	0.651	0.615	0.640	0.640	0.629	0.592
38	0.616	0.640	0.628	0.640	0.640	0.640	0.628	0.640	0.616
39	0.629	0.639	0.640	0.640	0.640	0.640	0.640	0.640	0.629
40	0.640	0.640	0.629	0.640	0.640	0.640	0.629	0.640	0.640
41	0.629	0.653	0.641	0.635	0.623	0.641	0.647	0.653	0.629
42	0.635	0.647	0.635	0.647	0.647	0.641	0.635	0.641	0.629
43	0.667	0.642	0.667	0.666	0.653	0.666	0.667	0.643	0.667
44	0.654	0.654	0.653	0.653	0.666	0.653	0.653	0.654	0.643
45	0.654	0.653	0.666	0.666	0.653	0.666	0.653	0.666	0.654
46	0.654	0.653	0.666	0.666	0.655	0.666	0.666	0.642	0.643
47	0.666	0.666	0.654	0.643	0.629	0.643	0.654	0.666	0.654
48	0.666	0.666	0.643	0.641	0.678	0.653	0.643	0.666	0.653
49	0.666	0.643	0.653	0.667	0.653	0.667	0.653	0.678	0.666
50	0.653	0.653	0.654	0.642	0.643	0.642	0.667	0.653	0.653
51	0.643	0.667	0.630	0.653	0.666	0.653	0.642	0.678	0.667
52	0.642	0.642	0.665	0.667	0.667	0.667	0.677	0.642	0.642

Transient time data for high-pressure injection with the Scienco pump at a system pressure of 275 kPa.

T sec	N1	N2	N3	N4	N5 grams/liter	N6	N7	N8	N9
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.012	0.023	0.012	0.000	0.000	0.000
10	0.000	0.000	0.000	0.023	0.023	0.023	0.000	0.000	0.000
11	0.000	0.006	0.028	0.051	0.063	0.051	0.028	0.011	0.000
12	0.000	0.028	0.057	0.086	0.103	0.086	0.057	0.028	0.000
13	0.011	0.080	0.126	0.015	0.171	0.148	0.126	0.080	0.011
14	0.022	0.126	0.148	0.217	0.217	0.206	0.148	0.126	0.022
15	0.057	0.148	0.217	0.228	0.240	0.228	0.217	0.148	0.057
16	0.102	0.149	0.228	0.252	0.263	0.252	0.228	0.194	0.102

17	0.126	0.228	0.252	0.263	0.241	0.274	0.263	0.228	0.126
18	0.182	0.240	0.263	0.252	0.229	0.252	0.263	0.240	0.171
19	0.217	0.263	0.241	0.218	0.218	0.218	0.241	0.263	0.217
20	0.228	0.240	0.207	0.230	0.262	0.241	0.218	0.252	0.228
21	0.258	0.276	0.287	0.275	0.292	0.275	0.293	0.265	0.258
22	0.270	0.287	0.281	0.310	0.339	0.304	0.287	0.287	0.259
23	0.311	0.322	0.346	0.369	0.380	0.369	0.357	0.346	0.300
24	0.334	0.246	0.380	0.391	0.403	0.391	0.357	0.346	0.323
25	0.334	0.357	0.391	0.415	0.391	0.415	0.391	0.334	0.334
26	0.322	0.391	0.403	0.403	0.391	0.403	0.403	0.391	0.346
27	0.357	0.403	0.403	0.402	0.425	0.402	0.403	0.403	0.357
28	0.380	0.403	0.414	0.425	0.402	0.425	0.414	0.403	0.380
29	0.403	0.414	0.425	0.414	0.414	0.414	0.425	0.414	0.403
30	0.403	0.425	0.414	0.391	0.402	0.391	0.414	0.425	0.403
31	0.404	0.410	0.405	0.428	0.445	0.428	0.405	0.410	0.404
32	0.416	0.416	0.428	0.439	0.439	0.439	0.428	0.422	0.404
33	0.418	0.442	0.430	0.465	0.453	0.465	0.430	0.442	0.418
34	0.430	0.442	0.453	0.453	0.476	0.453	0.465	0.442	0.430
35	0.442	0.453	0.465	0.476	0.453	0.476	0.465	0.453	0.442
36	0.442	0.465	0.465	0.442	0.442	0.442	0.465	0.453	0.442
37	0.442	0.465	0.442	0.453	0.476	0.453	0.442	0.465	0.442
38	0.441	0.442	0.453	0.465	0.442	0.465	0.465	0.442	0.453
39	0.453	0.453	0.430	0.442	0.418	0.442	0.453	0.453	0.453
40	0.442	0.465	0.418	0.430	0.418	0.430	0.418	0.465	0.442
41	0.460	0.466	0.447	0.443	0.460	0.443	0.447	0.472	0.454
42	0.472	0.447	0.437	0.454	0.454	0.454	0.443	0.447	0.466
43	0.502	0.490	0.490	0.515	0.490	0.515	0.490	0.490	0.502
44	0.478	0.490	0.502	0.490	0.466	0.490	0.502	0.490	0.478
45	0.490	0.502	0.490	0.490	0.515	0.490	0.490	0.515	0.490
46	0.502	0.490	0.502	0.503	0.490	0.503	0.502	0.490	0.502
47	0.502	0.502	0.502	0.502	0.502	0.502	0.515	0.490	0.502
48	0.490	0.515	0.502	0.466	0.454	0.466	0.514	0.515	0.490
49	0.478	0.502	0.454	0.465	0.466	0.465	0.466	0.502	0.478
50	0.502	0.466	0.466	0.466	0.466	0.466	0.478	0.478	0.490
51	0.502	0.466	0.466	0.479	0.467	0.479	0.466	0.478	0.502
52	0.478	0.466	0.479	0.466	0.479	0.466	0.479	0.466	0.466

Transient time data for high-pressure injection with the Scienco pump at a system pressure of 275 kPa and a smaller check value.

T sec	N1	N2	N3	N4	N5	N6	N7	N8	N9
					grams/liter				
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.168	0.013	0.000	0.000	0.000
6	0.000	0.000	0.026	0.000	0.477	0.271	0.026	0.000	0.000
7	0.000	0.000	0.284	0.013	0.541	0.502	0.284	0.000	0.000
8	0.000	0.156	0.502	0.271	0.541	0.541	0.502	0.168	0.000
9	0.000	0.438	0.541	0.502	0.554	0.541	0.541	0.451	0.000
10	0.091	0.541	0.553	0.541	0.566	0.541	0.553	0.528	0.065
11	0.426	0.522	0.529	0.541	0.542	0.554	0.535	0.542	0.413
12	0.497	0.529	0.548	0.541	0.548	0.542	0.548	0.542	0.497
13	0.530	0.543	0.543	0.548	0.530	0.543	0.543	0.543	0.530
14	0.530	0.543	0.543	0.543	0.543	0.543	0.543	0.543	0.543
15	0.530	0.543	0.555	0.530	0.568	0.581	0.568	0.543	0.530
16	0.543	0.543	0.543	0.568	0.543	0.530	0.543	0.543	0.543
17	0.543	0.543	0.543	0.530	0.543	0.543	0.556	0.543	0.543
18	0.543	0.530	0.530	0.543	0.556	0.543	0.543	0.543	0.543
19	0.543	0.568	0.543	0.556	0.530	0.543	0.543	0.543	0.543
20	0.543	0.543	0.530	0.543	0.543	0.543	0.543	0.543	0.543
21	0.499	0.557	0.557	0.557	0.551	0.551	0.551	0.564	0.499
22	0.538	0.551	0.557	0.544	0.557	0.551	0.557	0.551	0.538
23	0.546	0.522	0.559	0.572	0.572	0.572	0.559	0.509	0.546
24	0.546	0.572	0.572	0.572	0.546	0.572	0.597	0.572	0.546
25	0.559	0.572	0.546	0.559	0.559	0.559	0.572	0.572	0.559
26	0.572	0.572	0.572	0.572	0.572	0.572	0.572	0.572	0.572
27	0.572	0.559	0.572	0.559	0.585	0.559	0.559	0.559	0.572
28	0.572	0.559	0.572	0.572	0.559	0.572	0.585	0.572	0.572
29	0.572	0.572	0.572	0.572	0.572	0.572	0.572	0.572	0.559
30	0.559	0.572	0.559	0.572	0.559	0.572	0.559	0.585	0.559
31	0.559	0.559	0.572	0.559	0.572	0.559	0.572	0.559	0.559
32	0.559	0.572	0.559	0.572	0.559	0.585	0.559	0.572	0.559

Concentration consistency data for high-pressure injection with the FMI pump at a system pressure of 275 kPa.

T min	N1	N2	N3	N4	N5	N6	N7	N8	N9
					grams/liter				
1	0.624	0.637	0.637	0.637	0.630	0.637	0.637	0.637	0.624
2	0.643	0.643	0.637	0.630	0.643	0.637	0.637	0.643	0.637
3	0.637	0.631	0.631	0.625	0.625	0.625	0.631	0.631	0.637
4	0.637	0.631	0.631	0.631	0.631	0.631	0.631	0.631	0.637
5	0.631	0.643	0.643	0.643	0.649	0.643	0.643	0.636	0.631
6	0.624	0.637	0.637	0.637	0.630	0.637	0.637	0.637	0.624
7	0.630	0.637	0.637	0.637	0.637	0.637	0.637	0.630	0.630
8	0.643	0.643	0.630	0.637	0.637	0.637	0.630	0.643	0.618
9	0.643	0.643	0.637	0.643	0.637	0.637	0.643	0.643	0.637
10	0.643	0.643	0.637	0.637	0.637	0.637	0.637	0.643	0.637
11	0.643	0.643	0.637	0.643	0.643	0.643	0.643	0.643	0.643
12	0.637	0.643	0.637	0.649	0.649	0.643	0.637	0.637	0.637

Concentration consistency data for high-pressure injection with the Scienco pump at a system pressure of 275 kPa.

T min	N1	N2	N3	N4	N5	N6	N7	N8	N9
					grams/liter				
1	0.480	0.471	0.471	0.471	0.480	0.471	0.471	0.471	0.480
2	0.480	0.480	0.480	0.480	0.480	0.489	0.480	0.480	0.480
3	0.498	0.498	0.498	0.480	0.489	0.480	0.498	0.498	0.489
4	0.498	0.498	0.498	0.498	0.489	0.498	0.498	0.498	0.508
5	0.498	0.489	0.489	0.498	0.507	0.498	0.489	0.489	0.498
6	0.498	0.507	0.507	0.498	0.507	0.498	0.498	0.507	0.498
7	0.498	0.498	0.498	0.507	0.507	0.507	0.498	0.498	0.498
8	0.517	0.498	0.507	0.517	0.507	0.517	0.507	0.498	0.526
9	0.517	0.498	0.507	0.507	0.507	0.507	0.507	0.508	0.517
10	0.517	0.526	0.517	0.517	0.498	0.517	0.517	0.517	0.507
11	0.507	0.517	0.517	0.507	0.498	0.507	0.507	0.507	0.517
12	0.517	0.517	0.517	0.507	0.498	0.517	0.517	0.508	0.507

Concentration consistency data for high-pressure injection with the FMI pump at a system pressure of 171 kPa.

T min	N1	N2	N3	N4	N5 grams/liter	N6	N7	N8	N9
1	0.720	0.732	0.720	0.696	0.744	0.720	0.720	0.720	0.708
2	0.732	0.732	0.732	0.720	0.756	0.733	0.720	0.720	0.732
3	0.744	0.744	0.732	0.732	0.732	0.732	0.732	0.744	0.744
4	0.719	0.732	0.744	0.732	0.732	0.732	0.744	0.732	0.720
5	0.744	0.732	0.744	0.744	0.744	0.732	0.732	0.744	0.732
6	0.732	0.732	0.732	0.733	0.733	0.732	0.732	0.732	0.720
7	0.732	0.732	0.732	0.732	0.732	0.732	0.732	0.732	0.732
8	0.732	0.756	0.744	0.756	0.732	0.756	0.732	0.744	0.732
9	0.756	0.732	0.744	0.744	0.744	0.732	0.732	0.732	0.744
10	0.732	0.744	0.744	0.756	0.732	0.732	0.732	0.732	0.732
11	0.744	0.756	0.756	0.744	0.744	0.744	0.756	0.744	0.732
12	0.744	0.756	0.744	0.732	0.732	0.732	0.744	0.756	0.744

Concentration consistency data for high-pressure injection with the Scienco pump at a system pressure of 171 kPa.

T min	N1	N2	N3	N4	N5 grams/liter	N6	N7	N8	N9
1	0.614	0.601	0.588	0.614	0.601	0.614	0.588	0.601	0.588
2	0.646	0.614	0.614	0.628	0.614	0.628	0.628	0.614	0.628
3	0.614	0.614	0.628	0.641	0.628	0.641	0.628	0.614	0.614
4	0.628	0.614	0.628	0.614	0.641	0.614	0.628	0.614	0.614
5	0.632	0.628	0.628	0.641	0.628	0.628	0.628	0.628	0.628
6	0.646	0.628	0.628	0.614	0.628	0.614	0.628	0.628	0.628
7	0.614	0.628	0.628	0.614	0.614	0.614	0.628	0.628	0.614
8	0.632	0.614	0.628	0.628	0.628	0.628	0.628	0.614	0.628
9	0.628	0.628	0.614	0.628	0.628	0.628	0.614	0.614	0.628
10	0.646	0.628	0.641	0.641	0.628	0.628	0.628	0.628	0.641
11	0.614	0.641	0.641	0.641	0.628	0.641	0.628	0.628	0.614
12	0.632	0.655	0.641	0.614	0.628	0.614	0.628	0.641	0.614

Concentration consistency data for high-pressure injection with the FMI pump at a system pressure of 378 kPa.

T min	N1	N2	N3	N4	N5	N6	N7	N8	N9
				grams/liter					
1	0.463	0.463	0.475	0.463	0.463	0.463	0.475	0.463	0.463
2	0.475	0.475	0.486	0.486	0.486	0.486	0.475	0.475	0.475
3	0.475	0.475	0.475	0.486	0.475	0.475	0.475	0.475	0.475
4	0.475	0.475	0.475	0.486	0.486	0.475	0.475	0.475	0.475
5	0.475	0.463	0.475	0.486	0.486	0.486	0.475	0.451	0.475
6	0.475	0.475	0.486	0.475	0.486	0.486	0.475	0.475	0.475
7	0.475	0.475	0.475	0.463	0.463	0.463	0.463	0.475	0.475
8	0.475	0.486	0.486	0.486	0.486	0.486	0.463	0.463	0.463
9	0.475	0.463	0.463	0.463	0.475	0.463	0.463	0.463	0.475
10	0.475	0.475	0.486	0.486	0.486	0.486	0.486	0.475	0.475
11	0.486	0.486	0.475	0.486	0.475	0.486	0.475	0.486	0.475
12	0.475	0.475	0.475	0.475	0.475	0.475	0.475	0.475	0.475

Concentration consistency data for high-pressure injection with the Scienco pump at a system pressure of 378 kPa.

T min	N1	N2	N3	N4	N5	N6	N7	N8	N9
				grams/liter					
1	0.447	0.447	0.422	0.434	0.447	0.422	0.422	0.434	0.447
2	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.434
3	0.447	0.447	0.447	0.459	0.459	0.459	0.447	0.447	0.447
4	0.447	0.459	0.459	0.447	0.447	0.447	0.447	0.459	0.447
5	0.459	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.459
6	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447
7	0.459	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.459
8	0.447	0.459	0.447	0.447	0.459	0.447	0.447	0.447	0.447
9	0.447	0.459	0.447	0.447	0.447	0.447	0.447	0.459	0.447
10	0.447	0.472	0.459	0.447	0.447	0.447	0.472	0.459	0.447
11	0.472	0.459	0.459	0.459	0.447	0.447	0.459	0.459	0.472
12	0.459	0.459	0.447	0.447	0.472	0.447	0.459	0.459	0.459

Concentration consistency data for injection at the individual nozzles with the Scienco pump at a system pressure of 275 kPa and the fluid entrance to boom over fifth nozzle.

T min	N1	N2	N3	N4	N5 grams/liter	N6	N7	N8	N9
1	0.422	0.457	0.485	0.468	0.036	0.546	0.510	0.509	0.494
2	0.432	0.458	0.476	0.485	0.009	0.545	0.519	0.519	0.510
3	0.449	0.475	0.476	0.476	0.027	0.528	0.519	0.518	0.501
4	0.458	0.476	0.484	0.476	0.000	0.545	0.519	0.510	0.510
5	0.458	0.484	0.492	0.493	0.000	0.546	0.519	0.527	0.509
6	0.449	0.467	0.484	0.485	0.018	0.537	0.519	0.543	0.501
7	0.457	0.475	0.484	0.493	0.018	0.528	0.544	0.510	0.493
8	0.457	0.475	0.483	0.484	0.000	0.536	0.526	0.518	0.509
9	0.441	0.482	0.525	0.492	0.000	0.561	0.528	0.519	0.501
10	0.457	0.508	0.500	0.516	0.000	0.561	0.537	0.510	0.492
11	0.482	0.548	0.598	0.566	0.000	0.529	0.502	0.519	0.501
12	0.539	0.597	0.542	0.533	0.000	0.594	0.519	0.510	0.501

Concentration consistency data for injection at the individual nozzles with the Scienco pump at a system pressure of 275 kPa, and the fluid entrance to boom off set of nozzle five.

T min	N1	N2	N3	N4	N5 grams/liter	N6	N7	N8	N9
1	0.584	0.564	0.584	0.603	0.501	0.440	0.448	0.420	0.420
2	0.555	0.557	0.584	0.603	0.508	0.441	0.448	0.434	0.434
3	0.542	0.564	0.591	0.625	0.523	0.461	0.455	0.448	0.434
4	0.549	0.578	0.591	0.625	0.508	0.468	0.448	0.433	0.433
5	0.549	0.564	0.584	0.603	0.515	0.468	0.441	0.433	0.426
6	0.542	0.563	0.605	0.610	0.522	0.460	0.433	0.433	0.433
7	0.563	0.556	0.591	0.610	0.501	0.460	0.440	0.448	0.427
8	0.535	0.571	0.576	0.596	0.508	0.475	0.448	0.440	0.440
9	0.528	0.549	0.570	0.589	0.508	0.475	0.470	0.448	0.441
10	0.528	0.556	0.555	0.583	0.515	0.468	0.441	0.433	0.433
11	0.528	0.542	0.548	0.600	0.515	0.453	0.441	0.441	0.440
12	0.522	0.542	0.555	0.583	0.515	0.460	0.441	0.440	0.440

Concentration consistency data for injection at the individual nozzles with the FMI pump at a system pressure of 275 kPa, and the fluid entrance to boom off set of nozzle five.

T min	N1	N2	N3	N4	N5 (grams/liter)	N6	N7	N8	N9
1	0.608	0.661	0.660	0.653	0.615	0.570	0.570	0.551	0.492
2	0.602	0.621	0.641	0.651	0.576	0.518	0.505	0.498	0.505
3	0.602	0.615	0.641	0.658	0.576	0.524	0.505	0.498	0.492
4	0.595	0.615	0.634	0.645	0.576	0.524	0.505	0.498	0.498
5	0.589	0.608	0.628	0.645	0.582	0.537	0.505	0.505	0.498
6	0.582	0.595	0.621	0.638	0.582	0.524	0.505	0.498	0.498
7	0.589	0.602	0.634	0.645	0.576	0.537	0.505	0.505	0.498
8	0.589	0.615	0.634	0.638	0.576	0.544	0.511	0.511	0.498
9	0.595	0.615	0.628	0.638	0.582	0.537	0.505	0.492	0.498
10	0.589	0.608	0.641	0.645	0.576	0.537	0.505	0.505	0.498
11	0.595	0.608	0.621	0.638	0.576	0.524	0.505	0.498	0.498
12	0.595	0.602	0.628	0.638	0.576	0.537	0.488	0.505	0.498

Concentration consistency data for injection at the individual nozzles with the Scienco pump at a system pressure of 171 kPa, and the fluid entrance to boom off set of nozzle five.

T min	N1	N2	N3	N4	N5 (grams/liter)	N6	N7	N8	N9
1	0.635	0.661	0.661	0.673	0.623	0.559	0.546	0.546	0.559
2	0.648	0.648	0.673	0.686	0.622	0.572	0.559	0.547	0.559
3	0.648	0.648	0.673	0.686	0.622	0.572	0.559	0.559	0.559
4	0.648	0.661	0.673	0.686	0.622	0.584	0.559	0.559	0.572
5	0.648	0.635	0.673	0.686	0.622	0.584	0.559	0.572	0.572
6	0.648	0.648	0.673	0.686	0.622	0.584	0.559	0.572	0.572
7	0.648	0.648	0.673	0.686	0.622	0.584	0.559	0.559	0.572
8	0.661	0.648	0.661	0.686	0.622	0.597	0.572	0.572	0.572
9	0.635	0.635	0.661	0.673	0.622	0.597	0.559	0.572	0.572
10	0.648	0.635	0.661	0.686	0.622	0.597	0.572	0.572	0.572
11	0.635	0.635	0.661	0.686	0.622	0.597	0.572	0.572	0.572
12	0.635	0.635	0.661	0.686	0.622	0.584	0.572	0.572	0.572

Concentration consistency data for injection at the individual nozzles with the FMI pump at a system pressure of 171 kPa, and the fluid entrance to boom off set of nozzle five.

T min	N1	N2	N3	N4	N5 grams/liter	N6	N7	N8	N9
1	0.695	0.708	0.734	0.734	0.695	0.642	0.642	0.615	0.642
2	0.695	0.695	0.734	0.734	0.695	0.655	0.629	0.615	0.642
3	0.695	0.708	0.734	0.734	0.695	0.655	0.629	0.629	0.642
4	0.708	0.708	0.734	0.734	0.695	0.668	0.629	0.642	0.642
5	0.695	0.682	0.734	0.734	0.695	0.668	0.629	0.642	0.642
6	0.682	0.695	0.734	0.734	0.695	0.668	0.642	0.642	0.642
7	0.682	0.695	0.734	0.734	0.695	0.668	0.642	0.642	0.642
8	0.695	0.708	0.734	0.734	0.695	0.668	0.642	0.642	0.642
9	0.695	0.695	0.734	0.721	0.708	0.668	0.642	0.642	0.642
10	0.695	0.695	0.734	0.734	0.708	0.668	0.642	0.642	0.642
11	0.695	0.695	0.734	0.734	0.642	0.668	0.642	0.642	0.642
12	0.721	0.721	0.734	0.734	0.642	0.668	0.642	0.642	0.642

Concentration consistency data for injection at the individual nozzles with the Scienco pump at a system pressure of 378 kPa, and the fluid entrance to boom off set of nozzle five.

T min	N1	N2	N3	N4	N5 grams/liter	N6	N7	N8	N9
1	0.547	0.547	0.573	0.598	0.496	0.420	0.394	0.394	0.394
2	0.547	0.547	0.573	0.598	0.496	0.420	0.394	0.394	0.394
3	0.547	0.547	0.573	0.598	0.496	0.433	0.407	0.394	0.394
4	0.547	0.547	0.573	0.598	0.496	0.433	0.407	0.407	0.394
5	0.535	0.547	0.573	0.598	0.496	0.433	0.407	0.407	0.382
6	0.535	0.547	0.560	0.598	0.509	0.433	0.407	0.407	0.395
7	0.535	0.547	0.560	0.598	0.509	0.433	0.407	0.407	0.407
8	0.547	0.547	0.560	0.598	0.509	0.433	0.407	0.407	0.407
9	0.522	0.535	0.560	0.598	0.509	0.433	0.407	0.407	0.407
10	0.522	0.535	0.560	0.586	0.509	0.433	0.420	0.407	0.407
11	0.522	0.535	0.560	0.586	0.509	0.445	0.420	0.420	0.394
12	0.522	0.535	0.560	0.586	0.509	0.445	0.420	0.420	0.394

Concentration consistency data for injection at the individual nozzles with the FMI pump at a system pressure of 378 kPa, and the fluid entrance to boom off set of nozzle five.

T min	N1	N2	N3	N4	N5	N6	N7	N8	N9
				grams/liter					
1	0.645	0.721	0.683	0.696	0.606	0.492	0.492	0.479	0.479
2	0.658	0.657	0.695	0.683	0.606	0.492	0.492	0.479	0.466
3	0.645	0.632	0.670	0.696	0.606	0.504	0.492	0.479	0.466
4	0.645	0.632	0.670	0.696	0.594	0.517	0.492	0.492	0.466
5	0.632	0.632	0.658	0.683	0.594	0.504	0.492	0.492	0.466
6	0.632	0.632	0.658	0.696	0.606	0.517	0.492	0.492	0.479
7	0.632	0.632	0.658	0.696	0.594	0.530	0.492	0.492	0.492
8	0.645	0.632	0.658	0.696	0.594	0.530	0.492	0.492	0.479
9	0.632	0.645	0.658	0.683	0.619	0.517	0.492	0.492	0.466
10	0.632	0.632	0.658	0.683	0.594	0.517	0.492	0.492	0.466
11	0.632	0.632	0.658	0.696	0.594	0.530	0.492	0.492	0.466
12	0.632	0.658	0.696	0.722	0.607	0.530	0.492	0.492	0.466

Concentration consistency data for injection at the individual nozzles with the Scienco pump at a system pressure of 275 kPa using an 8 nozzle boom.

T min	N1	N2	N3	N4	N5	N6	N7	N8	N9
				grams/liter					
1	0.517	-	0.517	0.530	0.517	0.555	0.530	0.532	0.517
2	0.542	-	0.579	0.579	0.555	0.604	0.579	0.567	0.567
3	0.542	-	0.579	0.592	0.567	0.617	0.579	0.567	0.567
4	0.542	-	0.579	0.592	0.567	0.617	0.592	0.579	0.567
5	0.567	-	0.567	0.592	0.567	0.617	0.592	0.579	0.567
6	0.530	-	0.592	0.592	0.567	0.617	0.592	0.579	0.567
7	0.567	-	0.567	0.592	0.579	0.617	0.592	0.592	0.567
8	0.567	-	0.592	0.579	0.592	0.617	0.592	0.592	0.567
9	0.554	-	0.567	0.579	0.579	0.617	0.592	0.579	0.567
10	0.567	-	0.592	0.579	0.592	0.617	0.592	0.592	0.579
11	0.542	-	0.567	0.592	0.579	0.617	0.592	0.592	0.567
12	0.542	-	0.579	0.592	0.592	0.617	0.592	0.592	0.567

Concentration consistency data for conventional sprayer at 275 kPa.

T min	N1	N2	N3	N4	N5	N6	N7	N8	N9
					grams/liter				
1	0.719	0.705	0.705	0.719	0.705	0.719	0.705	0.705	0.705
2	0.705	0.705	0.705	0.719	0.705	0.705	0.719	0.705	0.705
3	0.705	0.705	0.705	0.705	0.705	0.705	0.705	0.705	0.705
4	0.705	0.705	0.705	0.705	0.705	0.705	0.719	0.705	0.705
5	0.705	0.705	0.705	0.705	0.705	0.705	0.719	0.705	0.705
6	0.705	0.719	0.705	0.719	0.705	0.705	0.719	0.705	0.705
7	0.705	0.705	0.705	0.705	0.705	0.705	0.719	0.705	0.705
8	0.705	0.705	0.705	0.705	0.705	0.705	0.719	0.705	0.705
9	0.705	0.705	0.705	0.705	0.705	0.719	0.705	0.705	0.705
10	0.705	0.705	0.705	0.705	0.705	0.719	0.705	0.719	0.705
11	0.705	0.705	0.705	0.705	0.705	0.705	0.705	0.705	0.705
12	0.705	0.705	0.705	0.705	0.705	0.705	0.705	0.705	0.705

Concentration consistency data for conventional sprayer at 171 kPa.

T min	N1	N2	N3	N4	N5	N6	N7	N8	N9
					grams/liter				
1	0.690	0.703	0.703	0.716	0.690	0.703	0.703	0.690	0.703
2	0.703	0.703	0.703	0.716	0.716	0.716	0.703	0.703	0.716
3	0.690	0.716	0.716	0.716	0.716	0.716	0.703	0.716	0.703
4	0.703	0.703	0.703	0.703	0.716	0.703	0.703	0.703	0.703
5	0.716	0.703	0.716	0.716	0.716	0.716	0.716	0.703	0.716
6	0.716	0.703	0.703	0.716	0.716	0.716	0.703	0.703	0.703
7	0.716	0.716	0.716	0.716	0.716	0.716	0.703	0.703	0.703
8	0.703	0.716	0.716	0.716	0.703	0.716	0.703	0.703	0.703
9	0.703	0.716	0.716	0.716	0.716	0.716	0.703	0.703	0.703
10	0.703	0.716	0.716	0.716	0.703	0.716	0.703	0.716	0.703
11	0.690	0.716	0.703	0.703	0.690	0.703	0.703	0.716	0.703
12	0.690	0.703	0.690	0.716	0.703	0.690	0.703	0.716	0.690

Concentration consistency data for conventional sprayer at 378 kPa.

T min	N1	N2	N3	N4	N5	N6	N7	N8	N9
					grams/liter				
1	0.719	0.719	0.719	0.719	0.710	0.719	0.719	0.705	0.719
2	0.719	0.719	0.719	0.719	0.719	0.719	0.719	0.719	0.719
3	0.719	0.719	0.719	0.719	0.719	0.719	0.719	0.719	0.719
4	0.719	0.719	0.719	0.719	0.719	0.719	0.719	0.719	0.719
5	0.719	0.719	0.719	0.719	0.719	0.719	0.719	0.719	0.719
6	0.719	0.719	0.719	0.705	0.719	0.719	0.719	0.719	0.719
7	0.719	0.719	0.719	0.719	0.719	0.719	0.719	0.719	0.719
8	0.719	0.719	0.719	0.719	0.719	0.719	0.719	0.727	0.719
9	0.719	0.719	0.719	0.719	0.719	0.719	0.719	0.719	0.719
10	0.719	0.719	0.719	0.719	0.719	0.719	0.719	0.727	0.719
11	0.719	0.719	0.705	0.719	0.719	0.719	0.705	0.719	0.719
12	0.719	0.719	0.705	0.719	0.719	0.719	0.705	0.719	0.705

VITA

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