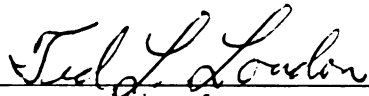


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CHEMIGATION TRANSPORT - A COMPUTER MODEL FOR TRANSPORT
OF A NON-SOLUBLE PARTICLE OR DROPLET WITHIN
A DISCHARGING AGRICULTURAL IRRIGATION PIPELINE.

By

Luke Eldon Reese

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

1986

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LUKE ELDON REESE
1986

ABSTRACT

**CHEMIGATION TRANSPORT - A COMPUTER MODEL FOR TRANSPORT
OF A NON-SOLUBLE PARTICLE OR DROPLET
WITHIN AN IRRIGATION PIPELINE.**

By

Luke Eldon Reese

Chemigation literature was searched for engineering theory related to transport and distribution, but little information was found. Chemigation field tests were conducted and the results were difficult to explain. Based upon these findings, a computer mathematical model was developed to simulate field tests. The objective for the model was to describe the horizontal and vertical transport of an immiscible rigid spherical particle or droplet while in residence in an irrigation system pipeline complete with discharging sprinklers. The model is based upon the physical and hydraulic properties of the irrigation system and the physical properties of the injected chemical.

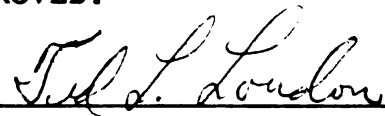
The Fortran V program was initially validated using two sets of data: a seedigation field trial with a one tower pivot and an insectigation study involving a model of a center pivot. An additional simulation was conducted on a chemigation study using a full scale (393.7 m, 1292 ft) linear move irrigation machine. With some appropriate assumptions, the trends found in the field studies were

Luke E. Reese

successfully simulated by the model. The simulation model results indicate that distribution problems to the sprinklers may occur as the specific gravity of the dispersed phase deviates from that of the continuous phase by more than .01. The model also produced results indicating that larger droplet sizes (>500 microns) caused distribution problems to the sprinklers with specific gravities of 0.9834 and 1.0074. The model seemed to indicate that droplets of less than 500 microns are desirable in the irrigation line.

While no complete data sets were available to completely test the model, it produced simulations that matched the trends seen in field experiments when reasonable estimates of missing data were used. In its present form, the model seems useful to predict whether a chemical of given physical characteristic will or will not be distributed along the total length of an irrigation system.

APPROVED:



Dr. Ted L. Loudon
Committee Chairman



Dr. Donald M. Edwards
Department Chairman

DEDICATION

To Sharon, my wife, who supported this work with
faith, love and encouragement

and

To Ashley, my daughter, who entered the world
smiling April 23, 1985 and filled
my heart with joy.

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When reminiscing about the experiences that I have had while in graduate school, I have come to realize that this manuscript is a result of the help and inputs of hundreds of people. I would like to take time to express my gratitude to some of the many people who contributed to this manuscript.

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Hundreds of additional names could be recognized for contributing to my dissertation, but space will not allow me to recognize each individually. However, to my many friends who helped me to complete this dissertation but not mentioned by name, I extend to you a heartfelt thank you.

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LIST OF SYMBOLS

A	Cross sectional area of pipe (cm^2)
AVG	Average depth caught (Eq. 4.1)
AVGDEV	Average deviation from average caught (Eq. 4.1)
c_d	Drag coefficient (dimensionless)
CU	Christiansen coefficient of uniformity
D	Inside pipe diameter (cm)
D_{max}	Maximum stable droplet diameter (cm)
D_p	Particle diameter (cm)
D_{p95}	Particle diameter corresponding to 95% volume (cm)
d	Diameter of outlet (cm)
e	Average height of pipe wall roughness (cm)
f	Fanning friction factor (dimensionless)
g	Acceleration due to gravity (cm/sec^2)
L	Distance between droplet and point on sprinkler center line flush with the pipe wall; also, radius of the surface for calculating sprinkler effect (cm)
LL	Radius to critical sprinkler velocity surface (cm)
N	Counter
Q	Pipe flow rate (cm^3/sec)
$q_{(N)}$	Sprinkler N flow rate (cm^3/sec)
q'	Flow rate through area of length r and unit thickness using average sprinkler flow velocity $\bar{V}_{(N)}$; also, equals flow from arc surface (cm^3/sec)
R	Radius of pipe (cm)

Re	Reynolds number (dimensionless)
Re_a	Particle Reynolds number defined by Eq. 2.12
R_p	Particle radius (cm)
r	Radius of outlet (cm)
s_n	Random sign
U	Mean pipe flow velocity (cm/sec)
U_E	Relative fluid velocity generally eddy velocity (cm/sec)
U_e	Eddy velocity approx. friction velocity (cm/sec)
U_t	Terminal settling velocity (cm/sec)
u^*	Friction velocity (cm/sec)
u_y	Horizontal flow velocity at distance y from pipe wall (cm/sec)
$\bar{V}_{(N)}$	Mean flow velocity from sprinkler N (cm/sec)
V_n	Particle velocity in the n^{th} encounter (cm/sec)
$\bar{V}_r$	Mean sprinkler effect velocity on surface of unit thickness at a radius of r away from the center point of the sprinkler center line flush with the pipe wall. Calculated using q' (cm/sec)
$\bar{V}_L$	Mean sprinkler effect velocity on surface of unit thickness at any radius of L away from the center point of the sprinkler center line flush with the pipe wall. Calculated using q' . L ranges from r to D . (cm/sec)
$\bar{V}_{LL}$	Mean sprinkler effect velocity on surface of unit thickness at a radius of LL away from the center point of the sprinkler center line flush with the pipe wall. Calculated using q' . Minimum sprinkler effect velocity. (cm/sec)
$X_{(N)}$	Horizontal distance between adjacent sprinklers (cm)
XR	Horizontal distance to next sprinkler center line (cm)
XS	Horizontal distance from last sprinkler center line (cm)

x_1	Sprinkler effect horizontal component for one eddy effect time step Δt (cm)
x_2	Horizontal displacement from horizontal flow velocity for one eddy effect time step Δt (cm)
YY	Vertical distance measured from outlet. Always positive and 0 at the outlet (cm)
y	Distance from closest pipe wall (cm)
y_1	Sprinkler effect vertical component for one eddy effect time step Δt (cm)
y_2	Vertical displacement from settling or eddy effect for one eddy effect time step Δt (cm)

Greek Symbols

ϵ	Resultant distance vector for one time step Δt of sprinkler effect (cm)
β	Angle between line between center point of sprinkler center line flush with the pipe wall and the droplet and the sprinkler center line (rad)
l	Eddy length (cm)
μ	Viscosity (g/cm sec)
ρ	Density (g/cm ³)
σ	Interfacial tension (dynes/cm)
τ	Eddy time (sec)
τ_E	Encounter time (sec)

Subscripts

c	Continuous phase
d	Dispersed phase

1.0 INTRODUCTION

Chemigation is defined as the application of agricultural chemicals by injecting the chemical into flowing irrigation water and distributing the chemical with the water. The first recorded research on chemigation was the study of the application of fertilizers through an irrigation system nearly 30 years ago by Bryan and Thomas (1958). Most chemigation use seems to have developed at the irrigator level from the desire to apply supplemental fertilizer. Fertilizer is still the major type of chemical applied through irrigation systems. Liquid fertilizer is the most common formulation injected, and it is generally completely soluble in the water volumes used. The distribution of a completely soluble chemical would essentially be identical to the distribution of the water.

In recent years, many other chemicals (herbicides, insecticides, fungicides, fumigants, etc.) have been tested for application through irrigation systems. Research on chemigation in general has not been able to keep up with the increased use of the practice. In many instances, the performance of these chemicals as measured by efficacy, or chemical effectiveness, has been as good as or better than the performance of the chemical when applied by other means. In cases where chemigation did not produce satisfactory

results, the reason is generally not known or reported. Using efficacy evaluations to infer chemical distribution uniformity is an indirect measurement at best. Chemigation may improve the efficiency of delivering the chemical to a targeted site, thus reducing the total amount of chemical necessary to achieve satisfactory control. If lower levels can achieve acceptable control, then uneven chemical distribution may appear satisfactory when evaluated by chemical efficacy. Efficacy studies predominate in the literature, but studies which provide data on actual chemical distribution are lacking, owing to difficulties in defining accurate sampling methods and the high costs of direct chemical concentration analysis. The ultimate objective of any chemical application is chemical efficacy. However, this evaluation technique does not always provide information which can be used to understand or improve the application technology.

Researchers are now beginning to investigate the theory and principles of chemigation especially in relation to non-soluble or immiscible formulations. With these chemicals, the water distribution uniformity cannot be used as an absolute measure of the chemical distribution uniformity. The irrigation water acts as a transport mechanism for an injected non-soluble chemical. Since a non-soluble chemical is only suspended in the irrigation water, the chemical may or may not be distributed as evenly as the water along the irrigation pipeline. The volume fraction of the chemical may

be less than ten parts per million. If large amounts of the chemical volume are contained in a few large droplets or particles, the distribution of the chemical to the individual sprinklers will probably be poor. The final chemical distribution to individual sprinklers is a function of the chemical particle or droplet size, the chemical physical properties and the irrigation system's hydraulic properties.

Research in transport theory has been conducted in the fields of transport engineering, civil engineering, and chemical engineering. The theory of chemigation using non-soluble chemicals is an applied engineering problem requiring the application of transport and hydraulic theory to an agricultural system. Groselle et al. (1984) conducted research to specifically study the theory of chemigation using non-soluble chemicals.

Field tests were performed by the author using a full scale linear move irrigation machine. The results raised numerous questions, so additional field tests were conducted using a center pivot machine and more direct sampling techniques. The results again raised questions, and multiple sampling costs limited further field tests. The results of the field experiments led to the development of a computer model to help understand the theory of chemigation when injecting a non-soluble chemical. It is expected that the model will simulate actual field conditions and predict field results prior to field tests. The model should

provide insight and guidance for field sampling, by generating information faster, improving field experimental efficiency and reducing the costs of experimentation.

The computer model developed is based on the physical and hydraulic properties of the irrigation system and the physical properties of the injected chemical. The model can be used to predict whether a known chemical particle or droplet size distribution can be distributed uniformly to the sprinklers along the length of the irrigation line. The model also can be used to predict the maximum particle or droplet size which will be distributed uniformly. In the case of seedigation, the process of injecting seed into the irrigation system for distribution with the water, the model can predict if a seed of known size and density can be distributed uniformly.

2.0 LITERATURE REVIEW

2.1 Introduction

A literature review on the entire topic of chemigation would be a weighty volume alone. Reese et al. (1984) noted seventy citations related to chemigation. Three national symposia have been held on chemigation in 1981, 1982 and 1985. Irrigation journals and popular magazines are currently devoting many articles to chemigation.

Chemical efficacy is the topic of most published chemigation research. Chemical efficacy studies reviewed herein are limited to studies using chlorpyrifos insecticide formulated as a non-emulsified product (Dursban* 6 insecticide). These studies are cited since the data can be used to validate the transport modeling of a non-soluble chemical during chemigation. Other literature reviewed is seedigation or the distribution of seeds by an irrigation system. This data is also useful for validation of a non-soluble transport model. Fluid mechanics and transport theory literature are reviewed for the variables important to the engineering theory of chemigation.

* Trademark of Dow Chemical Co. Midland, MI.

2.1.1 Chemigation Advantages

The major difference between chemigation and other chemical application techniques is the quantity of water applied with the chemical. Certain chemicals, such as liquid fertilizer, are readily applied during a regular irrigation cycle with a water application rate of 253,861 L/ha (27,154 gal/ac). For other chemicals such as fungicides and insecticides, a special run of the irrigation system is made at a lower water application rate of 25,386-63,465 L/ha (2,715-6,788 gal/ac). Typically for ground and aerial application methods, 388 L (100 gal) of water is applied over several hectares. In certain circumstances, the large volume of water used for chemigation provides an advantage over other application techniques. A large water volume can be advantageous for incorporating soluble soil chemicals or for penetrating through dense plant canopies. The large water volume can be used to strategically move and deposit the chemical at targeted sites.

Cost of application is a prominent advantage for the use of chemigation. Cost comparisons of chemigation to other application methods and other reasons for the use of chemigation are stated in Threadgill (1981, 1982). Chemigation is also attractive because existing equipment is used for dual purposes. As application techniques, chemigation and aerial application are basically the only two chemical application alternatives available to the producer when a crop canopy is in the later development

stages, such as silking corn. Chemigation is also a viable option when wet soil conditions would make ground equipment use very difficult.

2.1.2 Chemigation Disadvantages and Limitations

Chemigation, like any other application technology, has its disadvantages and limitations. An irrigation system does not look like a spray rig. The general appearance of irrigation water with the chemical added is like uncontaminated irrigation water; thus, warnings of chemical application must be posted on the site. Although human contact with the chemical should be avoided, the high dilution factor created by the high water volume would allow direct contact on the human body with little adverse health effect for most chemicals. One other human health concern is the re-entry time because the time for surface drying may be increased with the higher water volumes used in chemigation. Re-entry into the treated area should be avoided at least until the surfaces are dry or as specified by the chemical label, whichever is longer.

Chemigation is not an application technique that can be used by every irrigator. Chemigation is a chemical application technique which requires a high level of management for success and safety. The large water volume used with chemigation can prove to be disastrous if not used properly. The chemical may be removed from the targeted site and potentially removed from the treatment area if too

much water is used and if water runoff is allowed. The proper chemical formulation must be selected for the specific treatment target. To move a chemical into the soil, the chemical should be soluble. If a chemical is targeted for foliar application, certain additives, such as oils, can increase the foliar adherence, as reported by Young et al. (1981).

If chemigation is used on a moving irrigation system, such as a center pivot, an accurate injection rate must be calculated, calibrated and maintained. The one most prominent area for error in chemigation is the injection rate. In an article by White (1986), three out of six PhD's incorrectly calculated a fertigation injection rate for a center pivot using a chemigation worksheet. Two of the six incorrectly calculated a herbigation injection rate for the same center pivot using the worksheet. Accurate calculation of the injection rate is a necessity for accurate application. An irrigator should only use chemicals specifically labeled for application by chemigation. Irrigation Age (1986) has published a screening test to measure one's knowledge of chemigation, and the results of this test can be used to determine if chemigation is a viable option for the potential user, an irrigator. Again, to re-emphasize, chemigation is an application technology to be used only by conscientious, qualified irrigation managers.

2.1.3 Chemigation Use

Threadgill (1985) reported that eighty-five percent of the total chemigated area (4.6 million ha, 11.4 million ac) in the U.S. is chemigated with sprinkler irrigation based on a survey of extension irrigation specialists. He further stated that 42 percent, 62 percent and 4.2 percent of the sprinkler, trickle and surface irrigated lands, respectively, were chemigated at least once in 1983. The interest in chemigation is further exemplified by the present number of agricultural products labeled for chemigation. Irrigation Age (1986) reported forty-one chemicals presently labeled for chemigation.

2.2 Irrigation System Analysis

A sprinkler irrigation system consists of sprinklers strategically placed along a pipeline. Each sprinkler discharges a given amount of water from the water flowing in the pipeline. The sequential release of water changes the hydraulic characteristics of the pipeline at each sprinkler. This section will discuss the hydraulic characteristics of the pipeline and the corresponding equations.

2.2.1 Mean Pipe Flow Velocity

The flow in a pipe is a function of the velocity of the fluid and the cross sectional area of the pipe. The average pipe flow velocity is defined by the continuity or conservation of mass equation.

$$U = Q/A \quad (2.1)$$

Where: U = Mean pipe flow velocity (cm/sec)
 Q = Pipe flow rate (cm³/sec)
 A = Cross sectional area of pipe (cm²)

Figure 2.1 taken from Reese et al. (1984) shows the mean pipe flow velocity versus distance from inlet for three typical irrigation systems, two center pivots and one linear move. The mean pipe flow velocity is decreased as water is discharged from each sprinkler.

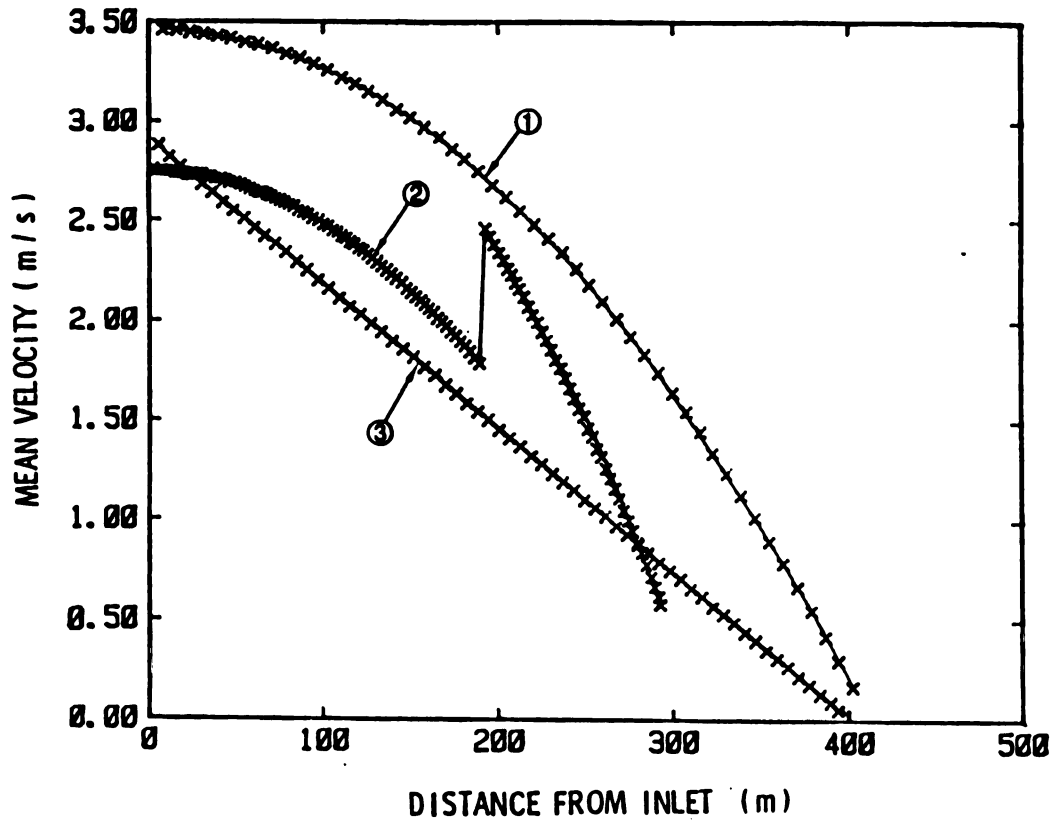
2.2.2 Reynolds Number

The Reynolds number is a dimensionless parameter used to express the degree of turbulence in pipe flow. The Reynolds number may not be a true indication of mixing, but it is a very commonly used number in the description of fluid flow. Flows with a Reynolds number less than 2000 are considered laminar. Flows with a Reynolds number greater than 4,000 are considered turbulent, and flows with a Reynolds number between 2,000 and 4,000 are considered transient (Streeter, 1966). The Reynolds number equation as taken from Streeter (1966) is:

$$R_e = DU\rho/\mu \quad (2.2)$$

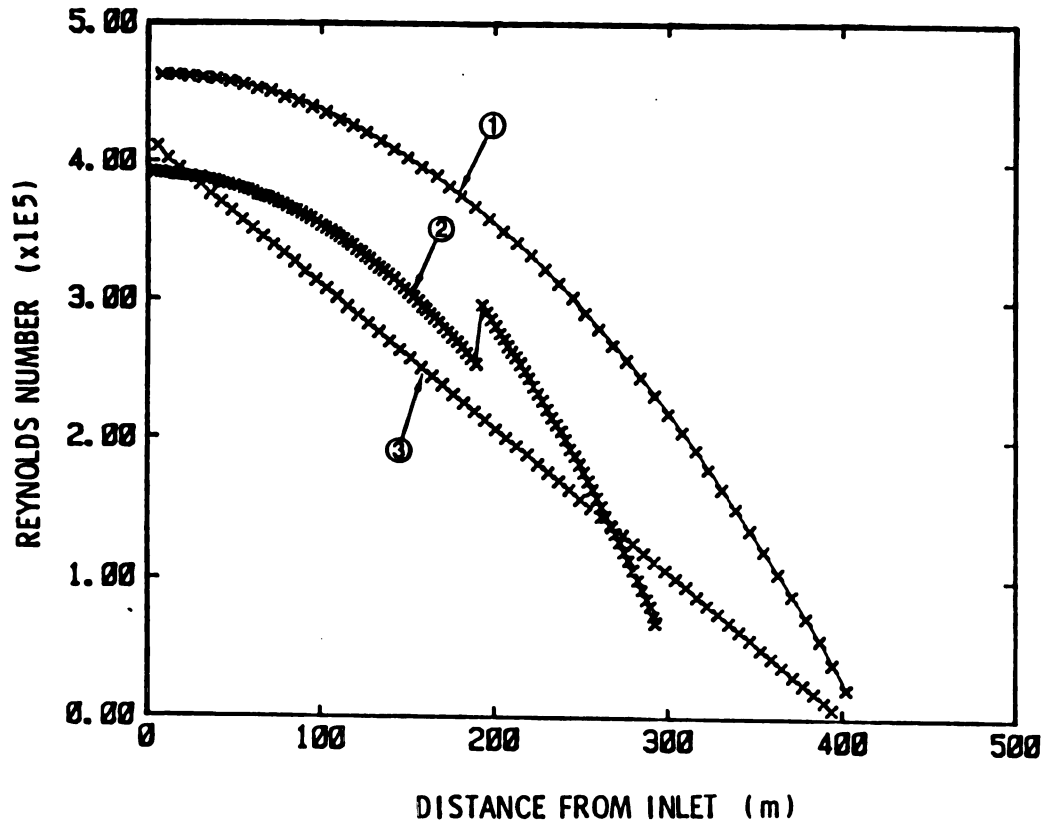
Where: R_e = Reynolds number (dimensionless)
 D = Inside pipe diameter (cm)
 U = Mean pipe flow velocity (cm/sec)
 ρ = Density (g/cm³)
 μ = Viscosity (g/cm sec)

Figure 2.2 taken from Reese et al. (1984) shows the Reynolds number versus distance from inlet for the same irrigation systems shown in Figure 2.1. The shapes of the



- ① 402 m (1320 ft), 63 L / s (1000 gpm) center pivot evenly spaced sprinklers with no end gun and 15.2 cm (6 ") pipe diameter.
- ② 293 m (957 ft), 57 L / s (905 gpm) at 276 kPa (40 psi) center pivot with continuous end gun operation and reduced pipe diameter 16.2 cm (6.395') to 13.7 cm (5.395 ") at 193 m.
- ③ 395 m (1296 ft), 60 L / s (950 gpm) at 276 kPa (40 psi) linear move evenly spaced sprinklers and 16.3 cm (6.407 ") pipe diameter.

FIGURE 2.1 MEAN PIPE FLOW VELOCITY VS. DISTANCE FROM INLET



- ① 402 m (1320 ft), 63 L / s (1000 gpm) center pivot evenly spaced sprinklers with no end gun and 15.2 cm (6") pipe diameter.
- ② 293 m (957 ft), 57 L / s (905 gpm) at 276 kPa (40 psi) center pivot with continuous end gun operation and reduced pipe diameter 16.2 cm (6.395") to 13.7 cm (5.395") at 193 m.
- ③ 395 m (1296 ft), 60 L / s (950 gpm) at 276 kPa (40 psi) linear move evenly spaced sprinklers and 16.3 cm (6.407") pipe diameter.

FIGURE 2.2 REYNOLDS NUMBER VS. DISTANCE FROM INLET

curves are identical to Figure 2.1 since the Reynolds number is a function of the mean pipe flow velocity and given fluid constants. The important point to observe is the magnitude of the numbers. The Reynolds number is well above the turbulence criterion for practically the entire length of all three systems.

2.2.3 Friction Factor

The friction factor in turbulent flow is based upon two dimensionless numbers, the Reynolds number and relative roughness, e/D . The variable e is the average height of the roughness of the pipe wall, and D is the inside diameter of the pipe. The friction factor is generally read from a plot of e/D on a graph of friction factor versus Reynolds number. An equation to calculate the friction factor when the factor is dependent upon both Reynolds number and the relative roughness is taken from Knudsen and Katz (1958):

$$1/\sqrt{f} = 4\log(D/e) + 2.28 - 4\log(1 + 4.67((D/e)/(R_e\sqrt{f}))) \quad (2.3)$$

Where: f = Fanning friction factor (dimensionless)
 D = Inside pipe diameter (cm)
 e = Average height of pipe wall roughness (cm)
 R_e = Reynolds number (dimensionless)

Equation 2.3 can be solved by iteration to calculate a friction factor for given flow conditions.

2.2.4 Friction Velocity

The flow velocity profile in a pipe is not equal to the average pipe flow velocity across all of the cross sectional area due to frictional effects from the pipe wall and

viscosity effects of the fluid. In analyzing this velocity profile, a term is needed for calculations called the friction velocity. The friction velocity, or the shear velocity, has the dimensions of velocity and is a constant for any given set of flow conditions. It is denoted by the symbol u^* and is defined by:

$$u^* = U \sqrt{f/2} \quad (2.4)$$

Where: u^* = Friction velocity (cm/sec)
 U = Mean pipe flow velocity (cm/sec)
 f = Fanning friction factor (dimensionless)

2.2.5 Pipe Flow Velocity Profile

Kundsen and Katz (1958) cited Equation 2.5 to calculate the velocity distribution profile for both rough and smooth tubes.

$$u_y = u^* (2.5 \ln(y/R) + 3.75 + (U/u^*)) \quad (2.5)$$

Where: u_y = Velocity at distance y from pipe wall (cm/sec)
 y = Distance from pipe wall (cm)
 R = Radius of pipe (cm)
 U = Average pipe flow velocity (cm/sec)
 u^* = Friction velocity (cm/sec)

2.3 Miscible Chemical Studies

Chemicals applied through irrigation systems can be broken down into two classes, miscible and immiscible. The engineering theory for the two classes is radically different. According to Webster's New Collegiate Dictionary (1973), miscible chemicals are capable of mixing in any ratio without separation into two phases. Generally, the

injected chemical must be completely soluble in the irrigation water to be considered miscible. Important considerations for miscible chemicals are the mixing of the chemicals and the mixing time. Forney (1986) stated the following regarding fluid mixing in pipes:

"In general, the distance necessary to achieve a desired degree of uniformity of concentration or temperature in a pipe by jet injection depends on the following quantities: ratio of jet-to-pipe diameter, geometry of the mixer, uniformity criterion, ratio of jet-to-pipe flow rates or velocities, ratio of specific gravities of the two feed streams, pipe or jet Reynolds number, surface roughness, and pipeline secondary currents."

The design constraints for selection of the best injection system for assisting in rapid mixing are as follows (Forney, 1986):

- "1. Desired mixing ratio of jet-to-pipe flow rates.
2. Pipe length available for mixing.
3. Required degree of uniformity of mixture.
4. Secondary current patterns within the pipeline upstream of the injection point.
5. Power requirements for the proposed mixer geometry."

For all chemicals, the most uniform chemical distribution would result from constant, uniform injection. The chemigation injection pumps used are typically positive displacement piston or diaphragm pumps. These pumps have a suction and discharge cycle; thus their output is not constant, but rather is pulsating. Plug flows of chemical are introduced into the irrigation system. The pulsations can be smoothed by increasing the frequency of the pumping cycle or by increasing the number of pumping chambers.

Forney (1986) showed concentration profile figures for good and poor mixing from jet injection. Fischbach (1970)

showed that an injected miscible chemical can be uniformly mixed across the pipe cross section before it reaches the first branching lateral line and/or sprinkler. However, the injection pulsations still exist, so the axial chemical distribution and the horizontal flow velocity determine the amount of time that chemical is allowed to discharge from each individual sprinkler. To model the distribution of a miscible chemical for pulsating injection, it becomes important to know the behavior of the chemical plug and its interfaces, to determine the amount of chemical discharged from each sprinkler. Axial mixing equations and flow velocity equations are used to predict the time required for a slug of injected chemical and its interfaces to pass a sprinkler outlet.

Hermann et al. (1974) studied the axial mixing phenomenon for branching solid set sprinkler irrigation systems. The objective of their study was "to develop methods to predict the effects of state of flow, of couplers and of branching flow on mixing and dilution of chemicals injected into operating sprinkler irrigation laterals". The injected chemical was miscible and injected as plugs with a leading and following interface within the irrigation water. The interface length and time to pass a branch were studied in relation to the total distance traveled. As a chemical plug passes a sprinkler, flow is discharged, the interface is shortened, and the pipe flow velocity is decreased. The interface length elongates faster in laminar

flow because of the velocity profile. In the literature reviewed by Hermann et al., the pertinent variables considered to affect the mixing process during steady state flow in a straight pipe were fluid density and viscosity, velocity of flow, pipe diameter, roughness and molecular diffusion coefficient. In turbulent flow, molecular diffusion would have little effect, and the Reynolds number (which is a function of the flow velocity) and relative roughness would have the major effect on mixing. Hermann et al. concluded that the interface length is shortened in proportion to the decrease in flow velocity where flow branches or discharges. In constant velocity flow, the interface length (ζ) is related to the distance (δ) traveled by the interface by $\zeta = k\delta^n$. Mixing in an ordinary lateral does not greatly reduce the length of the plug of material until the last sprinkler is reached. These conclusions would then tend to support the idea that, regardless of the injection technique, the chemical distribution outside the machine would be approximately the same as the water distribution for most irrigation systems.

2.4 Immiscible Chemical Two Phase Flow

For immiscible chemicals, the engineering theory is much more complex. An immiscible chemical will remain as a discrete phase when injected, thus the term "two phase flow" is used. Injected immiscible chemicals will be found in the irrigation water as separate identities such as droplets,

globules, particles, grains or micells. For chemigation the phase for the injected immiscible chemical is generally either liquid or solid. Since the injected chemical is suspended or dispersed, it is called the dispersed phase. The irrigation water, the continuous phase, is the second phase, and it will always be a liquid phase. An example of a chemigation liquid-liquid phase where the dispersed phase would act as droplets or globules is Dursban 6 plus oil (Loudon and Reese, 1985; Groselle et al., 1984; Cochran et al., 1984). An example of a chemigation liquid-liquid phase which would act as micells would be an emulsified formulation such as Lorsban* 4E insecticide plus oil (Larson, 1984). A chemigation liquid-solid phase, where the dispersed phase would be particles or grains, would be wettable powder formulations or seeds. Seeds distributed by seedigation are considered to be a dispersed phase since the phenomenon is consistent with the definition of immiscible two phase flow.

The distribution of a miscible chemical, as previously described, is primarily a function of the irrigation system's hydraulic properties. However, the distribution of an immiscible chemical during chemigation is a function of the chemical's physical properties plus the irrigation system's hydraulic properties. The density of the chemical is important in relation to how the chemical will travel in the fluid. Karabelas (1977) conducted a study on the

* Trademark of the Dow Chemical Co. Midland, MI.

vertical distribution of dilute suspensions in turbulent pipe flow. He states that, "In steady horizontal pipe flow, the density difference between a dispersed solid or liquid phase and the continuous phase can cause a nonuniform distribution of the dispersion in the pipe cross section".

If the density is significantly greater for the chemical than the carrier fluid, it may settle out before reaching the end of the irrigation system. If the density for the chemical is significantly less than the carrier fluid, it may float out and be distributed for only part of the irrigation system length.

The droplet or particle size determines the magnitude of the settling or buoyancy force. For a solid chemical particle or a seed, the size is essentially constant for the entire length of the irrigation system. A seed's size may increase slightly because there may be some absorption of water or may be decreased if the seed is split.

For an injected immiscible liquid, the droplet or globule size distribution is dependent upon many more factors. The initial droplet size distribution is determined by the chemical's physical properties and the injection nozzle's physical and hydraulic properties. The irrigation system's velocity profile and turbulence also contribute a shear force on each droplet. The magnitude of the shear force is dependent upon the droplet size and the relative position of the droplet in the cross section of the pipe. A maximum stable droplet size can be estimated for

liquid chemicals with known physical properties in a given flow condition. The final region for an immiscible liquid chemical droplet breakup during chemigation is at the sprinkler nozzle. The magnitude of the maximum velocity in the sprinkler nozzle may be 10 times the magnitude of the pipe flow velocity. The shear forces in the sprinkler nozzle have a significant influence on the final droplet distribution. These factors will be discussed in later sections.

2.5 Insectigation Efficacy Studies Using Chlorpyrifos

Chlorpyrifos is the active ingredient in Dow Chemical Co. insecticides Lorsban 4E and Dursban 6. Lorsban 4E is an emulsified product and Dursban 6 is non-emulsified. Dursban 6 is marketed as a commercial insecticide, and it is basically the technical product used in manufacturing Lorsban 4E. Of the two, only Lorsban 4E is currently labeled for application via chemigation. However, chemigation research has been conducted using both products. Both products are immiscible when injected into an irrigation system, but both have unique characteristics, as described in section 2.4, when used in chemigation. Mixing both products with oil as a carrier prior to injection helps to increase the foliar sticking capacity of the chemical (Young et al., 1981).

Young (1981, 1982) applied non-emulsified chlorpyrifos plus oil via chemigation and obtained effective control of

corn earworm and fall armyworm. In a comparison of the non-emulsified formulation plus oil and the emulsified formulation plus oil, both applied via chemigation, the emulsified formulation required seven additional applications for comparable control. This would indicate that a non-emulsified formulation plus oil may be more efficacious than the emulsified formulation. However, the droplet or globule size distribution of a non-emulsified formulation is a function of the injection system and the irrigation system's hydraulic properties, which are variable from system to system. The physical properties of oils are also variable and temperature dependent. The influence of this variability has to be checked, in order to confirm that the non-emulsified formulation is satisfactory for all systems and/or generally superior in performance to the emulsified product.

As stated previously, Young (1982) obtained effective fall armyworm control using the emulsified Lorsban 4E formulation plus oil. Larson (1984a) found the emulsified Lorsban 4E formulation plus oil to be an efficacious and economical method for insect control in corn. According to the Larson study conducted in Nebraska, "no significant reduction in control levels were seen throughout the state over a cross section of 150 pivots representing all major manufacturers, all types of nozzeling packages and pressures and all types of drives." Larson (1984) reported that Lorsban 4E alone would produce micells of microscopic size,

owing to surfactant effects. The breakup of the emulsified formulation is more dependent on the emulsifier than the injection and irrigation system. Therefore, with the emulsified formulation, the variability of the chemical droplets, or micells, is more controlled since the emulsifier is a constant.

Loudon and Reese (1985) used emulsified Lorsban 4E plus crop oil to control corn rootworm adult beetle by applying the chemical through a 393.7 m (1292 ft) linear move irrigation system. One objective of the study was to see if variation in control occurred along the length of the system. The formulation was found to give essentially 100 percent beetle kill for all spans, including the last span.

2.6 Engineering Studies Using Chlorpyrifos

Studies by Groselle et al. (1984) and Cochran et al. (1984) used non-emulsified Dursban 6 plus oil to study some engineering principles of chemigation. Young (1985) reported that the physical arrangement and characteristics of the chemical injection system play a significant role in the efficacy of a specific oil-pesticide formulation. In the Young study, a change in injection port orientation with all other factors held constant resulted in different insect control. It was hypothesized that the size or size distribution of the oil-pesticide droplets may have caused the control difference.

Cochran et al. (1984) used a center pivot simulator to

study the effect of pressure, nozzle and injection port orientation on the oil-insecticide droplet size distribution in the mainline flow and as emitted from a spray nozzle. The summary of Cochran et al.'s study using the non-emulsified formulation is as follows:

"A general conclusion from this study is that chemigation and irrigation system design can have a major influence on the droplet diameter of oil formulated chemicals applied via chemigation. In addition to the irrigation-chemigation system physical parameters, the physical properties of the oil-chemical formulation, the large variety of carrier oils available and the manner in which they control droplet breakup need to be examined."

The oils used in these oil-insecticide formulations vary greatly in their characteristics, such as specific gravity, viscosity, and surface tension. The characteristics of the oil are also a function of temperature.

Groselle et al. (1984) used a one sprinkler center pivot model to study the effect of injection port orientation, injector pump stroke frequency and irrigation sprinkler on the droplet size distribution of an oil-insecticide non-emulsified formulation. The chemical droplet size distribution in the mainline, as sampled immediately prior to entering the sprinkler nozzle, was significantly influenced by the injection pump frequency and the injection port orientation. The sprinkler nozzle was highly significant in reducing the mean droplet size diameter, as would be expected.

McLeod (1983) used a scale model of a center pivot irrigation system to study the distribution characteristics of Lorsban 4E, Lorsban 4E and non-emulsifiable 11N crop oil,

Lorsban 4E and emulsifiable crop oil, Dursban 6 and Dursban 6 and non-emulsifiable 11N crop oil. The scale model was based on a 1000 gpm pivot. The system was built using PVC pipe. The apparatus was constructed to allow the pipe to be rotated thus allowing the nozzles to take flow from the top or bottom of the pipe. Spraying Systems flow regulating orifice plates were used to achieve the desired discharge per outlet. The injection nozzle was a .64 cm (.25 in) tube flush with the top of the pipe. By photography through a clear pipe at the injection point, the droplet diameter of the Dursban 6 plus oil was determined to be in the "4,000-5,000 micron range". Later analysis of the same photographs showed many smaller droplets sizes. The ratio of Dursban 6 and 11N crop oil was 2/3:1, which should be buoyant. For this study, all results and conclusions were based on analytical concentration analysis. For the Dursban 6 plus oil formulation, the majority of the chemical was discharged between nozzles 1 through 17 when the nozzles were turned up. When the nozzles were turned down, 1 ppm exited nozzle 1 compared to an average of 292 ppm at nozzle 50. A large part of the chemical was found remaining in the pipe when the nozzles were in the down position, indicating that the chemical had floated to the top and was not discharged. This result exemplifies the effect of injected material density on the distribution.

Lorsban 4E contains an emulsifier. The emulsifier causes the injection droplet size to be much smaller, thus forming a more stable dispersion. McLeod (1983) found that

the Lorsban 4E distribution was much more uniform along the whole length of the system. However, concentration differences in the sprinkler output were observed along the length of the line, and the concentration trends were reversed for the nozzle placement on the pipe top compared to the bottom.

McLeod (1983) also found the Lorsban 4E plus oil formulation reduced uniformity but improved leaf retention, which further supports Young et al.'s (1981) conclusion of increased leaf deposition with the addition of oil. The increased leaf deposition with the addition of oil indicates that the use of oils with the formulations may be important, and research related to oil-chemical formulations should continue.

Young (1986) stated that injection port orientation studies and non-emulsified formulation studies have generated different efficacies. In one instance, insect control was observed for only the first two-thirds of the irrigation system using the non-emulsified formulation plus oil. These results together with McLeod's work (1983) would again suggest dispersion, transport and distribution problems may occur with large non-emulsified droplets. Young further states that efficacies have been influenced by water temperature. Water temperature would have an effect on the chemical physical properties. The variability of the droplets' physical properties, formation and size distribution plus the irrigation system hydraulic properties must be addressed.

2.7 Seedigation Research

White (1985) reported on seedigation research progress at the Coastal Plain Research Center, Tifton, Ga. The first experience with seedigation involved sowing turnip seed with a one-span pivot. After injecting the turnip seed, the ground was inspected, but no seeds were found. The seeds were located in the sand trap at the end of the pivot. The seeds were then injected with vegetable oil, and the seeds were "planted - perfectly". In the first attempt, the seed settled out before being distributed by the sprinklers. The apparent effect of the oil in the second attempt was to change the density of the seed, allowing it to be carried and distributed. White (1985a) reported on the seedigation research conducted by Valmont Industries, Valley, Neb. Valmont engineering has elected to test a "piggy-back" system instead of direct injection into the irrigation line. Quoting from the article, the reason for use of this system is as follows:

"The reasons direct injection into the main pipe doesn't work, said Chapman, is that water enters the pipe with a great amount of turbulence which calms as it moves further into the system, causing various natural reaction from the seeds. Seeds heavier than water will sink and bounce along the bottom of the pipe while seeds lighter than water will float to the top and exit the first available sprinkler. With the seeder hose, the high pressure and constant velocity keeps all seeds in suspension, and the sequencing gives a uniform broadcasting of the seed over the field. Chapman and associates know they can get a uniform broadcasting of most agricultural seeds, including corn, although some seeds will require an oil carrier."

John Chapman (1986), Valmont's vice president for engineering, stated that wheat seed settled to the bottom

and oat seeds floated to the top when injected directly into an irrigation line, as observed through a clear plexiglass section in the line.

2.8 Settling Velocity Analysis

Particles suspended in a fluid will settle or rise if the density of the material is different from the surrounding fluid. The rate of fall or rise is the settling velocity, and the magnitude of this velocity will increase until the drag forces on the particle equal the gravitational forces. When these forces are equal, and when no interference occurs from other particles or the pipe wall, the resultant settling velocity is called the "terminal" or "free settling" velocity.

2.8.1 Gravity Settling

The settling velocity is a function of the densities of the dispersed and continuous phase, the particle size and a dimensionless drag coefficient. The drag coefficient is a function of the particle's Reynolds number, shape and orientation. The particle Reynolds number is calculated using Equation 2.2 by substituting the particle diameter for the pipe diameter and the relative velocity between the particle and the main body of fluid for the average fluid velocity. An idealistic particle shape for modeling is spherical due to symmetry for all orientations. However, spherical is probably the least probable shape to occur in

two phase flow. Liquid droplets rise or fall at different rates compared to identical diameter rigid spheres. Small liquid droplets are essentially spherical, but internal circulation results in surface rotation and larger terminal settling velocities. As the liquid droplet diameter increases, the shape will deviate from spherical, and eventually oscillations of shape will occur which decrease the terminal velocities (Perry et al., 1984). A plot of the drag coefficient for spheres, disks and cylinders versus particle Reynolds number is found in Perry et al. (1984). For all liquid droplets, the terminal velocity can be strongly influenced by surface active ingredients such as surfactants.

The following terminal settling velocity equations are based upon the assumption of no wall or concentration effects. "These effects are generally not significant for container-to-particle-diameter ratios of 100 or more and for concentrations below 0.1% by volume" (Perry et al., 1984). Typically for chemigation, the concentration is much lower than 0.1% by volume. The equation for a free-falling, rigid, spherical particle from Perry et al. (1984) is:

$$U_t = \sqrt{4gD_p(\rho_d - \rho_c)/3\rho_c c_d} \quad (2.6)$$

Where: U_t = Terminal settling velocity (cm/sec)
 g = Acceleration due to gravity (cm/sec²)
 D_p = Particle diameter (cm)
 ρ_d = Particle density (g/cm³)
 ρ_c = Fluid density (g/cm³)
 c_d = Drag coefficient (dimensionless)

If the particle is accelerating, the drag coefficient

is influenced by the velocity gradient near the particle surface. Since the settling velocity is a function of the particle's Reynolds number, equations are derived for different ranges of Reynolds number. For particles with a Reynolds number less than 0.3, the velocity field around the sphere is symmetric and the equation is based on Stoke's law. The terminal settling velocity for Stoke's law region as taken from Perry et al. (1984) is:

$$U_t = gD_p^2(\rho_d - \rho_c)/18\mu_c \quad (2.7)$$

Where: U_t = Terminal settling velocity (cm/sec)
 g = Acceleration due to gravity (cm/sec²)
 D_p = Particle diameter (cm)
 ρ_d = Particle density (g/cm³)
 ρ_c = Fluid density (g/cm³)
 μ_c = Fluid viscosity (g/cm sec)

Particles with a Reynolds number between 0.3 and 1,000 are in an intermediate range and their terminal settling velocity is described by Equation 2.8 (McCabe and Smith, 1967).

$$U_t = 0.153g^{0.71}D_p^{1.14}(\rho_d - \rho_c)^{0.71}/\rho_c^{0.29}\mu_c^{0.43} \quad (2.8)$$

Where: U_t = Terminal settling velocity (cm/sec)
 g = Acceleration due to gravity (cm/sec²)
 D_p = Particle diameter (cm)
 ρ_d = Particle density (g/cm³)
 ρ_c = Fluid density (g/cm³)
 μ_c = Fluid viscosity (g/cm sec)

Particles with a Reynolds number between 1,000 and 350,000 are in Newton's law region, and their terminal settling velocity is described by Equation 2.9 (McCabe and Smith, 1967).

$$U_t = 1.74 \sqrt{gD_p(\rho_d - \rho_c)/\rho_c} \quad (2.9)$$

Where: U_t = Terminal settling velocity (cm/sec)
 g = Acceleration due to gravity (cm/sec²)

$$\begin{aligned} D_p &= \text{Particle diameter (cm)} \\ \rho_d &= \text{Particle density (g/cm}^3\text{)} \\ \rho_c &= \text{Fluid density (g/cm}^3\text{)} \end{aligned}$$

The drag coefficient in the Newton's law region is nearly constant at 0.44.

2.8.2 Turbulence Effect

Kubie (1980) investigated the effect of turbulent flows on the settling velocity of droplets. The study developed a simple, stochastic model of settling in turbulent flow and found that turbulence causes considerable retardation of still fluid settling velocity for a wide array of conditions. The turbulence factor considered to interfere the most with the settling velocity is the small scale eddies which are large energy dissipators. To analyze this effect, the random vertical component of each eddy encounter is summed for many eddies. The summed distance is divided by the time, and a resultant settling velocity is determined. A retardation coefficient is determined by dividing the resultant settling velocity by the still fluid settling velocity. For this study, the description of particle motion in an eddy is a function of inertia, gravitational and drag forces and the Stokesian added mass term. The equation to describe the motion of a spherical particle as taken from Kubie (1980) is:

$$\begin{aligned} \frac{4}{3}\pi R_p^3(\rho_d + 1/2\rho_c)dv_n/dt &= \frac{4}{3}\pi R_p^3(\rho_d - \rho_c)g \\ &+ 1/2\pi R_p^2 c_d \rho_c |s_n U_E - v_n| (s_n U_E - v_n) \end{aligned} \quad (2.10)$$

with

$$\begin{aligned} U_E &= U_e \quad \text{for } 0 \leq t < \tau_E \\ U_E &= 0 \quad \text{for } \tau_E \leq t \leq \tau \end{aligned}$$

Where: R_p = Particle radius (cm)
 ρ_d = Particle density (g/cm^3)
 ρ_c = Fluid density (g/cm^3)
 V_n = Particle velocity in the n^{th} encounter (cm/sec)
 t = Time from beginning of encounter (sec)
 g = Gravitational acceleration (cm/sec^2)
 c_d = Drag coefficient (dimensionless)
 s_n = Random sign
 U_e = Eddy velocity (approx. friction velocity, cm/sec)
 U_E = Relative fluid velocity (generally eddy velocity, cm/sec)
 τ_E = Encounter time (sec)
 τ = Eddy time (sec)

Equation 2.10 can be solved by a numerical solution and a particle velocity calculated for each eddy encounter. Since the particle's Reynolds number changes for each time step of the numerical solution, the drag coefficient of the particle must be calculated for each time step using Equation 2.11 (Kubie, 1980).

$$c_d = 24/\text{Re}_a((1+(\text{Re}_a/60)^{5/9})^{9/5}) \quad (2.11)$$

Where: c_d = Drag coefficient
 Re_a = Particle Reynolds number defined by Eq. 2.12

$$\text{Re}_a = (2R_p\rho_c|s_nU_E - V_n|)/\mu_c \quad (2.12)$$

Where: Re_a = Reynolds number (dimensionless)
 R_p = Particle radius (cm)
 ρ_c = Fluid density (g/cm^3)
 s_n = Random sign
 U_E = Relative fluid velocity (generally eddy velocity, cm/sec)
 V_n = Particle velocity (cm/sec)
 μ_c = Fluid viscosity (g/cm sec)

Kubie made several simplification assumptions as follows:

1. A particle goes immediately from one eddy encounter to the next.
2. A particle remains in the eddy for the entire encounter; thus, the dwell time, or time outside an eddy, equals 0.
3. The initial particle velocity for encounter n is the final particle velocity for encounter $n-1$.

4. All of the particle motion is in the vertical plane with the random sign used to determine which direction. Random motion in the other two directions is ignored.

5. The eddies are assumed to decay instantaneously.

6. The velocity of the eddies, the duration of the eddy time and the dwell time are constant for all encounters.

Even with the numerous simplifying assumptions, the approach shows that turbulence has a significant effect on the particle settling velocity.

2.9 Droplet Analysis in Liquid-Liquid Two Phase Sys.

When using a non-emulsified formulation, such as Dursban 6 plus oil, the dispersed phase forms droplets upon injection, as discussed in section 2.4. The initial droplet formation at the injection point and subsequent forces acting on the droplet distribution will be discussed. The sampling techniques for determining a liquid droplet distribution will also be discussed. The same general sampling techniques can be used for particulate matter.

2.9.1 Droplet Breakup and Distribution

A dispersed liquid droplet distribution is formed and influenced by three separate mechanisms in an irrigation system. The initial droplet size distribution is created by the injection nozzle. The droplets are then subjected to shear forces in the flowing water from velocity gradients. Finally, the droplet distribution is influenced by the shear forces in the sprinkler nozzle.

2.9.1.1 Injection Nozzle Breakup

The initial and, possibly, the final droplet size distribution of an injected immiscible liquid chemical is determined at the injection nozzle. The subject of nozzle or jet break-up has been studied extensively in the chemical engineering field and several empirical relationships have developed. In almost all of the equations, the droplet size is a function of the injection nozzle velocity, the injection nozzle inside diameter, the density difference, gravity, and interfacial tension of the chemicals. The droplet size is also influenced by the orientation of the nozzle into the flow and the relative point of injection in relation to the flow velocity profile (Groselle et al., 1984). Four forces which affect droplet formation at the injection nozzle are the buoyancy force (caused by the density difference) and the kinetic force (associated with fluid flowing out of the nozzle) which are opposed by the interfacial tension force at the nozzle tip and the continuous phase drag force (Heertjes and de Nie, 1971).

The droplet distribution formed is a function of the injection velocity and can be broken down according to three flow regions in a droplet diameter versus time of formation plot: the non-jetting region, the jetting region and the atomization region. At low nozzle velocities, droplets are formed at the nozzle tip which is considered non-jetting. As the nozzle velocity is increased, a jet is formed breaking up into droplets at some distance from the nozzle,

creating the jetting region. At still higher nozzle velocities, the jet disappears and very small droplets are formed at the tip, which is the atomization region (Skelland and Johnson, 1974). Heertjes and de Nie (1971) show a characteristic plot of the droplet volume versus formation time for droplet release from a capillary. Figure 2.3 is taken from the Heertjes and de Nie plot and shows the four regions of droplet formation. Regions I and II have been studied extensively. Region I is basically the non-jetting region, and the droplet volume is basically constant. Regions II, III and IV are in the jetting region. In region IV, the average droplet diameter is approximately twice the jet diameter, which is related to the nozzle diameter by empirical relationships (Godfrey and Hanson, 1982). Atomization occurs for droplet formation times which are less than the time beginning region IV in Figure 2.3.

In a jetting system, Null and Johnson (1958) and Skelland and Johnson (1974) have developed procedures to determine the droplet volume or size in liquid-liquid systems. Kitamura et al. (1982) reported on the stability of jets in liquid-liquid systems. The droplet size in a jetting situation is a function of the jet stability which is affected by the relative velocities of the two phases. Kitamura and Takahashi (1982) studied the breakup of jets in power law Non-Newtonian -- Newtonian liquid systems. Non-Newtonian fluids have shear rates which are temperature dependent, while Newtonian fluids are not temperature

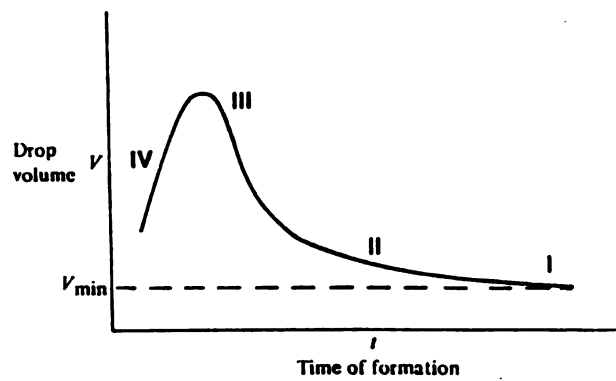


FIGURE 2.3 DROPLET FORMATION FROM A CAPILLARY VS RELEASE TIME (After Heertjes and de Nie, 1971)

dependent. Water is a Newtonian fluid while oils are Non-Newtonian. Injecting Dursban 6 plus oil into an irrigation system would create a Non-Newtonian -- Newtonian liquid system. The results indicated that Non-Newtonian jets in a Newtonian fluid are not as stable as a jet of Newtonian fluid.

In relation to chemigation, the data base is basically nonexistent for droplet breakup at the injection nozzle. Most injection nozzles being used are not even classified as non-jetting, jetting or atomizing. Soo (1967) reports that liquid atomization can produce particle sizes in the range of approximately 10-5,000 microns. McLeod (1983) found Dursban 6 plus oil droplets ranging from "4,000-5,000 microns". Groselle (1984) found droplets just prior to entering the sprinkler nozzle in the range of 10-340 microns. Injection systems are probably unique to each and every irrigation system. The relative velocity between the two fluids at the injection point would definitely be system specific and would also depend on injection nozzle orientation and the point of injection in the cross sectional area. The injection velocity is generally a pulsating velocity caused by the injection pump as described in section 2.3. This is another variable which is system specific.

2.9.1.2 Stable Droplet Size

The droplet distribution that is created at the

injection point is dispersed in the flowing irrigation water. As the droplets travel downstream with the irrigation water, they are subjected to shear forces. A natural inclination would be to relate the shear force magnitude to the turbulence magnitude. Many investigators have looked at droplet breakup in turbulent fields, and the one common cause of breakup found in most reports is elongation deformation. Elongation deformation is caused by a velocity gradient in which one side of a droplet is subjected to a higher fluid velocity field. This would tend to stretch and elongate the droplet. If the stretching force exceeds the surface tension of the droplet, the droplet will breakup. In the case of pipe flow, the greatest velocity gradient is near the pipe wall. Collins and Knudsen (1970) observed that the droplet breakup was near the pipe wall.

The resistance of the droplet to being divided is a function of the chemical physical properties and the droplet's physical size. The magnitude of the shear force is a function of the irrigation physical and hydraulic properties. The relative position of the droplet in the pipe and the droplet size determine the amount of the shear force. As droplet size decreases for a given chemical and given flow conditions, the droplet is more stable. If an unstable droplet is in residence in given flow conditions long enough, it will be broken down into stable droplets. Sleicher (1962) investigated the maximum stable drop size

than can exist in the turbulent pipe flow of two immiscible liquids. Sleicher measured the Reynolds number that left 80% of a group of equal diameter droplets intact. He called this the maximum stable droplet size for the given Reynolds number. From his experiments, Sleicher developed Equation 2.13 to determine the maximum stable droplet size.

$$D_{\max} \rho_c U^2 / \sqrt{\mu_c U / \sigma} = 38(1 + 0.7(\mu_d U / \sigma)^{0.7}) \quad (2.13)$$

Where: $D_{\max}$ = Maximum stable droplet diameter (cm)
 μ_c = Fluid viscosity (g/cm sec)
 μ_d = Particle viscosity (g/cm sec)
 U = Mean pipe flow velocity (cm/sec)
 σ = Interfacial tension (dynes/cm)
 ρ_c = Continuous phase density (g/cm³)

Sleicher found the equation to correlate all of his experimental data within 35%

Collins and Knudsen (1970) continued the investigation of drop-size distributions in turbulent flows by developing a mathematical model to describe the process. The model showed that the breakup process produces two daughter drops of approximately equal volume and one very small satellite droplet. The existence of a maximum stable droplet size is evident from the comparison of model results and experimental data. They also found breakup to be in the neighborhood of the pipe wall. The model is stochastic, so a probability of breakup is needed for every droplet size and for every contact near the pipe wall. This breakup probability function is system dependent. Another unknown is the relationship between daughter and satellite droplet sizes.

Karabelas (1978) used a Rosin-Rammler, or upper limit

log probability type of distribution function, to predict a D_{p95} droplet size. D_{p95} stands for the droplet size at which 95% of the material is contained in droplets of this size or less. Karabelas also re-examined the data of Collins and Knudsen (1970) using the distribution function. The prediction equation developed from the distribution function is:

$$D_{p95}/D = 4.0(D\rho_c U^2/\sigma)^{-0.6} \quad (2.14)$$

Where: D_{p95} = Particle diameter corresponding to 95% volume (cm)

D = Inside pipe diameter (cm)
 ρ_c = Continuous phase density (g/cm³)
 U = Mean pipe flow velocity (cm/sec)
 σ = Interfacial tension (dyne/cm)

Karabelas found that the droplet data did indeed fit a Rosin-Rammler type of equation and found the equation to fit his and Collins and Knudsen's data adequately.

2.9.1.3 Sprinkler Nozzle Breakup

The last region for droplet breakup is through the sprinkler nozzle. The nozzle can be considered as a very small tube or pipe. Thus, the previous section's discussion is valid for the breakup in the sprinkler nozzle. The major difference is the magnitude of the shear in the nozzle. Typically the velocity in the sprinkler nozzle may be 10 times greater than in the irrigation pipe. Groselle et al. (1984) has shown the sprinkler nozzle to be highly significant in the droplet breakup process. Young (1985) indicated that the magnitude of the shear force is also a function of the nozzle type. Percy and Sleicher (1983)

found significant droplet breakup for the flow of immiscible liquids through an orifice in a pipe.

Some breakup may occur as the fluids are ejected from the sprinkler nozzle into the air. Particle breakup in this region will not be addressed further in this discussion.

2.9.2 Droplet Coalescence

Coalescence is an important consideration when modeling the transport of droplets since droplet size affects the transport theory. If two droplets combine or coalesce the resultant size will be increased. Sleicher (1962) states that coalescence rates are negligible if the dispersed phase is less than 0.5 percent of the total volume of the two phase volumes. Chemigation-dispersed phases are generally much less than 0.5 percent.

2.9.3 Sampling Techniques

The selection of a method for sampling or determining a droplet distribution is determined by the droplet size range and the system's physical parameters. Figure 2.4 is taken from Soo (1967) and relates particle sizes to other physical parameters. The appropriate method of measurement is also influenced by the particle size or range of particle sizes. Measurement of liquid droplets generally will require an optical photographic recording method, followed by measurement and recording. The photographic technique may be a photo microscope or a high speed camera. One major

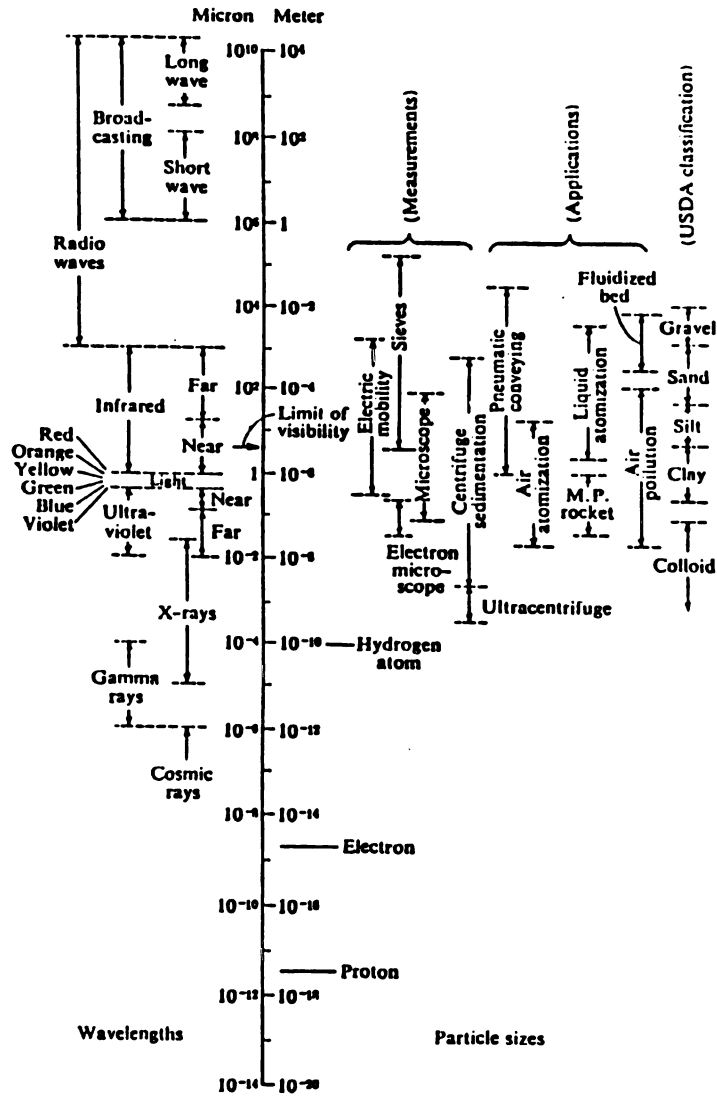


FIGURE 2.4 PARTICLE SIZES IN RELATION TO OTHER PHYSICAL QUANTITIES (After Soo, 1967)

difficulty of photographic techniques for large droplet size ranges is the focal length. If the droplet range is large, only part of the distribution will be in focus. Another problem with larger droplet sizes is the droplet distortion and the interpretation of an effective diameter. In situ photo techniques of the droplets in the flow were used by Sleicher (1962), Collins and Knudsen (1970) and McLeod (1983). Groselle et al. (1984) and Cochran et al. (1984) sampled from the line and photographed externally. A sampling device used for sampling internally within the cross sectional pipe area is described by Karabelas (1977). Other techniques include the use of laser systems, as described by Hewitt et al. (1982). Laser measurement is non-intrusive, but the instrumentation is very complex. The lower limit for laser measurement is approximately 1 micron. A laser will generally measure a distribution range of two decades (5 to 500 microns, for example).

2.10 Modeling Two Phase Flow Systems

Modeling and the dynamic study of two phase systems is generally performed by either of two methods, as described by Soo (1967):

- "1. Treating the dynamics of single particles and then trying to extend to a multiple particle system in an analogous manner as in molecular (kinetic) theory.
2. Modifying the continuum mechanics of single-phase fluids in such a way as to account for the presence of particles."

Durst et al. (1984) made the following observation regarding two methods for modeling:

"To predict particulate two-phase flows, two approaches are possible. One treats the fluid phase as a continuum and the particulate second phase as single particles. This approach, which predicts the particle trajectories in the fluid phase as a result of forces acting on particles, is called the Lagrangian approach. Treating the solid as some kind of continuum, and solving the appropriate continuum equations for the fluid and particle phases, is referred to as the Eulerian approach."

The Lagrangian approach seems to be the logical selection in attempting to model a chemigation system since the particle position is important and the dispersed phase is dilute. This method determines the velocities and trajectories of particles by numerical solution. In modeling a chemigation system, the ultimate objective is to determine the physical location of the droplet as it passes by an outlet to a sprinkler. The physical location of the droplet with respect to each sprinkler outlet determines at which sprinkler the droplet will be discharged.

3.0 OBJECTIVE

The objective of this research was:

To develop a mathematical computer model to describe the horizontal and vertical transport of an immiscible rigid spherical particle or droplet while in residence in an irrigation system pipeline complete with discharging sprinklers.

Specific sub-objectives for the simulation model were:

- 1) to determine the effect of droplet size on the distribution of the chemical to the sprinklers
- 2) to determine the effect of relative density on the distribution of the chemical to the sprinklers.
- 3) to determine the effect of turbulence on the distribution of the chemical to the sprinklers.
- 4) to determine the effect of the sprinklers on the distribution of the chemical.

4.0 Field Data for Model Justification

4.1 Engineering Studies Using Chlorpyrifos

In October of 1984, a full scale linear move irrigation system (Valley Rainger, Model 9770) was used to conduct a study similar to that of Groselle et al. (1984). The system was 393.7 m (1292 ft) long with an inside pipe diameter of 16.27 cm (6 5/8 in). The objective of this field study was to collect external samples and determine the uniformity of the chemical along the length of the machine. The mean pipe flow velocity and Reynolds numbers for this system are as shown for the linear move system plotted in Figures 2.1 and 2.2, respectively.

The technique used for chemical distribution determination was the same photographic droplet counting and measurement technique as was used by Groselle et al. (1984) and Cochran et al. (1984). The same non-emulsified chemical formulation with oil was used (Dursban* 6 insecticide + salad grade soybean oil mixed 1:2 by volume) at the same application rate (560 g/ha of chlorpyrifos). System output was caught in glass containers precharged with 100 cc of water. The theory for the counting and measurement technique is that the chemical/oil droplets slowly settle to

* Trademark of the Dow Chemical Company, Midland, MI.

the bottom of the container since they have a specific gravity approximately equal to pure water, but slightly higher than chlorinated water (Groselle et al., 1984). Cochran et al. (1984) found the formulation to be denser than water at temperatures less than 21 degrees C. Once settled, the droplets were photographed with a photo microscope.

Figure 4.1 is a plot of the water distribution versus horizontal position in pipe diameters for the linear system used. The water application coefficient of uniformity using Christiansen's uniformity coefficient equation (Equation 4.1) was 93.1%. A uniformity coefficient of 85 percent is considered acceptable..

$$CU = ((AVG-AVGDEV)/AVG)100 \quad (4.1)$$

Where: CU = Christiansen coefficient of uniformity
 AVG = Average depth caught
 AVGDEV = Average deviation from average

The chemical was injected into the system at a mean injection rate of 253 ml/min (4 gph) with a diaphragm injection pump (Milton Roy Frame A 20 gph Model# FR131-117). The injection port was a 0.635 cm (1/4 in) diameter stainless steel tube positioned in the center of the pipe in a downstream configuration, as shown by Groselle (1984).

The irrigation system traversed over the catch containers at 2.7 m/min (8.85 ft/min) applying 0.297 cm (0.12 in) of water. The water temperature was approximately 11 degrees C. Samples were collected every 9.14 m (30 ft) along the length of the system in 10 cm diameter, 4 cm tall,

300 ml culture dishes. The dishes were placed on 0.914 m (3 ft) high stands and initially contained 100 ml of distilled water. The water helped prevent the droplets from plating out on the glass surfaces. The water application rate used added an average additional 16.9 ml of water-chemical mixture to the sample collection containers. The dishes had a reduced diameter top ring of 85 mm approximately 1 cm in height. This ring helped prevent splash-out and provided for tight fitting lids for transporting the samples out of the field. The samples were manually transported from the sampling sites to a microscope set up in the field. Oil-Red-O dye was added to the oil-chlorpyrifos mixture at 0.1% by volume prior to injection. The dyed chemical droplets in the catch container were photographed. The droplets were counted and their diameters measured from the slides.

The droplet size range and mean for each container vs distance are shown in Figure 4.2. The mean diameter for all 524 droplets counted was 20.7 microns; the droplet diameter for a droplet of mean volume was 28.7 microns. These values compare to droplet sizes for the same material by Groselle et al. (1984) of 15.1 microns for the mean droplet diameter and 24.9 microns for the mean volume droplet diameter, using a 400 pulse/min injection pump. However, Groselle's means are samples taken from the discharge of one sprinkler with a round nozzle area of 0.079 cm^2 (0.012 in^2). The sprinklers on the linear system were control droplet sprinklers with nozzle areas of approximately 0.70 cm^2 (0.11 in^2). The

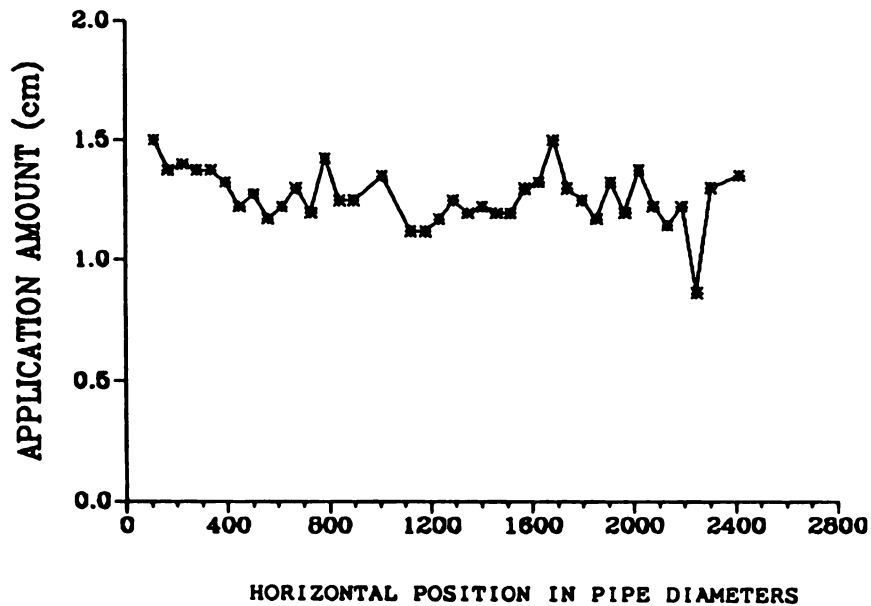


FIGURE 4.1 WATER DISTRIBUTION VS. POSITION ALONG SYSTEM LENGTH (KBS LINEAR, REESE, 1984)

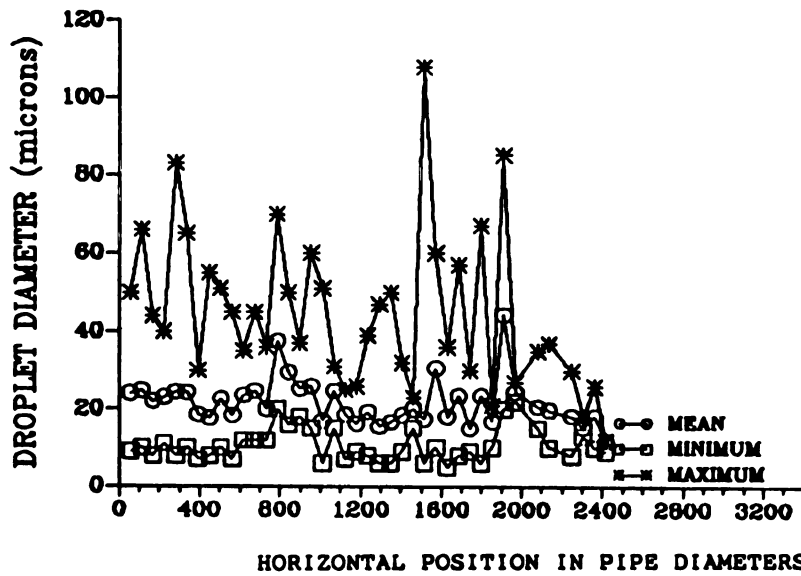


FIGURE 4.2 DROPLET DIAMETER MAXIMUM, MINIMUM, AND MEAN VS. POSITION ALONG SYSTEM LENGTH (KBS LINEAR, REESE, 1984)

injection pump used in the study had a 117 pulse/min injection frequency.

The volume of the individual droplets photographed in each container was calculated and summed. This value was then compared to the amount of chemical that should have been collected for that given area using the rate of injection and the speed of travel. The amount of chemical caught in containers was compared to the expected chemical amount to produce complete chemical recovery. Figure 4.3 is a plot of the chemical recovery versus distance. Due to the low chemical recovery as indicated by the caught and measured droplets, and without analytical chemical analysis as an indication of chemical recovery, this field sampling droplet data presents some questions. The mean chemical recovery for all containers was 31.2%. However, the slides were generally taken in the areas of densest droplet frequency; thus, this percentage is biased high. The Christiansen coefficient of uniformity for the chemical volume recovered was 20.6%. The number of droplets recovered and counted in this experiment were not consistent with the findings of Groselle et al.'s model experiment. However, Groselle et al. did not report a chemical mass balance for their experiments. The chemical recovery suggests that the chemical may not have been delivered to the sprinklers, but rather collected in the end of the machine, possibly because of the internal chemical droplet size and the chemical density. Without a chemical analysis

of samples, the sampling technique would not allow one to make a firm conclusion for this hypothesis, and no analysis was made of the chemical possibly remaining in the irrigation machine pipeline at the end of the test.

In November 1985, further research was conducted with the assistance of Dow Chemical Company Personnel using a center pivot (Lockwood, Model 2286), but using direct chemical concentration analysis and internal sampling to detect concentration gradients. Tests were conducted using the emulsified product, Lorsban* 4E insecticide, plus soybean oil and the non-emulsified product, Dursban 6, plus soybean oil. The chemical application rates were the same as were attempted in the 1984 study.

The uniformity of water application for the pivot was checked and a uniformity coefficient of 88 percent was found. Figure 4.4 is a plot of the water distribution versus distance for the center pivot used. The major uniformity problem observed was the higher application near the end of the system caused by the end gun, which is common to many pivots.

Sampling ports and an injection port were fabricated from 3/8 inch OD by 20 ga stainless steel tubing. A Spraying Systems nozzle assembly was attached to the end of the injection tube to facilitate nozzle selections. The injection nozzle used in the test was a flat fan nozzle tip drilled out to a 0.635 cm (1/4 in) inside diameter. The injection port was placed in the center of the pipe with the

* Trademark of Dow Chemical Co. Midland, MI.

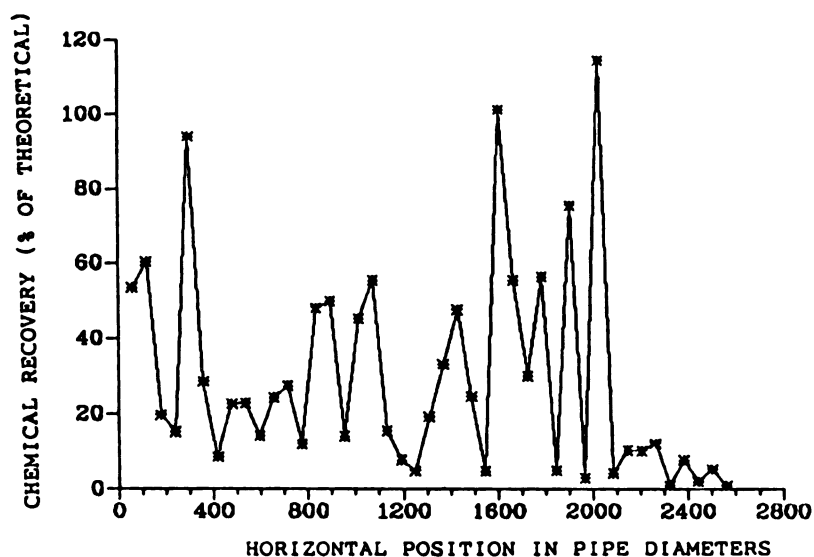


FIGURE 4.3 CHEMICAL RECOVERY PERCENTAGE VS. POSITION ALONG SYSTEM LENGTH (KBS LINEAR, REESE, 1984)

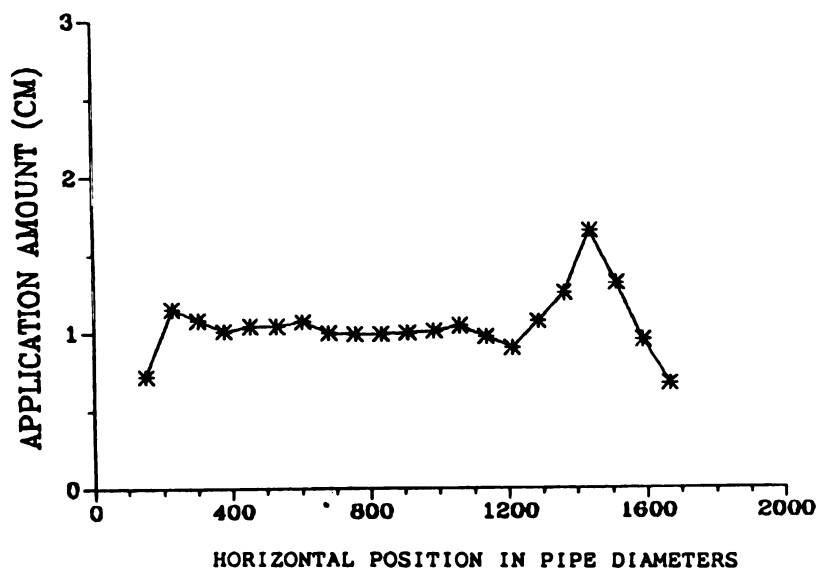


FIGURE 4.4 WATER DISTRIBUTION VS. POSITION ALONG SYSTEM LENGTH (RICE PIVOT, REESE, 1985)

outlet end facing downstream.

L-shaped sampling ports were inserted at two locations along the pipeline, 55 and 962 pipe diameters from the point of injection. The sampling ports were adjustable in the vertical plane to allow for sampling across the pipe's cross section. The pivot pipeline had an inside diameter of 12 cm (4 3/4 in), and the inside diameter of the sampling tube was 0.775 cm (.305 in). Five vertical positions were sampled. Vertical position 3 was the center line of the pipe. Vertical position 2 was 2.54 cm (1 in) above the center line and position 4 was 2.54 cm (1 in) below. Vertical position 1 was 5.08 cm (2 in) above the center line, and vertical position 5 was 5.08 cm (2 in) below the center line. A third sampling site was located near the end tower or 1,568 pipe diameters from the injection point. This sample collection was not from an inserted sampling tube, but rather only from a sprinkler mounting coupler at the top of the pipe. A sample was collected at site 3 only when vertical position 1 samples were being collected at horizontal sites 1 and 2.

Procedures for sample collection conformed to a protocol developed in cooperation with The Dow Chemical Co. Samples were taken in a random, complete block with respect to time for three replications of both Lorsban 4E plus soybean oil and Dursban 6 plus soybean oil both mixed in a 1:2 ratio. Both formulations were injected at a rate of 560 g/ha (1/2 lb/ac) of chlorpyrifos. Samples were collected in clean bottles and capped immediately to avoid

contamination since the chemical concentration was only expected to be approximately 15 ppm. The samples were put on ice and taken to Dow Chemical Co. Product Department Analytical labs in Midland, MI for chemical analysis. Samples were analyzed according to a standard analytical technique for chlorpyrifos (McLeod, 1983). The concentrations were found to be much lower than were expected based on the injection rate. A second laboratory procedure was used in which the sample bottles received an additional solvent rinse, and this rinse solution was added to the initial sample. These concentrations were found to be in the range of the calculated value to be expected. This result indicated that the chemical was sticking to the glass container. This could also be a partial explanation for the low chemical recovery for the 1984 experiment where the chemical may have plated out and adhered to the glass sample collection containers.

For a complete test, thirty-three samples should have been collected with fifteen samples each from horizontal locations 1 and 2, and three samples from horizontal location 3. Multiple sample losses were incurred in the field and in a laboratory refrigerator malfunction prior to the second analysis. Twenty-six Dursban 6 samples were analyzed resulting in a mean concentration of 16.67 ppm and a standard deviation of 7.12 ppm. Thirty-two Lorsban 4E samples were analyzed for a mean concentration of 14.97 ppm and a standard deviation of 6.34 ppm. The Lorsban showed

slightly less variation, as would be expected for the emulsified formulation.

Statistical comparison of the concentrations across the cross sectional area was not possible because of sample losses, but the trend for the non-emulsified formulation (Dursban 6) seemed to indicate a concentration gradient, especially at horizontal sampling location 1, as shown in Figure 4.5. The trend at horizontal location 1 was for a higher concentration towards the top of the pipe. At horizontal location 2, the highest concentration was in the center of the pipe, indicating settling. Again, these results are only speculative since missing data is involved.

The concentration gradient for the emulsified formulation (Lorsban 4E) showed the same type of trend with higher concentrations in the top of the pipe at horizontal sampling location 1, as shown in Figure 4.6. The highest concentration is at the center of the pipe at horizontal position 2, but the variation across the pipe seems to be less compared to the variation of the Dursban 6 gradient at horizontal location 2.

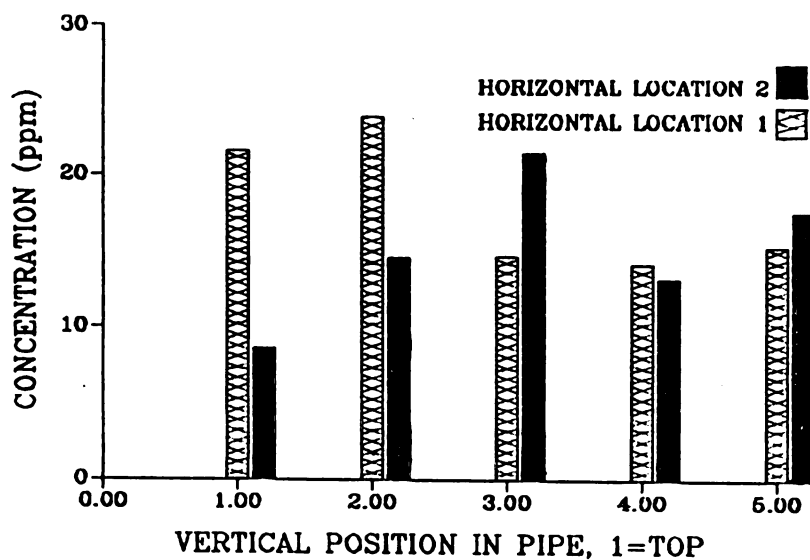


FIGURE 4.5 DURSBAN 6 MEAN CONCENTRATION PROFILE, MEAN OF 3 REPLICATIONS (RICE PIVOT, REESE, 1985)

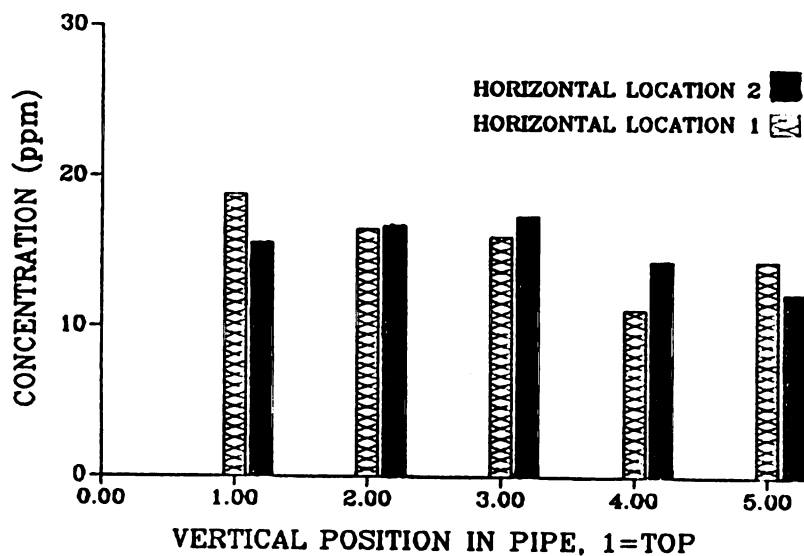


FIGURE 4.6 LORSBAN 4E MEAN CONCENTRATION PROFILE, MEAN OF 3 REPLICATIONS (RICE PIVOT, REESE, 1985)

5.0 MODEL DESCRIPTION

5.1 Introduction

The decision to develop a model was based primarily on the lack of explanation for some chemigation chemical output results derived only from field data. The model developed traces the horizontal and vertical path of a spherical particle of constant shape and size in the irrigation line. Since the model has been developed for both liquid and solid dispersed phases, the terms "droplet" and "particle" will be used interchangeably in the model description. Theory and plausible assumptions are the foundation for the model. Literature was searched for closely related topics, but literature was not found for all areas related to this study. The initial development of a model required several simplifying assumptions. The trends from McLeod (1983) were used for the initial testing of the model.

The droplet distribution introduced or created at the injection point is an input into the model. If working with liquid-liquid dispersions, it is assumed that the droplet distribution is stable and is not broken up by the turbulence or velocity gradients. Liquid droplets are also assumed to be spherical regardless of size. The last two assumptions may be disputed but are needed for

simplification of the initial model. The effect of the sprinkler nozzle on the droplet or particle distribution outside the machine is not addressed.

This model is only a transport and distribution model describing the delivery of the dispersed phase to the sprinklers. The method selected for modeling the two phase system is to treat the irrigation water as the continuum similar to the Lagrangian approach described by Durst et al. (1984). The dispersed phase is transported within the continuous phase with the assumption that the relative velocity between the two phases is zero or that no slip occurs between the phases. This assumption does not hold true when the particle encounters an eddy which produces internal relative motion within the continuous phase. Momentum transfer from the dispersed phase to the continuous phase is neglected due to the small fraction of the dispersed phase compared to the continuous phase. Heat transfer between phases is not accounted for. It is assumed that mass transfer between phases is insignificant.

The model takes into account the physical properties of the chemical and the hydraulic properties of the fluid surrounding the particle or droplet. The physical model has been simplified to a two dimensional model instead of a three-dimensional one. The physical model describes the flow along the vertical plane through a major vertical diameter. It thus becomes like the flow between two parallel plates, but the symmetry of pipe flow allows for

the use of pipe flow equations in two dimensions. The horizontal and vertical position of the droplet in relation to a sprinkler determines the fate of the droplet, whether discharged at the sprinkler outlet or not. Individual droplet or particle paths are traced until it is either discharged through a sprinkler or until it reaches the end of the pipe. The distribution of individual droplets from a sprinkler is recorded as an output file for a given droplet distribution input file.

The horizontal and vertical positions of a droplet or particle in a pipeline at any point in time are a function of residence time, horizontal pipe flow velocity, settling velocity, turbulence and sprinkler effect. Time enters the process in time steps, velocity calculations and distance calculations. The exact chronological time at which a droplet or particle is discharged is not considered important and is not recorded.

5.2 Irrigation System Geometry and Hydraulics

An irrigation line consists of a pipe with sprinklers attached at specified distances to simulate either a single lateral, a center pivot or a linear move machine. This section will describe the mechanics and geometry of an irrigation line and the relationship to the model. Figure 5.1 is a cross section for the major vertical axis of a partial irrigation line and will be used for the entire discussion in this section. The irrigation pumping system

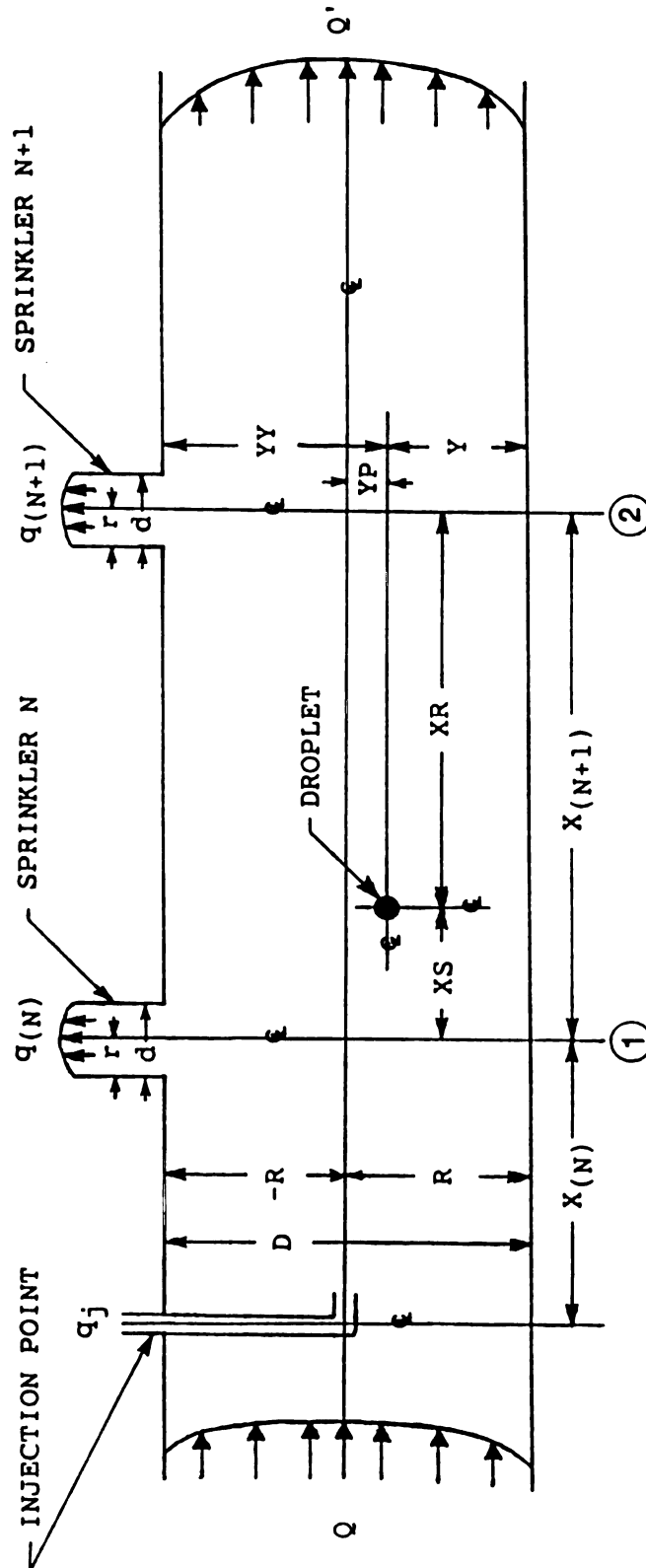


FIGURE 5.1 PIPE CROSS SECTION DIAGRAM ACROSS MAJOR VERTICAL AXIS

is designed to deliver the total cumulative water volume required by all the sprinklers. For any irrigation system, a known flow volume (Q) enters the pipe. The irrigation line is assumed circular with a given inside radius (R). Using Equation 2.1, the calculated pipe area and Q, a mean pipe flow velocity is derived.

$$U = Q/A \quad (2.1)$$

Where: U = Mean pipe flow velocity (cm/sec)
 Q = Pipe flow rate (cm³/sec)
 A = Cross sectional area of pipe (cm²)

However, a pipe flow velocity profile is developed as shown in Figure 5.1 due to frictional effects. The horizontal flow velocity at any point in the pipe cross section can be calculated using Equation 2.5.

$$u_y = u^*(2.5 \ln(y/R) + 3.75 + (U/u^*)) \quad (2.5)$$

Where: u_y = Velocity at distance y from pipe wall (cm/sec)
 y = Distance from pipe wall (cm)
 R = Radius of pipe (cm)
 U = Mean pipe flow velocity (cm/sec)
 u^* = Friction velocity (cm/sec)

The velocity profile is symmetrical around the center line of the pipe; therefore, the center line of the pipe was designated as position 0 and the pipe walls are at a distance R and -R from the center line. The top pipe wall is -R from the center line, and the bottom wall is +R from the center line. This identification method was selected in order to use symmetry in the flow calculations and to identify which side of the center line the particle is on.

The distance between sprinklers (variable array X) and the discharge from each sprinkler (variable array q) is an

input into the model, either as a data statement or as a data file. The distance between sprinklers is from center line to center line and equal to the sum of variables XS and XR. As flow passes by a sprinkler (N), a given amount of flow $q_{(N)}$ is discharged, thus changing the Q in the pipe. The change in the pipe Q results in new hydraulic properties in the pipe based on the new Q. It is assumed that the transition of flow characteristics due to the change in Q occurs at the center line of the sprinkler. From Figure 5.1, flow characteristics change at position (1) and (2). For example, the flow used for calculation prior to reaching position (1) is Q while the flow used for calculations between positions (1) and (2) is $Q - q_{(N)}$ or the total flow entering minus the flow discharged by sprinkler N. The flow used for calculations past position (2) is $Q - (q_{(N)} + q_{(N+1)})$ or the total flow minus the flow of sprinklers N and N+1.

The vertical position of the droplet or particle (variable YP) at any point in time is measured from the pipe centerline. YP is either negative or positive to indicate which side of the center line the droplet resides on. The vertical position of the droplet or particle is also related to the sprinkler by variable YY. The sprinkler can be located either on the top or bottom of the pipe. YY is 0 at the sprinkler regardless of whether the sprinkler is on the top or bottom of the pipe. YY is always positive and can have a maximum value equal to the inside pipe diameter (D). The horizontal position of a particle or droplet is related

to the distance past a sprinkler (XS) and/or the distance to the next sprinkler (XR). These distances are also used to determine when the sprinkler effect on the droplet or particle begins and ends, as will be discussed in section 5.3.

5.3 Sprinkler Effect Geometry

The sprinkler effect on the vertical position of a droplet or particle is a complex and vague subject. The magnitude and chaotic nature of the turbulence near the irrigation sprinkler compounds the problem. No literature was found to directly address this scenario. A major simplifying approach is to use the continuity or conservation of mass equation, Equation 2.1. Assuming that the droplet moves with the water, the lift on the particle or droplet is a function of the sprinkler discharge, the relative vertical and horizontal position of the particle from the sprinkler and the amount of time that the particle is under the lifting influence of the sprinkler. The amount of time that the sprinkler has an effect on the particle is a function of the horizontal flow velocity. The droplet or particle is discharged through the sprinkler if it is lifted to a specified distance from the sprinkler and is at a horizontal position within the bounds of the sprinkler outlet diameter.

Figure 5.2 has been drawn to help explain the logic. Each sprinkler (N) has a discharge flow rate of $q_{(N)}$ at a

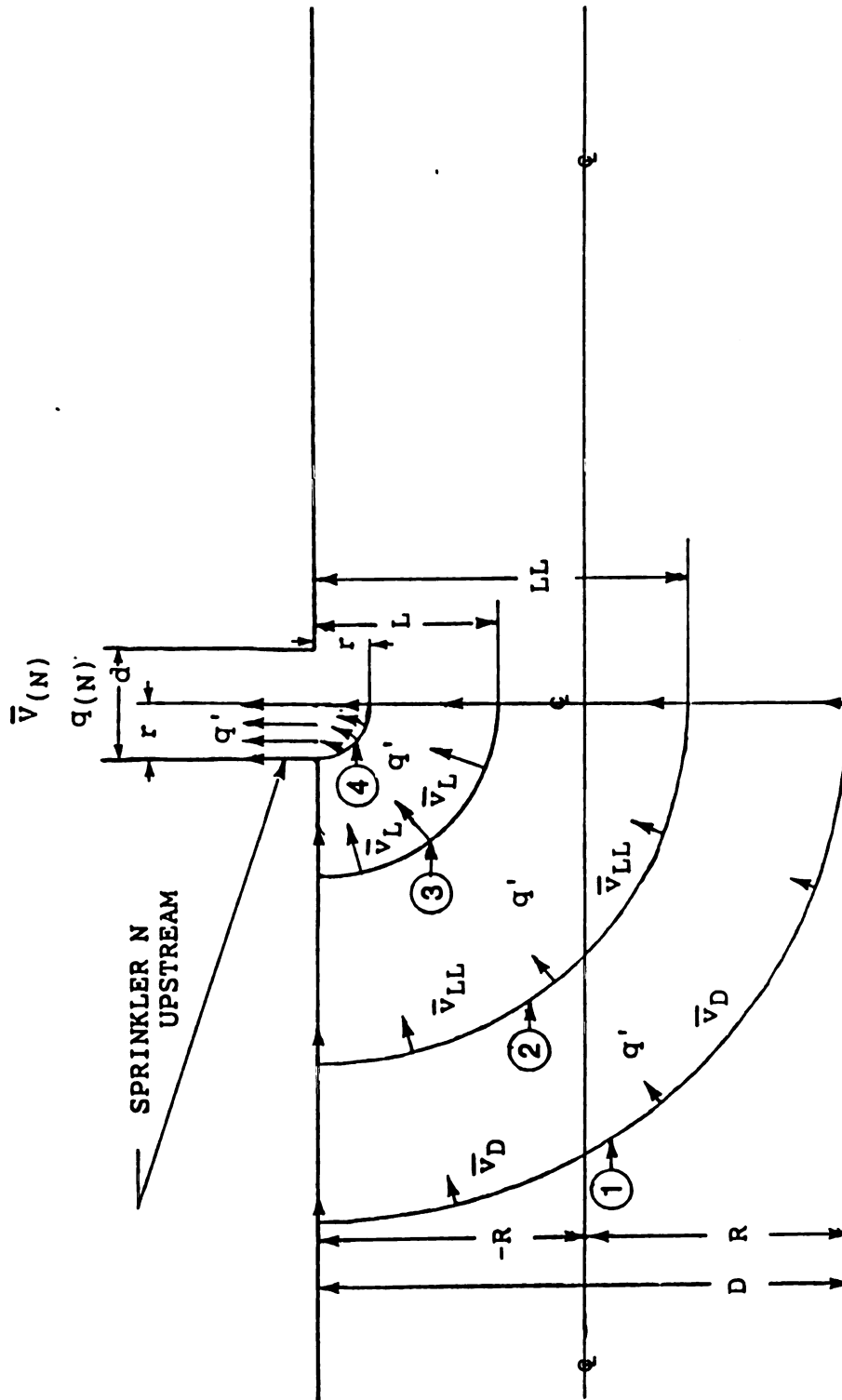


FIGURE 5.2 SPRINKLER EFFECT DIAGRAM FOR UPSTREAM SIDE OF SPRINKLER. ① CRITICAL RADIUS FOR CALLING SPRINKLER SUBROUTINE. ② MINIMUM VELOCITY RADIUS FOR CONSIDERING SPRINKLER EFFECT. ③ RADIUS WHERE DROPLET RESIDES. ④ CRITICAL RADIUS WHICH BOUNDS THE DISCHARGE REGION.

mean velocity of $\bar{V}_{(N)}$. The sprinkler effect thus is a function of the velocity of the water toward the nozzle. As the water comes closer to the sprinkler inlet, the average velocity increases to a maximum equal to the average velocity $\bar{V}_{(N)}$ in the sprinkler inlet .

For calculating the average velocity $\bar{V}_{(N)}$ out the sprinkler, it is of benefit to have a common dimension for all the sprinklers. If all the sprinklers on the line are of common make and model, the inlet into the sprinkler body may be of common size. Each sprinkler on an irrigation line is attached to the line by a coupler which is generally a pipe coupler welded on top of a hole cut in the irrigation pipeline. It may be assumed that the inside dimension of the couplers are equal in size. It is also assumed that the coupler or sprinkler inlet is smooth and flush with the inside pipe wall. The model needs an input of a common sprinkler dimension to calculate the average velocity of the discharging flow. If we use the radius of the coupler as (r) , the average velocity ($\bar{V}_{(N)}$) with a given $q_{(N)}$ is:

$$\bar{V}_{(N)} = q_{(N)} / \pi r^2 \quad (5.1)$$

The sprinkler effect is now subdivided into an upstream side and a downstream side, with the sprinkler center line being the dividing line. The sprinkler effect is symmetrical about the sprinkler center line, but the pipe flow characteristics are changed at the center line. Figure 5.2 shows only the upstream effect since the downstream effect is symmetrical. To determine the sprinkler effect for the

two dimensional model, only the flow discharged from an area of unit thickness at the major vertical axis is considered. Using the average velocity calculated in Equation 5.1, we can determine the flow (q') for a narrow area of the inlet that is (r) long and unit thickness Δz wide in Equation 5.2.

$$q' = \bar{V}_{(N)} r \Delta z \quad (5.2)$$

Now we hypothesize that the flow q' toward the small area passes through successive cylindrical shapes in two dimensional analysis. We again assume continuity that the flow q' into the inlet from between the two parallel plates, representing the top and bottom of the pipe, is based upon an average velocity multiplied by an area. The cylindrical shaped surfaces are scribed by a radius measured from the point on the sprinkler center line flush with the pipe wall. Since we are concerned with only one side of the sprinkler, the cylindrical shape is based on 1/4 of the circumference of the cylinder. For the radius r and the same q' and unit thickness Δz , the average velocity through the cylindrical surface due to the sprinkler effect is given by Equation 5.3. This circular surface is indicated by (4) in Figure 5.2.

$$\bar{V}_r = q' / (\pi r \Delta z / 2) \quad (5.3)$$

As the radius increases, the surface area increases and the average velocity of flow toward the sprinkler inlet decreases; therefore, when a particle is further away from the sprinkler, the sprinkler effect decreases. For any radius (L), we substitute L for r in Equation 5.3 and combine with Equation 5.2 to produce Equation 5.4 for the

average velocity ($\bar{v}_L$) through the cylindrical surface at any L. This cylindrical surface is indicated by (3) in Figure 5.2.

$$\bar{v}_L = 2\bar{v}_{(N)}r/\pi L \quad (5.4)$$

The unit thickness Δz is the same in Equations 5.2 and 5.3 thus Equation 5.4 is a relationship based on the two radii.

To model the sprinkler effect, an assumption must be made as to when, that is at what position in the pipe, to initiate and terminate the sprinkler effect. Each sprinkler on a center pivot generally has a different flow rate $q_{(N)}$. The different flow rates for each sprinkler also produce a different $\bar{v}_{(N)}$ and $\bar{v}_L$ for each sprinkler. It was, therefore, assumed that the sprinkler effect would be initiated at a common minimum sprinkler effect velocity for all sprinklers. The surface where the minimum velocity occurs is described by the radius LL and is indicated by (2) in Figure 5.2. For a center pivot, LL will increase for successive sprinklers up to a possible maximum equal to the pipe diameter D.

With the model, the sprinkler velocity effect is determined in a subroutine that is entered when the vertical and horizontal position of the droplet is within the bounds described by the circular surface at a radius of D, the sprinkler center line and the pipe wall on the sprinkler side. The circular surface at a radius of D is indicated by (1) in Figure 5.2. However, entry into the subroutine will only cause a sprinkler effect if the distance (L) to the droplet is less than the distance LL.

It is assumed that when a droplet is at a distance less than or equal to the radius of the outlet (r), the droplet is discharged by the sprinkler. Therefore, the surface indicated by ④ in Figure 5.2 is the bound for droplet discharge.

Figure 5.3 will be used to relate the sprinkler velocity effect to the droplet's vertical and horizontal position. As a droplet or particle approaches the sprinkler, it is at a known vertical distance (YY) and a known horizontal distance (XR) from the sprinkler. The center of the sprinkler outlet is a reference point and is defined by the point on the sprinkler center line that is flush with the inside pipe wall. The angle β between the center line of the sprinkler and the line between the center of the sprinkler outlet and the droplet is the arctan (XR/YY). This angle can then be used to calculate the distance (L) between the droplet and the center of the sprinkler outlet. L is then the radius for the cylindrical surface from which the average sprinkler velocity effect is calculated using the same q' calculated in Equation 5.2. The cylindrical surface described by L is indicated by ② in Figure 5.3. Since L in Figure 5.3 is less than LL the minimum velocity indicated by ① in Figure 5.3, a droplet on this surface is considered under the effect of the sprinkler pull.

The sprinkler effect is divided into time steps Δt . The time step selected for evaluation is based on the eddy

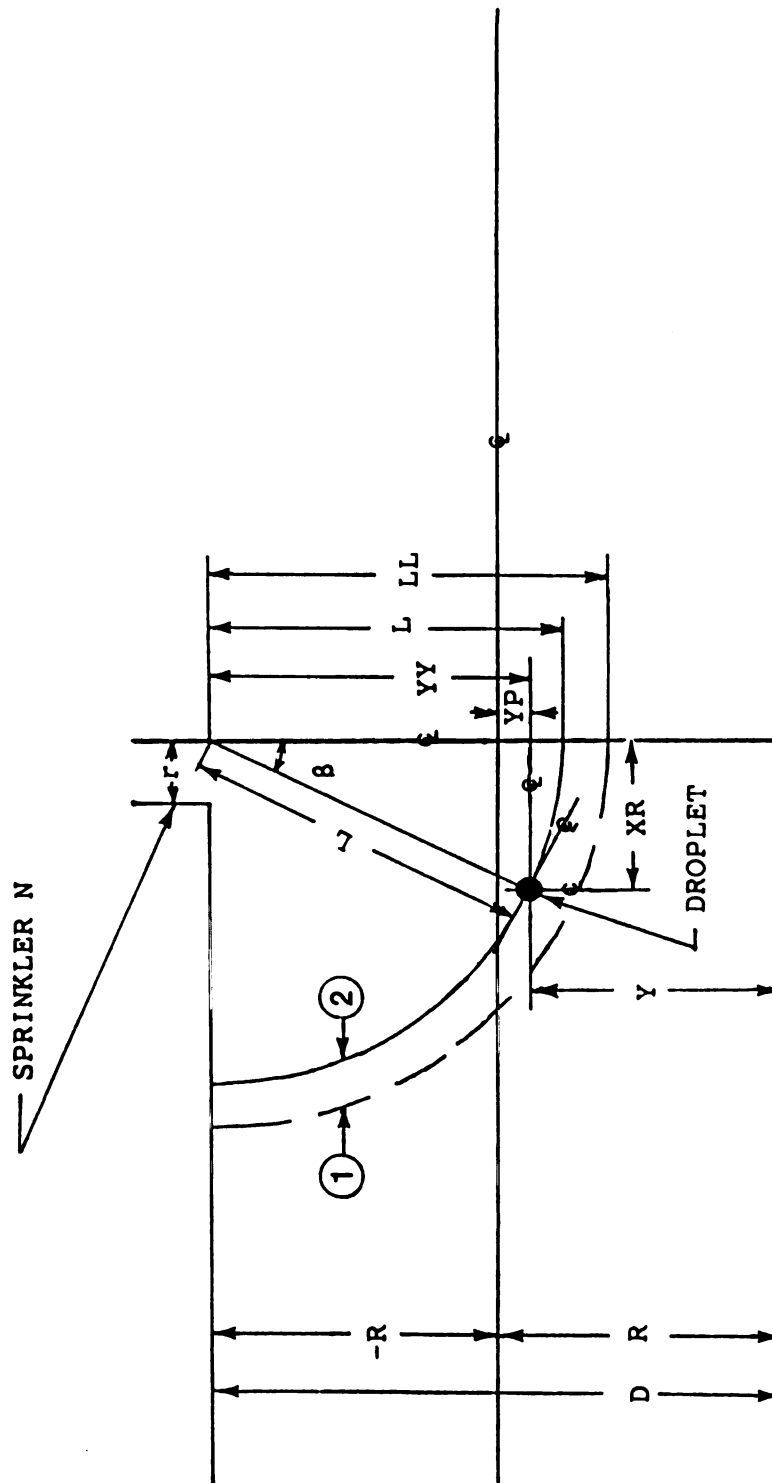


FIGURE 5.3 RELATIONSHIPS OF DROPLET HORIZONTAL AND VERTICAL POSITION TO SPRINKLER INLET. ① MINIMUM VELOCITY RADIUS FOR CONSIDERING SPRINKLER EFFECT, VELOCITY IS A CONSTANT FOR ALL SPRINKLERS. ② RADIUS WHERE DROPLET RESIDES.

length and eddy time which will be discussed in section 5.4.1 and 5.4.5. Figure 5.4 is a schematic of the sprinkler effect for one time step. Assume that a droplet is at a distance L away from the sprinkler inlet, as shown by position 1 in Figure 5.4. A sprinkler velocity effect is calculated for the time step which is the average flow velocity toward the sprinkler inlet from the circular surface at the radius L . The velocity is converted to a distance vector ϵ shown in Figure 5.4 by multiplying the average surface velocity, $\bar{v}_L$, by the time step Δt . ϵ is a resultant vector and must be broken into horizontal and vertical components by using the angle β . If β equals 90 degrees, the distance traveled is completely horizontal since the particle is traveling against the pipe wall. If β equals 0 degrees, the distance traveled is completely vertical towards the sprinkler inlet. The horizontal pipe flow displacement (x_2) in time Δt is added to sprinkler horizontal displacement (x_1) for the total horizontal displacement. The vertical eddy, or settling, displacement (y_2) is added to the sprinkler vertical displacement (y_1) for the total vertical displacement. When all the components have been summed for one time step, a new position is defined, as shown by position 2 in Figure 5.4. Position 2 is then used for the calculation of the next time step.

As explained in section 5.2 the pipe flow hydraulic characteristics change at the sprinkler center line. When a

droplet is on the upstream side of a nozzle and XR is less than or equal to 0.0, the center line has been passed, and the pipe flow hydraulic characteristics are changed. However, the sprinkler effect and discharge are not affected by this change. All calculations are identical on the downstream side due to symmetry, except the horizontal distance component produced by the sprinkler effect is in the opposite direction of the mass flow or negative. Figure 5.5 is a summary of the distance components for both upstream and downstream sprinkler effect. Again for downstream, if the droplet is at a distance L away from the sprinkler inlet which is greater than LL , then the sprinkler effect is terminated.

5.4 Model Assumptions and Flowcharts

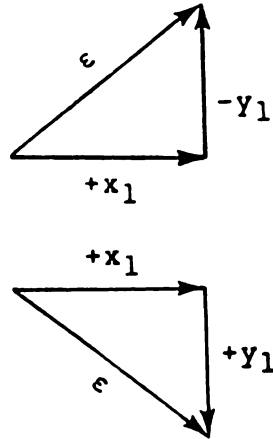
Flowcharts have been drafted for the main program and subroutines of the model. The flowcharts will be used in the following sections along with narrative to further explain the model logic and assumptions.

5.4.1 Program MAIN

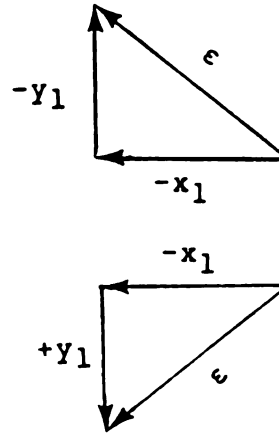
The program for the model has been divided into a main driver program and five subroutines. Figure 5.6 is a flowchart of the main program. A listing of the variables used in the program source code can be found in Appendix A. The program was designed as a user friendly interactive program with many of the input variables entered from the

SPRINKLER EFFECT WITH SPRINKLER ON TOP AND BOTTOM OF PIPE

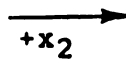
UPSTREAM EFFECT



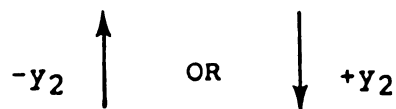
DOWNSTREAM EFFECT



HORIZONTAL PIPE FLOW EFFECT



VERTICAL SETTLING OR EDDY EFFECT



RESULTANT HORIZONTAL DISPLACEMENT = $x_2 \pm x_1$

RESULTANT VERTICAL DISPLACEMENT = $\pm y_2 \pm y_1$

FIGURE 5.5 SUMMARY OF DISPLACEMENTS AND CONDITIONS FOR ONE TIME STEP WHEN UNDER THE EFFECT OF THE SPRINKLER.

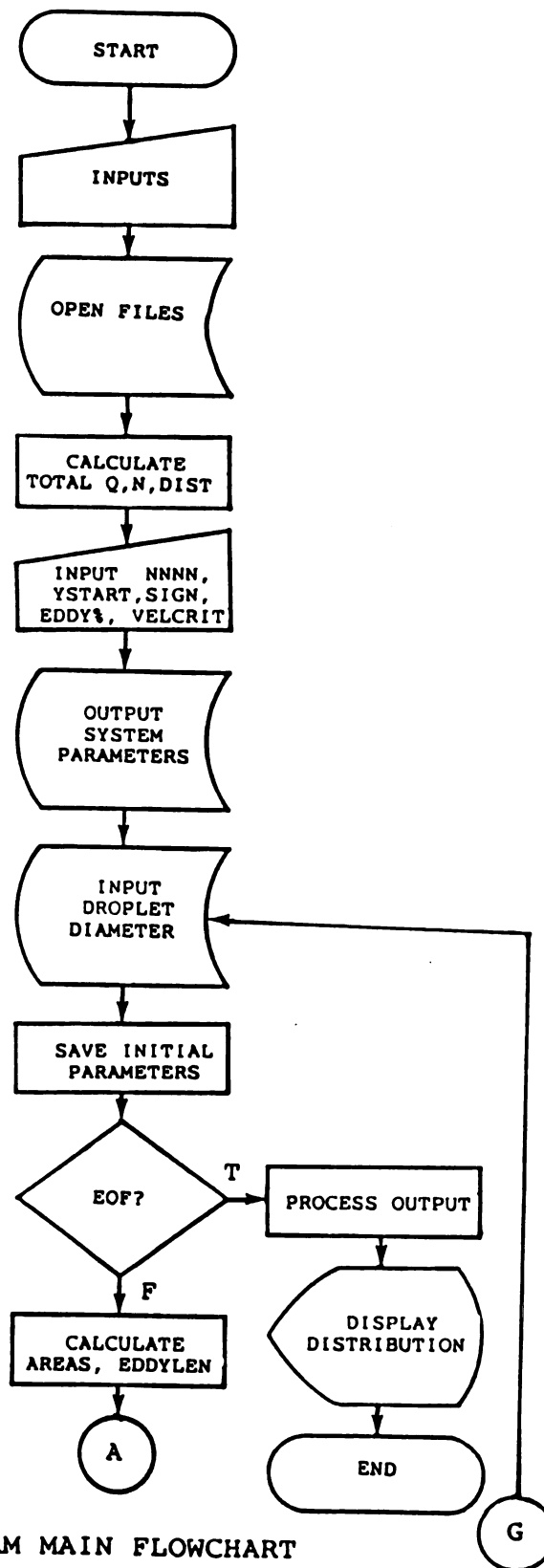


FIGURE 5.6 PROGRAM MAIN FLOWCHART

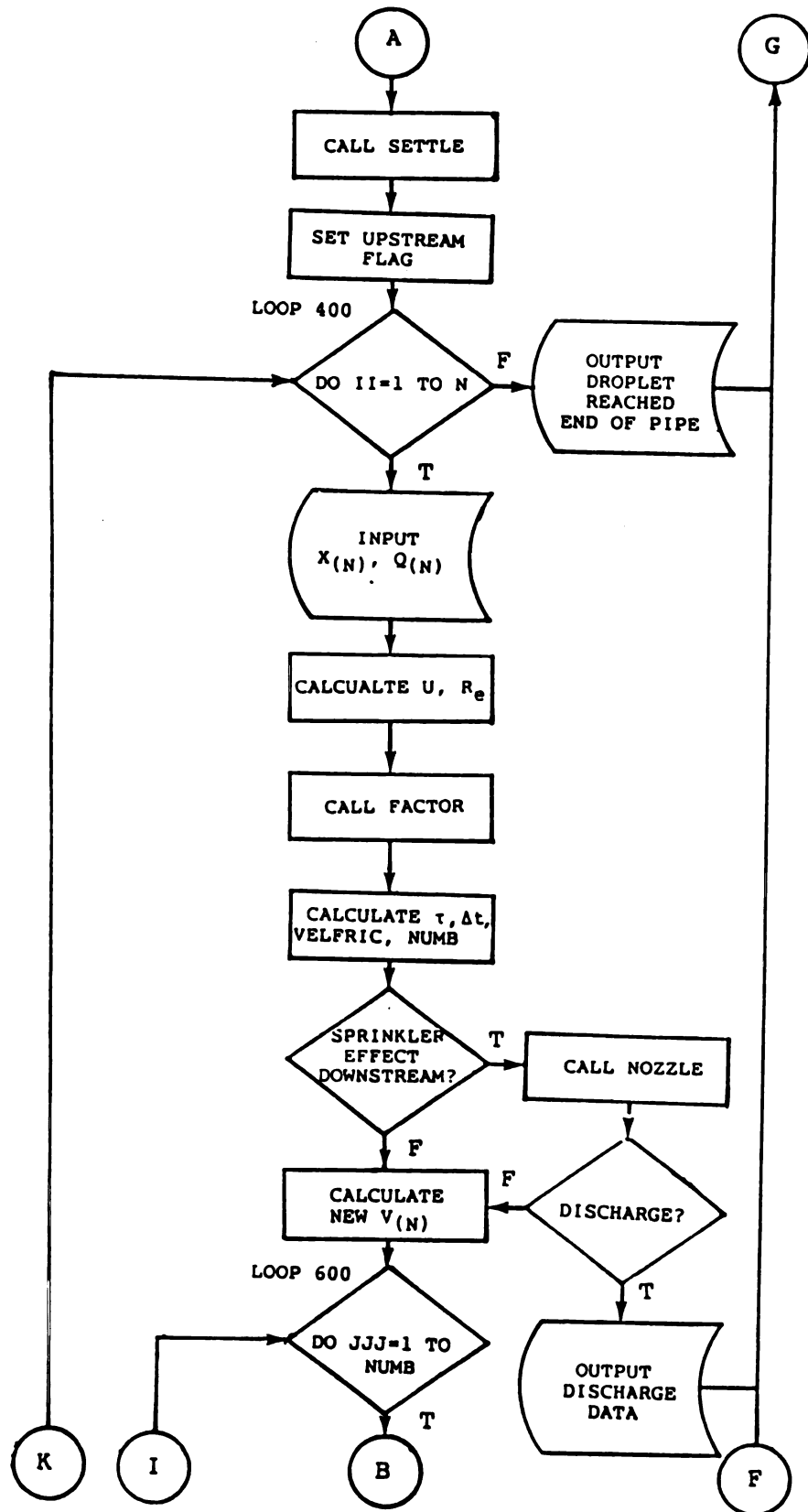


FIGURE 5.6 (CONTINUED)

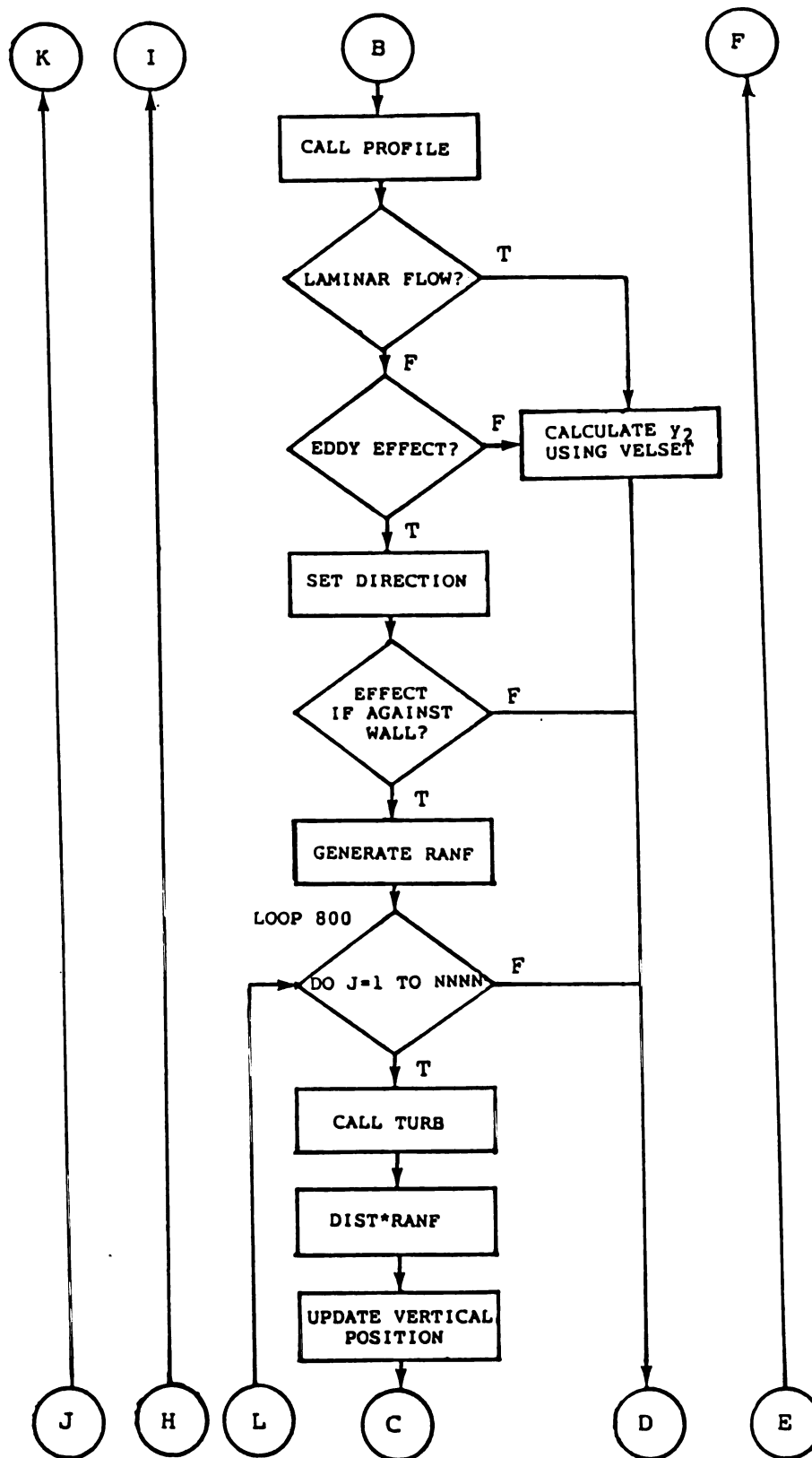


FIGURE 5.6 (CONTINUED)

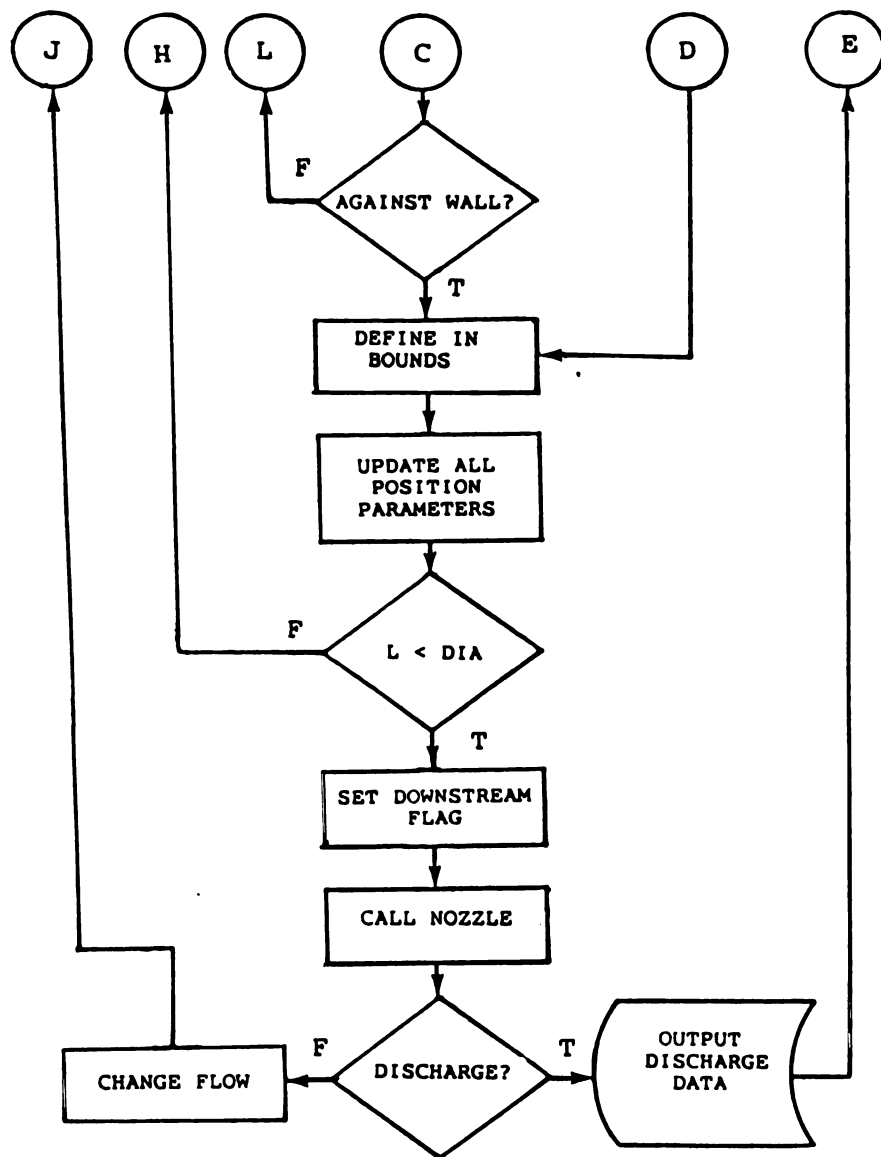


FIGURE 5.6 (CONTINUED)

keyboard. The inputs for the model are listed in Table 5.1. Input and output files are opened. Input files are intended for inputting a given droplet distribution. Output files are used to record the model parameters, the droplet size, the sprinkler number where discharge occurred and statistical data.

The total flow, distance and number of sprinklers are determined for the system used. The program version, date, time, model parameters and the summed system values are output to the output file for reference. All system parameters and physical properties are entered only once for each run of the program. The model traces the path of an individual droplet until it is discharged by a sprinkler or reaches the end of the pipe. The droplet distribution is entered individually either from a data statement or data file. The initial system parameters are saved and initialized to input values for each droplet path traced. When the last droplet path is traced, the program processes the droplet distribution for each sprinkler and execution terminates.

The first calculations after a droplet size is entered are system flow characteristics. The distance between the injection point and the center line of the first sprinkler and the distance between the center lines of sequentially consecutive sprinklers are each considered a subsystem with constant flow characteristics, as described in section 5.2. Pipe flow characteristics are calculated for each

TABLE 5.1 MODEL INPUTS

1. Distance between sprinklers (data array)
 2. Flow rate for each sprinkler (data array)
 3. Continuous phase density
 4. Dispersed phase density
 5. Continuous phase viscosity
 6. Initial droplet velocity
 7. Number of iterations per eddy encounter
 8. Sprinkler position on pipe, top or bottom
 9. Pipe inside diameter
 10. Pipe roughness
 11. Outlet or sprinkler inlet inside diameter
 12. Initial vertical starting position in the cross section
 13. Percentage of the horizontal length affected by eddies
 14. Particle or droplet diameter distribution
 15. Date and time
-

consecutive subsystem and are used for program execution until the next subsystem is reached. The pipe area and outlet area are calculated and are constant.

Previous discussion stated that velocities were calculated, but distances were the needed parameter. The relationship between distance and velocity is a function of a time. The program is used to calculate the horizontal velocity in relation to vertical position. However, the time must be determined to calculate the distance traveled. By dividing a given horizontal distance by a given horizontal velocity, a time is derived. Among the parameters of the model, the one critical distance measurement that is assumed constant is the eddy length of the small scale eddies. Kubie (1980) states that a good approximation of the eddy length is Equation 5.5.

$$l = 0.2R \quad (5.5)$$

Where: l = Eddy length (cm)
 R = Pipe radius (cm)

Each subsystem length is subdivided by eddy length. This is the number of iterations, or loop passes, to complete the subsystem length. A horizontal velocity is calculated at the vertical position for each loop pass. This velocity is divided into the eddy length to determine the time required to travel the eddy length. Multiplying this time by the settling velocity determines the vertical displacement for the eddy length or loop pass if the eddy length is not occupied by an eddy.

In the case of the eddy effect, a time step must be

calculated first for numerical solution of the particle motion differential equation (Equation 2.10) which will be described in section 5.4.5. The average velocity in the eddy is approximated by the friction velocity calculated by Equation 2.4.

$$u^* = U \sqrt{f/2} \quad (2.4)$$

Where: u^* = Friction velocity (cm/sec)
 U = Average pipe flow velocity (cm/sec)
 f = Fanning friction factor (dimensionless)

An eddy time described by Equation 5.6 can then be calculated from the eddy length and friction velocity.

$$\tau = l/u^* \quad (5.6)$$

Where: τ = Eddy time (sec)
 l = Eddy length (cm)
 u^* = Friction velocity (cm/sec)

The eddy time is further divided by the number of iterations per eddy to yield a Δt .

The settling velocity for the droplet of input size is determined in subroutine SETTLE. The settling velocity equations will be discussed in section 5.4.2. A velocity value in units of cm/sec is returned to the main program.

A flag is set to declare that the droplet is on the upstream side of the first sprinkler and not under sprinkler effect. Loop 400 (see Figure 5.6) is set for the total number of sprinklers or subsystems. The first pass through the loop calculates the pipe flow parameters of the first subsystem and consecutive passes calculate the parameters of consecutive subsystems. If the loop maximum is exceeded, the droplet has reached the end of the pipe without being

discharged, and output is sent to the output file to indicate such. Parameters calculated are the mean pipe flow velocity (Equation 2.1) and Reynolds number (Equation 2.2). Subroutine FACTOR is executed to determine the friction factor for the section using Equation 2.3. The friction velocity is then calculated using Equation 2.4.

$$1/\sqrt{f} = 4\log(D/e) + 2.28 - 4\log(1 + 4.67(D/e)/Re\sqrt{f})) \quad (2.3)$$

Where: f = Fanning friction factor (dimensionless)
 D = Inside pipe diameter (cm)
 e = Average height of pipe wall roughness (cm)
 Re = Reynolds number (dimensionless)

The number of eddy lengths in the subsystem length is determined. Using the eddy length and friction velocity, an eddy encounter time and Δt are calculated.

The model checks to see if the droplet is on the downstream side of a sprinkler and under the sprinkler effect. The decision is based on the setting of flags set in program MAIN and subroutine NOZZLE. If the program has called subroutine NOZZLE from an upstream position, loop 400 is incremented and new pipe flow values are calculated for the next subsystem and control is returned to subroutine NOZZLE. The downstream sprinkler effect calculations are then completed prior to returning to the main program calculations. When subroutine NOZZLE is called, a flag is returned to indicate if the droplet or particle was discharged. If the flag is true, output is sent to the output file indicating droplet size and sprinkler number where discharge occurred. The next droplet is input, and loop 400 execution starts again from the point of injection

with the initial parameters. The input value for the sprinkler discharge and calculated average velocity out the outlet occur after the calling of subroutine NOZZLE for downstream calculations. This placement allows the values to be entered prior to the first call for subroutine nozzle upstream calculation. More importantly, this placement allows the outlet flow characteristics to remain constant for upstream and downstream calculations for the same sprinkler

For loop 600, the number of cycles is determined by dividing the subsystem length into eddy lengths as just described. The loop counter maximum for each subsystem is initialized to increment to a value which would exceed the maximum number of eddies in the subsystem length. The loop will increment until the sprinkler effect is activated when LL is less than or equal to D and control is given to subroutine NOZZLE. Loop 600 is exited when control returns from subroutine NOZZLE. On return from subroutine NOZZLE on the upstream calculations, XR equals 0. If the droplet is not discharged, loop 400 is accessed and the next subsystem flow parameters are calculated. Subroutine NOZZLE is accessed again for the downstream calculations.

In loop 600, subroutine PROFILE is called for each eddy length to calculate the horizontal flow velocity at the vertical position of the droplet. The next step in loop 600 is to determine if the eddy length is occupied by an eddy. If an eddy is present, then the vertical position of the

droplet will be influenced by the eddy. If the Reynolds number indicates laminar flow, the eddy effect is neglected.

If the eddy length is not occupied by an eddy or if laminar flow exists, the droplet vertical displacement for that eddy length is a function of the settling velocity. The eddy length, which is the horizontal displacement for each cycle of loop 600, is divided by the horizontal velocity to determine the time required to travel the length. This time is multiplied by the terminal settling velocity previously calculated in subroutine SETTLE to determine the vertical displacement. The horizontal and vertical positions of the droplet are then updated. In the flow between two plates, the plates are physical bounds which restrict the movement of the droplet. The calculations do not know that physical bounds exist so the vertical coordinate must be checked after each update to make sure that the physical bounds are not exceeded. If the absolute value of YP is greater than the radius of the pipe, it is assumed that the droplet is against the pipe or plate wall. The vertical position is then changed to a YP value one droplet radius away for the wall.

If the eddy length is occupied by an eddy, the vertical displacement is a function of the eddy, and the terminal settling velocity is not used for that cycle. Gravitational forces are included in the equation used for the particle motion (Equation 2.10). Kubie (1980) assumed that eddies had either a positive or negative vertical effect on a

droplet. He also neglected any movement of the droplet in the x and z coordinate planes and assumed that all of the eddy movement of the droplet was in the vertical (y) coordinate plane. He further assumed that eddies were consecutive and the vertical direction of travel (positive or negative) was determined by a randomly generated sign. This model uses some different assumptions from those of Kubie. The velocity of the particle is determined by the same equation of particle motion given in Equation 2.10. Kubie was only interested in the retardation effect of the turbulence on the terminal settling velocity. The model developed here keeps track of the vertical position of the droplet in relation to the horizontal position. However, the vertical plane containing the centerline of the pipe is the dominate zone of interest; therefore, the other two planes are again neglected. Since the eddy length is very small in comparison to the subsystem length, the number of eddies per subsystem is very large. For a standard 6 inch irrigation line and a subsystem length of 25 feet, the number of eddies would approach 500. For a 40 acre pivot 700 feet long, the number of eddy lengths would be nearly 14,000. Since the number of encounters is large per simulation, it is assumed that the random direction in the horizontal plane would cancel the eddy effect on the horizontal displacement in the long term. The horizontal eddy effect would at most cause a shift in the time at which the droplet would reach the sprinkler effect and possible

discharge. The model is only concerned with the point of discharge and not the time of discharge. For the third dimension (z axis), the same assumptions hold true so on the average a droplet would reside within the vertical plane drawn through the pipe center line. This assumption is the basis for using a two-dimensional analysis.

In relation with the vertical displacement caused by an eddy, it is known that the velocity vector calculated by the particle motion equation (Equation 2.10) is a resultant of three one-dimensional vectors. The vertical component vector can range from 0 to 100 percent of the resultant vector. Since the trajectory of the vector is not known, the vertical component cannot be calculated. The vertical displacement is the variable needed so another random number between 0 and 1 is generated and multiplied by the resultant vector to obtain the vertical displacement vector component.

It is also assumed that eddies are not continuous and consecutive. The percentage of eddy lengths actually occupied by an eddy is input as a variable. If the eddy length is not occupied by an eddy, there is no eddy vertical position effect on the droplet for that particular eddy length and vertical displacement occurs due to the terminal settling velocity. Of the eddy lengths occupied, equal probability is given for positive or negative vertical displacement. The direction is selected again by a randomly generated number. If the droplet is presently against the plate wall, the random eddy direction determines if the

droplet will be pulled away from the wall. If the direction causes the droplet to be pushed towards the wall, the eddy effect is by-passed and the droplet remains at a vertical position against the wall.

When an eddy occurs, the eddy time is divided into smaller time steps for numerical solution of the particle motion differential equation, Equation 2.10 in numerical form is:

$$V_n = V_{n-1} + \Delta t(((\rho_d - \rho_c)g)/(\rho_d + 1/2\rho_c) + ((3c_d\rho_c |s_n U_E - V_{n-1}| (s_n U_E - V_{n-1})) / (8R_p(\rho_d + 1/2\rho_c)))) \quad (5.7)$$

with
$$\begin{aligned} U_E &= U_e & \text{for } 0 &\leq t < \tau_E \\ U_E &= 0 & \text{for } \tau_E &\leq t \leq \tau \end{aligned}$$

Where: R_p = Particle radius (cm)
 ρ_d = Particle density (g/cm³)
 ρ_c = Fluid density (g/cm³)
 V_n = Particle velocity in time step n (cm/sec)
 t = Time from beginning of encounter (sec)
 g = Gravitational acceleration (cm/sec²)
 c_d = Drag coefficient (dimensionless)
 s_n = Random sign
 U_e = Eddy velocity (approx. friction velocity, cm/sec)
 U_E = Relative fluid velocity (generally eddy velocity, cm/sec)
 τ_E = Encounter time (sec)
 τ = Eddy time (sec)
 Δt = Time step (sec)

The method of solution is a backwards step solution. Loop 800 is the control loop for calling subroutine TURB. Subroutine TURB is called once for each time step Δt . The magnitude of Δt is a function of the input value for the number of iterations per eddy. The accuracy of the answer is increased by increasing the number of iterations, but the amount of computer time is also increased immensely. The acceptable accuracy level is thus compromised against

computer time. Subroutine TURB returns the resultant distance vector ϵ since a velocity is calculated and the time step length is known. The resultant distance vector is multiplied by the random vertical number to determine the vertical displacement. The vertical position of the droplet is updated and the physical bounds are checked. If the droplet is beyond the physical bounds, the vertical position is redefined as against the wall and loop 800 is exited. The initial velocity for time step n is the velocity from time step $n-1$. The particle velocity of time step $n-1$ is returned to subroutine turb for time step n . The random vertical factor is generated once for each eddy encounter and is used for determining the vertical displacement for each cycle of loop 800.

When the vertical turbulence effect is completed, new horizontal and vertical positions are calculated and restricted to the bounds, if necessary. The vertical distance (YY) to the sprinkler inlet is calculated. Angle beta is determined and length L is determined. The calling of subroutine NOZZLE at this point indicates that the droplet is within the sprinkler influence and on the upstream side of the sprinkler. When subroutine NOZZLE is called, loop 600 control is terminated. A flag is reset to call subroutine NOZZLE for the downstream calculations. Droplet discharge is checked upon return from subroutine NOZZLE.

5.4.2 Subroutine SETTLE

Subroutine SETTLE calculates the terminal settling velocity of a droplet or particle. Figure 5.7 is a flowchart of subroutine SETTLE. The passing variables from the main program are the phase densities, gravitational acceleration, droplet diameter and continuous phase viscosity. An additional passing variable from subroutine SETTLE to the main program is the settling velocity.

Subroutine SETTLE first compares the densities of the phases to determine if the dispersed phase will rise or fall. If the dispersed phase is buoyant, Equation 5.8 has been derived for the terminal settling velocity as follows:

$$U_t = ((-2/9)gR_p^2(\rho_c - \rho_d))/\mu_c \quad (5.8)$$

Where: U_t = Terminal settling velocity (cm/sec)
 g = Gravitational acceleration (cm/sec²)
 ρ_c = Fluid density (g/cm³)
 ρ_d = Particle density (g/cm³)
 R_p = Particle radius (cm)
 μ_c = Fluid viscosity (g/cm sec)

The negative sign on the constant 2/9 in Equation 5.8 indicates that the settling velocity is upward since a negative pipe radius is at the top of the pipe (See Figure 5.1).

If the particle or droplet is more dense than the carrier fluid, it will settle as reported in section 2.8. The rate of fall is a function of the viscosity and density of the fluid around the particle in relation to the particle density. The rate of fall has been broken into three regions, as indicated in section 2.8.1. To select which

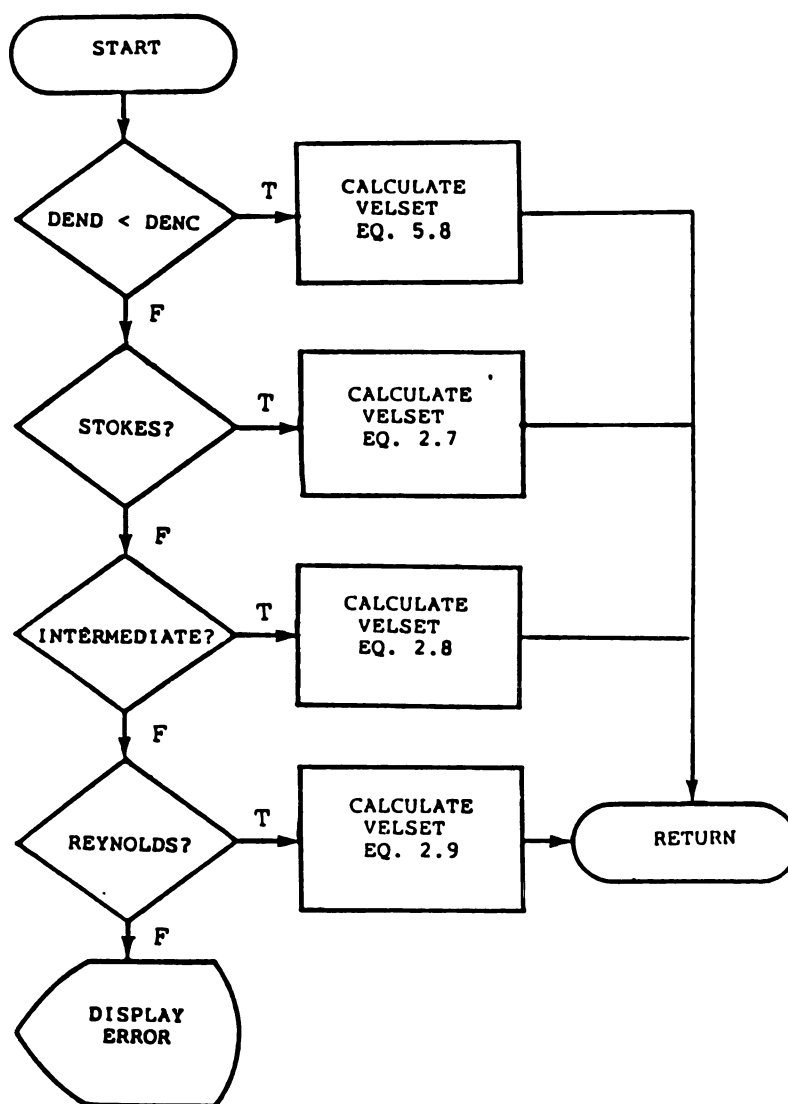


FIGURE 5.7 SUBROUTINE SETTLE FLOWCHART

region the droplet is in, McCabe and Smith (1967) derived an equation based on these regions:

$$AK = D_p(g\rho_c(\rho_d - \rho_c)/\mu_c^2)^{1/3} \quad (5.9)$$

Where: AK = Derived constant (dimensionless)

D_p = Particle diameter (cm)

g = Gravitational acceleration (cm/sec²)

ρ_c = Fluid density (g/cm³)

ρ_d = Particle density (g/cm³)

μ_c = Fluid viscosity (g/cm sec)

If AK is less than 3.3, Stoke's Law (Equation 2.7) is used for determining the terminal settling velocity. If AK is greater than or equal to 3.3 and less than 43.6, the intermediate region equation (Equation 2.8) is used. If AK is greater than or equal to 43.6 and less than 2,360, the Newton's law region equation (Equation 2.9) is used. If AK is greater than 2360, an error message is displayed.

$$U_t = gD_p^2(\rho_d - \rho_c)/18\mu_c \quad (2.7)$$

Where: U_t = Terminal settling velocity (cm/sec)

g = Acceleration due to gravity (cm/sec²)

D_p = Particle diameter (cm)

ρ_d = Particle density (g/cm³)

ρ_c = Fluid density (g/cm³)

μ_c = Fluid viscosity (g/cm sec)

$$U_t = 0.153g^{0.71}D_p^{1.14}(\rho_d - \rho_c)^{0.71}/\rho_c^{0.29}\mu_c^{0.43} \quad (2.8)$$

Where: U_t = Terminal settling velocity (cm/sec)

g = Acceleration due to gravity (cm/sec²)

D_p = Particle diameter (cm)

ρ_d = Particle density (g/cm³)

ρ_c = Fluid density (g/cm³)

μ_c = Fluid viscosity (g/cm sec)

$$U_t = 1.74 \sqrt{gD_p(\rho_d - \rho_c)/\rho_c} \quad (2.9)$$

Where: U_t = Terminal settling velocity (cm/sec)

g = Acceleration due to gravity (cm/sec²)

D_p = Particle diameter (cm)

ρ_d = Particle density (g/cm³)

ρ_c = Fluid density (g/cm³)

5.4.3 Subroutine FACTOR

Subroutine FACTOR calculates the Fannings friction factor for a given set of flow conditions. Figure 5.8 is a flowchart of subroutine FACTOR. The passing variables from the main program are the pipe diameter, the average height of the wall roughness and the flow Reynolds number. An additional passing variable from subroutine FACTOR to the main program is the friction factor (F).

The friction factor is initialized to .002 and is incremented by .0001 for each additional cycle through loop 2000. Loop 2000 is set for 1000 iterations, so the loop is valid for a friction factor range of (.002 to .102). Equation 2.3 is used to determine the friction factor. When Equation 2.3 is within 0.1 of being an equivalent equation, the friction factor is selected and loop 2000 is exited and control returns to the main program. If loop 2000 exceeds its maximum limit, an error message is displayed.

5.4.4 Subroutine PROFILE

Subroutine PROFILE calculates the horizontal flow velocity at any point in the cross section of the pipe. Figure 5.9 is a flowchart of subroutine PROFILE. The passing variables from the main program are the present position of the droplet (YP), pipe radius, friction velocity, average pipe flow velocity and particle radius. An additional passing variable from subroutine PROFILE to the main program is the horizontal flow velocity at position YP.

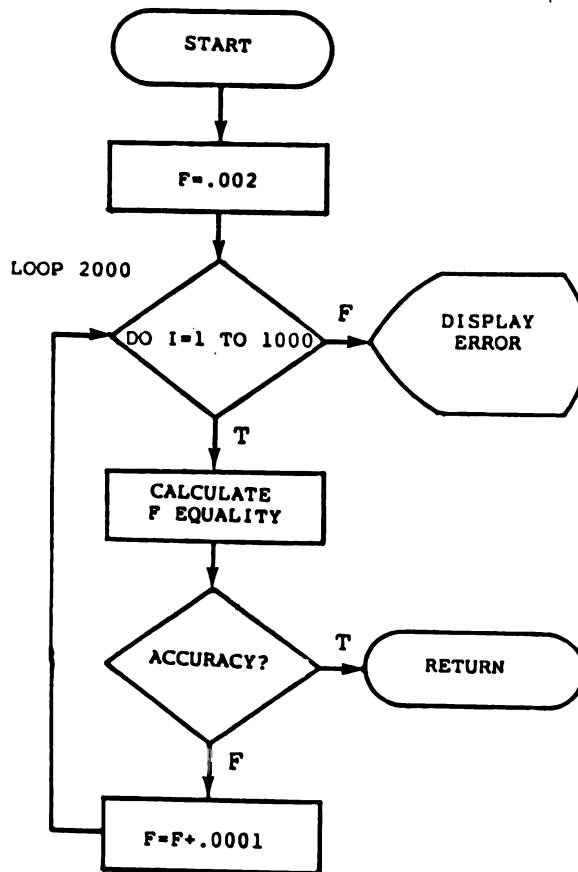


FIGURE 5.8 SUBROUTINE FACTOR FLOWCHART

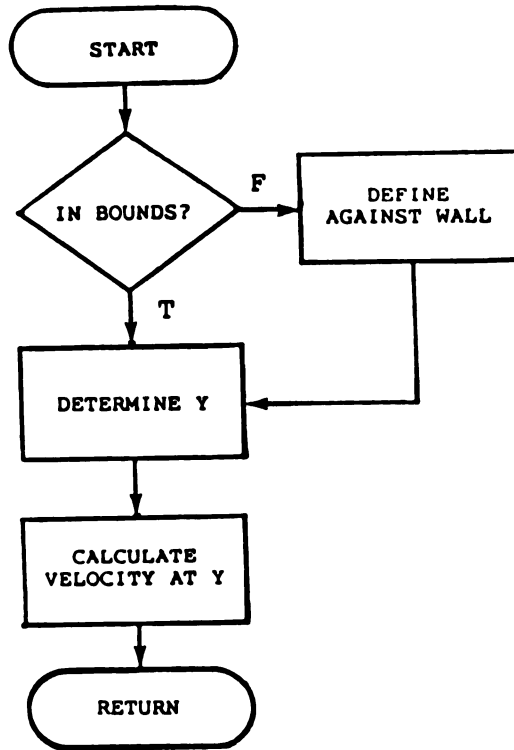


FIGURE 5.9 SUBROUTINE PROFILE FLOWCHART

Subroutine profile first checks to make sure that the droplet is in the physical bounds of the system and changes the vertical position to be against the wall if necessary. The distance (Y) away for the pipe wall is determined and the horizontal flow velocity is determined using Equation 2.5.

$$u_y = u^*(2.5\ln(y/R)+3.75+(U/u^*)) \quad (2.5)$$

Where: u_y = Velocity at distance y from pipe wall (cm/sec)
 y = Distance from pipe wall (cm)
 R = Radius of pipe (cm)
 U = Mean pipe flow velocity (cm/sec)
 u^* = Friction velocity (cm/sec)

5.4.5 Subroutine TURB

Subroutine TURB calculates the turbulence effect on a droplet from the small scale large energy eddies. Figure 5.10 is a flowchart of subroutine TURB. The passing variables from the main program are the droplet radius, the phase densities, fluid viscosity, friction velocity, gravitational acceleration, the random direction sign, the droplet velocity from previous time step and Δt . An additional passing variable from subroutine TURB to the main program is the resultant distance traveled in the time step.

Subroutine TURB first determines the particle Reynolds number using Equation 2.12. The drag coefficient is then calculated using Equation 2.11.

$$c_d = 24/Re_a((1+(Re_a/60)^{5/9})^{9/5}) \quad (2.11)$$

Where: c_d = Drag coefficient
 Re_a = Particle Reynolds number defined by Eq. 2.12

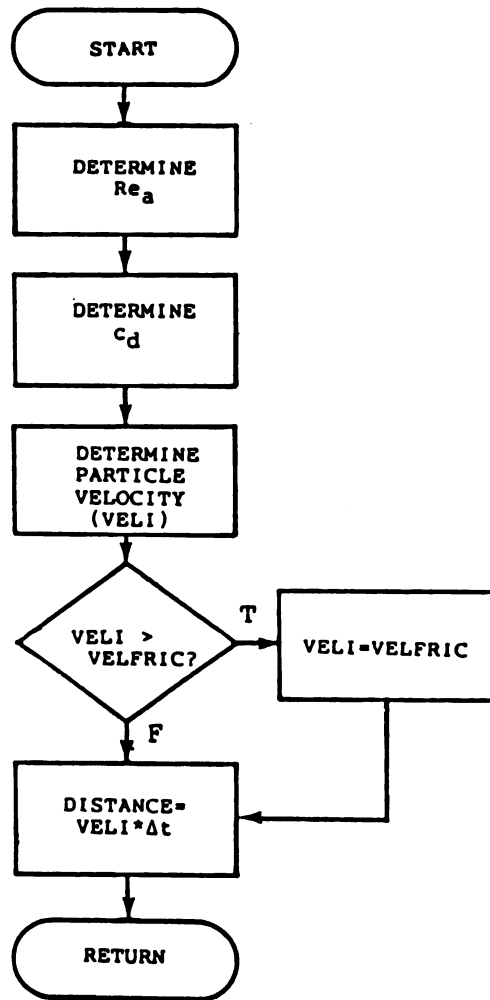


FIGURE 5.10 SUBROUTINE TURB FLOWCHART

$$Re_a = (2R_p \rho_c |s_n U_E - V_n|) / \mu_c \quad (2.12)$$

Where: Re_a = Reynolds number (dimensionless)
 R_p = Particle radius (cm)
 ρ_c = Fluid density (g/cm³)
 s_n = Random sign
 U_E = Relative fluid velocity generally eddy velocity (cm/sec)
 V_n = Particle velocity (cm/sec)
 μ_c = Fluid viscosity (g/cm sec)

The droplet velocity is calculated for the time step using a numerical solution for Equation 2.10 shown as Equation 5.7. The droplet velocity is assumed to never exceed the eddy velocity or the friction velocity. If this bound is exceeded, the droplet velocity is reset to the friction velocity value. The droplet velocity is multiplied by the time step to determine the distance traveled. The distance traveled is the resultant distance not the vertical displacement. The resultant distance is returned to the main program where a random factor is used to convert the distance into the vertical component. The horizontal component is assumed to be random and would only influence the chronological time of discharge and is therefore ignored.

5.4.6 Subroutine NOZZLE

Subroutine NOZZLE calculates the effect of the sprinkler on the vertical and horizontal positions of the droplet as it passes under the sprinkler. Figure 5.11 is a flowchart of subroutine NOZZLE. The logic for subroutine NOZZLE has been discussed extensively in section 5.3. The passing variables from the main program to subroutine NOZZLE

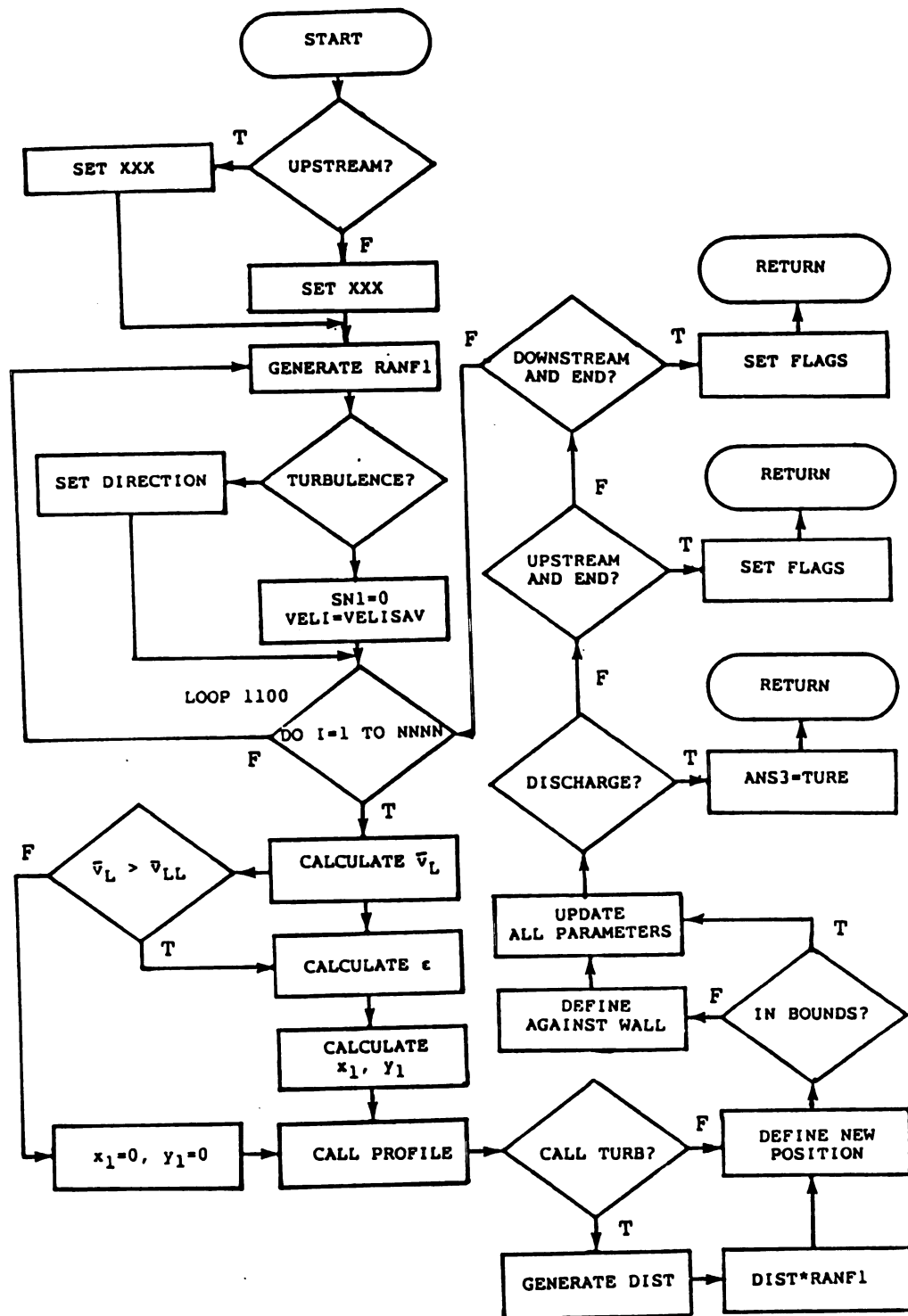


FIGURE 5.11 SUBROUTINE NOZZLE FLOWCHART

include all major variables since subroutines PROFILE and TURB are called internally. It is assumed that the eddy effect can occur even under the sprinkler. Subroutine NOZZLE returns logical variables to the main program, indicating whether the droplet has been discharged and if the droplet is on the upstream or downstream side.

Subroutine NOZZLE checks to determine if the droplet is on the upstream or downstream side. The decision is made by a flag setting from the main program. If on the upstream side, distance XR decreases down to 0. If on the downstream side XS increases. A random factor is generated for use in determining the vertical distance component for an eddy. A check is made to see if the eddy length is occupied by an eddy using the same probability used in the main program. If an eddy is present, the random direction sign of the eddy is generated. The sprinkler effect is treated in terms of eddy lengths just as the length between sprinklers. The time steps used in subroutine nozzle are the same steps described in section 5.4.1. Loop 1100 maximum limit count is set at a magnitude greater than the number of eddy lengths in the length XR. When loop 1100 is completed for one eddy length, a new eddy length is initiated until the droplet is discharged or until the sprinkler effect is terminated by returning control to the main program.

For each time step of loop 1100, the following equations are executed. The average flow velocity at the circular surface at a radius L from the sprinkler is

calculated using Equation 5.4. This velocity is a result of the sprinkler pulling the water toward it and is described in section 5.3. Using the time step, the velocity is converted to distance. The distance is then converted to the horizontal and vertical distance components as shown in Figure 5.4 and described in section 5.3. Subroutine PROFILE is called and the horizontal flow velocity is determined. The horizontal velocity is multiplied by Δt to obtain horizontal distance. If the eddy length is occupied by an eddy, subroutine TURB is called by the same procedure described in the main program and the resultant velocity and distance is calculated. This distance vector is then converted to the vertical component by the random factor. If the eddy length is not occupied by an eddy, the vertical displacement is determined using the settling velocity and Δt . The horizontal and vertical positions of the droplet are then updated using all the distances calculated. The droplet position is checked for physical bounds, and the vertical position is changed to reside against the pipe wall, if necessary. The droplet position parameters in relation to the sprinkler are updated. The subroutine then checks to see if the droplet has been moved into discharge position. The droplet is assumed to be discharged if the horizontal position is between the horizontal bounds of the outlet and if LL is less than the outlet radius. If the droplet position satisfies these conditions, a flag is set indicating discharge and control returns to the main program.

If the droplet is not discharged, two further conditions are checked. If the droplet is just upstream of an outlet centerline (i.e. XR is less than 0), flags are set to cause the main program to calculate new pipe flow characteristics and return to subroutine nozzle for downstream calculations. If the downstream calculations are being executed, control will return to the main program when L is greater than LL , as shown in Figures 5.2 and 5.3. Flags are set to indicate that downstream calculations have been completed, and the droplet is on the upstream side of the next sprinkler.

6.0 MODEL DEVELOPMENT, VERIFICATION AND VALIDATION

6.1 Introduction

The model was initially constructed to trace the path of a droplet with no turbulence effect. This simple model determined when the droplet floated out or settled to the pipe wall. This model could determine the maximum droplet size that could remain entrained in non-turbulent flow for the entire length of a simulated irrigation line. However, it was limited in that a droplet of given size always followed the same path. Turbulence was then added in the form of particle motion caused by turbulent eddies. This component then distributed particles of a given size to more than one position along the irrigation line, based upon the amount of turbulence in the irrigation line. The distribution would probably be close to a normal distribution, and may be skewed for a center pivot because of increasing sprinkler effect. This turbulence component made the model much more dynamic and realistic.

The effect of sprinklers on the droplet path was also examined. The initial attempts used an area in the pipe to calculate an average flow velocity through the area toward a sprinkler based on the sprinkler flow rate. Several types of area calculations were tested, including rectangle,

semicircle and circle. Each area changed the magnitude of the sprinkler effect, but no literature was found to help validate the approach. The next approach related the mean sprinkler flow rate to the mean flow rate toward the sprinkler inlet by two radii. One radius used was the sprinkler inlet radius, while the other was the distance from the center of the sprinkler to the position in the flow where the droplet resides. This approach was felt to be more realistic in relation to the geometry of the irrigation system.

The computer model was first programmed in GW-Basic on a personal computer. Each major component (settling velocity, friction factor, horizontal pipe flow velocity, sprinkler effect and turbulence effect) of the model was written as a subroutine. The subroutines were then linked to the main driver program. With the addition of turbulence to the first model, the computer processing time escalated. To simulate a typical .4 km (1/4 mile) pivot using 100 time steps per eddy, the number of calculations easily exceeded one million per droplet simulated. Computer time became a limiting factor, so the program was converted to Fortran V and uploaded to a mainframe Cyber 750. On a personal computer in 8 to 10 hours, 50 to 100 droplet paths could be simulated using compiled Basic and an 8087 chip. The mainframe version is able to simulate hundreds of droplet paths in minutes; however, the limiting factor is cost.

The flowcharts shown in Chapter 5 (Figures 5.6-5.11)

were drawn for an interactive program. The program variable list is presented in Appendix A, and the model source code as used to model an actual linear move irrigation machine is presented in Appendix B. The source code in Appendix B does not have the interactive entry coding included. Data statements are used since the program was generally executed as a batch job.

6.2 Model Inputs and Outputs

Model inputs were listed in Table 5.1. Model output is the size of the droplet and the sprinkler number where discharge occurs. Cumulative droplet frequency and volume are determined for each sprinkler and for droplets not discharged.

6.3 Model Verification

The theoretical equations (settling velocity, friction factor, friction velocity, horizontal pipe flow velocity, sprinkler effect and turbulence effect) were first tested in subroutines. Values calculated with the subroutines were verified for calculation accuracy using a hand calculator. The values were also compared to chart or table values, where applicable, to check for precision.

6.4 Model Validation

The validation of a model is one of the most critical steps in model development. If a model is to be useful, it

must be valid and able to produce reasonable answers. A model is generally only valid for data sets which were used in the validation process or similar data sets, until additional validations can be conducted. The dynamics of a model are tested when the model is tested for more diversified data sets. A model may be found to be grossly incorrect with additional validations. A model then can be refined according to any additional data sets.

This model is presently based upon the trends of limited field tests and hydraulic theory. Some areas of the theory are also grey areas, such as turbulence and the sprinkler effect. The development of this model is one of the first steps for understanding the engineering theory of chemigation. However, the true validation of the model will be a continual process involving additional field testing. The initial validation of the model for this thesis shows that the model will predict the trends of completed field studies.

6.4.1 Data Limitations

The search for a data set containing all of the variables listed in Table 5.1 was not successful. For liquid-liquid systems, good droplet distribution data within the irrigation line is best described as nonexistent. Generally, one or more of the other parameters are missing such as density, viscosity, water temperature, complete system design (sprinkler spacing and discharge), injection

point vertical position in the irrigation line, and accurate inside pipe diameter and sprinkler inlet diameters. In using the model, the sensitivity of the model to certain parameters requires measurements to a higher degree of accuracy than normally used in the field. One example is the density of the chemical material, since density seems to be a significant variable. Density needs to be measured to the fourth decimal place.

Two studies were used for model validation. The studies selected were the insecticide test conducted by McLeod (1983) and a seedigation test conducted by the Agricultural Engineering Department at the Coastal Plain Experiment Station, Tifton, GA. Both of these studies required additional assumptions to test the model. However, insectigation and seedigation have different engineering characteristics, thus testing the model dynamics. Also, the two situations should test the model flexibility and at least determine if the model will reasonably simulate the trends of actual field tests.

6.4.2 McLeod (1983)

The first field test results used for validation were from an "iconic" center pivot insectigation study conducted by McLeod (1983). The data used for the model simulation was gathered from McLeod (1983) and from personal communication (McLeod, 1986). The major parameters used in the simulation are listed in Table 6.1. The chemical

TABLE 6.1 MODEL SIMULATION INPUTS FOR MCLEOD (1983) STUDY
MIDLAND, MI

VARIABLE	MAGNITUDE	UNITS
System Length	129.5	m
Total Flow Rate	61.1**	L/min
Pipe Inside Diameter	5.08	cm
Pipe Roughness (e)	0.015	cm
Sprinkler Spacing (uniform)	2.59	m
Sprinkler Inlet Diameter	0.635	cm
Total Number of Sprinklers	50	
Sprinkler Position	Top or Bottom	
<u>CONTINUOUS PHASE (WATER)</u>		
Temperature	10.0	degrees C
Density	0.9997	g/cm ³
Viscosity	0.013076	g/cm sec
<u>DISPERSED PHASE (DURSBAN 6 + 11N CROP OIL 2/3:1)</u>		
Density	0.9834	g/cm ³
Droplet Size	(500-6000)	microns
Vertical Starting Position (From Pipe Center Line YP)	-1.9	cm

** See Figure 6.1 For Outflow Characteristics

injected was Dursban 6* insecticide and 11N crop oil mixed in a 2/3:1 ratio. This test can be simulated with the model since this formulation forms droplets and is immiscible.

The center pivot model was a 5.08 cm (2 in) PVC pipe with orifices to simulate the flow from a center pivot. Figure 6.1 is a graph of the sprinkler discharge flow rates versus pipe diameters. The curve is typical of a center pivot where most of the flow rate is directed to the outer limits of the pivot. Figure 6.2 illustrates the distribution of the flow by showing the cumulative flow percentage versus position along the length of the machine expressed in pipe diameters. The plot shows that approximately 25% of the water volume is discharged in the first 50% of the system, while approximately 25% of the water volume is discharged in the last 14-15% of the system.

Figure 6.3 is a plot of the pipe Reynolds number vs position along the system length, expressed in pipe diameters. The point of interest from this plot is the magnitude of the Reynolds number. The Reynolds number plot for the actual pivot modeled, shown as curve 1 in Figure 2.2, shows that the magnitude of the numbers are different by a factor of 10. The model enters transition flow at a much earlier distance than an actual system. The model also enters laminar flow for the last few outlets which is not common to most pivots. The difference in the magnitude of the Reynolds numbers for the model and an actual system may

* Trademark of the Dow Chemical Company, Midland, MI.

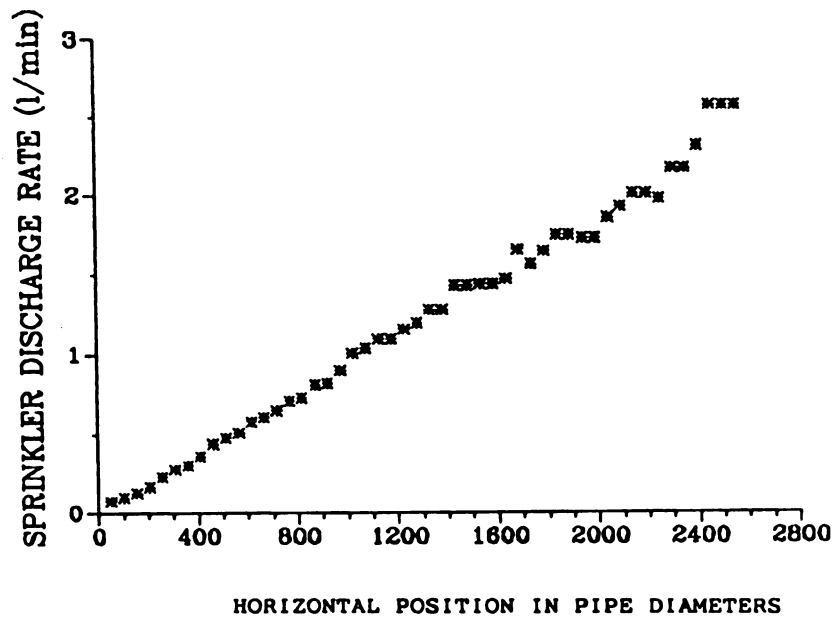


FIGURE 6.1 SPRINKLER DISCHARGE RATE VS POSITION ALONG A MODEL CENTER PIVOT MACHINE (MCLEOD, 1983)

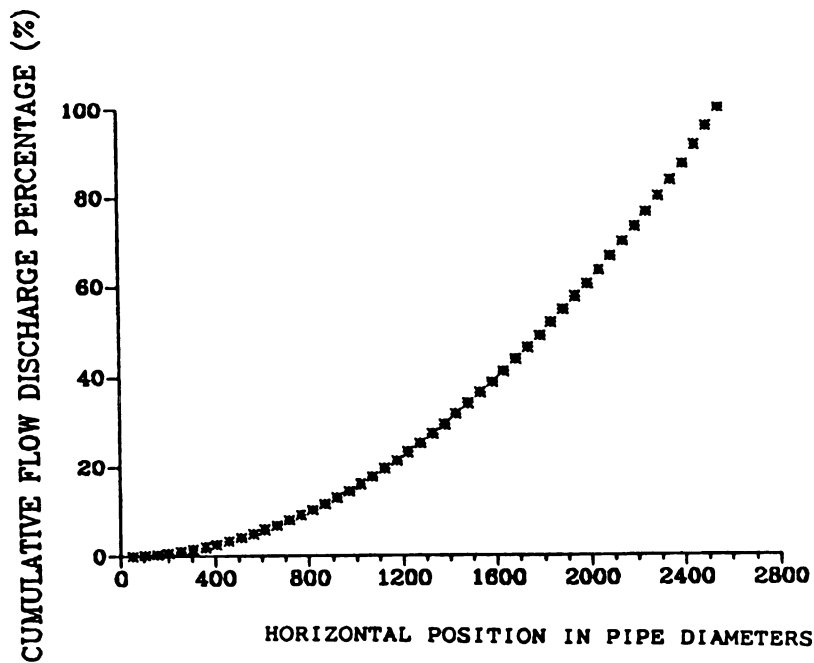


FIGURE 6.2 CUMULATIVE WATER DISCHARGE PERCENTAGE VS POSITION ALONG A MODEL CENTER PIVOT MACHINE (MCLEOD, 1983)

indicate that the results may not reflect an actual system. However, since this study is concerned with how well the computer model matches the performance data for the "iconic" model condition, the question of whether the "iconic" model reflects actual system performance is not of importance.

Figure 6.4 relates the characteristic velocities in the McLeod system. A plot of the type should indicate the magnitude of differences in the various velocities in the irrigation system. The mean pipe flow velocity decreases by 96% from upstream of the first outlet to just upstream of the last outlet. The mean pipe flow velocity is a factor in determining the horizontal transport velocity for the droplet. The friction velocity decreases by 94% from upstream of the first outlet to just upstream of the last outlet. The friction velocity is used in determining the turbulence effect and may be used as a measure of the ability of the system to keep a second phase in suspension. The low friction velocity near the end of the system may indicate potential problems for maintaining a homogeneous dispersion. The mean sprinkler inlet velocity increases by 3100% from upstream of the first outlet to just upstream of the last outlet. This velocity is a measure of the sprinkler pull on a droplet. Assuming that a droplet approaches each sprinkler at the same vertical position, the force pulling a droplet toward an outlet increases with successive outlets on a center pivot. The zone of influence of the outlet into the pipe flow is not known. It is highly

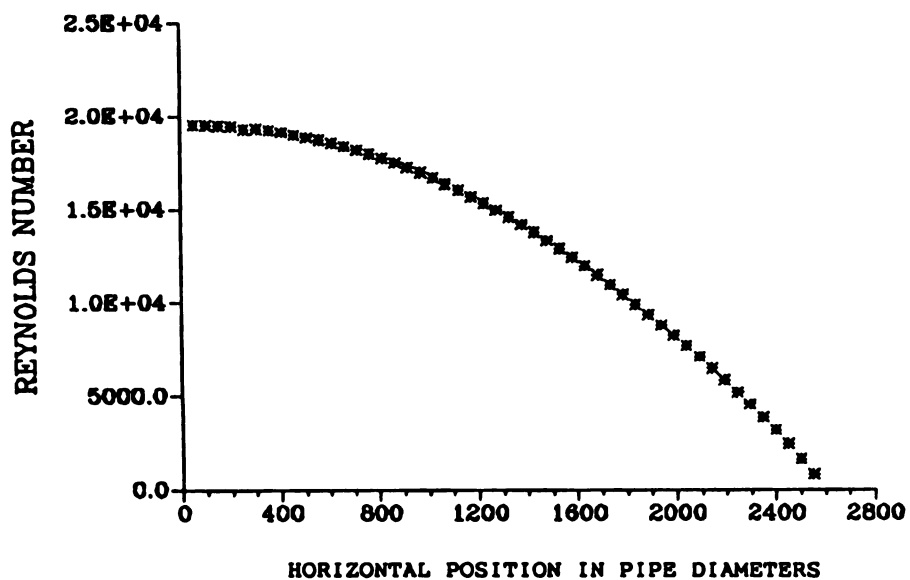


FIGURE 6.3 REYNOLDS NUMBER VS POSITION ALONG A MODEL CENTER PIVOT MACHINE (MCLEOD, 1983)

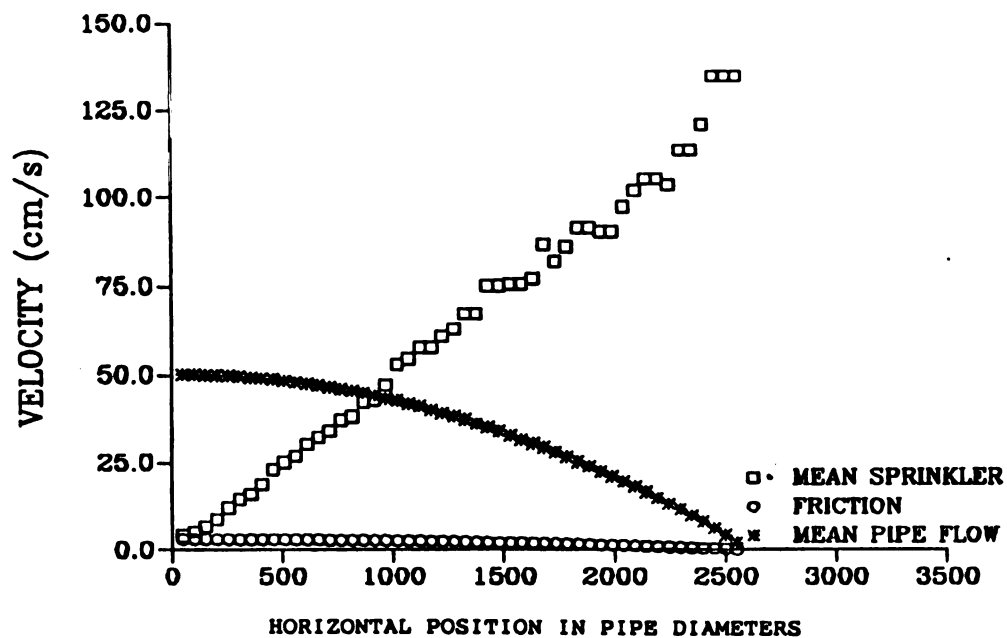


FIGURE 6.4 VELOCITY VS POSITION ALONG A MODEL CENTER PIVOT MACHINE (MCLEOD, 1983)

likely that the zone of influence does not extend across the entire pipe cross section. If a droplet is greatly removed vertically as it approaches an outlet, it could possibly pass by the outlet with little or no vertical displacement.

Dursban 6 has a density of approximately 1.16 g/cm^3 , and 11N crop oil has a density of approximately 0.860 g/cm^3 . A linear prediction equation for Durban 6 density in relation to temperature is:

$$\hat{Y} = 1.174 - 0.001C \quad r^2 = 1.0 \quad (6.1)$$

Where: $\hat{Y}$ = Dursban density (g/cm^3)
 C = Temperature (degrees C)
 r^2 = Linear determination coefficient

A linear prediction equation for 11N crop oil density in relation to temperature is:

$$\hat{Y} = 0.8679 - 0.00042C \quad r^2 = .979 \quad (6.2)$$

Where: $\hat{Y}$ = 11N crop oil density (g/cm^3)
 C = Temperature (degrees C)
 r^2 = Linear determination coefficient

Dursban 6 mixed with 11N crop oil at a 2/3:1 ratio would have a density of approximately 0.9834 g/cm^3 at 10 degrees C, compared to water at $.9997 \text{ g/cm}^3$ for a specific gravity of 0.9837. This formulation would then be bouyant in 10 degrees C water.

McLeod (1983) reported droplet sizes photographed in a clear pipe section near the injection point in the "4000-5000 micron range". Initial runs of the model using this droplet size produced unrealistic results. When the outlets were on the top of the pipe, all of the chemical was discharged out of the first sprinkler. When the outlets

were on the bottom of the pipe, all of the chemical remained in the pipe past the last outlet. Additional runs using smaller droplet sizes produced some distribution along the horizontal line. Slides of the droplets in the clear pipe were obtained from McLeod for more detailed determination of the droplet distribution. Eight slides were obtained, and the pipe dimension was used as a crude scale. Ninety-three droplets that were in reasonable focus were counted. Figure 6.5 is a frequency distribution vs droplet size range for the droplets counted. Indeed, the distribution range was found to be much larger. Droplets were found to range from 500 to >6000 microns. However, the volume of a droplet is a cubed function of the droplet radius. Droplet volumes were determined, and a cumulative percent droplet frequency and volume versus droplet size range are plotted in Figure 6.6. Of the total chemical volume, the major proportion is contained in the larger droplet sizes which constitute a small proportion of the number of droplets. Looking at the droplets greater than 3000 microns, the number of these droplets constitute only 30% of the droplet count but they constitute greater than 80% of the total droplet volume.

Additional assumptions required to simulate the system are the vertical position from which the droplet path begins. Since the injection is made flush at the top of the pipe perpendicular to the pipe centerline, the initial entry into the flow is vertical. It was assumed that the droplets began horizontal travel at .635 cm (1/4 in) away from the

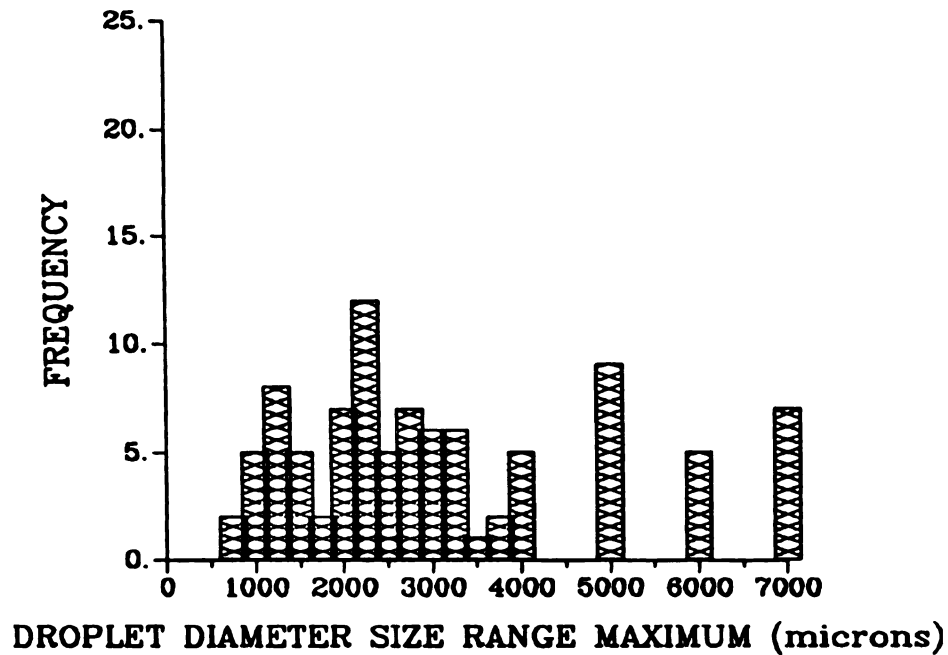


FIGURE 6.5 DROPLET FREQUENCY VS DROPLET DIAMETER SIZE RANGE MAXIMUM (MCLEOD, 1983) DURSBA 6 + 11N CROP OIL 2/3:1, N=93 (PLOTTED AT MAXIMUM END OF RANGE)

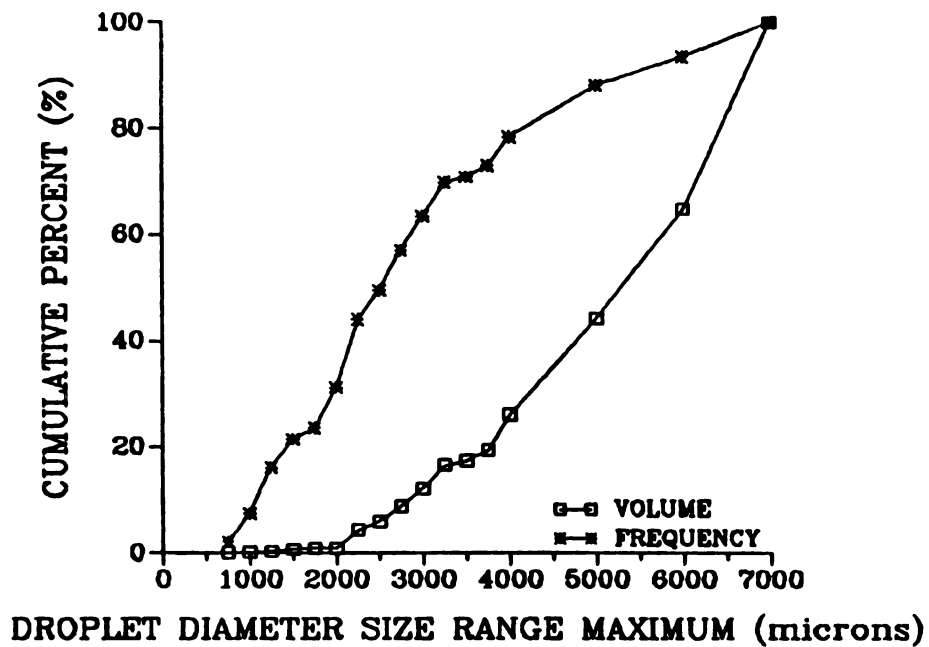


FIGURE 6.6 CUMULATIVE DROPLET FREQUENCY AND DROPLET VOLUME VS DROPLET DIAMETER SIZE RANGE MAXIMUM (MCLEOD, 1983) (PLOTTED AT MAXIMUM END OF RANGE)

pipe wall or 1.91 cm (1.75 in) above the pipe center line. The injection nozzle was .635 cm (1/4 in) in diameter, and the injection rate was approximately 46 ml/min (.73 gph).

The droplet distribution shown in Figure 6.5 was then simulated with the computer model, with the sprinklers on both the top and bottom of the pipe. To obtain the same uniformity of distribution of the chemical that is designed for the water distribution, the cumulative chemical volume distribution curve should match the cumulative percent water discharge curve (Figure 6.2). Figure 6.2 will be used as the accepted standard cumulative distribution curve for both water and chemical.

For the first simulation the outlets were on the top of the pipe, and the percent of the residence time that a droplet spent in an eddy encounter was set at 20%. The critical sprinkler effect velocity (v_{LL}) at which the sprinkler effect is activated was set at 80% of the critical discharge velocity (v_r) found on the circular surface one outlet radius (r) from the first sprinkler outlet inlet (See Figure 5.2). This critical velocity allowed the sprinkler effect activation limit (LL) to increase to the pipe diameter before the last sprinkler. Figure 6.7 is a plot of the model simulation showing cumulative chemical volume discharge percentage versus position along the pivot. Figure 6.7 is not even close to matching sprinkler discharge, the curve for the carrier fluid shown in Figure 6.2. Figure 6.7 shows that greater than 99% of the chemical

volume was discharged out the first outlet. Chemical was discharged as far as the seventh outlet. The droplets sizes discharged at the seventh sprinkler were in the 500-750 micron diameter range. Another simulation was run increasing the residence time spent in eddies to 40%. Again, slightly more than 99% of the chemical volume was discharged at outlet 1, but chemical was discharged as far as outlet 16. McLeod (1983) reported that the major proportion of the chemical was discharged between outlets 1 and 17 when the outlets were on the top of the pipe. McLeod's observations were only based on measurements taken at outlets 1, 17, 34 and 50.

Figure 6.8 shows the identical simulation shown in Figure 6.7, except the outlets are now on the bottom of the pipe. The injection point remained on the top of the pipe and the eddy time remained at 20%. Figure 6.8 shows the cumulative percentage chemical discharged versus pipe diameters. Again, Figure 6.8 does not even come close to matching the water discharge curve in Figure 6.2. In this simulation, the major proportion of the chemical is carried to the far end of the system. Approximately 77% of the chemical volume was discharged by the last three sprinklers. Chemical was discharged as early as outlet 5. Fifteen percent of the material remained in the pipe and was not discharged. McLeod (1983) reported that the chemical was discharged in the last third of the system. He also reported that a substantial amount of chemical was found

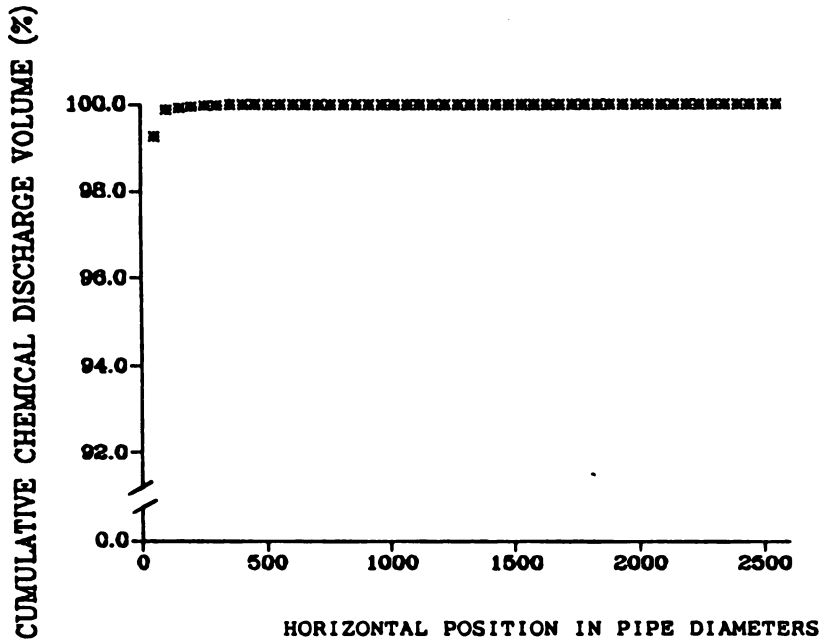


FIGURE 6.7 CUMULATIVE CHEMICAL DISCHARGE VOLUME VS POSITION
ALONG A MODEL CENTER PIVOT MACHINE (MCLEOD, 1983)
EDDY TIME = 20%, YSTART=-1.91, TEMP. = 10 C
SPRINKLER LOCATION = TOP OF PIPE

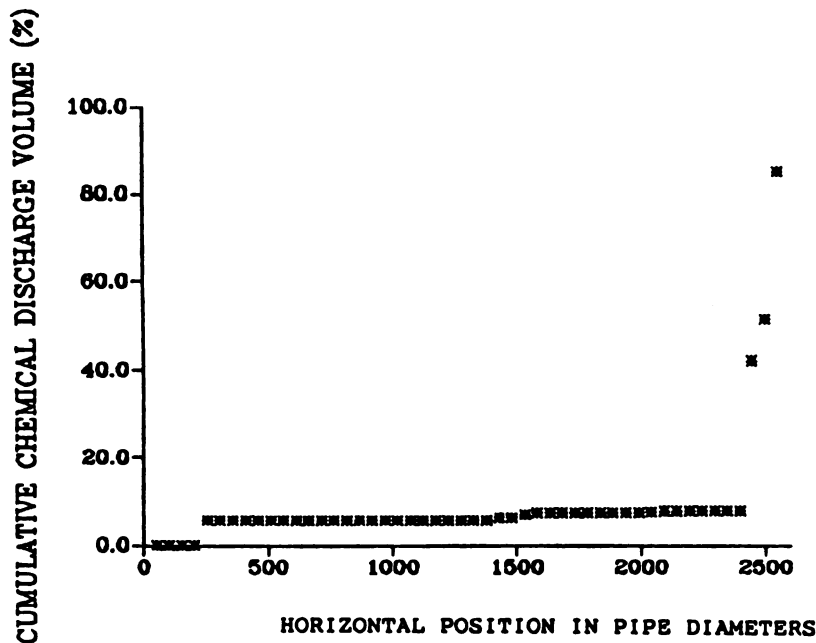


FIGURE 6.8 CUMULATIVE CHEMICAL DISCHARGE VOLUME VS POSITION
ALONG A MODEL CENTER PIVOT MACHINE (MCLEOD, 1983)
EDDY TIME = 20%, YSTART=-1.91, TEMP. = 10 C
SPRINKLER LOCATION = BOTTOM OF PIPE

remaining in the pipe when purged at the end of the test.

The velocities in the system have been examined by discussing Figure 6.4. One velocity not yet discussed is the terminal settling velocity of the droplets. Figure 6.9 is a plot of the terminal settling velocities at three temperatures for various droplet sizes of the 2/3:1 Dursban:oil mixture. The sizes range from 6000 to 400 microns. The terminal settling velocity was calculated using Equation 5.8. The velocities are plotted as positive values but the mixture is buoyant and would float or rise. The magnitude of the velocity for the larger droplet ranges is quite large, especially in comparison to the friction velocity shown in Figure 6.4. The friction velocity could be used as a measure of the ability to keep the dispersed phase in suspension. Figure 6.10 is a plot of smaller droplet sizes with an enhanced vertical scale and shows the magnitude of the settling velocity to be greatly reduced. The effect of temperature on the terminal settling velocity should also be noted from the two plots. Temperature can have a significant effect on the terminal settling velocity.

For the purpose of validation, the trends of McLeod's 1983 study seemed to have been modeled. Considering the magnitude of the settling velocity of the 4000-6000 micron droplets in relation to the amount of turbulence to keep them in suspension, the chemical distribution seems rather reasonable. McLeod's raw data show the distribution of the chemical in the study had a wider spread than the model

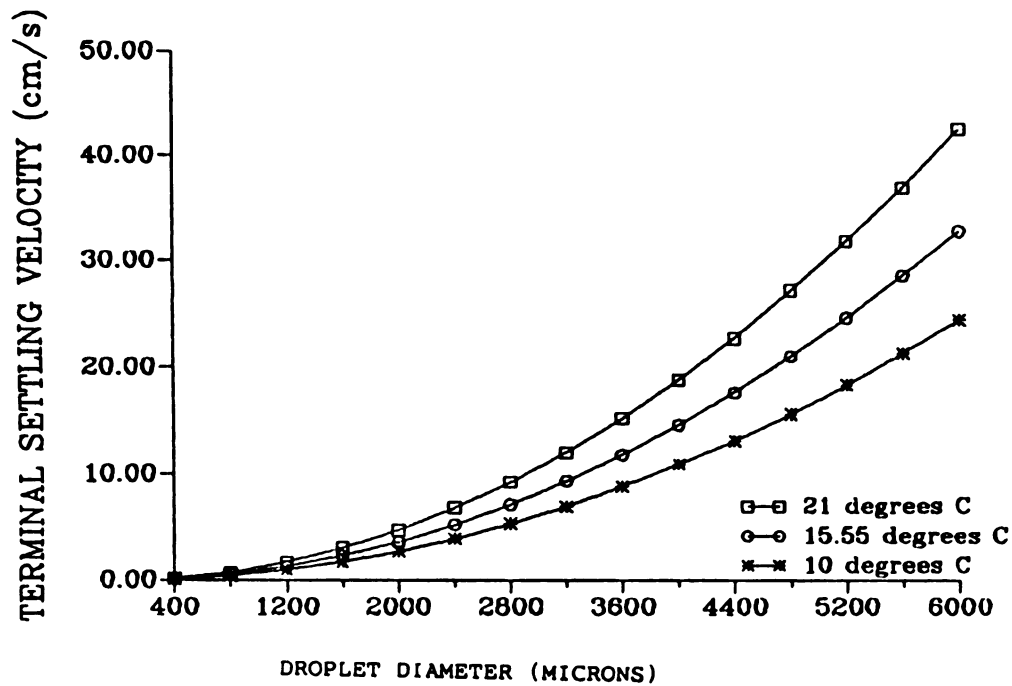


FIGURE 6.9 TERMINAL SETTLING VELOCITY VS DROPLET SIZE
(MCLEOD, 1983) DURSBN 6 + 11N CROP OIL 2/3:1

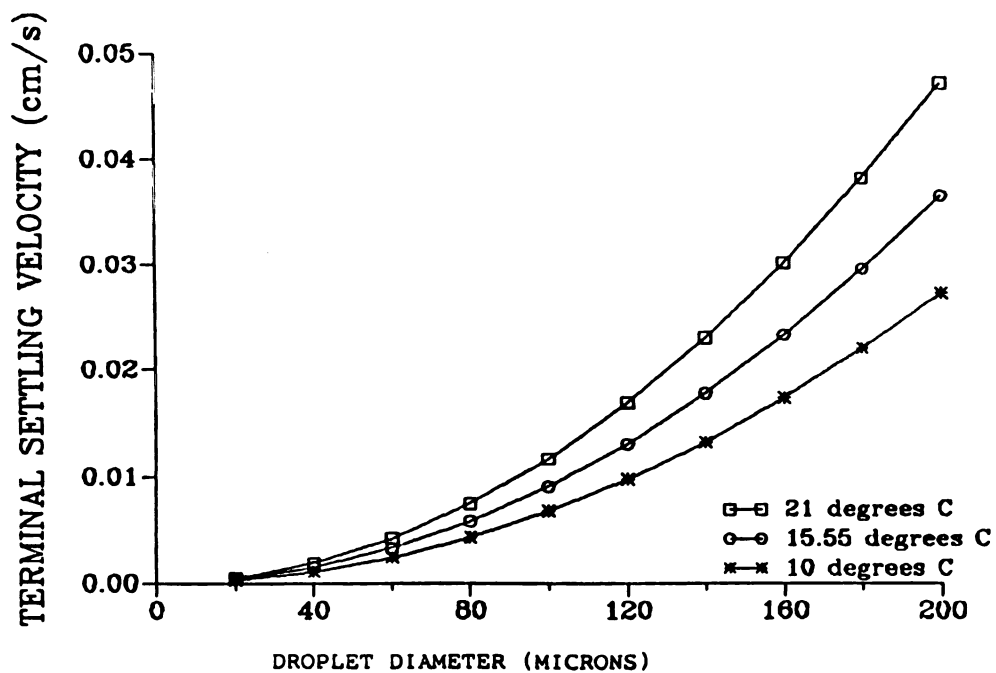


FIGURE 6.10 TERMINAL SETTLING VELOCITY VS DROPLET SIZE
(MCLEOD, 1983) DURSBN 6 + 11N CROP OIL 2/3:1

predicted. Several reasons exist that may help to explain the model's inability to produce results with more precision. The droplet distribution counted in the slides was only an approximate distribution, and the number of droplets counted was extremely low. The model's simulated distribution for droplets in the 500 micron range seemed more characteristic of the field results. Five-hundred microns was, by the visual observation of the slides, the lower limit of the focus of the photographic equipment. In addition, only clear and recognizable chemical droplets were counted. This more than likely resulted in eliminating many smaller droplets from being included in the count.

The large droplets (5000 microns or greater) were also observed to be distorted. These droplets were clearly focused and some elongation deformation was occurring. In a quick check of the D_{p95} droplet size of this material in the flow regime upstream of the first outlet, a 6000 micron droplet is on the border line of stability using equation 2.14. Some of the larger droplets may have split considering the calculated stable droplet size and the visually observed droplet deformation. Splitting would have increased the chemical distribution.

The inlets to the orifices were assumed to be 0.635 cm (1/4 in) when in fact the opening may have been smaller. The size of the larger droplets may, in fact, be larger than the inlets. To discharge these larger droplets out of these inlets, some shearing may have occurred, and part of the

chemical may have remained in the pipe in one or more smaller droplets.

The present simulation model is not programmed to handle a droplet split during the simulation of a droplet path. A split of the larger droplets would likely have resulted in a wider spread chemical distribution. Models have been developed to model the splitting of the droplet in pipe flow, and this may be a needed feature of this model in the future.

However, considering the magnitude of the settling velocity of the 4000 to 6000 micron droplet range, the degree of turbulence to keep these sizes in suspension may not be feasible. Therefore, a most realistic practical solution is to create a droplet distribution with a smaller mean diameter at the injection point to help maintain suspension. The volume in one 5000 micron droplet is equivalent to the volume in 1,000 - 500 micron droplet or 1,000,000 - 50 micron droplets. The terminal settling velocity for a 5000, 500, and 50 micron droplet of the 2/3:1 Dursban:oil mixture at 10 degrees C is approximately 29, <1 and <.01 cm/sec (11.41, .39 and .004 in/sec), respectively. Two breakup methods can be used, mechanical or chemical. The mechanical method is to design the injection system such that smaller droplets are produced. The chemical method is an addition of emulsifiers to the mixture to change the surface tension and reduce the mean droplet diameter. The present trend in the chemical industry is to add emulsifiers.

Another possible cause of the wider distribution in the field results versus the model is solubility. The model assumes no mass transfer between the phases. Chlorpyrifos formulations are actually soluble in water up to a concentration of approximately 3 ppm. In normal injection, this would constitute only a 5 to 10% reduction in the chemical volume. However, the magnitude of some of McLeod's (1983) raw data could possibly be explained by solubility due to the low concentrations of chlorpyrifos found. The solubility would also tend to widen the distribution which is evident in the field data, but not in the simulation data.

The simulation results then seem to be reasonable. The results of the simulation tend to indicate that a droplet size of less than 500 microns is desirable and even less than 100 micron would be more desirable. With the smaller droplet sizes, the problem of maintaining suspension is reduced due to the decreased settling velocity. The total volume is also contained in more droplets, which would probably result in a more desirable distribution from improved homogeneity of the two phase flow.

6.4.3 Seedigation

The second study used for validation is some seedigation work performed by the Agricultural Engineering Department, Coastal Plain Experiment Station, Tifton GA. The data for this experiment was obtained from contacts with

Dr. Dale Threadgill, Dr. John Young and Mr. David Cochran. The study included some of the first seedigation attempts, and again, much data needed for the simulation model was missing. The study was basically an experiment to determine if a pivot could be used to distribute seed, so limited quantitative data was collected. Much of the data used in the model simulation was based on memory and was obtained by personal communication with Cochran (1986). The study was conducted using a single tower pivot located at Camilla, GA. The pivot was a Lockwood (Model# 1981-2205) system using low angle impact sprinklers with controlled droplet size nozzles.

The system parameters used in the simulation model are listed in Table 6.2. The assumptions for the missing values will be explained. Figure 6.11 shows the sprinkler discharge flow rate versus pipe diameters for the system. The curve is also characteristic of a center pivot with the major proportion of the flow being discharged at the far extremities. Figure 6.12 is a cumulative percent flow volume versus position along the machine. The same characteristics are evident as discussed in Figure 6.2. Figure 6.12 will be used as a standard curve for comparison of the seed discharge curves.

Figure 6.13 is a plot of the system's Reynolds number versus position along the machine. The magnitudes are greater than McLeod's (1983) study using a "iconic" model of a 400 m (1310 ft) pivot. These numbers are also similar in

TABLE 6.2 MODEL SIMULATION INPUTS FOR SEEDIGATION STUDY
(ONE TOWER PIVOT, CAMILLA, GA)

VARIABLE	MAGNITUDE	UNITS
System Length	49.9	m
Total Flow Rate	299.8**	L/min
Pipe Inside Diameter	12.065	cm
Pipe Roughness (e)	0.015	cm
Sprinkler Spacing	Variable	m
Sprinkler Inlet Diameter	1.91	cm
Total Number of Sprinklers	17	
Sprinkler Position	Top	
<u>CONTINUOUS PHASE (WATER)</u>		
Temperature	21.0	degrees C
Density	0.9979	g/cm ³
Viscosity	0.009846	g/cm sec
<u>DISPERSED PHASE (TURNIP SEED + 11N CROP OIL)</u>		
Density	0.9949-1.0000	g/cm ³
Droplet Size	2498-2485	microns
Vertical Starting Position (From Pipe Center Line YP)	Variable	cm

** See Figure 6.11 For Outflow Characteristics

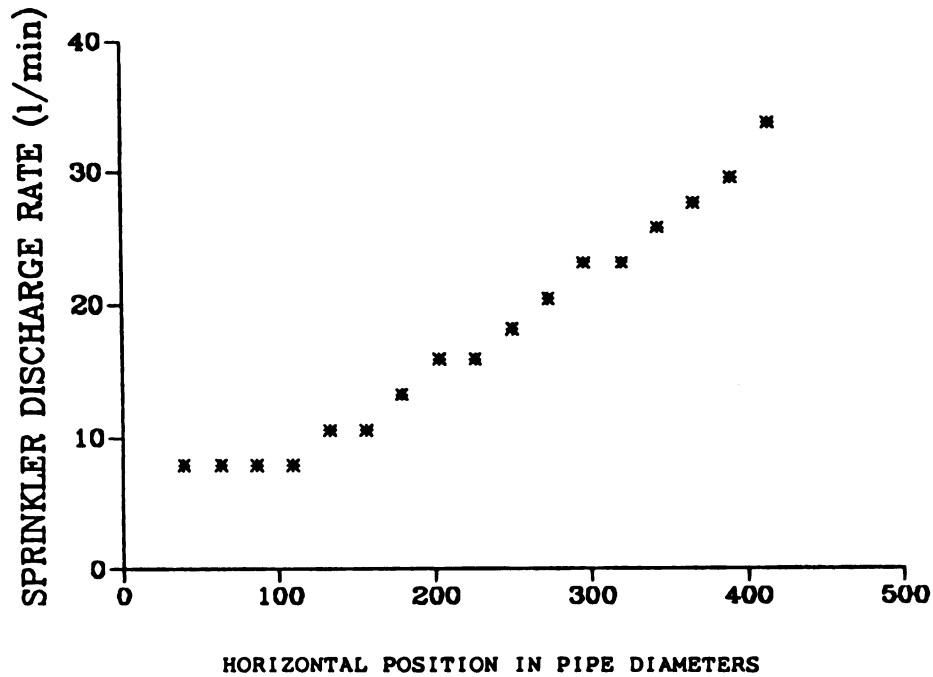


FIGURE 6.11 SPRINKLER DISCHARGE RATE VS POSITION ALONG A 49.9 M ONE TOWER PIVOT (CAMILLA, GA.)

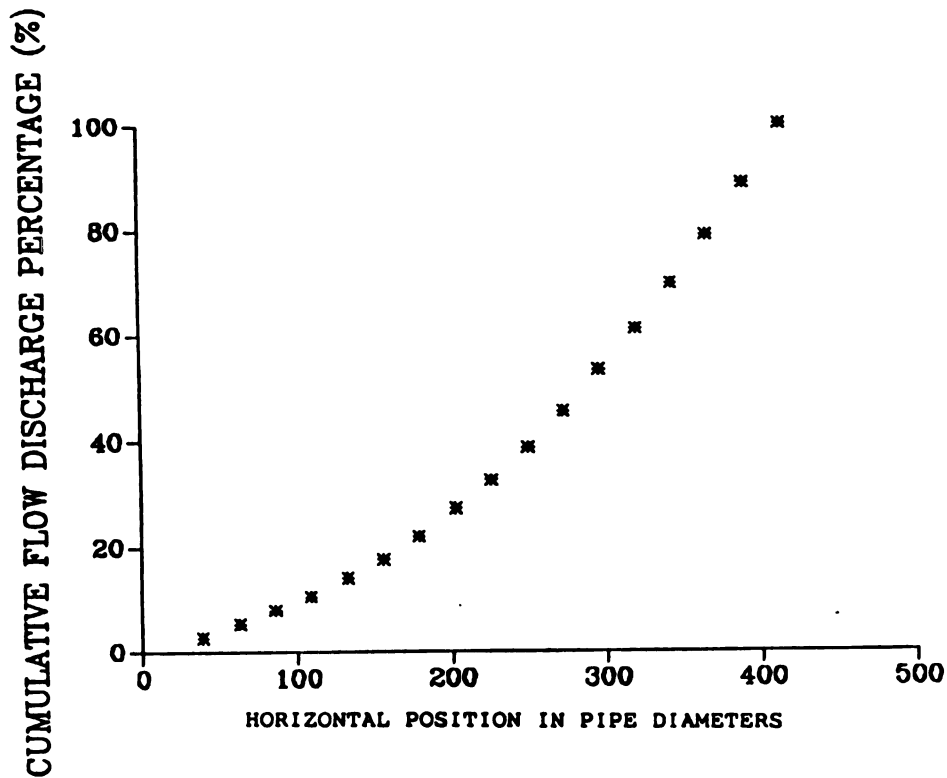


FIGURE 6.12 CUMULATIVE DISCHARGE PERCENTAGE VS POSITION ALONG A 49.9 M ONE TOWER PIVOT (CAMILLA, GA.)

magnitude to the last span of the full scale 402 m (1320 ft) pivot shown in Figure 2.2.

Figure 6.14 is a plot of the various flow velocities in the system. The mean pipe flow velocity decreases by 88.8% from upstream of the first sprinkler to just upstream of the last sprinkler. The friction velocity decreases by 86.3% from upstream of the first sprinkler to just upstream of the last sprinkler. The mean flow in the sprinkler inlet increases by 324% from the first sprinkler to the last sprinkler. Since McLeod's model is based on a system which would be 10 times longer than this system, the difference in the sprinkler inlet velocity difference should differ by a factor of 10.

The seedigation study used turnip seed for distribution. Plain turnip seed was injected into the system and was not distributed. The seeds were found in the sand trap at the end of the pivot. The seeds were then mixed with 11N crop oil, and satisfactory distribution was obtained by visual observation of the ground. However, quantitative data values were not obtained. The simulation model was tested using these these conditions with some additional assumptions.

Turnip seed fit the assumptions of the simulation model rather nicely since they are spheroidal in shape. Turnip seeds were measured with a micrometer and found to be approximately 1,550 microns in diameter with a standard deviation of 15 microns. A bulk density of the seeds was

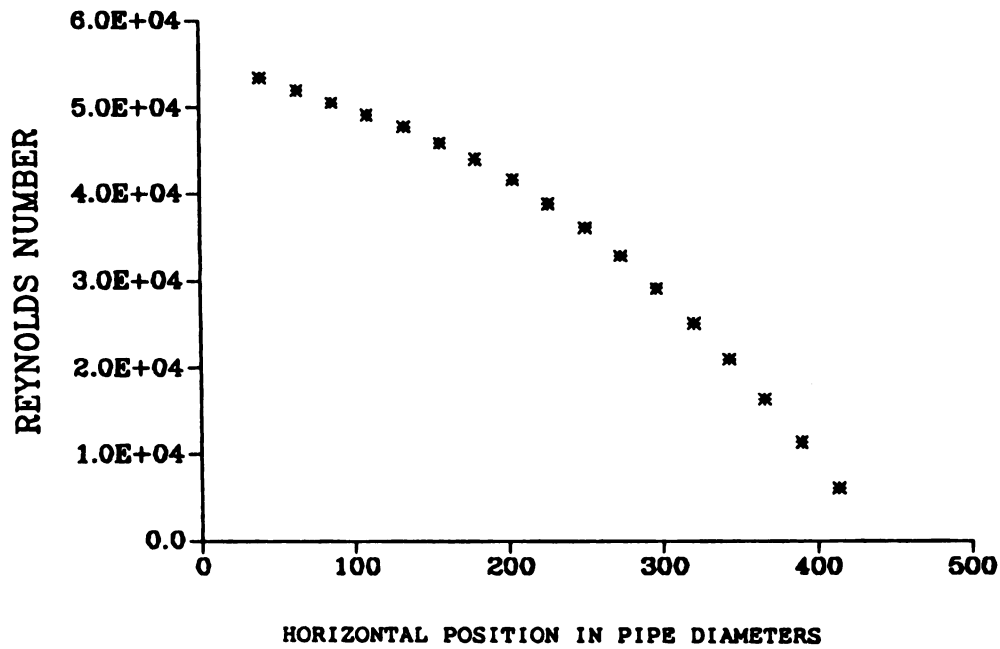


FIGURE 6.13 REYNOLDS NUMBER VS POSITION ALONG A 49.9 M ONE TOWER PIVOT (CAMILLA, GA.)

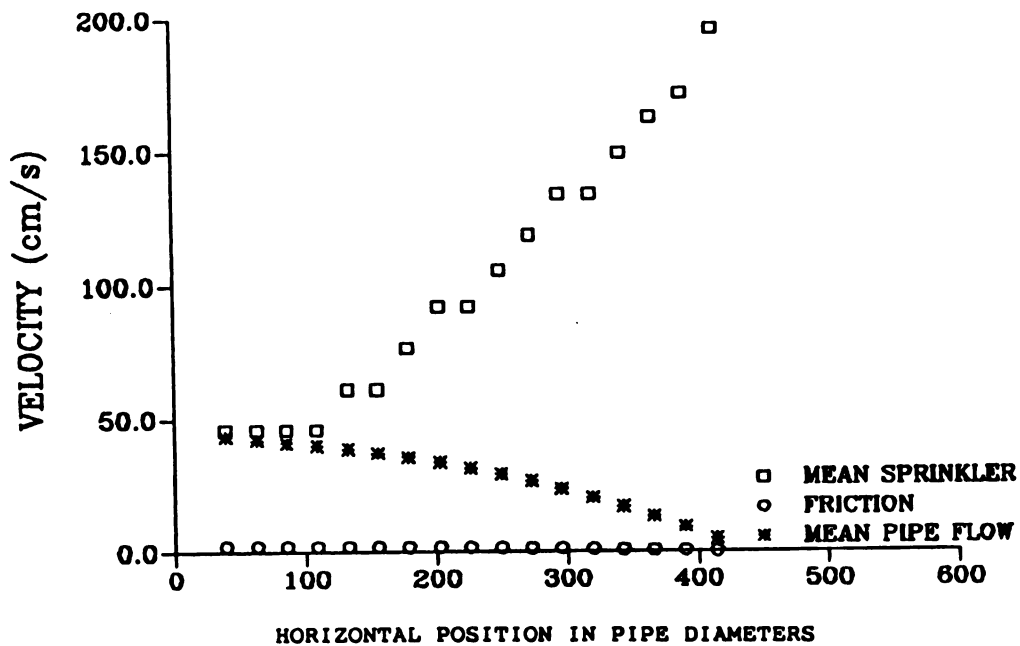


FIGURE 6.14 VELOCITY VS POSITION ALONG A 49.9 M ONE TOWER PIVOT (CAMILLA, GA)

determined to be 1.296 g/cm^3 . Assuming a void fraction of 10%, the density of the seeds would be 1.44 g/cm^3 , which is the density used for calculations.

In the field test, a 11N crop oil-seed mixture was injected at a rate of 4,675 cc/ha (4 pt/ac). Seeds, 280 g/ha (1/4 lb/ac), made up 195 cc/ha (0.17 pt/ac) of the injected mixture. Therefore, the volumetric ratio of the seeds to 11N crop oil was approximately 1:23. To simulate this situation, it was assumed that a single seed was coated with a film of oil. In essence, the oil was assumed to have created a larger effective seed diameter and decreased the effective density. The effective oil-seed droplet diameter is based only on effective specific gravity calculations and not according to actual measurements of oil volume adhering to a turnip seed. It was assumed that the density of the effective droplet must be close to the density of the 21 degree C water (Cochran, 1986) which would be 0.9979 g/cm^3 . A volume of oil was added to a 1,550 micron seed until the specific gravity was 1.0 in reference to 21 degree C water. Figure 6.15 is a plot of effective specific gravity for a 2,485 to 2,503 micron turnip seed-oil effective droplet size range. It was assumed that only part of the total oil volume was used in coating the seed. The remaining oil volume was assumed to be discharged as oil droplets which probably would not be detected by visual observation. It was also assumed that the seed-oil droplets would not be of uniform size or volume, but rather some

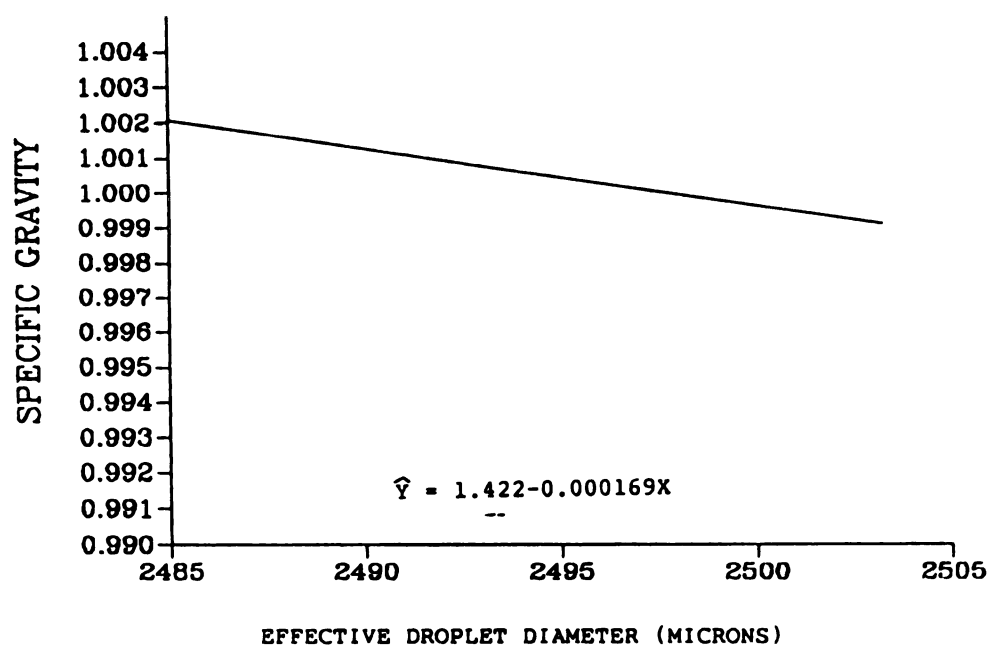


FIGURE 6.15 SPECIFIC GRAVITY VS EFFECTIVE DROPLET DIAMETER
TURNIP SEED + 11N CROP OIL

distribution existed. For the simulations, the oil volume was varied by a given percentage, and the fraction of this percentage that was added to each seed was determined by a random factor (RANF). For example, the standard effective droplet size was set at 2,498 microns, which has a specific gravity of 1. The volume of oil was varied by $\pm 1\%$ times the random number, thus producing droplets ranging in size from 2,491 to 2,498 micron with a density range of 0.9989 to 0.9979 g/cm³ or a specific gravity range of 1.0010 to 1.0000. The random factor is completely random, so equal probability is given to the occurrence of each droplet size in the size range.

The injection point was the next need for an assumption. Cochran (1986) stated that the injection point was either of two places, before the top pivot elbow or in the mainline feeding the pivot. The mainline feeding the pivot possibly has three elbows prior to entry into the overhead pipe. This injection situation greatly complicated defining the vertical position from which the droplets start. It was therefore assumed the seed-oil droplets had a probability of being at any vertical position upon exiting the top pivot elbow. Random numbers were again generated. A random number determined if the droplet was above or below the pipe center line, and another random number determined the vertical position of the droplet. This assumption gives equal probability for the vertical starting position to be at any position in the pipe cross section.

The first simulations used only turnip seed with no oil added. Fifty 1,550 micron seeds with a density of 1.44 g/cm^3 were used for each simulation. The percentage of the residence time spent in an eddy encounter was set at 20%. The critical sprinkler effect velocity ($\bar{v}_{LL}$) at which the sprinkler effect is activated was set at 68% of the critical discharge velocity ($\bar{v}_r$) (See Figure 5.2). This critical velocity allowed the sprinkler effect activation limit (LL) to increase to approximately 90% of the pipe diameter at the last sprinkler. Figure 6.16 is a plot of the simulation. The cumulative percentage discharged and injected curves are compared to the standard water discharge curve (Figure 6.12). Of the 50 seeds injected, 96% remained in the irrigation system. Of the discharged seed, the site of discharge was near the end of the system where the sprinkler effect is at a maximum. The eddy time was then increased to 40%, and the results are shown in Figure 6.17. Again, the number of seeds not discharged was high at 94%. The first seed was discharged at an earlier sprinkler since increasing the eddy time helps maintain a suspension. The trends for both of these simulations fit the trends of the field results, where the seeds were not distributed but were found in the sand trap at the end of the system.

The first simulations using oil used an oil volume that was varied by -1% times a random number. The specific gravity for this size range is greater than or equal to 1.0, so this droplet range would settle without turbulence or

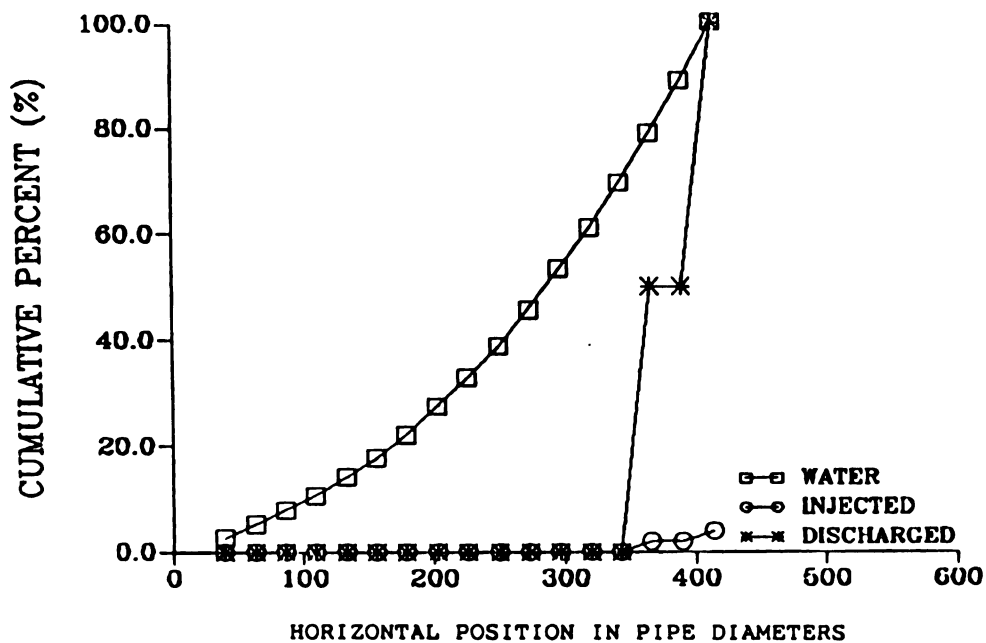


FIGURE 6.16 SIMULATED CUMULATIVE PERCENT WATER, SEED INJECTED AND SEED DISCHARGED VS POSITION ALONG A 49.9 M ONE TOWER PIVOT (CAMILLA, GA.) TURNIP SEED WITHOUT OIL
DIAMETER= 1,550 MICRON DENSITY = 1.44 G/CM³
EDDY TIME = 20% YSTART_RANGE -R TO R

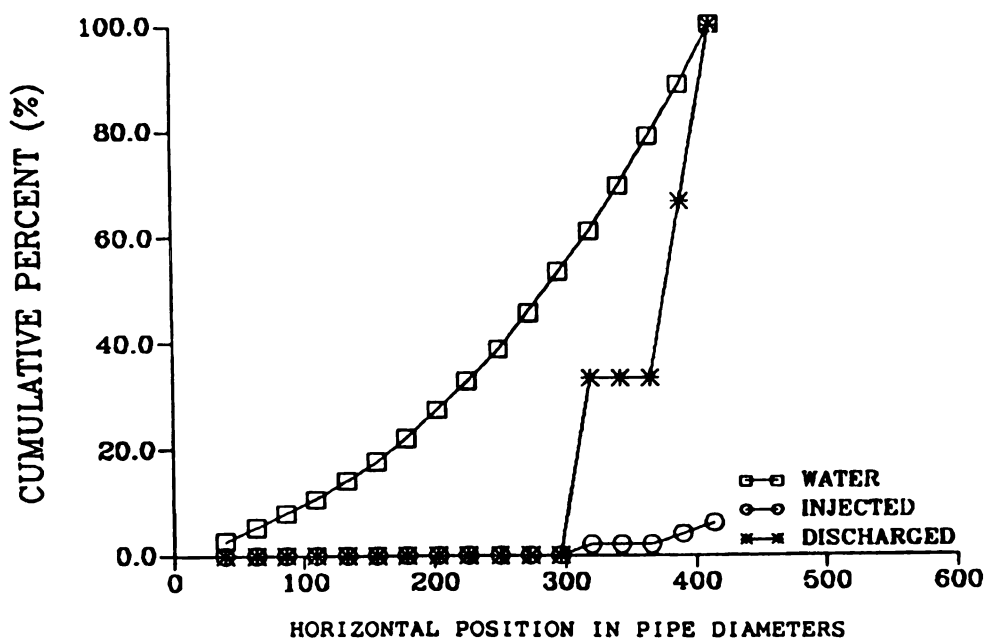


FIGURE 6.17 SIMULATED CUMULATIVE PERCENT WATER, SEED INJECTED AND SEED DISCHARGED VS POSITION ALONG A 49.9 M ONE TOWER PIVOT (CAMILLA, GA.) TURNIP SEED WITHOUT OIL
DIAMETER= 1,550 MICRON DENSITY = 1.44 G/CM³
EDDY TIME = 40% YSTART RANGE -R TO R

sprinkler effect. Figure 6.18 is a simulation using an eddy time of 20%. This simulation seemed to follow the same shape as the water distribution curve, but was elevated at the beginning of the system. The % discharge curve fits the water distribution curve especially well near the end of the system. The percent of the total number of injected seeds discharged was 74%. The mean sprinkler number where discharge occurred was 8.62, with a standard deviation of 5.54.

Figure 6.19 is a plot of the same simulation, except the eddy time is increased to 30%. The curve shape for Figures 6.18 and 6.19 are similar in shape while the elevated levels at the beginning of the curves in Figure 6.18 seem to be shifted more to the right in Figure 6.19. The increase in turbulence effect served to carry the lighter density seed-oil droplets farther in the system thus shifting the distribution. The increase in eddy time also increased the total percentage discharged to 83%. The mean sprinkler number where discharge occurred was 8.43 with a standard deviation of 4.91. The increase in the eddy time did not significantly change the mean sprinkler of discharge, but rather clustered the distribution and increased the total discharge percentage.

Figure 6.20 is a plot of the same simulation using 40% eddy time. The distribution is again shifted and clustered near the center of the system. The mean sprinkler number where discharge occurred was 8.07, with a standard deviation

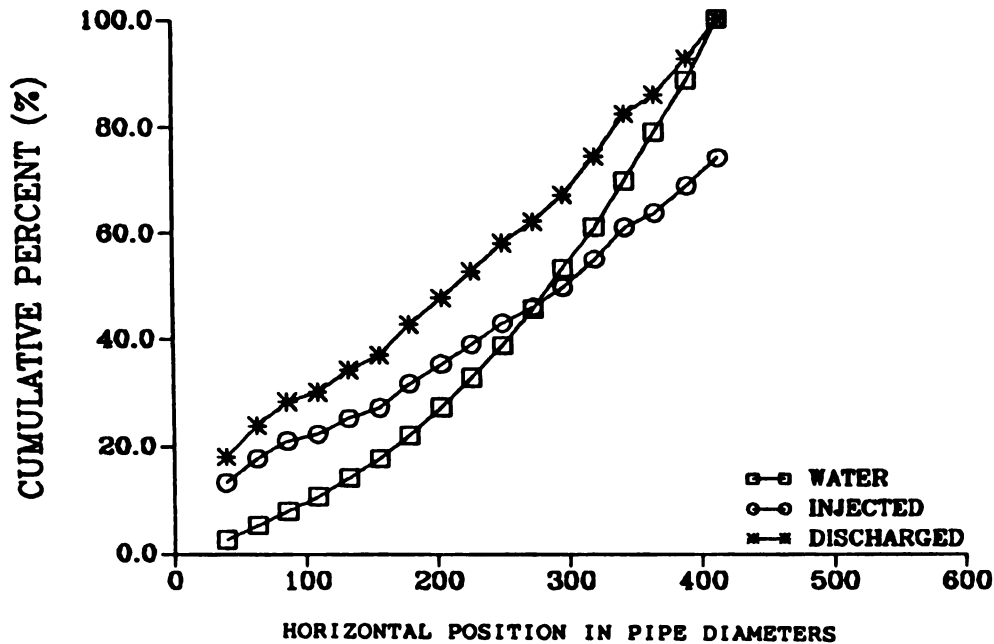


FIGURE 6.18 SIMULATED CUMULATIVE PERCENT WATER, SEED INJECTED AND SEED DISCHARGED VS POSITION ALONG A 49.9 M ONE TOWER PIVOT (CAMILLA, GA.) TURNIP SEED WITH OIL
DIAMETER= 2498-2491 MICRONS SP. GRAV.= 1.0-1.001 G/CM³
EDDY TIME= 20% YSTART RANGE= -R TO R

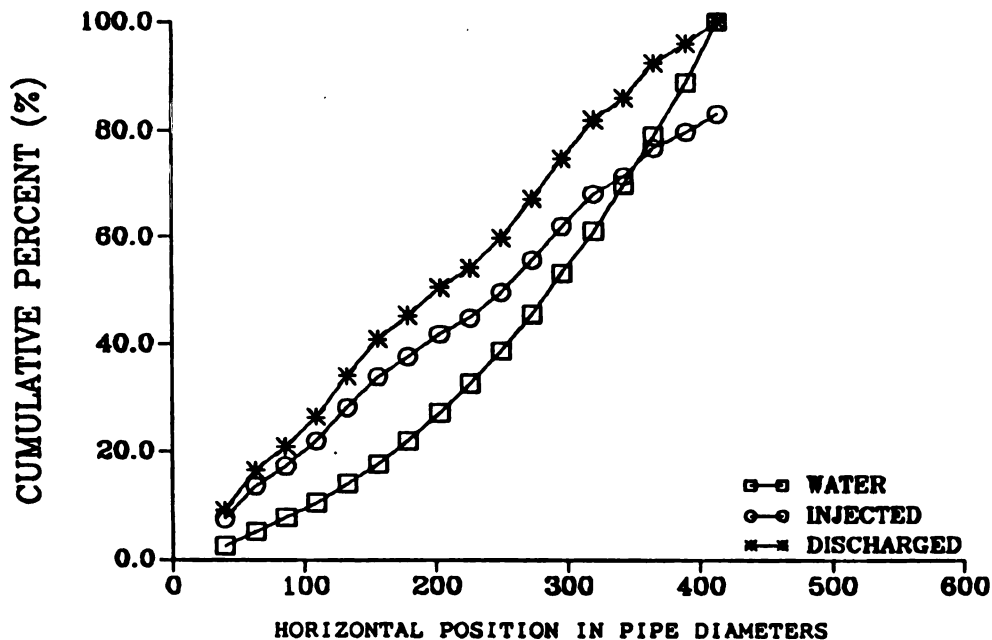


FIGURE 6.19 SIMULATED CUMULATIVE PERCENT WATER, SEED INJECTED AND SEED DISCHARGED VS POSITION ALONG A 49.9 M ONE TOWER PIVOT (CAMILLA, GA.) TURNIP SEED WITH OIL
DIAMETER= 2498-2491 MICRONS SP. GRAV.= 1.0-1.001 G/CM³
EDDY TIME= 30% YSTART RANGE= -R TO R

of 4.86. The increase in eddy time also increased the total percentage discharged to 88.7%. However, the distribution curves do not fit the water distribution curve as well near the end of the system. The increase in eddy effect caused the distribution to be discharged earlier and become more compacted. The shape of the distribution curves is also approaching a linear function for the first two thirds of the system.

The oil volume was then varied by +1% times a random factor. This simulation resulted in droplets in the 2,498 to 2,503 micron droplet size range, with a density range of 0.9979 to 0.9970 g/cm³. The specific gravity for this range is 1.0 to .9991, which would cause this droplet size range to be buoyant. Figure 6.21 is a plot of this simulation. The cumulative percentage discharge and total percentage curves are identical since all of the injected seeds were discharged. The shape of the curves do not match the shape of the water distribution curve. The buoyancy of the droplets seen to have caused the droplets to "float out", thus causing the distribution to be skewed to the left. The seeds were only distributed as far as sprinkler number 15 of the 17 sprinkler machine. The results of this simulation are consistent to the results of the McLeod (1983) simulation where the large (>2,000 micron) buoyant droplets were discharged very early in the system when the outlet are on the top of the pipe. In this simulation, the droplets which were carried the farthest were closer to the density of the water.

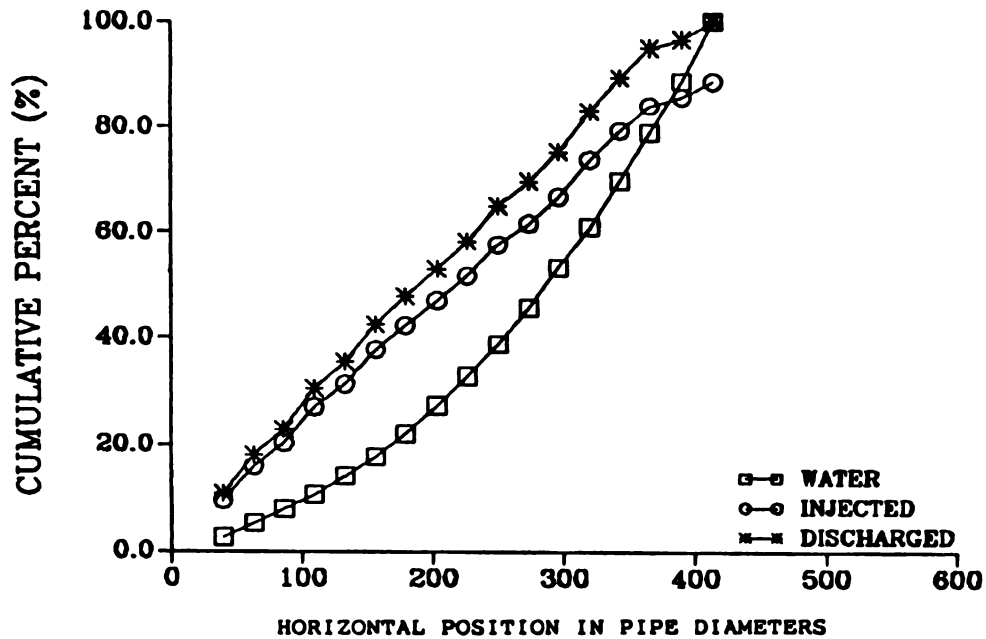


FIGURE 6.20 SIMULATED CUMULATIVE PERCENT WATER, SEED INJECTED AND SEED DISCHARGED VS POSITION ALONG A 49.9 M ONE TOWER PIVOT (CAMILLA, GA.) TURNIP SEED WITH OIL
DIAMETER= 2498-2491 MICRONS SP. GRAV.= 1.0-1.001 G/CM³
EDDY TIME= 40% YSTART RANGE= -R TO R

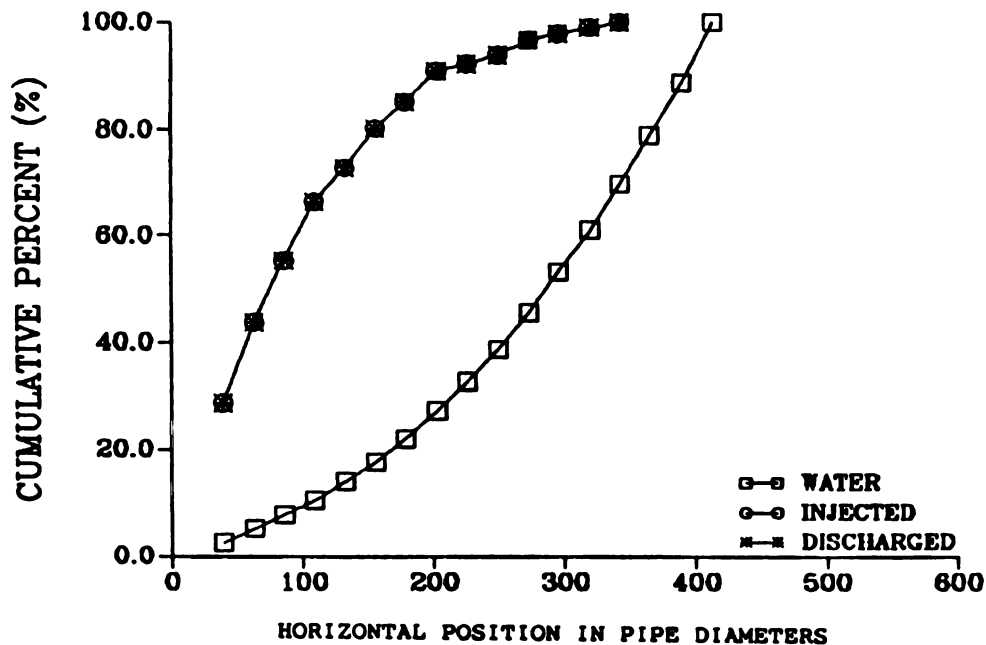


FIGURE 6.21 SIMULATED CUMULATIVE PERCENT WATER, SEED INJECTED AND SEED DISCHARGED VS POSITION ALONG A 49.9 M ONE TOWER PIVOT (CAMILLA, GA.) TURNIP SEED WITH OIL
DIAMETER= 2503-2498 MICRONS SP. GRAV.= 0.997-1.0 G/CM³
EDDY TIME= 20% YSTART RANGE= -R TO R

In looking at the simulation results, it was observed that the seeds with a starting position near the pipe walls were being distributed at the extremes of the irrigation system. Droplets starting near the top pipe wall were generally discharged out the first two sprinklers. The assumption of complete randomness for the starting position across the whole pipe diameter was questioned. This could be some of the cause for the elevated levels at the beginning of the system. A different probability distribution function for the random generator which would simulate the pipe flow velocity profile distribution would probably be the best method to test. However, to test the hypothesis, the starting position of the droplets was restricted, and the completely random generator was used again. The starting position was restricted near both pipe walls by assuming that no droplet starting position could occur within 0.60 cm of the pipewall. This value restricted the starting position to within 90% of the pipe radius measured from the pipe center line. Figure 6.22 is a simulation using the same -1% oil volume variation with an eddy time of 20%. Here the curves match the water distribution curve much better than the curves of Figure 6.18, the identical simulation with no restriction on the starting position. The extremes of the curves also better match the water distribution. The mean sprinkler number where discharge occurred is 8.74 with a standard deviation of 5.49, which is compared to 8.62 and 5.54 for the simulation shown in Figure

6.18. Of the total number of seeds injected, 74.7% are discharged compared to 74% for Figure 6.18. As far as discharge statistics, the two simulations are the same, but the shape of the distribution curve seems to have been improved using the restricted starting position assumption.

In Figure 6.23, the same simulation is shown, except the eddy time is increased to 30%. The same types of trends are observed with a shifting and clustering of the distribution near the center of the system.

A simulation was tested with varying the oil volume by -2% times a random factor. This would produce a seed:oil droplet distribution range of 2,485 to 2,498 microns with a density range of 1.0000 to 0.9979 g/cm³. The specific gravity for this size range would range from 1.0021 to 1.0000. This simulation used an eddy time of 40% and the restricted starting position assumption. The results of this simulation are shown in Figure 6.24. The shape of the % discharged curve matches the shape of the water distribution curve better than any simulation previously reported. The extremities of the curves are well matched; however, the percentage of the total number of injected seeds that are discharged is only 58.3%. The increased number of more dense seed:oil droplets resulted in a substantial decrease in the percentage discharge.

The terminal settling velocity of a 1,550 micron turnip seed with a density of 1.44 g/cm³ is 58.7 cm/sec in 21 degree C water. Figure 6.25 is a plot of the terminal

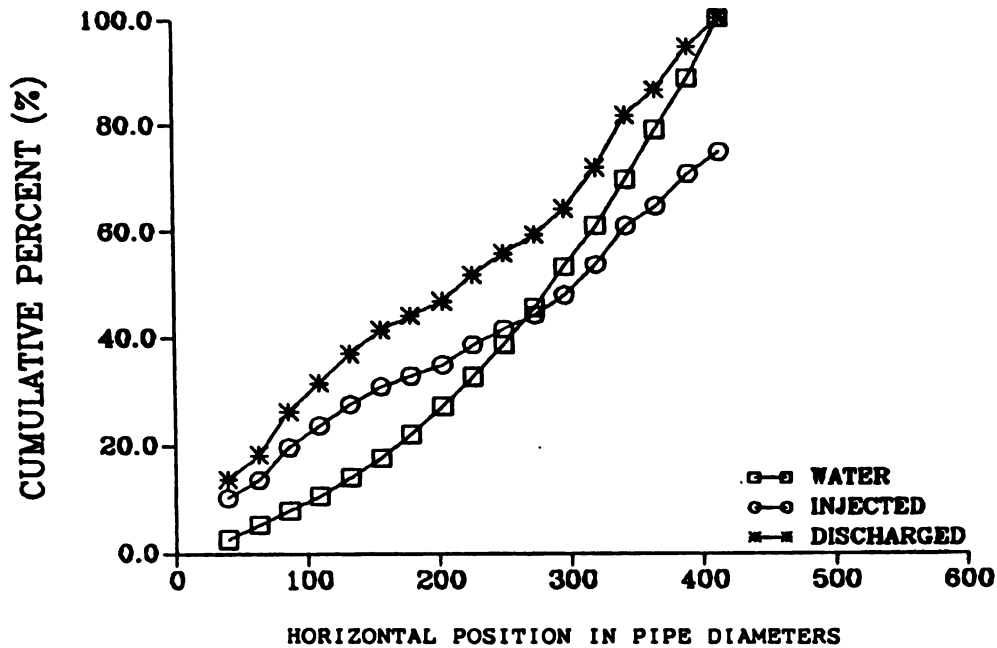


FIGURE 6.22 SIMULATED CUMULATIVE PERCENT WATER, SEED INJECTED AND SEED DISCHARGED VS POSITION ALONG A 49.9 M ONE TOWER PIVOT (CAMILLA, GA.) TURNIP SEED WITH OIL
DIAMETER= 2498-2491 MICRONS SP. GRAV.= 1.0-1.001 G/CM³
EDDY TIME= 20% YSTART RANGE= -.9R TO .9R

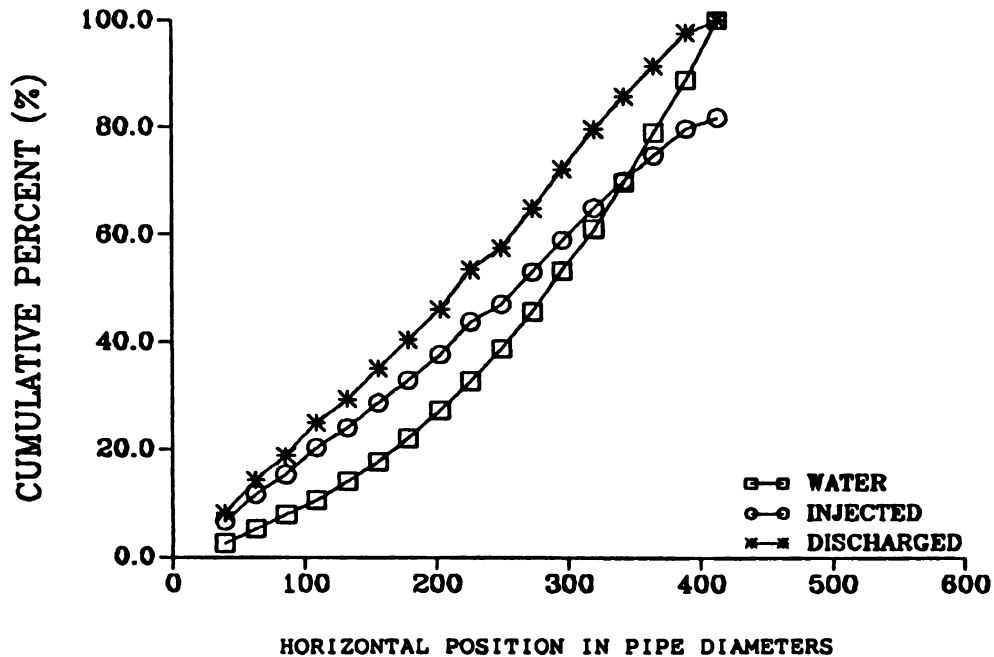


FIGURE 6.23 SIMULATED CUMULATIVE PERCENT WATER, SEED INJECTED AND SEED DISCHARGED VS POSITION ALONG A 49.9 M ONE TOWER PIVOT (CAMILLA, GA.) TURNIP SEED WITH OIL
DIAMETER= 2498-2491 MICRONS SP. GRAV.= 1.0-1.001 G/CM³
EDDY TIME= 30% YSTART RANGE= -.9R TO .9R

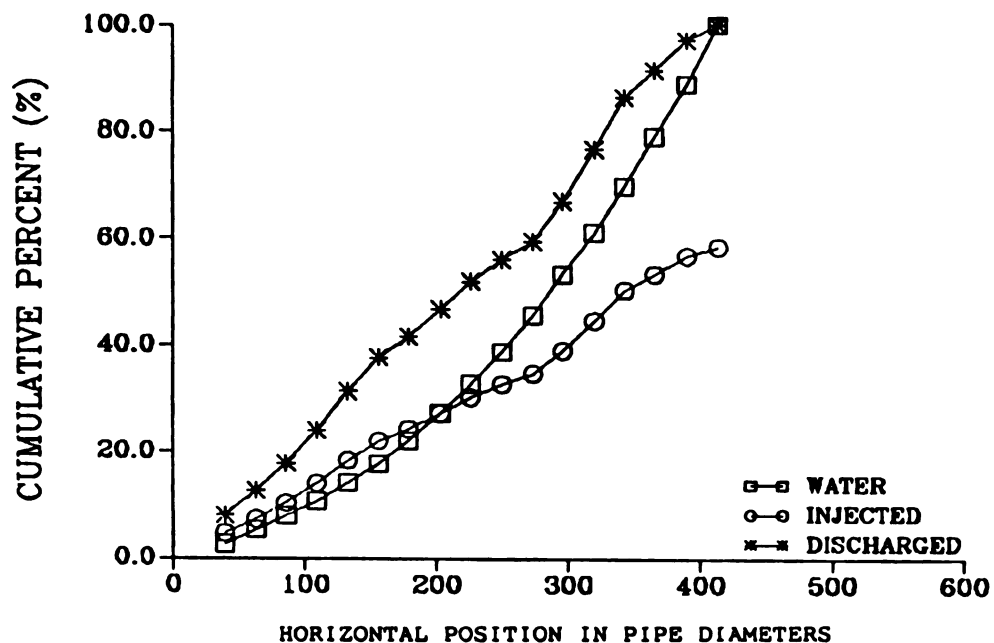


FIGURE 6.24 SIMULATED CUMULATIVE PERCENT WATER, SEED INJECTED AND SEED DISCHARGED VS POSITION ALONG A 49.9 M ONE TOWER PIVOT (CAMILLA, GA.) TURNIP SEED WITH OIL
DIAMETER= 2498-2485 MICRONS SP. GRAV.= 1.0-1.0021 G/CM³
EDDY TIME= 40% YSTART RANGE= -.9R TO .9R

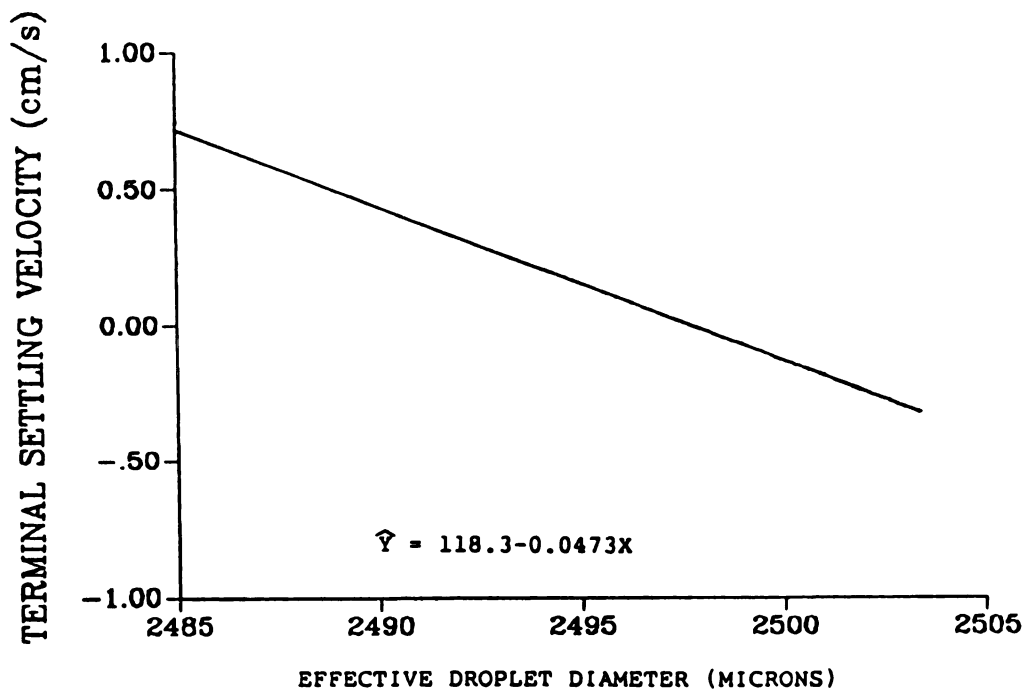


FIGURE 6.25 TERMINAL SETTLING VELOCITY VS EFFECTIVE DROPLET DIAMETER, TURNIP SEED+11N CROP OIL
SPECIFIC GRAVITY= 0.997 TO 1.0021, TEMP.= 21 DEGREES C

settling velocity for the oil-seed droplet size ranges used for the simulations. A 2,498 micron droplet has the same effective density as the water; therefore, the settling velocity is 0.0. Increasing the oil variation from -1% to -2% increased the settling velocity by only 0.11%. Comparing these velocity magnitudes to the velocities plotted in Figure 6.14, the influence of the settling velocity for the seed with no oil is a dominant velocity. Adding the oil helps minimize this dominance.

As a summary of the simulation of the seedigation study, the simulation model was found to be capable of producing reasonable results based upon some reasonable assumptions. Using the same assumptions for both the seeds alone and the seeds with oil generated results consistent with the observed field results. The simulation again signaled potential distribution problems using large (>2000 micron) buoyant droplets. The simulation model also indicated the need to keep the specific gravity of the two phases as close to 1.0 as possible.

6.5 Model Simulations

As indicated in chapter 4, some field studies were performed which justified the need for a model. The model will now be used to simulate one of the experiments to examine what the model will predict. The experiment that will be simulated was performed in 1984 and is discussed in section 4.2. The model will require some additional

assumptions with respect to droplet size distribution.

The modeled system is a linear move irrigation system which would also be comparable to a solid set irrigation line as related to hydraulic properties. Figure 6.26 is a plot of the sprinkler discharge versus horizontal position in pipe diameters. In general, each sprinkler is discharging the same amount of water. Some deviation is observed in Figure 6.26 because some sprinklers are varied to compensate for the pressure loss in the line. Figure 6.27 is a cumulative discharge percentage versus location along the machine and is the standard curve to compare with the chemical discharge curve just as Figures 6.2 and 6.12. Since the sprinklers are discharging relatively equal amounts of water, Figure 6.27 is a linear curve. A plot of the Reynolds numbers for this system is the linear depicted in Figure 2.2. The magnitude of the Reynolds number for this system discharging water at 11 degrees C would range from above 330,000 to above 5,000, so this system is quite turbulent for the entire system length. These magnitudes are reduced from the magnitudes found in Figure 2.2, which is based on a higher design flow rate.

Figure 6.28 is a plot of the velocities in the system. The friction velocity which is initially 12.95 cm/sec (5.10 in/sec) is substantially higher than any of the other systems modeled. The mean pipe flow velocity decreases by 98% from upstream of the first sprinkler to upstream of the last sprinkler. The friction velocity decreases by 97.8%

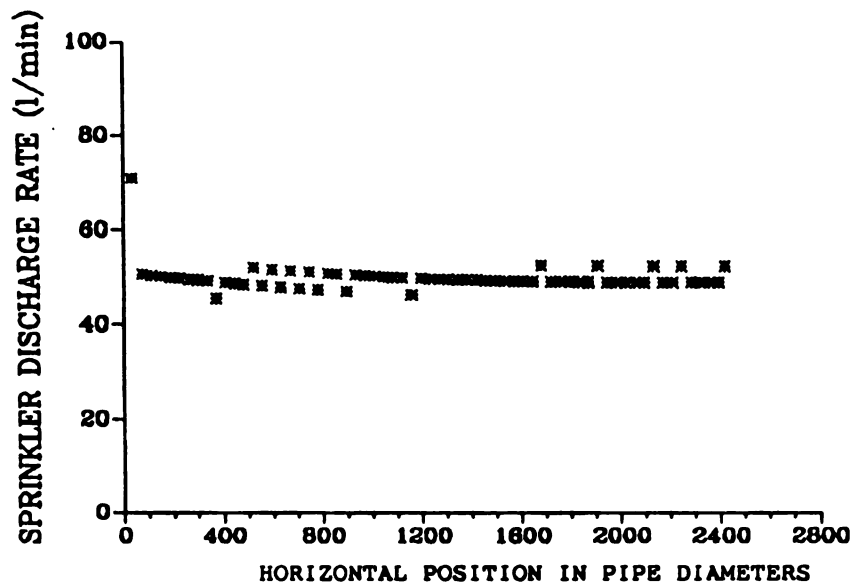


FIGURE 6.26 SPRINKLER DISCHARGE RATE VS LOCATION ALONG A 394 M LINEAR MOVE MACHINE (KBS LINEAR, REESE, 1984)

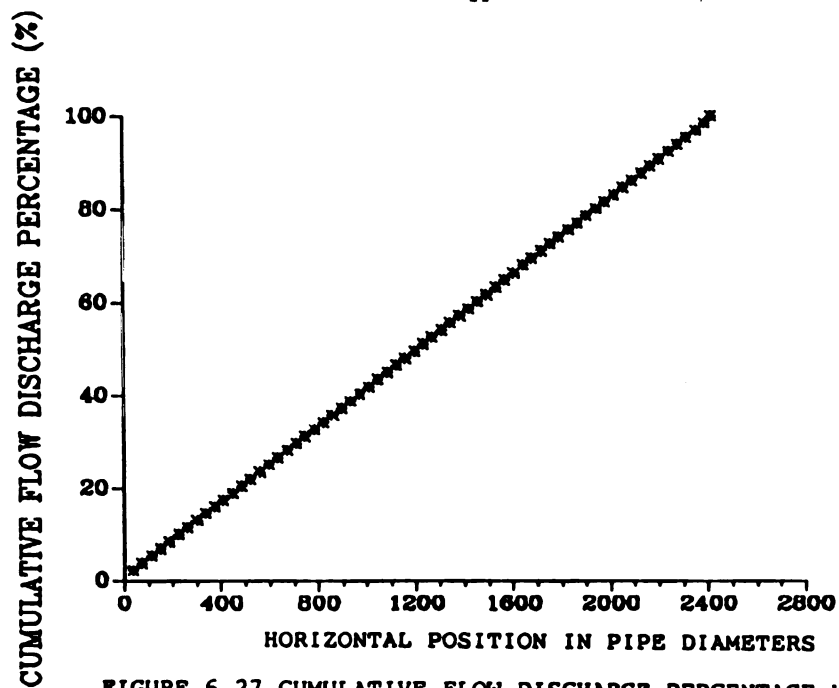


FIGURE 6.27 CUMULATIVE FLOW DISCHARGE PERCENTAGE VS LOCATION ALONG A 394 M LINEAR MOVE MACHINE (KBS LINEAR, REESE, 1984)

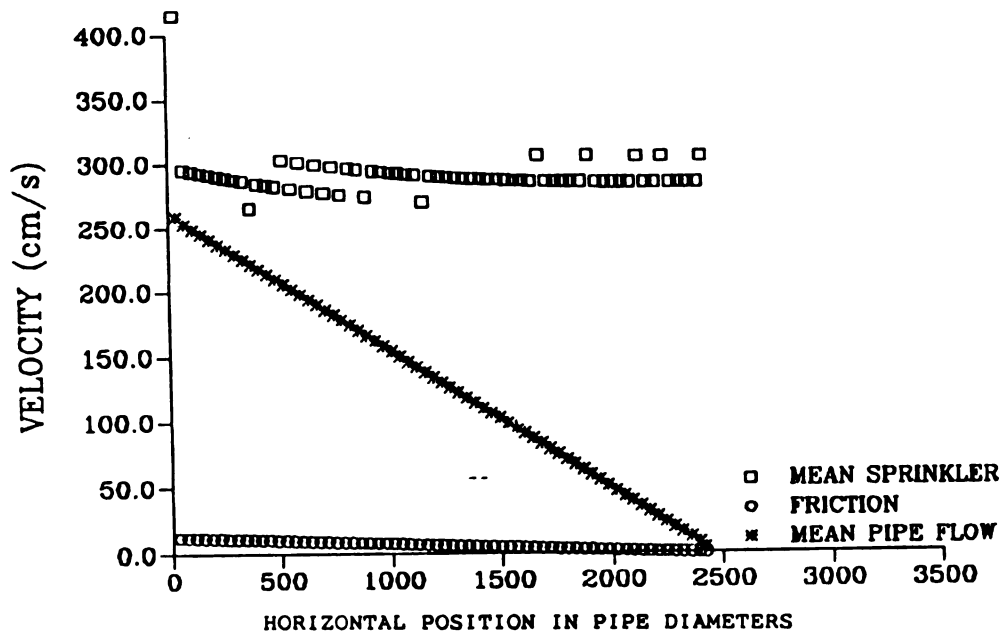


FIGURE 6.28 VELOCITY VS LOCATION ALONG A 394 M LINEAR MOVE MACHINE (KBS LINEAR, REESE, 1984)

from upstream of the first sprinkler to upstream of the last sprinkler. The mean sprinkler inlet velocity remains relatively constant since all sprinklers are discharging at a fairly constant rate.

Table 6.3 lists the major inputs into the simulation model for this system. The chemical injected into the system was Dursban 6 plus salad grade soybean oil mixed in a 1:2 ratio. The temperature of the water was approximately 11 degrees C. At this temperature, Dursban 6 would have an approximate density of 1.163 g/cm^3 , and soybean oil would have a density of approximately 0.9296 g/cm^3 . The mixture would then have a density of approximately 1.0074 g/cm^3 and a specific gravity of 1.0078. Soybean oil is more dense than 11N crop oil. These droplets would have a slightly larger terminal settling velocity than the droplets of equal size plotted in Figures 6.9 and 6.10.

The droplet distribution in the irrigation line was not measured. However, using the parameters for the injection system and some equations from Godfrey and Hanson (1982) for estimation purposes, it is quite possible that droplets of 5,000 microns and less were formed at the injection point. Using equation 2.14, the D_{p95} droplet size for this flow regime would be approximately 1,500 microns. Since the injection system was similar to Mcleod (1983), the droplet distribution in Figure 6.5 was simulated in this system.

The critical sprinkler effect velocity ($\bar{v}_{LL}$) was set at 53 cm/sec (20.9 in/sec) or 40% of the first sprinkler

TABLE 6.3 MODEL SIMULATION INPUTS FOR REESE (1984) STUDY
(KBS LINEAR, HICKORY CORNERS, MI)

VARIABLE	MAGNITUDE	UNITS
System Length	393.7	m
Total Flow Rate	3231.6**	L/min
Pipe Inside Diameter	16.2738	cm
Pipe Roughness (e)	0.015	cm
Sprinkler Spacing	Variable	m
Sprinkler Inlet Diameter	1.905	cm
Total Number of Sprinklers	65	
Sprinkler Position	Top	
<u>CONTINUOUS PHASE (WATER)</u>		
Temperature	11.0	degrees C
Density	0.9996	g/cm ³
Viscosity	0.012748	g/cm sec
<u>DISPERSED PHASE (DURSBAN 6 + SOYBEAN OIL 1:2)</u>		
Density	1.0074	g/cm ³
Droplet Size	(500-6000)	microns
Vertical Starting Position (From Pipe Center Line YP)	0.0	cm

** See Figure 6.26 For Outflow Characteristics

discharge velocity ($\bar{v}_r$) (See Figure 5.2). The eddy time was set at 20%. Figure 6.29 is a plot of the simulation. Only 5.22% of the injected chemical volume was discharged. Chemical was discharged as far as sprinkler number 48. Discharged droplets ranged in size from 584-2,921 microns. Droplets which were not discharged ranged in size from 1,461-6,426 microns.

The critical sprinkler effect velocity ($\bar{v}_{LL}$) was increased to 79.2 cm/sec (31.2 in/sec) or 60% of the first sprinkler discharge velocity ($\bar{v}_r$). This would then decrease the sprinkler effect on the droplets. Figure 6.30 is a plot of this simulation. The change in sprinkler effect had no effect on the droplet sizes discharged or not discharged. The percentage of chemical volume discharged was only 6.1%. The farthest sprinkler where discharge occurred was sprinkler 34. The chemical discharge distributions for Figures 6.29 and 6.30 are basically the same.

In the field test, an indirect chemical mass balance using Figure 4.5 accounted for only approximately 31% of the injected chemical volume being discharged. This calculation is based on an uniform distribution of chemical droplets on the glass collection container bottom. However, the slides were always taken in the area of greatest droplet frequency and sometimes the only area with droplets. Therefore, a more realistic estimation of the chemical recovery would be 5-10% which is consistent with the model's simulated discharge.

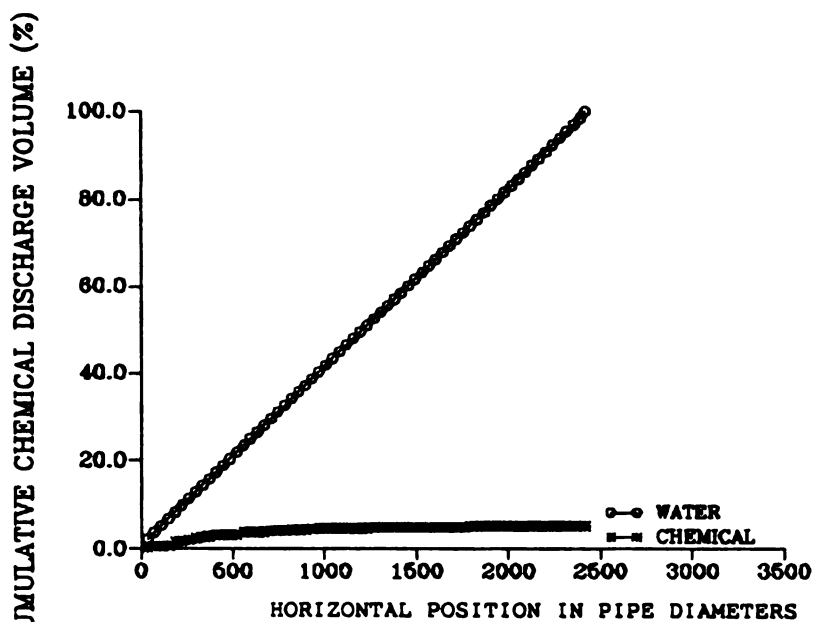


FIGURE 6.29 CUMULATIVE PERCENT WATER AND SIMULATED CHEMICAL VOLUME DISCHARGED VS POSITION ALONG A 394 M LINEAR MOVE MACHINE (KBS LINEAR, REESE, 1984)
DURSBAN 6 + SOYBEAN OIL 1:2, YSTART= 0, TEMP= 11 C
EDDY TIME= 20%, CRITICAL SPRINKLER VELOCITY= 53 CM/SEC

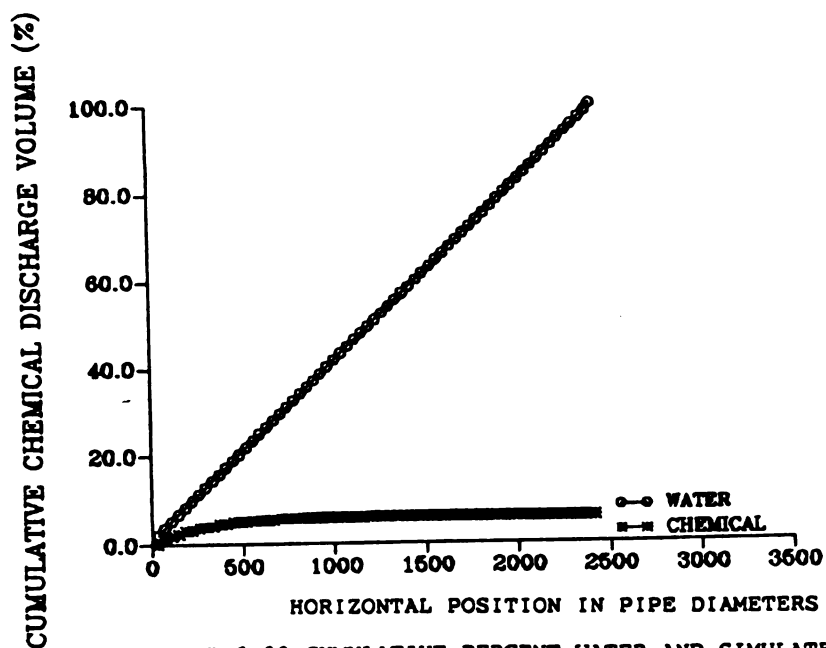


FIGURE 6.30 CUMULATIVE PERCENT WATER AND SIMULATED CHEMICAL VOLUME DISCHARGED VS POSITION ALONG A 394 M LINEAR MOVE MACHINE (KBS LINEAR, REESE, 1984)
DURSBAN 6 + SOYBEAN OIL 1:2, YSTART= 0, TEMP= 11 C
EDDY TIME= 20%, CRITICAL SPRINKLER VELOCITY= 79 CM/SEC

Some other interesting trends should be noted. In the field, the containers near the far end of the irrigation system had few or no droplets. The model simulated little or no discharge near the far end of the system. The model also simulated discharge rates near the beginning of the system that were consistent with the field tests. The largest external droplet was found in a container at approximately 1,600 pipe diameters, or approximately sprinkler number 43. This is also consistent with the model simulation where the farthest distance that the larger droplets (between 2,000 and 2,500 microns) were discharged was between sprinklers 32 and 48. This simulation is based on a hypothetical droplet size distribution; however, the distribution is probably realistic based on gross estimation equations and the field results.

Droplets were found in all but one or two of the collection containers which is not modeled by the simulation model. However, the larger size droplets ($>2,000$ microns) were probably split in the turbulent flow which is not modeled by the present model version. Smaller droplet sizes (<500 microns) were probably also in the initial distribution. Both of these factors would tend to spread the distribution and increase the percent discharged.

Based upon some assumptions, the model predicted that the majority of the chemical volume would not be discharged. This is consistent with a hypothetical conclusion reached from the limited quantitative field test results. This

simulation again points to the catastrophic results which may occur with large droplets ($>2,000$ microns). The specific gravity also plays an important role in maintaining the droplet suspension for the entire system length and should be kept as close to 1.0 as possible.

7.0 SUMMARY

7.1 Model Results

Reasonable simulation results were obtained for three distinctively different studies involving seedigation and insectigation. While no complete data sets were available to completely test the model, it produced simulations that matched the trends seen in field experiments when reasonable estimates of missing input data were used. In its present form, the model seems useful to predict whether a chemical of given physical characteristics will or will not be distributed along the total length of an irrigation machine of given characteristics.

For liquid-liquid two phase systems, the droplet size distribution created at the injection point is extremely important in determining the distribution of the chemical to the sprinklers. The specific gravity of the two phases also is of major importance in determining the distribution of the chemical to the sprinklers. Large droplet sizes (>500 micron diameter) at the injection point resulted in poor distribution with a specific gravity of 0.9834 at 10 degrees C. For a wide ranged droplet distribution (500-6,000 microns), a high percentage of the total chemical volume was contained in a relatively small number of large droplets.

With this type of skewed droplet volume and frequency distribution and specific gravity, the homogeneity of the water-chemical mixture is probably poor, and poor distribution should be expected. Similar poor distribution model results were produced when simulating an actual linear move machine, using the same droplet size distribution data at a specific gravity of 1.0074.

A droplet size of <500 microns in the flow is desirable for two reasons. First, the terminal settling velocity of smaller droplets is reduced compared to larger droplets, thus allowing the hydraulic properties of the flow to keep the droplets in suspension longer. Secondly, for a given amount of injected chemical and assuming constant volume for both sizes, a 10 fold decrease in droplet diameter would result in a 1,000 fold increase in droplet number. The mere increase in droplet numbers and the increase in suspending properties would serve to improve the mixture homogeneity and increase the probability of a better distribution for smaller droplet sizes.

The specific gravity of the two phases must be kept close to 1.0. When the specific gravity was varied from 1.0, an increase in settling or bouyancy of the chemical with respect to the water was observed. When mixing seed with a carrier oil, it is also important to keep the seed-oil effective specific gravity close to 1.0.

Significant distribution problems resulted when the settling velocity was in the same direction as the sprinkler

effect velocity (i.e. injected chemical buoyant with sprinklers on the top of the pipe). The suspending turbulence forces were not able to control the additive effect of the sprinkler and settling velocities; therefore, the distributions were skewed accordingly.

7.2 Model Capabilities

It was concluded that the model had some degree of flexibility since two completely different systems were modeled. The model also has the capacity to vary many of the major component effects by use of coefficients. These coefficients are presently set to match limited field results and are based on limited theory. Reasonable results were obtained when 20-30% of the residence time was spent in an eddy encounter. However, the percentage may be a function of the Reynolds number and may be system dependent. The assumed sprinkler effect based on the continuity equation and the relationship between velocity and position below the sprinkler seemed to work reasonably well. However, the actual extent of the sprinkler effect into the pipe flow and the variation caused by increased sprinkler discharge rates is still unknown since no actual experimental data exist.

7.3 Model Limitations

The model is a significant step forward in beginning to understand the engineering theory of chemigation. Future model validations and tests with more actual field data will

serve to test the model's true value for simulation. Some divergence problems were incurred using Equation 2.10 for small droplet sizes (<100 microns). Limiting the particle motion velocity to a maximum equal to the friction velocity appeared to resolve the problem.

7.4 Validation Data

The model has served to help visualize at least some of the important parameters involved in the chemigation process. Engineering theory and data was found to be extremely limited in relation to chemigation. Most reviewed studies did not list the hydraulic properties of the irrigation and injection system, so that any conflicting efficacy data could not be evaluated using engineering theory.

To model the process, many variable measurements are necessary and generally to a higher degree of accuracy than measured in the field. A mere observation of the second phase as buoyant is not acceptable. Density should be measured to the fourth decimal place. See Table 5.1 for the needed model inputs. Obtaining good droplet distribution data for a liquid-liquid two phase system within the irrigation pipeline is extremely difficult.

All chemigation field studies related to engineering theory should include a mass balance. Field results may not be sufficiently complete to be of value without a mass balance to validate the findings. All field studies must

be conducted with proper and functional safety equipment. No chemigation field test should be conducted without all the required safety equipment to protect the water supply, the environment, the operator and the public.

8.0 CONCLUSIONS

8.1 Model Results

1. Simulation model results exhibited the same trends as found in three chemigation field tests.
2. Injected particle or droplet diameters should be less than 500 microns for distribution.
3. Droplet or particle diameters of less than 100 microns are desirable for a good distribution
4. A droplet diameter size range should not have a 10 fold change in magnitude, or poor distribution will likely result.
5. The specific gravity of the two phases must be as close to 1.0 as possible in order to expect good distribution, especially with larger droplet sizes. Variation should begin in the third decimal place.
6. Eddy times of 20-30% seemed to produce reasonable results.
7. Sprinkler effects calculations, using the continuity equation, seemed to produce reasonable results.

8.2 Validation Data

1. Engineering theory and data is extremely limited in the chemigation literature base.

2. Obtaining good droplet distribution data within the irrigation pipeline is extremely difficult.
3. Any future chemigation field study should include a mass balance for the chemical.
4. Chemical properties and system properties should be measured for all studies, in order to make comparisons and duplicate experiments.
5. Density and temperature should be measured, for both the chemical and water, for all experiments. Density should be measured to the fourth decimal place.

9.0 RECOMMENDATIONS FOR FUTURE RESEARCH

Since this work is the initial work for modeling the transport of a non-soluble chemical in an irrigation line, the list of related questions is long. From the 1 1/2 years spent in developing this model, the following recommendations for future research are listed:

1. Much additional field data collection and analysis is needed for validation. The value of the model for simulation has not been established for a full scale system. Controlled field tests need to be performed to obtain complete data sets for complete validation. A complete data set would include measurements for all variables listed in Table 5.1.
2. A complete model sensitivity analysis needs to be performed once the model is validated with a complete set of field data.
3. The model has detected field data weaknesses. Future work needs to address the question of obtaining good droplet distribution data within the irrigation pipeline. Laser technology may be the solution for this problem. The desired degree of field measurement accuracy needs to be established for many of the model parameters (i.e. density, viscosity, temperature, etc.).
4. The effect of the injection nozzle and injection system

physics on the droplet distribution created at the injection point in a liquid-liquid two phase system needs to be further researched and modeled. The initial research for the injection nozzle can be found in chemical engineering literature.

5. The theory of the sprinkler effect needs to be validated and researched. The sprinkler may have a limited effect into the pipe cross section.

6. The effect of droplet breakup in the turbulent flow can be modeled by employing existing models, and then this model can be extended. This would allow the droplet distribution to change after the initial injection droplet distribution.

7. Continued work is needed to validate the interaction of the engineering theory contained in this model. Possible other engineering theory alternatives may be found that may improve the results and increase the computer efficiency.

8. Efficacy studies need to be conducted to determine the optimum insecticide-oil droplet size needed at the plant. This data can then be used along with the distribution model to attempt to create the needed droplet size.

9. The present simulation model should be extended to include the effect of the droplets passing through the sprinkler nozzle on the droplet size distribution.

APPENDIX A
SOURCE CODE VARIABLE LIST

**LIST OF SOURCE CODE NOMENCLATURE
(STATISTICAL VARIABLES OMITTED)**

<u>NAME</u>	<u>TYPE</u>	<u>UNITS</u>	<u>DESCRIPTION</u>
A	Real	cm ²	Pipe cross sectional area
AK	Real		Settling velocity selection variable
AN	Real	cm ²	Sprinkler inlet area
ANS	Logical	T/F	Upstream/downstream flag
ANS	Logical	T/F	Upstream/Downstream flag
ANS3	Logical	T/F	Discharge flag
BETA	Real	radians	Angle between sprinkler center line and line DISTARC
CD	Real		Drag coefficient
COEFF	Real		Sets critical sprinkler effect according to v_r
DATE	Char\$		Date
DELTAT	Real	sec	Time step in turbulence
DENC	Real	g/cm ³	Continuous phase density
DEND	Real	g/cm ³	Dispersed phase density
DIA	Real	cm	Pipe diameter
DIAN	Real	cm	Outlet diameter
DIAP	Real	cm	Particle diameter
DIST	Array	cm	Distance between consecutive sprinklers
DISTARC	Real	cm	Distance between droplet and point on sprinkler center line flush with the pipe wall
DISTNOZ	Real	cm	Distance between two sprinklers

DISTREM	Real	cm	Distance to next sprinkler center line
DISTTOT	Real	ft	Total system length
DISTSUM	Real	cm	Distance from last sprinkler center line
DIST1	Real	cm	Distance equal to eddy length
DIST4	Real	cm	Vertical distance displaced per eddy encounter
DIST5	Real	cm	Distance traveled in one time step of nozzle caused by sprinkler effect
DIST6	Real	cm	Horizontal component of DIST5
DIST7	Real	cm	Vertical component of DIST5
E	Real	cm	Average height of pipe wall roughness
EDDYTIM	Real		Fraction of time spent in eddy encounters
EDLEN	Real	cm	Eddy length
F	Real		Fanning friction factor
FACTOR1	Real		Random factor to convert resultant vector to vertical component
FINC	Real		Increment for friction factor calculation
GRAV	Real	cm/sec ²	Gravitational acceleration
I	Integer		Loop counter
IFREQ	Array		Droplet frequency counter for each sprinkler
II	Integer		Loop counter = number of sprinklers
J	Integer		Loop counter
JJJ	Integer		Loop Counter
JK	Integer		Droplet counter

KKKKK	Integer		Loop Counter
N	Integer		Number of sprinklers
NNNN	Integer		Number of iterations per eddy encounter
NUMB	Integer		Number of eddy lengths between sprinklers
PI	Real		PI
Q	Real	cm ³ /sec	Total flow (metric)
QN	Array	cm ³ /sec	Flow rate per sprinkler
QNOZ	Real	cm ³ /sec	Flow rate for sprinkler
QSAVE	Real	cm ³ /sec	Saves Q
QTOT	Real	gpm	Total flow (english)
RAD	Real	cm	Pipe radius
RADP	Real	cm	Particle radius
RE	Real		Reynolds number
REA	Real		Particle Reynolds Eq. 2.12
SIGN	Real		Sprinkler location -1=top 1=bottom
SN1	Real		Random sign for eddy direction
TAL	Real	sec	Eddy encounter time
TERM	Real		Calculation variable Fanning friction factor
TERMA	Real		Calculation variable Fanning friction factor
TERMB	Real		Calculation variable Fanning friction factor
TERM1	Real		Calculation variable Particle motion equation
TERM2	Real		Calculation variable Particle motion equation
TERM3	Real		Calculation variable Particle motion equation

TIME	Real	sec	Time for velocity calculations
TIMEX	Char\$		Execution time
VELAVG	Real	cm/sec	Mean pipe flow velocity
VELCRIT	Real	cm/sec	Critical sprinkler effect velocity
VELFRIC	Real	cm/sec	Friction velocity
VELI	Real	cm/sec	Initial particle velocity
VELISAV	Real	cm/sec	Storage variable for initial particle velocity
VELSET	Real	cm/sec	Terminal settling velocity
VELY	Real	cm/sec	Horizontal velocity at position y
VERSION	Char\$		Program version and revision date
VISC	Real	g/cm sec	Viscosity
VN	Real	cm/sec	Mean flow velocity in outlet
VN1	Real	cm/sec	Mean flow velocity from surface
VNFIRST	Real	cm/sec	Mean sprinkler velocity for first sprinkler
VNLAST	Real	cm/sec	Mean sprinkler velocity for last sprinkler
VOL	Array	cm ³	Chemical discharge volume summation for each sprinkler
VOLD	Real	cm ³	Droplet volume
XXX	Real	cm	Horizontal distance from sprinkler center line
Y	Real	cm	Distance from closest pipe wall
YP	Real	cm	Vertical distance from pipe center line
YSTART	Real	cm	Saves starting YP
YY	Real	cm	Absolute vertical distance between the particle and the sprinkler

Y1	Real	cm	Distance displaced
Y3	Real	cm	Vertical Displacement

APPENDIX B
PROGRAM SOURCE CODE LISTING

PROGRAM SOURCE CODE (KBS LINEAR, REESE, 1984)

```

PROGRAM MAIN(DATA1,OUTPUT,TAPE6=DATA1,TAPE7=OUTPUT)
C CHEMIGATION TRANSPORT MODEL
C DROPLET TRANSPORT, VERSION 1.0, FORTRAN, LAST REVISION 5/23/86
C BY LUKE E. REESE, AGRICULTURAL ENGINEERING DEPT., MI. STATE UNIV.
C DIMENSION VARIABLES
  REAL F,VEL(100),DIST(100),QN(100),VOL(100)
  INTEGER IFREQ(66)
  REAL VELSET,AK
  CHARACTER DATE*15,TIMEX*15,VERSION*60
  LOGICAL ANS,ANS2,ANS3
  PRINT*, '          CHEMIGATION TRANSPORT MODEL'
  PRINT*, '          VERSION 1.0, FORTRAN, LAST REV. 5/23/86'
  PRINT*, 'LUKE E. REESE, AGRICULTURAL ENGR. DEPT., MI. STATE UNIV.'
  PRINT*, '          (C) COPYRIGHT BY LUKE ELTON REESE, 1986'
  PRINT*, '          ALL RIGHTS RESERVED '
  PRINT*, '*****'
C DECLARE VERSION NUMBER
  VERSION=' REESE, 1.2, KBSLINEAR, LAST REV. 5/23/86'
C INPUT DATA ARRAY FOR SPRINKLER SPACING (FT)
  DATA (DIST(I),I=1,65)/18.,19.97,20.9,20.21,20.17,19.61,20.27,
+19.86,20.27,19.29,19.48,20.2,19.73,20.27,19.71,20.12,20.16,19.76,
+20.06,19.94,19.88,20.21,20.17,19.61,20.27,19.86,20.27,19.71,
+20.11,19.97,20.2,19.73,20.27,19.68,20.11,20.2,19.76,20.06,19.94,
+19.88,20.3,20.13,19.55,20.27,19.86,20.27,19.82,19.95,20.02,20.2,
+19.73,20.27,19.68,20.11,20.2,19.76,20.06,19.94,19.88,20.3,20.14,
+19.55,20.27,19.86,13.83/
C INITIALIZE FREQUENCY AND VOLUME SUMMATION COUNTERS TO 0
  DATA (IFREQ(I),I=1,66)/66*0/
  DATA (VOL(I),I=1,66)/66*0.0/
C INPUT DATA ARRAY FOR SPRINKLER DISCHARGE RATE (GPM)
  DATA (QN(I),I=1,65)/18.73,13.34,13.28,13.22,13.17,13.12,13.06,
+13.01,12.96,12.00,12.86,12.82,12.77,13.70,12.69,13.61,12.61,
+13.53,12.54,13.46,12.48,13.39,13.35,12.39,13.30,13.26,13.23,
+13.21,13.18,13.16,12.21,13.11,13.09,13.07,13.05,13.03,13.02,
+13.01,12.99,12.98,12.96,12.95,12.94,12.93,13.83,12.92,12.91,
+12.90,12.89,12.89,13.79,12.88,12.87,12.87,12.87,12.86,13.76,
+12.86,12.86,13.76,12.86,12.86,12.86,12.86,13.76/
C DECLARE EDDY TIME (DECIMAL), PI, GRAVITATIONAL ACCEL. (CM/SEC2)
  EDDYTIM=0.2
  PI=3.14159265
  GRAV=980.
C DECLARE CONTINUOUS PHASE DENSITY (G/CM3)
  DENC=.9996
C DECLARE DISPERSED PHASE DENSITY (G/CM3)
  DEND=1.0074
C DECLARE CONTINUOUS PHASE VISCOSITY (G/CM SEC)

```

```

      VISC=.012748
C  DECLARE INITIAL DROPLET VELOCITY AND SAVE (CM/SEC)
      VELI=.0
      VELISAV=VELI
C  DECLARE NUMBER OF ITERATIONS PER EDDY
      NNNN=50
C  DECLARE PIPE ROUGHNESS (CM)
      E=.015
C  DECLARE SPRINKLER POSITION 1=BOTTOM OF PIPE, -1=TOP OF PIPE
      SIGN=-1
C  DECLARE SPRINKLER INLET AND PIPE INSIDE DIAMETERS (CM)
      DIAN=1.905
      DIA=16.2738
C  CALCULATE PIPE RADIUS (CM)
      RAD=DIA/2.
C  DECLARE INITIAL VERTICAL STARTING POSITION, YSTART (CM)
      YP=0.0
C  INITIALIZE SUMMATION COUNTERS TO 0
      N=0
      DISTTOT=0.
      Q=0.
      QTOT=0.
C  DETERMINE TOTAL SYSTEM FLOW (Q), DIST. (DISTTOT) AND NO. OF SPR. (N)
      DO 10 I=1,65
      N=N+1
      DISTTOT=DISTTOT+DIST(I)
      QTOT=QTOT+QN(I)
      Q=Q+QN(I)
10    CONTINUE
C  SAVE INITIAL STARTING POSITION AND TOTAL FLOW
      YSTART=YP
      QSAVE=Q
C  WRITE TO OUTPUT FILE ALL SYSTEM PARAMETERS CONVERTED TO METRIC WHEN
C  NECESSARY
      WRITE(7,20)VERSION
20    FORMAT( A)
C  WRITE(7,25)DATE,TIMEX
C 25    FORMAT( ' RUN DATE= ',A,1X,' TIME= ',A)
      WRITE(7,30)DEND
30    FORMAT( ' DROPLET DENSITY G/CM**3= ',F8.5)
      WRITE(7,40)DENC
40    FORMAT( ' FLUID DENSITY G/CM**3= ',F8.5)
      WRITE(7,50)VISC
50    FORMAT( ' VISCOSITY G/CM SEC= ',F8.5)
      WRITE(7,70)QTOT*3.785412
70    FORMAT( ' TOTAL FLOW LPM= ',F6.1)
      WRITE(7,80)DIA
80    FORMAT( ' PIPE DIAMETER CM= ',F7.4)
      WRITE(7,90)E
90    FORMAT( ' PIPE ROUGHNESS CM= ',F6.4)
      WRITE(7,100)DISTTOT/3.281
100   FORMAT( ' SYSTEM LENGTH M= ',F6.1)
      WRITE(7,105)N
105   FORMAT( ' TOTAL NO. OF SPRINKLERS= ',I6)

```

```

WRITE(7,110)YSTART
110  FORMAT( ' STARTING POSITION      CM= ',F6.2)
      WRITE(7,120)SIGN
120  FORMAT( ' NOZZLE POSITION        = ',F6.0)
      WRITE(7,125)EDDYTIM
125  FORMAT( ' EDDY PERCENT          = ',F4.2)
C  CALCULATE PIPE AND SPRINKLER INLET AREA (CM2)
      A=(PI*(DIA**2.))/4.
      AN=(PI*(DIAN**2.))/4.
C  DETERMINE AND SET CRITICAL VELOCITY AT WHICH SPRINKLER EFFECT IS
C  ACTIVATED (CM/SEC)
      VNFIRST=QN(1)*63.08333/AN
      VNLAST=QN(N)*63.08333/AN
      COEFF=.4
      WRITE(7,126)COEFF
126  FORMAT( ' SPRINKLER COEFFICIENT= ',F5.2)
      VELCRIT=VNFIRST/PI*COEFF
      PRINT*, ' VEL AT r= ',VNFIRST/PI, ' VELCRIT= ',VELCRIT
C  CALCULATE EDDY LENGTH
      EDLEN=.2*PI
C  SET HORIZONTAL DISPLACEMENT FOR ONE TIME STEP EQUAL TO EDDY LENGTH
      DIST1=EDLEN
C  INITIALIZE STATISTICAL COUNTERS TO 0
      JK=0
      PCVOLT=0
      VOLT=0
      DIAPT=0
      JCOUNT=0
      JCOUNT1=0
      SPRINKT=0
      SPRINKA=0
      SPSS=0
      VOLD=0
      DIAPA=0
      DIAPSS=0
      VOLA=0
      VOLSS=0
      VOLA=0
      VOLD=0
      Z=0.
C  SET DO LOOP TO RUN 100 DROPLETS
      DO 200 KKKKK=1,100
C  READ DROPLET DIAMETER FROM INPUT FILE (CM)
      READ(6,205,END=201)DIAP
205  FORMAT( F6.4)
C  CALCULATE DROPLET RADIUS (CM)
      RADP=DIAP/2.
C  INCREMENT COUNTER
      JK=JK+1
C  SET STARTING POSITION AND TOTAL FLOW TO SAVED VALUES
      YP=YSTART
      Q=QSAVE
C  DETERMINE SETTLING VELOCITY FOR DROPLET
      CALL SETTLE(DEND,DENC,GRAV,DIAP,VISC,VELSET)

```

```

C  CONVERT FLOW TO CM3/SEC
    Q=Q*63.08333333
C  SET FLOW TO UPSTREAM
    ANS=.FALSE.
C  SET DO LOOP TO NUMBER OF SPRINKLERS
    DO 400 II=1,N
C  INITIALIZE COUNTERS TO 0
    TIMESUM=0.
    DISTSUM=0.
    DISTREM=0.
C  CONVERT DISTANCE TO CM
    DISTNOZ=DIST(II)*30.478513
C  CALCULATE MEAN PIPE FLOW VELOCITY
    VELAVG=Q/A
C  CALCULATE REYNOLDS NUMBER
    RE=DIA*VELAVG*DENC/VISC
C  DETERMINE FRICTION FACTOR
    CALL FACTOR(F,DIA,E,RE)
C  CALCULATE FRICTION VELOCITY
    VELFRIC=VELAVG*((F/2)**.5)
C  DETERMINE NUMBER OF EDDY LENGTHS IN DISTANCE.  FOR LOOP MAXIMUM
C  THE NUMB IS MULTIPLIED BY 1.5
    NUMB=DISTNOZ/EDLEN*1.5
C  CALCULATE EDDY TIME
    TAL=EDLEN/VELFRIC
C  CALCULATE DELTA T
    DELTAT=TAL/NNNN
C  CALL NOZZLE IF FLAGS INDICATE DOWNSTREAM
    IF(ANS) THEN
        ANS2=.TRUE.
        CALL NOZZLE(NNNN,DELTAT,DIAN,VN,DISTARC,BETA,YP,RAD,SIGN,
+DISTSUM,HOZDIST,XXX,YY,ANS,ANS2,ANS3,RADP,DISTREM,VELI,VELISAV,
+VELFRIC,VELAVG,DENC,DEND,VISC,GRAV,VELSET,RE,EDDYTIM,VELCRIT)
C  CHECK FOR DISCHARGE
    IF(ANS3) GO TO 500
    ENDIF
C  CONVERT FLOW TO CM3/SEC
    QNOZ=QN(II)*63.08333333
C  CALCULATE MEAN FLOW VELOCITY IN SPRINKLER INLET
    VN=QNOZ/AN
C  DO LOOP FOR SPAN BETWEEN CONSECUTIVE SPRINKLERS
    DO 600 JJJ=1,NUMB
C  CALL PROFILE TO DETERMINE HORIZONTAL VELOCITY, VELY
    CALL PROFILE(YP,RAD,VELFRIC,VELAVG,VELY,RADP)
C  UPDATE XR AND XS
    DISTSUM=DISTSUM+DIST1
    DISTREM=DISTNOZ-DISTSUM
C  THIS SECTION CALCULATES THE TURBULENCE EFFECT
C  IF LAMINAR FLOW, NO EDDY EFFECT
    IF(RE.LT.2000.) THEN
C  DETERMINE TIME FOR SETTLING
        TIME=DIST1/VELY
C  DETERMINE VERTICAL DISPLACEMENT
        Y1=TIME*VELSET
    
```

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C  UPDATE POSITION
    YP=YP+Y1
C  DEFINE IN BOUNDS
    IF(YP.GT.RAD) YP=RAD-RADP
    IF(YP.LT.(-RAD)) YP=RADP-RAD
C  LEAVE EDDY EFFECT
    GO TO 700
    ENDIF
C  DETERMINE IF EDDY LENGTH IS OCCUPIED BY EDDY AND DIRECTION
    SN1=RANF()
    IF(SN1.LE.(.5*EDDYTIM)) THEN
        SN1=1
    ELSEIF(SN1.GE.(1.-(.5*EDDYTIM))) THEN
        SN1=-1
    ELSE
        SN1=0
C  IF EDDY LENGTH IS NOT OCCUPIED BY EDDY DETERMINE VERTICAL
C  DISPLACEMENT USING SETTLING VELOCITY .
    TIME=DIST1/VELY
    Y1=TIME*VELSET
    YP=YP+Y1
    IF(YP.GT.RAD) YP=RAD-RADP
    IF(YP.LT.(-RAD)) YP=RADP-RAD
C  SET DROPLET VELOCITY TO SAVED VALUE
    VELI=VELISAV
C  LEAVE EDDY EFFECT
    GO TO 700
    ENDIF
C  DETERMINE IF THE DROPLET IS AGAINST THE WALL AND IF THE EDDY
C  DIRECTION WILL PULL IT AWAY FROM THE WALL. IF NOT LEAVE EDDY EFFECT
    IF(YP.EQ.(-RAD+RADP).AND.SN1.EQ.(-1)) GO TO 700
    IF(YP.EQ.(RAD-RADP).AND.SN1.EQ.1) GO TO 700
C  DETERMINE THE RANDOM VERTICAL COMPONENT MULTIPLICATION FACTOR
    FACTOR1=RANF()
C  SET DO LOOP FOR NUMBER OF ITERATIONS PER EDDY
    DO 800 J=1,NNNN
C  CALL TURB TO DETERMINE DROPLET VELOCITY
    CALL TURB(NNNN,RADP,DENC,SN1,VELFRIC,VELI,VISC,GRAV,DEND,DELTAT,
    +DIST4,SIGN)
C  CONVERT TO VERTICAL DISPLACEMENT BY RANDOM FACTOR
    Y3=DIST4*FACTOR1
C  UPDATE VERTICAL POSITION
    YP=YP+Y3
C  DEFINE IN BOUNDS
    IF(YP.LT.(-RAD)) YP=RADP-RAD
    IF(YP.GT.RAD) YP=RAD-RADP
800  CONTINUE
C  IF END OF SPAN HAS BEEN REACHED CHANGE FLOW VALUES
700  IF(DISTREM.LE.0.) GO TO 610
C  DETERMINE YY
    IF(SIGN.EQ.1.) THEN
        IF(YP.GE.0.) YY=RAD-YP
        IF(YP.LT.0.) YY=RAD+ABS(YP)
    ELSE
        YY=RAD+YP

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      ENDIF
C   DETERMINE XXX, BETA, DISTARC OR L
      XXX=DISTREM
      BETA=ATAN(XXX/YY)
      DISTARC=XXX/SIN(BETA)
C   CALL NOZZLE IF L IS LESS THAN DIA
      IF(DISTARC.LT.DIA) THEN
C   SET DOWNSTREAM FLAG
      ANS2=.FALSE.
      CALL NOZZLE(NNNN,DELTAT,DIAN,VN,DISTARC,BETA,YP,RAD,SIGN,
+DISTSUM,HOZDIST,XXX,YY,ANS,ANS2,ANS3,RADP,DISTREM,VELI,VELISAV,
+VELFRIC,VELAVG,DENC,DEND,VISC,GRAV,VELSET,RE,EDDYTIM,VELCRIT)
C   CHECK FOR DISCHARGE
      IF(ANS3) THEN
        GO TO 500
      ELSE
        GO TO 610
      ENDIF
    ENDIF
C   START NEXT EDDY LENGTH
600   CONTINUE
C   CHANGE FLOW TO INDICATE SPRINKLER DISCHARGE
610   Q=Q-QNOZ
C   START NEXT SPAN
400   CONTINUE
C   OUTPUT DROPLET SIZE AND FINAL POSITION OR DISCHARGE LOCATION
950   FORMAT( I4,F8.0,I3)
500   WRITE(7,950)JK,DIAP*10000,II
C   CALL STATISTICS FREQUENCY AND VOLUME COUNTER SUBROUTINE
      CALL FREQ(II,DIAP,IFREQ,VOL,VOLD)
C   CALCULATE STATISTIC SUMMATIONS-
      IF(II.EQ.66) THEN
        JCOUNT1=JCOUNT1+1
      ELSE
        JCOUNT=JCOUNT+1
        SPRINKT=SPRINKT+II
        SPRINKA=SPRINKT/JCOUNT
        SPSS=SPSS+(II**2.)
      ENDIF
      DIAPT=DIAPT+DIAP
      DIAPSS=DIAPSS+(DIAP**2.)
      DIAPA=DIAPT/JK
      VOLT=VOLT+VOLD
      VOLA=VOLT/JK
      VOLSS=VOLSS+(VOLD**2.)
C   NEXT DROPLET
200   CONTINUE
C   CALCULATE AND PRINT STATISTICS
201   SPDS=((JCOUNT*SPSS-(SPRINKT**2.))/(JCOUNT*(JCOUNT-1)))**.5
      VOLSD=((JK*VOLSS-(VOLT**2.))/(JK*(JK-1)))**.5
      DIAPSD=((JK*DIAPSS-(DIAPT**2.))/(JK*(JK-1)))**.5
      PRINT*,', '
      PRINT*,', N= ',JK,' MEAN DROPLET DIA CM= ',DIAPA,
+ ' STD DEV= ',DIAPSD

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PRINT*, ' '
VOLDIA=((VOL*3./(4.*PI))**1./3.)*2.
PRINT*, ' MEAN VOLUME DROPLET DIA CM= ',VOLDIA
PRINT*, ' '
PRINT*, ' N= ',JCOUNT, ' MEAN SPRINKLER DISCHARGED= ',SPRINKA,
+' STD DEV= ',SPSD
PRINT*, ' '
PRINT*, ' N= ',JK, ' MEAN DROPLET VOLUME DISCHARGED CM3= ',VOLA,
+' STD DEV= ',VOLSD
PRINT*, ' '
WRITE(7,969)
DO 980 JJ=1,66
PCVOL=VOL(JJ)/VOLT*100.
PCVOLT=PCVOLT+PCVOL
WRITE(7,970)JJ,IFREQ(JJ),VOL(JJ),PCVOL,PCVOLT
980 CONTINUE
969 FORMAT( ' SPR. NO.      FREQ      CUM VOLUME CM3      PERCENT
+CUM PERCENT ' )
970 FORMAT( 15,6X,15,6X,F6.2,8X,F6.2,8X,F6.2)
990 CONTINUE
END
C *****
C SUBROUTINE FOR FREQUENCY AND VOLUME SUMMATION FOR EACH SPRINKLER
C FOR DROPLETS NOT DISCHARGED.
SUBROUTINE FREQ(II,DIAP,IFREQ,VOL,VOLD)
REAL VOL(66),VOLD
INTEGER IFREQ(66)
VOLD=0.
PI=3.14159265
C CALCULATE DROPLET VOLUME
VOLD=(4./3.)*PI*(DIAP/2.)**3.
IF(II.EQ.1) THEN
IFREQ(1)=IFREQ(1)+1
VOL(1)=VOL(1)+VOLD
ELSE IF(II.EQ.2) THEN
IFREQ(2)=IFREQ(2)+1
VOL(2)=VOL(2)+VOLD
ELSE IF(II.EQ.3) THEN
IFREQ(3)=IFREQ(3)+1
VOL(3)=VOL(3)+VOLD
.
.
.
ELSE IF(II.EQ.N) THEN
IFREQ(N)=IFREQ(N)+1
VOL(N)=VOL(N)+VOLD
ELSE IF(II.EQ.END OF PIPE) THEN
IFREQ(END OF PIPE)=IFREQ(END OF PIPE)+1
VOL(END OF PIPE)=VOL(END OF PIPE)+VOLD
ENDIF
RETURN
END
C *****
C SUBROUTINE TO DETERMINE SPRINKLER EFFECT

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      SUBROUTINE NOZZLE(NNNN,DELTAT,DIAN,VN,DISTARC,BETA,YP,RAD,SIGN,
+DISTSUM,HOZDIST,XXX,YY,ANS,ANS2,ANS3,RADP,DISTREM,VELI,VELISAV,
+VELFRIC,VELAVG,DENC,DEND,VISC,GRAV,VELSET,RE,EDDYTIM,VELCRIT)
C  DECLARE VARIABLES
      LOGICAL ANS,ANS2,ANS3,ANS4,ANS5
      PI=3.14159265
C  SET DISCHARGE FLAG TO NO DISCHARGE
      ANS3=.FALSE.
      DIA=RAD*2.
C  SET HORIZONTAL DISTANCE FROM SPRINKLER CENTER LINE
      IF(ANS2) THEN
        XXX=DISTSUM
      ELSE
        XXX=DISTREM
      ENDIF
      DO 1000 J=1,100
C  SAME EDDY EFFECT CALCULATIONS AS FOUND IN MAIN PROGRAM
      FACTOR1=RANF()
      SN1=RANF()
      Y3=0.
      DIST4=0.
      IF(SN1.LE.(.5*EDDYTIM)) THEN
        SN1=1
      ELSEIF(SN1.GE.(1.-(.5*EDDYTIM))) THEN
        SN1=-1
      ELSE
        SN1=0
      VELI=VELISAV
      ENDIF
      DO 1100 I=1,NNNN
C  CALCULATE VELOCITY AT CYLINDRICAL SURFACE AT L
      VN1=(VN*DIAN)/(DISTARC*PI)
C  DETERMINE IF SPRINKLER EFFECT IS ACTIVATED
      IF(VN1.LT.VELCRIT) THEN
C  DECLARE DISTANCE TRAVELED ACCORDING TO SPRINKLER EFFECT ACTIVATION
      DIST5=0.0
      ELSE
        DIST5=VN1*DELTAT
      ENDIF
C  CALCULATE HORIZONTAL AND VERTICAL COMPONENTS
      DIST6=SIN(BETA)*DIST5
      DIST7=COS(BETA)*DIST5
C  CALCULATE VELOCITY COMPONENTS AS IN MAIN PROGRAM
      CALL PROFILE(YP,RAD,VELFRIC,VELAVG,VELY,RADP)
      IF(RE.LT.2000.) GO TO 1200
      IF(YP.EQ.(-RAD+RADP).AND.SN1.EQ.(-1)) GO TO 1200
      IF(YP.EQ.(RAD-RADP).AND.SN1.EQ.1) GO TO 1200
      IF(SN1.NE.0.) THEN
        CALL TURB(NNNN,RADP,DENC,SN1,VELFRIC,VELI,VISC,GRAV,DEND,DELTAT,
+DIST4,SIGN)
        Y3=DIST4*FACTOR1
      ENDIF
C  UPDATE VERTICAL AND HORIZONTAL POSITIONS
1200 IF(SN1.EQ.0.) THEN

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      YP=YP+SIGN*DIST7+VELSET*DELTAT
      ELSE
      YP=YP+SIGN*DIST7+Y3
      ENDIF
C  DEFINE IN BOUNDS
      IF(YP.LT.(-RAD)) YP=RADP-RAD
      IF(YP.GT.RAD) YP=RAD-RADP
C  CALCULATE YY
      IF(SIGN.EQ.1) THEN
      IF(YP.GE.0) YY=RAD-YP
      IF(YP.LT.0) YY=RAD+ABS(YP)
      ELSE
      YY=RAD+YP
      ENDIF
C  UPDATE POSITION PARAMETERS
      IF(ANS2) THEN
      XXX=XXX-DIST6+VELY*DELTAT
      DISTSUM=DISTSUM-DIST6+VELY*DELTAT
      ELSE
      XXX=XXX-DIST6-VELY*DELTAT
      DISTSUM=DISTSUM+DIST6+VELY*DELTAT
      ENDIF
      BETA=ATAN(XXX/YY)
      DISTARC=XXX/SIN(BETA)
C  DETERMINE IF DISCHARGE OCCURRED
      IF(XXX.LT.(DIAN/2.)).AND.DISTARC.LT.(DIAN/2.)) THEN
C  SET DISCHARGE FLAG
      ANS3=.TRUE.
      RETURN
      ENDIF
C  CHECK FOR TERMINATION OF SPRINKLER EFFECT AND SET FLAG ACCORDINGLY
      IF(ANS2) THEN
      IF(DISTARC.GT.DIA) THEN
      ANS=.FALSE.
      RETURN
      ENDIF
      ELSE
      IF(XXX.LE.0.) THEN
      ANS=.TRUE.
      RETURN
      ENDIF
      ENDIF
C  NEXT TIME STEP
1100 CONTINUE
C  NEXT EDDY LENGTH
1000 CONTINUE
      END
C *****
C  SUBROUTINE FOR CALCULATING TERMINAL SETTLING VELOCITY
      SUBROUTINE SETTLE(DEND,DENC,GRAV,DIAP,VISC,VELSET)
C  CHECK FOR SETTLING DIRECTION
      IF (DEND.LT.DENC) THEN
      VELSET=(((-2./9.)*GRAV*(DENC-DEND)*(DIAP/2.))**2.)/VISC)
      ELSE

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C  CALCULATE SETTLING REGION
    AK=DIAP*(GRAV*DENC*(DEND-DENC)/VISC**2.))**(1./3.)
    IF (AK.LT.3.3) THEN
C  CALCULATE SETTLING VELOCITY BY STOKES LAW
    VELSET=GRAV*DIAP**2*(DEND-DENC)/(18*VISC)
    ELSE IF (AK.GE.3.3.AND.AK.LT.43.6) THEN
C  CALCULATE SETTLING VELOCITY VY INTERMEDIATE EQUATION
    VELSET=.153*GRAV**.71*DIAP**1.14*(DEND-DENC)**.71/(DENC**.29*
    +VISC**.43)
    ELSE IF (AK.GE.43.6.AND.AK.LT.2360) THEN
C  CALCULATE SETTLING VELOCITY BY REYNOLDS EQUATION
    VELSET=1.74*(GRAV*DIAP*(DEND-DENC)/DENC)**.5
    ELSE
    PRINT*, 'ERROR IN SETTLING VELOCITY CALCULATIONS'
    END IF
    END IF
    RETURN
    END
C *****
C  SUBROUTINE TO DETERMINE FANNING FRICTION FACTOR
    SUBROUTINE FACTOR(F,DIA,E,RE)
C  INITIALIZE F AND F INCREMENT
    F=.002
    FINC=.0001
    DO 2000 I=1,1000
C  CALCULATE EQUALITY
    TERMA=1/F**.5
    TERMB=(4*(.4342944819*LOG(DIA/E)))+2.28-(4*(.4342944819*LOG(1+
    +4.67*((DIA/E)/(RE*F**.5))))
    TERM=ABS(TERMA-TERMB)
C  CHECK FOR ACCURACY
    IF (TERM.LT.(.1)) GO TO 2100
    F=F+FINC
2000  CONTINUE
C  RETURN F WHEN ACCURACY IS ACHEIVED
2100  RETURN
    END
C *****
C  SUBROUTINE TO CALCULATE HORIZONTAL FLOW VELOCITY AT Y
    SUBROUTINE PROFILE(YP,RAD,VELFRIC,VELAVG,VELY,RADP)
C  DEFINE IN BOUNDS
    IF(YP.LT.(-RAD)) YP=RADP-RAD
    IF(YP.GT.RAD) YP=RAD-RADP
C  DETERMINE Y
    IF(YP.GE.0) THEN
    Y=RAD-YP
    ELSE
    Y=RAD+YP
    ENDIF
C  CALCULATE VELOCITY AT Y
    VELY=VELFRIC*(2.5*(LOG(Y/RAD))+3.75+(VELAVG/VELFRIC))
    RETURN
    END
C *****

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C  SUBROUTINE TO CALCULATE DROPLET VELOCITY DURING AN EDDY ENCOUNTER
    SUBROUTINE TURB(NNNN,RADP,DENC,SN1,VELFRIC,VELI,VISC,GRAV,DEND,
      +DELTAT,DIST4,SIGN)
C  INITIALIZE DISPLACEMENT TO 0
    DIST4=0.0
C  CHECK THAT DROPLET VELOCITY DOES NOT EXCEED FRICTION VELOCITY
    IF((ABS(VELI)).GT.VELFRIC) THEN
        VELI=SN1*VELFRIC
        GO TO 3100
    ENDIF
C  CALCULATE PARTICLE REYNOLDS NUMBER
    REA=(2*RADP*DENC*(ABS(SN1*VELFRIC-VELI)))/VISC
    IF(REA.LE.0.001)THEN
        VELI=SN1*VELFRIC
        GO TO 3100
    ENDIF
C  CALCULATE DRAG COEFFICIENT FOR A SPHERICAL PARTICLE
    CD=(24/REA)*((1+(REA/60)**(5./9.))**(9./5.))
C  CALCULATE PARTICLE VELOCITY IN ONE TIME STEP
3000  TERM1=((DEND-DENC)*GRAV)/(DEND+.5*DENC)
      TERM2=3.*CD*DENC*(ABS(SN1*VELFRIC-VELI))*(SN1*VELFRIC-VELI)
      TERM3=8.*RADP*(DEND+.5*DENC)
      VELI=VELI+DELTAT*(TERM1+TERM2/TERM3)
C  CHECK THAN VELI IS LESS THAN FRICTION VELOCITY
    IF ((ABS(VELI)).GT.VELFRIC) VELI=SN1*VELFRIC
C  DETERMINE RESULTANT DISPLACEMENT
3100  DIST4=VELI*DELTAT
      RETURN
      END

```

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