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TOWER MOVEMENT EFFECT ON THE DISTRIBUTION UNIFORMITY ALONG THE PATH OF TRAVEL IN CENTER-PIVOT IRRIGATION SYSTEMS

presented by

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has been accepted towards fulfillment of the requirements for

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Major professor

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TOWER MOVEMENT EFFECT ON THE DISTRIBUTION UNIFORMITY ALONG THE PATH OF TRAVEL IN CENTER-PIVOT IRRIGATION SYSTEMS

BY

MARIO FUSCO JR.

A THESIS

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

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Department of Agricultural Engineering

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ABSTRACT

TOWER MOVEMENT EFFECT ON THE DISTRIBUTION UNIFORMITY ALONG THE PATH OF TRAVEL IN CENTER-PIVOT IRRIGATION SYSTEMS

By

Mario Fusco Jr.

Because of the intermittent movement of the support towers on electrically driven center-pivot systems, they are believed to produce less uniform water distribution along the path of travel than hydraulically driven systems. Uniformity along the path of travel may be an important factor during chemigation, especially for low water applications.

A computer model of a Center-Pivot System was developed and validated with field data. The model was used to run simulations of both traditional and LEPA (Low Energy Precision Application) systems. Simulations were run with the systems towers moving both continuously and intermittently. The importance of other parameters (design and management) were also addressed.

The results showed that for all practical purposes the uniformity coefficients (Wilcox-Swaile Uniformity Coefficient, UCW) along the path of travel with the towers

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moving continuously were equal to 100%. With the towers moving intermittently uniformity coefficient as low as 82.9 and 15.3% were found for traditional and LEPA systems respectively . Among other parameters studied, the magnitude of the wetted radius and alignment angle affected the uniformity the most. Generally, the smaller the alignment angle the higher UCW values. However, the alignment effect was more obvious for patterns with smaller wetted radius as in LEPA Systems.

These findings point to the importance of considering the uniformity along the path of travel as well as radially from the pivot-point as a measure of center-pivot water application distribution, specially when evaluating LEPA Systems.

Approved Ted L. Loudon 4/6/95

Major Professor Date

Approved Thomas H Burkhardt 4/6/95

Department Chairperson Date

In memory of my mother Nylza and my brother Reinaldo

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First I would like to thank my wife Mimi and my wonderful sons Alex and Erik for all their love, support, encouragement and patience, for without them this work would never be finished. I would also like to thank my father and mother-in-law for their never ending support. Special thanks to Dr. T. Loudon for the opportunity he has given me and for his patience throughout this journey. Thanks to my committee members, Dr. Von Bernuth and Dr. Alocilja for their comments and suggestions. Last but not least, my special gratitude to Dan Rajzer for his help in the field data collection and to his brother Cris Rajzer for allowing me to conduct the field experiment in his farm.

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I- INTRODUCTION

Irrigation, the science and art of artificially applying water to plants, has been credited with the flourish and decay of early civilizations. It is believed that the increased stability of food resources brought about through irrigation has allowed the shift from nomadic food gathering groups to societies with semi or permanent dwellings (Cuenca, 1989). Ancient irrigation works, some at least 4000 years old can still be found in Egypt, Iraq, India and China. In the western hemisphere most of the early irrigation works are found in Peru, Mexico and in the southwest of the United States of America. In Arizona, traces of old canal distribution systems are still visible today (Taylor and Ashcroft, 1972).

Today the importance and the economic impact of irrigation can be appraised by knowing that the total global irrigated area, 223 million ha (FAO, 1977), representing only 13% of the total global arable land is responsible for 34% of the total crop production (FAO, 1979).

A. IRRIGATION SYSTEMS

Irrigation systems can be classified as:

1. Surface Irrigation
2. Sub-surface Irrigation
3. Microirrigation
4. Sprinkler Irrigation

1. SURFACE IRRIGATION

Surface irrigation systems are the systems that deliver and spread water over a field by gravity, and for that reason they are also termed gravity systems. They were the first irrigation systems used by mankind when water was allowed to spill over the banks of rivers and flood adjacent lower land. Today many other surface methods are used which include Contour Ditch Irrigation (flooding or wild flooding), Border Irrigation, Contour Levee Irrigation and Furrow Irrigation. The average irrigation efficiency of surface systems is usually low but such systems are the predominant irrigation systems in the world. The 1987 U.S. Census reported that about 58% of the total nation's irrigation was accomplished by surface methods, a large percentage, but a decrease from the 75% reported in the 1974 U.S. Census.

2. SUBSURFACE IRRIGATION

Subsurface irrigation or subirrigation is any irrigation method in which the water is applied below the surface of the soil. There are two ways this can be accomplished. Most commonly the level of a shallow water table is controlled allowing the capillary water to reach the root zone. A second method, subsurface drip, uses underground lines and applicators to apply water below the soil surface. The 1987 U.S. Census reported that 581,940 acres were being irrigated by subirrigation systems, a 6.6% decrease from 1984, representing only 1.2% of the total irrigated acreage.

3. MICROIRRIGATION

Microirrigation Irrigation is the method of frequent and slow application of water to the soil near the plant. The water is applied through low rate outlet devices called emitters, placed along selected points on the distribution lines. Microirrigation research began in Germany about 1869. The development of economical plastic pipe manufacturing and of emitters in Israel in the 1950's, made its field use practical. The 1987 U.S. Census reported an area of 866,731 acres under drip irrigation, mainly in California, Florida, and Texas, a 3.5% increase from 1984. Despite the increase, the area under drip irrigation represents only about 2% of the total irrigated area.

4. SPRINKLER IRRIGATION

Sprinkler Irrigation Systems consist basically of a pumping unit, a network of tubes or pipes to convey the water (main and lateral(s)), and sprinkler heads or nozzles attached to the lateral(s) for sprinkling water over the land surface. A sprinkler irrigation system is commonly classified by the movement of its lateral. Systems are classified as Solid Set, Set-Move Irrigation Systems (hand-move, tow-move, side-roll and big-gun), and Continuous-Move Systems (center-pivot systems, linear-move systems and traveler sprinkler systems). There was a 9% increase from 1984 to 1987 in the acreage irrigated by sprinkler methods (1987 U.S. Census), representing roughly 40% of the total irrigated area. This increase is due to the increase of area under center pivot systems. Land under other methods of sprinkler irrigation has decreased.

B. NEED OF STUDY

It is no surprise that with escalating labor costs, systems suitable to automation are increasing in popularity. Suitability to automation and to application of chemicals through the irrigation water (chemigation) in addition to high efficiency and uniformity of application, explain the increase acreage under microirrigation and center pivot sprinkler irrigation.In center-pivot systems, the uniformity of application becomes very critical when doing chemigation, especially in light application of pesticides (fungicides and insecticides). Traditionally, in the evaluation of center-pivot systems the uniformity of application is measured radially (along the lateral). The measurement of the radial uniformity assesses the adequacy of the design (sprinkler types, flowrates and spacing) but tells us little about the effect of the lateral movement on the uniformity of application. Hanson and Wallender (1986) were the first to study the uniformity along the path of travel and related it in part to the start and stop movement of the towers in electrically driven systems. It is believed by many that because of the stop and go lateral movement (intermittent movement), electrically driven center-pivot systems produce less uniform application along the path of travel than hydraulically driven systems. If such a belief is proven it will increase the popularity of hydraulic systems among chemigators. In Michigan, more than 300,000 acres are being irrigated (U.S.Census, 1987). Over half of the irrigated area is under center pivot systems, mainly in corn for grain or seed, vegetables, irish potatoes and soybeans. Of 816 irrigated farms growing corn only 137 farms applied fertilizers and only 15 applied pesticides in the irrigation water. For other crops the proportion is still lower. The survey data from U.S. Census (1987) tells us that the majority of Michigan farmers are not making use of the chemigation technology available to them. For some, the time required in handling a chemigation operation is a distraction from other management responsibilities. For others the lack of knowledge of how their actual system would perform is an impediment in the adoption of chemigation.

C. OBJECTIVES

The overall goal of this study is to determine how the lateral movement of electrically driven center-pivot systems affects the uniformity along the path of travel as compared to hydraulic systems. The objectives of this research are:

1) to develop a program to assist the average farmer and/or dealer in his decision in choosing among the different sprinkler packages currently available in the market;
2) to evaluate the distribution uniformity along the path of travel of center-pivot and LEPA systems for different sprinkler packages commonly used in Michigan;
3) to determine the suitability of these sprinkler packages in the application of chemicals through the irrigation water (chemigation);
4) to determine how different design parameters, i.e., alignment angle between towers, guide-tower timer setting, wetted radius, and sprinkler pattern shape, affect the uniformity of water application along the path of travel.

II- LITERATURE REVIEW

The evaluation of sprinkler packages used in center-pivot systems requires some knowledge of the system as well as the parameters studied to make their performance evaluation. Among all the parameters, the uniformity of application is undoubtedly the most important and will receive most attention. In this section the equations, coefficients and conversion factors will be written as they are found in the literature, predominantly in English units. In other sections they will be expressed in the SI units.

A. SYSTEM DESCRIPTION

A center-pivot system consists of a single sprinkler lateral with one end fixed, the pivot point, and the other end moving in a circle about the pivot. Pressurized water is supplied at the pivot-point, and the lateral is supported by wheel-towers and trusses and/or cables. In general the towers are driven by electric motors, but some systems are driven by hydraulic oil motors or water driven rachets. Lateral length varies. It can be as short as 60 m or as long as 800 m, but the most common size is about 400 m (1/4 mile long). The span between towers is usually dictated by the slope of the field; it is shorter in fields with higher slopes. Therefore, more towers, or drive units, are necessary to support the system under increasing slopes. The pivoting lateral is kept aligned by controlling the movement of the towers. Each tower is equipped with a control box which turns the tower motor ON or OFF depending on the position of adjacent towers. To irrigate the corner areas that normally would be left unwetted, some of the center-pivot systems have a large sprinkler (end gun) at the end of the lateral. Other systems have a swing arm to accomplish the same task and these are usually called corner-systems. Figure 1 shows a typical layout of a center-pivot system.

B. HYDRAULICS OF CENTER-PIVOT SYSTEMS

Knowledge of lateral and sprinkler hydraulics is necessary to understand the design criteria of center-pivot systems. Proper design is critical in having a system with high water application uniformity. The determination of the pressure distribution along the lateral will assist the designer engineer in the selection of appropriate sprinklers for a desired discharge. A sprinkler working in the right pressure range will have an adequate distribution pattern.

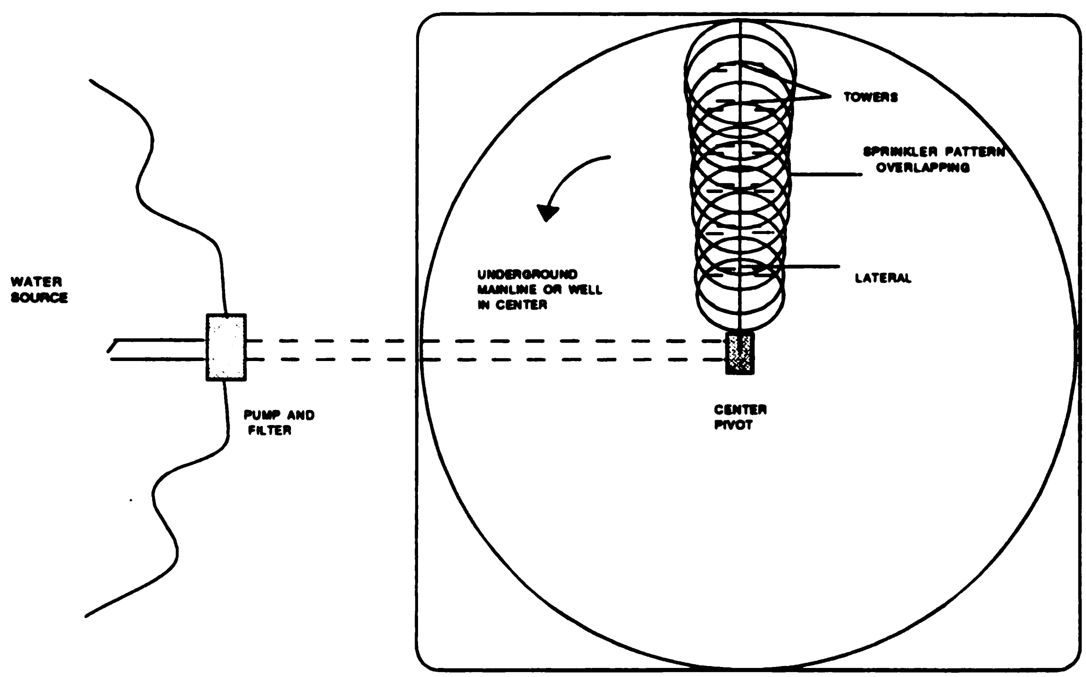

Figure 1. Typical Center-Pivot System layout.

1- SPRINKLER HYDRAULICS

The theoretical discharge of a nozzle can be computed from the orifice flow equation:

$$Q = AC_d\sqrt{2gH} \qquad \ldots II\text{-}1$$

where:

Q = discharge

A = area of the orifice

C_d = the coefficient of discharge

g = the acceleration of gravity

H = the pressure head.

This equation can be written in general form as:

$$Q = KC_d AP^{0.5} \qquad \ldots II\text{-}2$$

where:

P = the pressure at the nozzle

K = a constant of proportionality that depends of the units being used.

In cases where the sprinkler has more than one nozzle the discharge of an individual sprinkler can be computed as:

$$Q=\sum_{i=1}^{n} KC_{di}\, A_i\, P_i^{0.5} \qquad ...\ II\text{-}3$$

2- LATERAL HYDRAULICS

In a center-pivot system, water is introduced at the pivot point and flows through the lateral toward the outer end supplying individual sprinklers. The energy at the pivot point must be equal to or greater than the energy requirement of the last sprinkler plus the total energy lost due to friction along the pipe and components in the lateral.

a. PIPE ENERGY LOSS EQUATIONS

Many empirical equations such as Darcy-Weisbach, Hazen-Williams, Scobey, etc., can be used to compute the friction loss in a pipe. The Darcy-Weisbach is probably more rationally based than the others, since it can be derived by dimensional analysis, and has received wide acceptance (Jeppson, 1982). The Darcy-Weisbach equation is given by:

$$h_f = f\,\frac{L\ V^2}{D\ 2g} \qquad ...\ II\text{-}4$$

where:

h_f = the head loss

f = the friction factor

L = the pipe length

D = the pipe diameter

V = the average velocity

g = the acceleration of gravity.

For most commercial pipes, the friction factor, f, can be determined directly from the Moody diagram (Figure 2) with corresponding relative roughness, e/D, and the Reynolds number (R_e). For laminar flow (R_e < 2100) the friction factor is given by:

$$f = \frac{64}{R_e} \qquad \ldots II\text{-}5$$

For the transition region the friction factor can be determined by implicitly solving the Colebrook equation,

$$\frac{1}{\sqrt{f}} = 1.14 - 2\,Log\left(\frac{e}{D} + \frac{9.35}{R_e\sqrt{f}}\right) \qquad \ldots II\text{-}6$$

where:

e = pipe equivalent sand grain size

D = pipe diameter

e/D = pipe relative roughness.

This equation is the basis for the Moody diagram. A table with values of e (equivalent sand grain size) for different pipe materials and the Moody diagram can be found in Streeter (1985) and in others fluid mechanics text books.

Swamee and Jain (1978) developed an explicit equation for the friction factor, which facilitates computer calculations:

$$f = \frac{1.325}{\left[L_n\left(\frac{e}{3.7D}+\frac{5.74}{R_e^{0.9}}\right)\right]^2} \qquad \ldots\ II\text{-}7$$

This equation was shown to be valid within ranges of:

$0.01 \geq e/D \geq 10^{-6}$ and $10^{8} \geq R_e \geq 5000$

The energy losses in the system components generally denoted as minor losses, are usually small compared to total pipe friction losses and usually are accounted for by adding 10% to the total pipe friction loss. The component losses can also be computed using the equation:

$$h_m = K\left(\frac{V^2}{2g}\right) \qquad \ldots\ II\text{-}8$$

where:

h_m = the component head loss

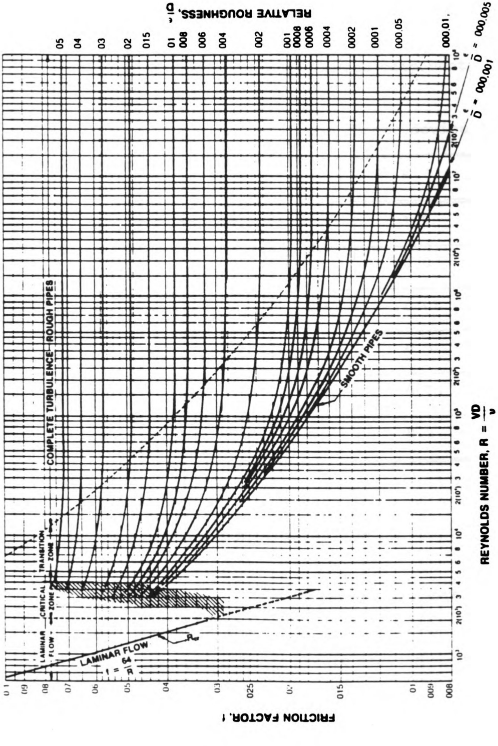

Figure 2. The Moody diagram.

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K = the component friction loss coefficient

Table 1 gives the values of K for the most common components.

Table 1. Friction Loss Coefficients for some common devices.

DEVICE	K
TEE, Through Side Outlet	1.8
Globe Valve (fully open)	10.0
Rounded Entrance	0.05
Square Entrance	0.5
Gradual contraction	0.04
Abrupt contraction	0.5

b. LATERAL PRESSURE DISTRIBUTION

Heermann and Kincaid (1970), referring to work in branching flow done by Vennard and Dentoni (1954), used numerical techniques to determine the pressure distribution in a center-pivot lateral. They used the ratios:

$$d_p / D \leq 0.2$$

where:

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d_p = the diameter of the branching line (riser)

D = diameter of the main line (lateral).

and

$$q / Q < 0.3$$

where:

q = the branch discharge (sprinkler)

Q = the discharge in the upstream main line section.

For the range of the second ratio, the total head loss for the flow continuing along the main line (lateral) is negligible. Their results showed that the head loss for the flow into the riser is given approximately by the equation:

$$h_r = \frac{V^2}{2g} EXP\left(9.2\frac{q}{Q}\right) \qquad \ldots II\text{-}9$$

They concluded that the head loss into the risers would affect the sprinkler-head pressures but would not affect the total loss in the lateral. The procedure used to calculate the pressure distribution along the lateral was (starting at the outer end): evaluate the sprinkler discharge (in gpm) using any of the equations derived by Heermann and Hein (1968) (Equation II-10 and 11); compute the discharge and the head loss in each lateral section (between adjacent sprinklers) moving toward the pivot point. The sprinkler discharge is given by:

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$$q_i = d\ W\ R_i \frac{(R_{i+1} - R_{i-1})}{K} \qquad \text{... } II\text{-}10$$

where:

q_i = the discharge of the i^{th} sprinkler, in gpm

d = the desired depth, in inches

W = the angular velocity of the sprinkler line, in radian/hour

R_i = the distance from the i^{th} sprinkler to the pivot-point, in feet (ft),

K = 192 (gpm.h/in.ft^2), constant that includes the conversion factor.

or by specifying the total system discharge rather than the desired depth and angular velocity by the relation:

$$q_i = Q\ R_i \frac{(R_{i+1} - R_{i-1})}{R_n} \qquad \text{... } II\text{-}11$$

where:

Q = the total system discharge, in gpm

R_n = the radial distance from the pivot point to the last sprinkler on the line.

In their analysis they found that for a 0.152 m (6 in) pipe-diameter center-pivot system with 396 m (1300 ft) lateral, a pressure drop of 103 - 138 Kpa (15 - 20 psi) is commonly found. This results in high pumping costs and a higher pressure than the required for the smaller sprinklers close to the pivot and lower pressure for the larger sprinklers toward the outer end of the lateral. Lower pressures result in large water droplet sizes and a reduction of the soil intake rat. Their suggestion to reduce pumping cost and provide a more uniform pressure distribution was to reduce the pressure loss by increasing the pipe diameter.

Chu and Moe (1972) derived an analytical solution for the total pressure loss and for the distribution of the head loss along the lateral. Starting with the energy equation, they found that the total pressure loss is given by the equation:

$$h_0 - h_R = h_m \frac{B(m+1,0.5)}{2} \qquad \ldots II\text{-}12$$

where:

h_0 = the pressure head at the pivot point, in feet

h_R = the pressure head at the end of the lateral, in feet

h_m = the friction head loss of the lateral operating as a supply line, in feet

B(m+1, 0.5) = the beta function

The friction head loss of the lateral operating as a supply line, h_m is given by:

$$h_m = \frac{R\ C\ Q_0^m}{D^n} \qquad \ldots\ II\text{-}13$$

where:

Q_0 = the total system discharge, in gpm

C = the roughness factor of the lateral pipe

D = the diameter of the lateral, in feet

R = the radius of the irrigated area

m, n = constants in the slope of the energy grade line, S_f, as given by Christiansen (1942).

The distribution of the pressure head loss along the lateral is given by the equation:

$$\frac{(h_r - h_R)}{(h_0 - h_R)} = 1 - \left(\frac{15}{8}\right)\left(X - \frac{2X^3}{3} + \frac{X^5}{5}\right) \qquad \ldots\ II\text{-}14$$

where:

X = the ratio r/R

r = the distance from the sprinkler to the pivot-point

R = the radius of the irrigated area

h_r = the pressure head at r

h_R = the pressure head at the end of the lateral

h_0 = the pressure head at the pivot-point.

They also derived an equation for the distribution of the discharge:

$$Q = Q_0 \left(1 - \frac{r^2}{R^2}\right) \qquad \ldots II\text{-}15$$

where:

Q_0 = the total system discharge

Q = the discharge at distance r from the pivot

The validity of these equations was verified by comparison with field data.

Iterative solutions used in flow analysis in pipe network such as Hardy-Cross, Newton-Raphson (Wood and Rayes, 1981), and the Linear Theory Method (Wood and Charles, 1972), can also be used in the analysis of sprinkler systems. However, the discussion of these methods is beyond the scope of this work. A complete discussion of these methods can be found in Jeppson (1982).

Saldivia (1988) did an analysis of sprinkler irrigation systems, including minor losses, using the Finite Element Method (FEM). His results were compatible with results obtained using the Linear Theory Method. The advantages of using the FEM as he stated, are: less computer memory used for storage, and that it is not necessary to change the computer code when analyzing different systems. Pandey

(1989) also used the FEM in the analysis of center-pivot systems in which auxiliary sprinklers were added to the lateral. These auxiliary sprinklers would start operating at the time the end-gun was off. By doing so, the pump operating point remained constant, resulting not only in a saving of energy but also in a better distribution uniformity.

C. CENTER-PIVOT DESIGN CONSIDERATIONS

Christiansen (1941) was one of the first researchers to do extensive tests on stationary agricultural sprinklers to determine the most important factors affecting the water distribution. He found out that for a stationary sprinkler, the water is applied at a relatively constant rate (at any particular point) and that the rate of application decreased with the distance from the sprinkler. The pattern of this variation is often called sprinkler distribution pattern or profile. Christiansen also determined that among the many factors influencing a sprinkler distribution pattern, the operating pressure, wind and sprinkler speed of rotation were the most important ones. At high pressures most of the water is deposited near the sprinkler while at low pressures most of the water was deposited in a ring on the edge of the pattern, a pattern normally called doughnut shape. The sprinkler pattern produced by unfavorable wind conditions (4.5 - 6.7 m/s or 10 - 14 mph) were asymmetrical with most of the water deposited near the sprinkler. A high sprinkler rotation speed also had the effect of reducing the wetted area and therefore increasing the application rate.

Kohl (1974) studying the water droplet size distribution from medium size agricultural sprinklers also determined the importance of the operating pressure in affecting the shape of the sprinkler pattern. He referred to work done by Merrington and Richardson (1947) stating that the mean diameter of droplets formed from jet breakup is inversely dependent on the jet's velocity relative to the surrounding air. Since jet velocity is proportional to water pressure, higher pressure produce smaller droplets. Also, since the speed of the droplet decreases faster with the decrease of the droplet diameter, smaller droplets will fall closer to the nozzle. Kohl also studied the effect of the nozzle size. He concluded that although smaller nozzles produce a smaller mean drop size than larger nozzles, its effect is less than the pressure effect. Operating smaller nozzles at low pressure can produce larger mean drop sizes than larger nozzles operating at higher pressure. Figure 3 shows the typical distribution patterns of an impact sprinkler operating under low, normal and high pressures.

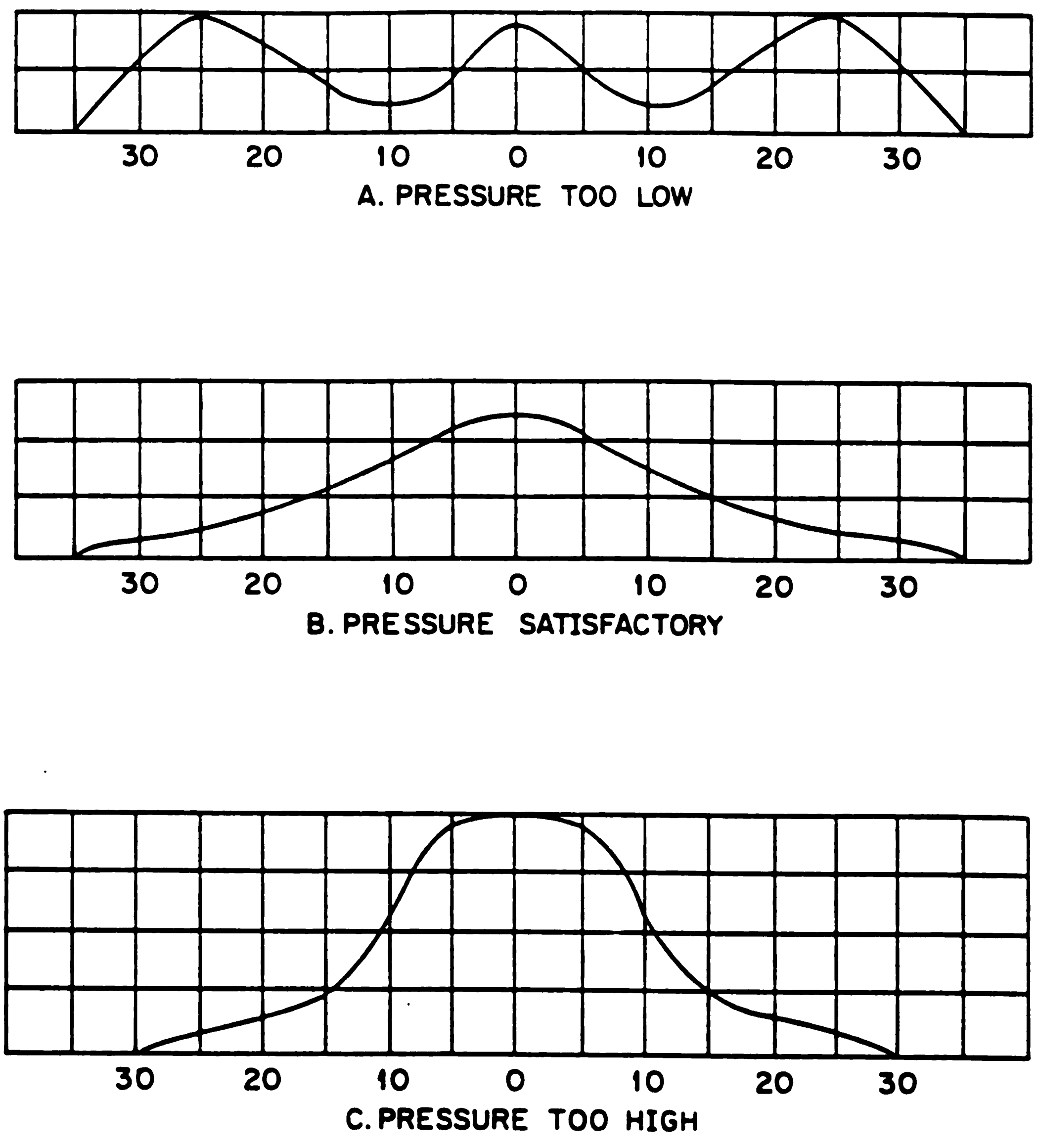

Figure 3. Typical distribution pattern of impact sprinklers operating under low, normal and high pressure.

In the case of continuous move systems, the water application rate at a given point is not constant. It is zero until the moment the first sprinkles start to wet the point, it increases as the system approaches and reaches a maximum as the system is directly over the point and starts decreasing as the system moves away. Finally it becomes zero after the last droplets wet the particular point. The application rate is a function of the nozzle size, nozzle operating pressure, sprinkler spacing, sprinkler type and distance from the pivot point. For a center-pivot system, the average application rate varies from a low value close to the pivot-point to higher values toward the end of the lateral. Pair (1978) illustrates with a figure (Figure 4 redrawn here) why the application rate must increase toward the outer end of the lateral. In a 402 m (1320 feet) system, the same volume of water must be applied through 54 m (177 feet) of lateral covering the outside one-fourth of the area irrigated as through the 201 m (660 feet) of lateral over the inner one-fourth of the area. He also stated "... *water application rate varies along a center-pivot because of the time water is applied per unit length of lateral decreases from the center pivot to the outer end* ... " . For that reason the area being irrigated by the end of the lateral is the one more subject to potential runoff.

The spacing between sprinklers as well as their

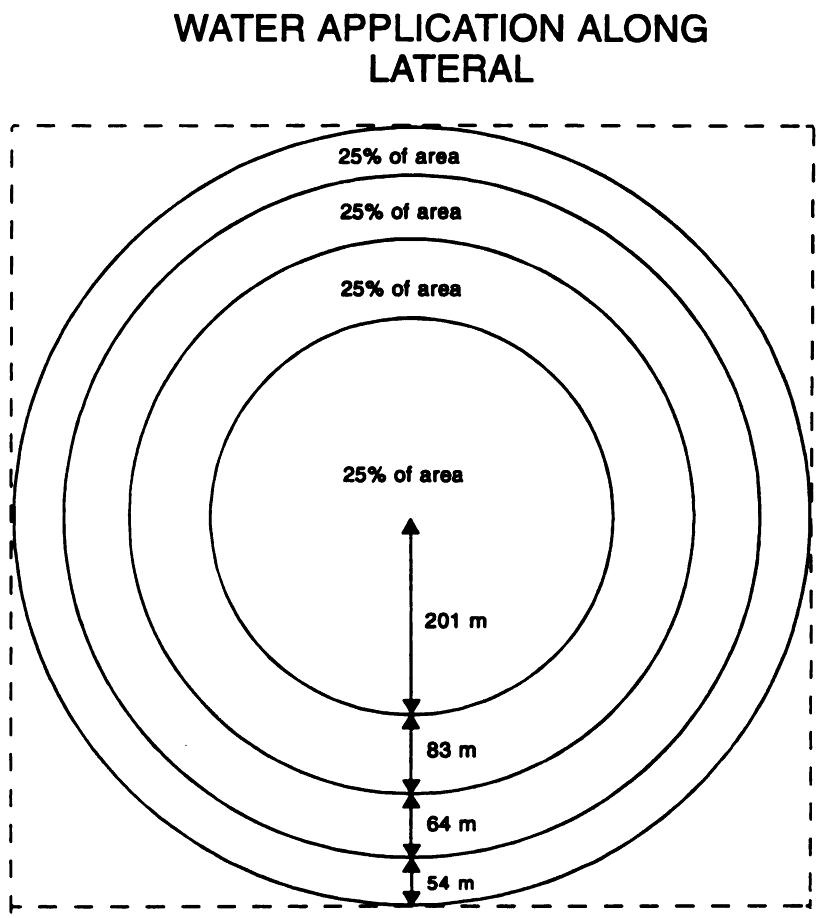

Figure 4. Lateral section lengths for uniform water distribution.

distribution pattern, as mentioned before, is of great importance in affecting the water application. The most common sprinkler type and spacing arrangements used by the industry are:

I - Using increasingly larger sprinklers (conventional impact sprinklers) toward the end of the lateral and maintaining the sprinkler spacing constant. One disadvantage of this arrangement is the use of a large sprinkler at the end of the lateral. Although these sprinklers have a lower average application rate, since they wet a large area, their instantaneous application rate (i.e. the rate at which water is applied to a given point on the soil surface during an instant in time (James and Stillmunkes, 1980) is higher. In some soils, high instantaneous application rates can cause soil dislodgement and increase the potential for runoff and erosion. One advantage of a larger sprinkler is the potential for better overlapping of the patterns from different sprinklers.

II- Using all medium size conventional impact sprinklers with increasing nozzle size toward the outer end and with decreasing spacings toward the end of the lateral.

III- Using spray nozzles with increasing nozzle sizes toward the outer end with a constant spacing between them. This arrangement is the one commonly used in low pressure center pivot systems.

IV- Using spray nozzles mounted on spray booms which are themselves mounted across the center-pivot lateral with the objective of increasing the area of application and therefore reducing the application rate.

V- Using Low Energy Precision Application (LEPA) packages in which drop tubes are used to lower the sprinkler discharge head or a furrow drop (Fangmeier et al. , 1990). Besides having a low energy requirement, this arrangement has the advantage of a more precise application, and a smaller drifting loss resulting in an increased water application efficiency.

Figure 5 illustrates the first three arrangements and figures 6a-6d show the different heads used in LEPA systems.

When designing a center-pivot system it is desired to match the application rates to the soil intake rate to avoid potential runoff. Potential runoff is the portion of the water applied at rates exceeding the soil intake rate.

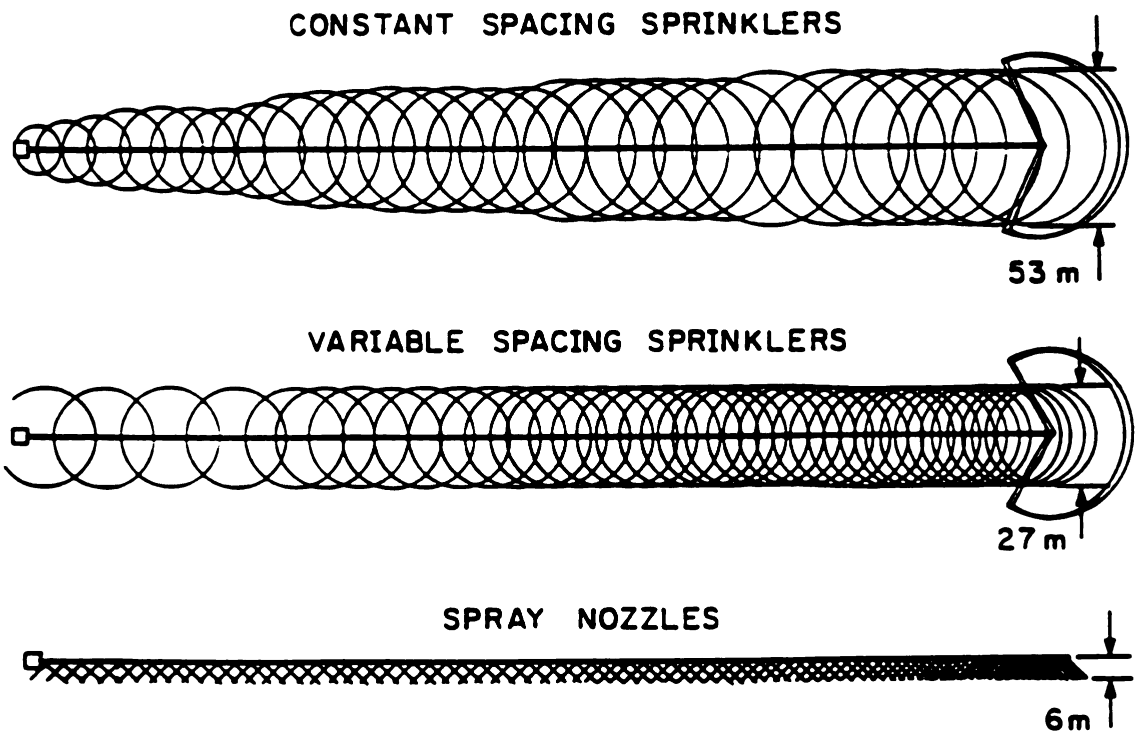

Figure 5. Different sprinkler arrangements along the lateral.

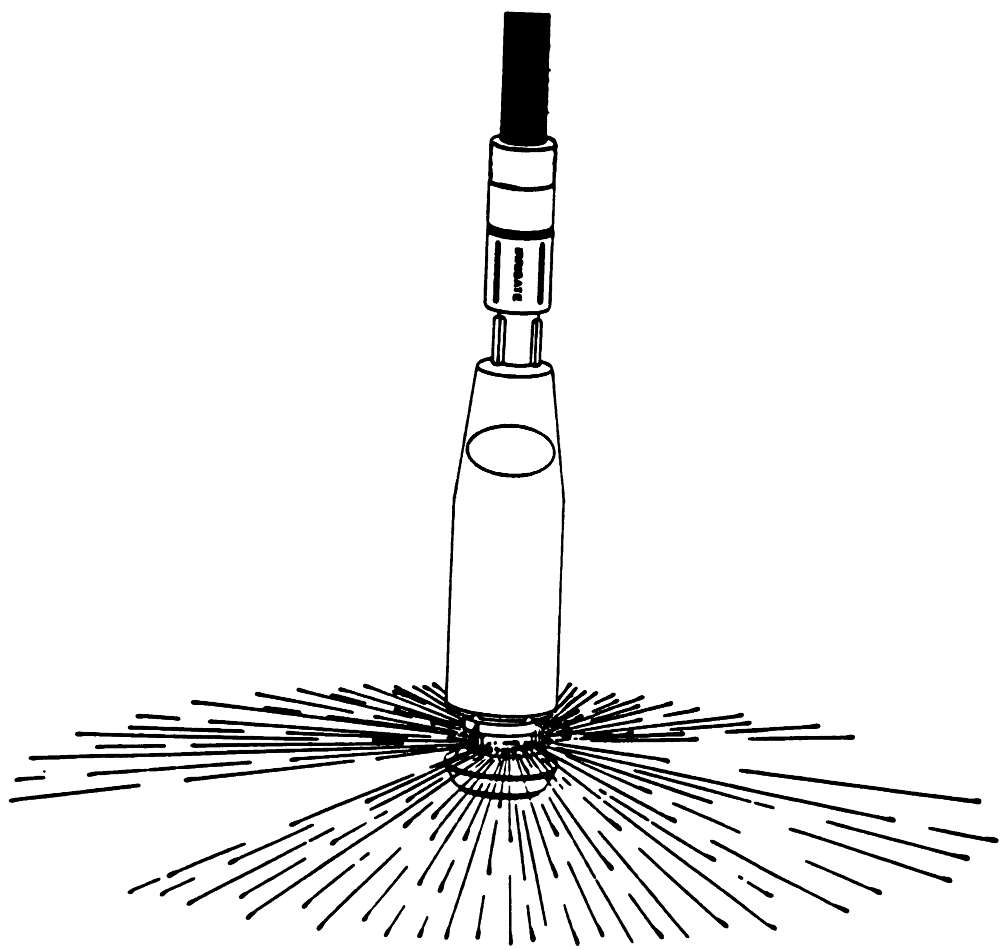

Figure 6b. LEPA head operating in spray mode.

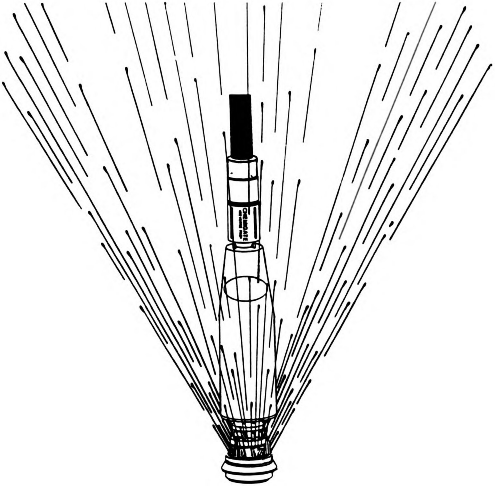

Figure 6c. LEPA head operating in chemigation mode.

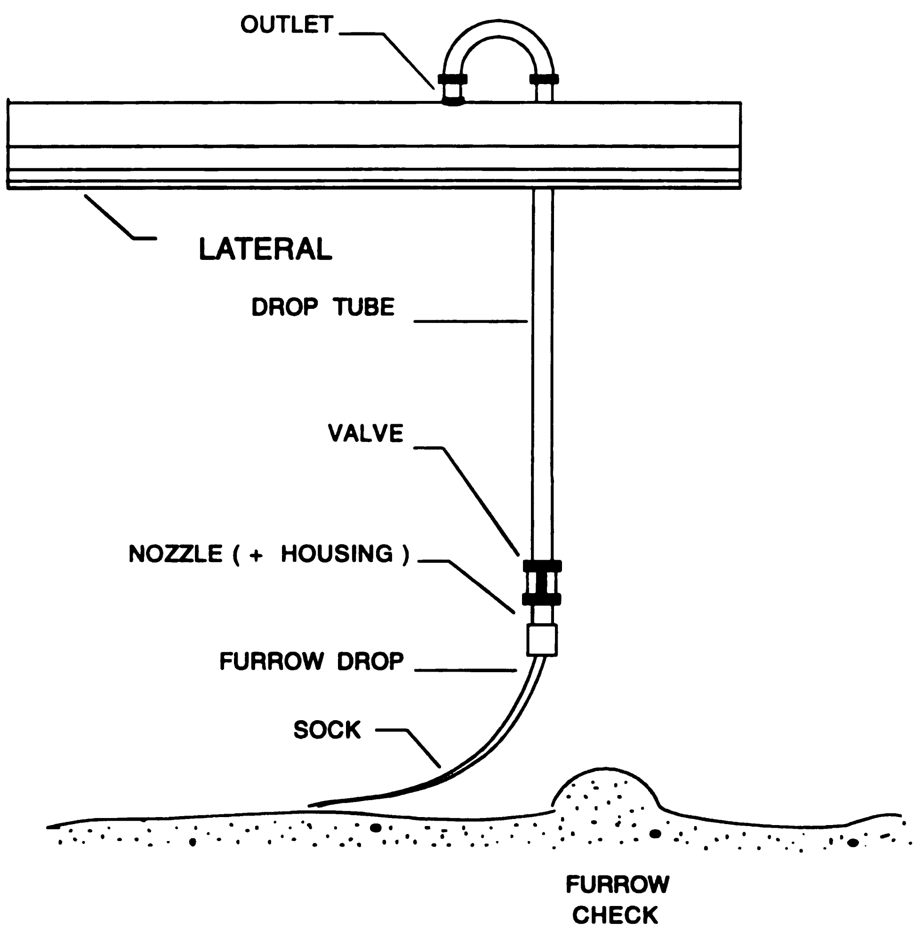

Figure 6d. Schematic of a furrow drop used in a LEPA systems.

The empirical formula:

$$I = kt^{n} \qquad \ldots II\text{-}16$$

where:

I = the intake rate

t = the time, in hours

k and n are constants for the given soil.

has been widely used to represent the soil intake rate because it provides good fit with experimental data. An analysis by Heermann and Hein (1968), assuming a constant soil intake rate, found that the potential runoff was proportional to the distance from the pivot point. Kincaid et al. (1969) using equation II-17 showed that potential runoff can be substantial near the pivot point. They explained " ... *even though peak application rates are lower, these rates are reached at a time when intake rates are also lower.*". Figure 7 illustrate this concept. They continued questioning the validity of using the soil intake function given by equation II-17, since it assumes that the intake rate is independent of the application rate during the initial period of application (period prior to saturation) , which is not valid for a moving sprinkler irrigation system. Under moving sprinkler irrigation systems the soil is gradually saturated rather than suddenly

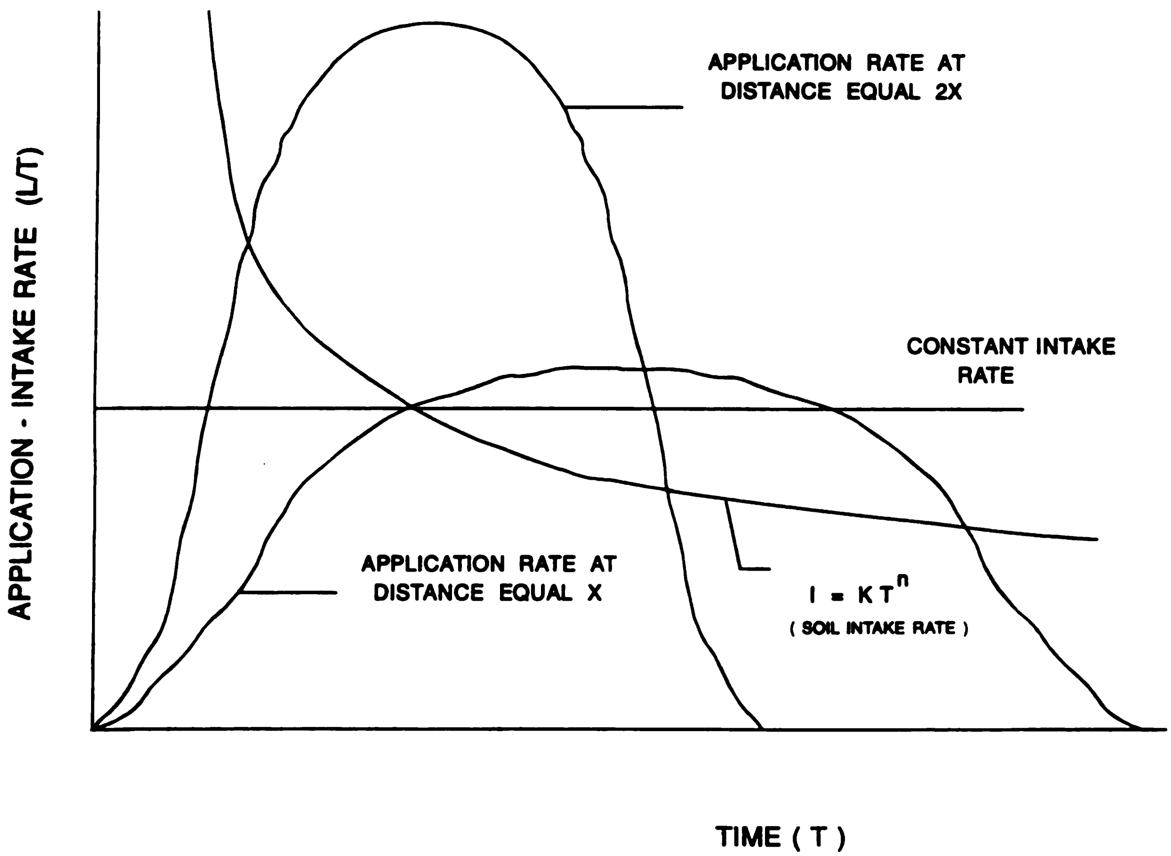

Figure 7. Potential run-off for Elliptical Pattern Sprinklers at different distances from the pivot-point.

flooded. Assuming that the intake at any time depends on the volume infiltrated up to that time, they proposed the use of a modified intake rate for the period prior to when potential runoff begins, given by:

$$I_m = I/Z \qquad ...II-17$$

where:

I = the intake rate function given by equation (II-16)

$Z = D_a / D_p$

where:

D_a = the depth applied up to the time potential runoff begins

D_p = maximum depth that could be applied before potential runoff begins

For the period after potential runoff begins the intake function is given by the same equation (equation II-17) , but using a new time, t - Δt. The intake function in this case is given by:

$$I = k\ (\ t\text{-}\Delta t\ )^n \qquad ...\ II-18$$

where:

Δt = the amount of time by which the intake function given by equation II-16 must be delayed so that it will pass through the intersection between the application rate curve and the modified intake rate (I_m).

Figure 8 helps clarifying this concept. Their results showed that using the modified intake rate function had the effect of reducing the predicted potential runoff and a better prediction of the actual runoff could be made.

Dillon et al.(1972) proposed a design procedure that would not only match the center-pivot system to the soil with no potential runoff occurring, but also to the crop. Soil sprinkler intake curves developed by the State Office of the Soil Conservation Service, Temple, Texas (Vittetoe, 1970) were used. These soil curves were grouped into soil intake families and the coefficients of equation II-16 for each family is presented in table 2. Assuming that the

Table 2. Equation II-17 coefficients for different SCS soil intake families.

INTAKE FAMILIES	K	n
PULLMAN AND LIKE SOILS	0.810	-0.69
0.5 INTAKE SOIL	0.880	-0.615
0.3 INTAKE SOIL	0.520	-0.860

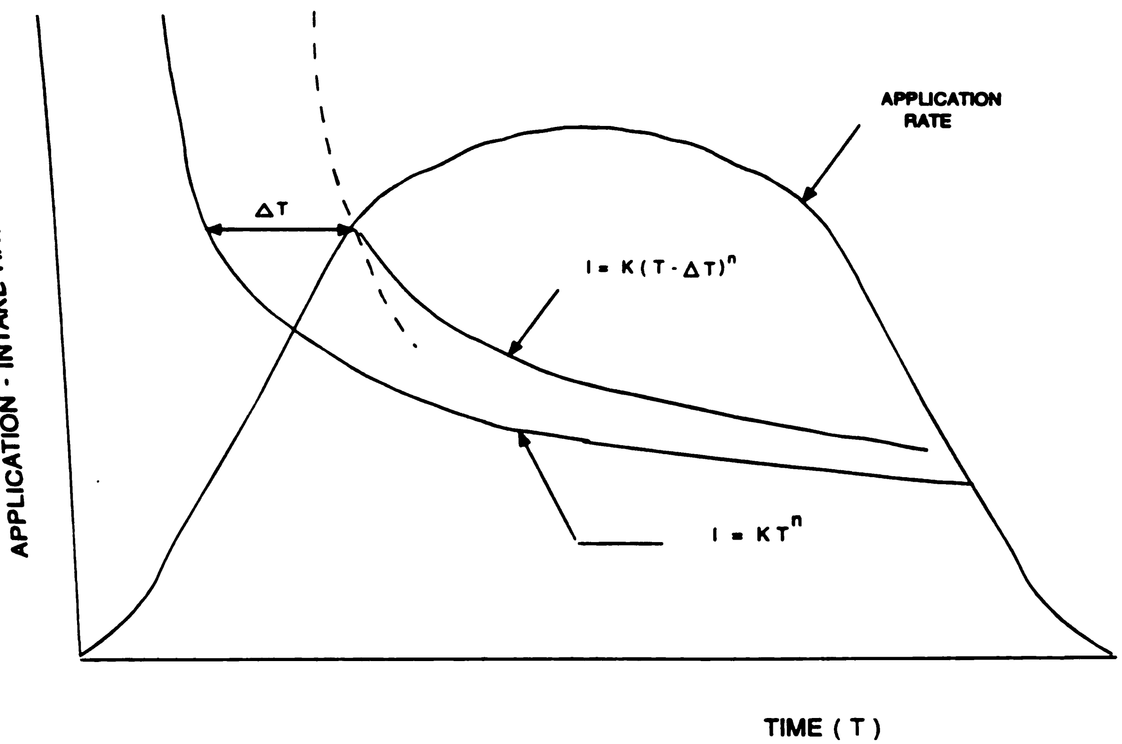

Figure 8. Modified Intake Function.

water is being applied uniformly and in an elliptical pattern the maximum application rate occurs somewhere at the end of the system. They proposed an equation to determine the approximation of the average maximum application rate (in./h) of the last few sprinklers given as:

$$h = 122.5\frac{Q}{Rr} \qquad \ldots II-19$$

where:

Q = the system capacity, in gpm

R = the radius of coverage of the system, in ft.

r = the radius of coverage of the last few sprinklers, in ft.

With knowledge of the maximum application rate and surface storage allowance (Shockley, 1968), the maximum time required for the elliptical pattern to pass a point can be determined by superimposing the elliptical pattern on the particular soil's sprinkler intake curve, See figure 9 . The minimum design speed can be determined by:

$$V = \frac{r}{30t} \qquad \ldots II-20$$

where:

r = the radius of the last few sprinklers, in ft.

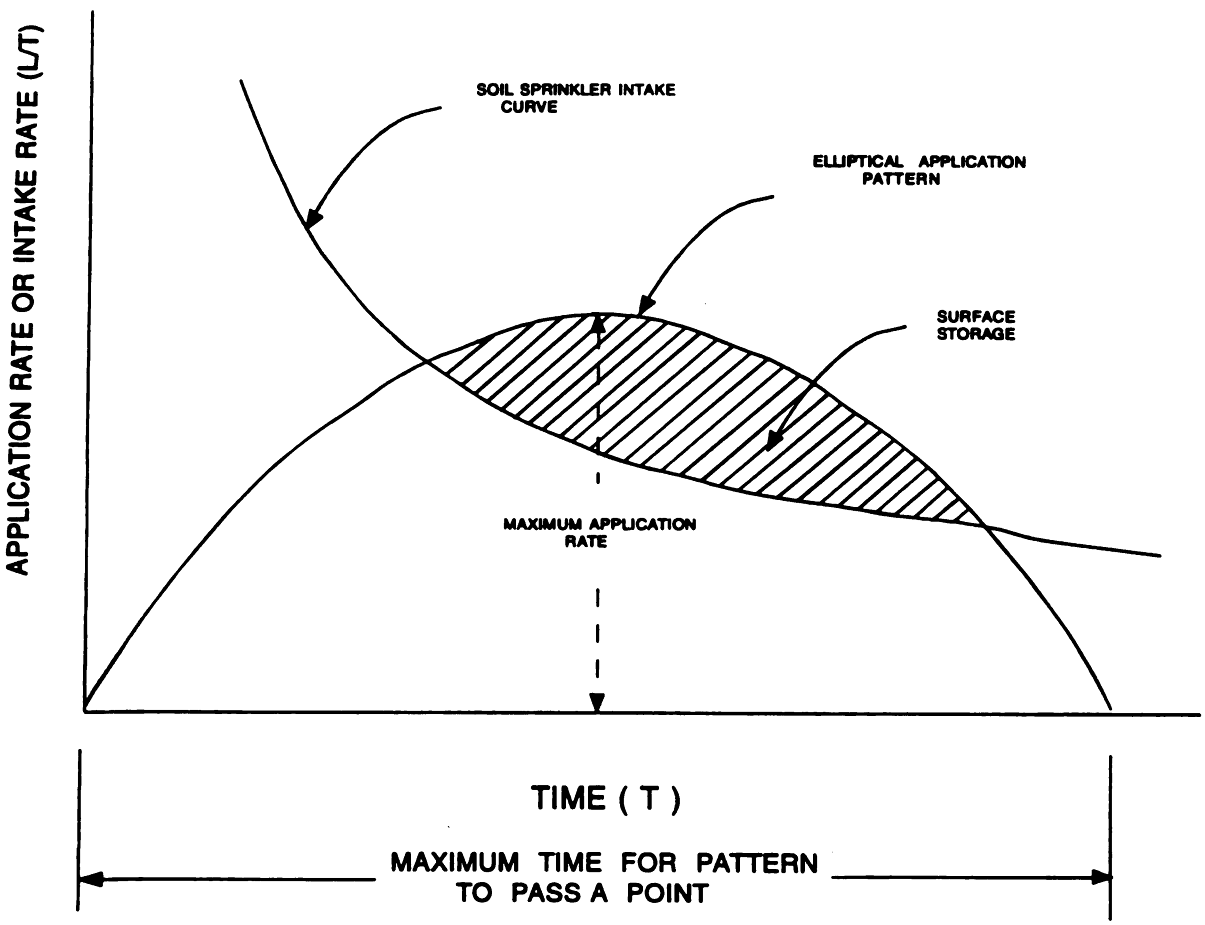

Figure 9. Maximum application rate of Elliptical application pattern by super-imposing the application distribution pattern on the soil intake curve.

t = the maximum time required for the elliptical application pattern to pass a point.

The minimum design time, in hours, to complete one revolution can be easily determined by:

$$T = \frac{2\pi R_L}{60V} \qquad ...II\text{-}21$$

where:

R_L = the distance from the pivot to the last tower, in ft.

V = the minimum design speed determined by the equation II-20.

Finally, the average net depth, in inches, can be calculated by:

$$D_N = \frac{PT}{24} \qquad ...\ II\text{-}22$$

where:

P = the peak water use, in in./day. It varies for different crops and climates.

T = the minimum design time.

D. UNIFORMITY COEFFICIENTS

Over the past many researchers have proposed different uniformity coefficients in order to express the uniformity of water application in a field. Different sprinkler irrigation systems have been compared on the basis of such coefficients.

Christiansen (1941), in order to compare different sprinkler patterns and to determine how different spacings would affect the distribution of water, introduced an expression which he called "uniformity coefficient" given as:

$$Cu = 100\left(1 - \frac{\sum d}{mn}\right) \qquad \ldots II\text{-}23$$

where:

m = the mean of the observations

n = the number of observations

d = the absolute value of the deviation of individual observations from the mean value.

As can be seen, an absolute uniform distribution ($\sum d = 0$) will be represented by an uniformity coefficient of 100%. Today this coefficient is usually referred to as the "Christiansen Uniformity Coefficient", and in this present study it will be denoted by UCC.

Wilcox and Swailes (1947) instead of using the sum of the absolute deviation from the mean, have used the sum of the squares of the deviation from the mean to define a new coefficient, given as:

$$UCW = 100\left(1 - \frac{S}{\overline{X}}\right) \qquad \ldots II\text{-}24$$

where:

S = the standard deviation of the observations

$\overline{X}$ = the mean of the observations.

The relation $S/\overline{X}$ is known as the coefficient of variability.

The USDA (Cridle et al., 1956) introduced the following parameter for the evaluation of overlapped sprinkler patterns:

$$PE_U = \frac{\Sigma X_i^*}{n^*\overline{X}} \qquad \ldots II\text{-}25$$

where:

PE_U = the USDA Pattern Efficiency

ΣX^*_i = the sum of the lowest 25 percent of the observations

n^* = the number of observations used in computing ΣX^*_i

$\overline{X}$ = the average of all observations in the pattern

Hart (1961), when testing the overlap of patterns of a wide range of sprinkler sizes (4 to 300 gpm) operating at normal pressures and at reasonable spacings, showed that the distribution of the observations approximated a normal (Gaussian) distribution. Assuming a normal distribution curve, the mean of the absolute deviation from the mean equals approximately 0.798 S, where S is the standard deviation of the sample. Substituting in the equation of UCC (Christiansen Uniformity Coefficient), a new uniformity coefficient was obtained:

$$UCH = 1 - 0.798 \frac{S}{\overline{X}} \qquad ...II\text{-}26$$

This coefficient is known as Hawaiian Sugar Planters Association (HSPA) Uniformity Coefficient . Hart also stated that assuming a normal distribution the USDA Pattern Efficiency could be written in terms of the coefficient of variability. He showed that the value of point $\sum X^*_i$ / n^* corresponds to a value $\overline{X}$ - 1.27S . Substituting in equation II-25, an equation relating pattern efficiency and cv can be written as:

$$PE_H = 1 - 1.27\frac{S}{\overline{X}} \qquad ... II\text{-}27$$

Benami and Hore (1964) questioned the adequacy of using both UCC and UCW coefficients. They showed that the same UCC values could be found for different distributions even though one distribution was far superior than the other. They pointed out the weakness of the UCC as in not giving more emphasis to deviations below the mean, which are usually considered to be more critical than deviations above the mean. With respect to the UCW they stated that although it does give added weight to the extreme readings it still does not adequately differentiate between satisfactory and unsatisfactory distribution patterns. For that reason they proposed a new coefficient known as Benami and Hore Uniformity Coefficient. This coefficient considers the deviations from the mean of the group of observations above and below the general mean, and it is given by the relationship:

$$A = \frac{C_1}{C_2} \qquad \text{... } II\text{-}28$$

where:

$$C_1 = M_b - \frac{\Sigma |\ X\ |_b}{N_b} \qquad \text{... } II\text{-}29$$

and

$$C_2 = M_a + \frac{\Sigma|X|_a}{N_a} \qquad ...II\text{-}30$$

where:

M_a = the mean of the group of readings above the general mean.

M_b = the mean of the group of readings bellow the general mean.

N_a = the number of observations above the general mean.

N_b = the number of observations bellow the general mean.

$|X|$ = the absolute deviation from the group mean.

Benami and Hore stated "*... by considering the ratio of deviations below to deviations above the general mean, the new coefficient lays particular stress on deviations below the general mean. At the same time, the coefficient takes into account that deviations near the general mean are not as important as deviations further from the general mean.*". The expression given above is sufficient for pattern comparison purposes, for recommendation purposes they suggested using an absolute value of A, referenced to a value of one hundred, given by:

$$A = 166 \frac{C_1}{C_2} \qquad \ldots II\text{-}31$$

The coefficient A, can also be computed more readily using the equation:

$$A = 166 \frac{N_a}{N_b} \frac{[\ 2T_b + D_b M_b\ ]}{[\ 2T_a + D_a M_a\ ]} \qquad \ldots II\text{-}32$$

where:

T_a = the sum of the readings above M_a

T_b = the sum of the readings below M_b

D_a = the difference between the number of observations below and above M_a, for the group above the general mean.

D_b = the difference between the number of observations above and below M_b, for the group below the general mean.

Benami and Hore claimed two important advantages in using their new coefficient instead of UCC and UCW. The first advantage is that the coefficient A is a better index of the degree of pattern uniformity, that is, different values of A were found when comparing two different pattern distributions with same UCC values. The second advantage is that the differences between different distribution patterns are more pronounced due to the wider range in values of A. Values of A greater than one hundred can be found.

Beale and Howel (1966) showed that the USDA Pattern Efficiency was of the same form as UCC, but only accounting for the mean deviation of the lowest 25% precipitation values. They also proposed a new coefficient which they called High Pattern Efficiency (HPE), expressed as:

$$HPE = 100\left[1 - \frac{(\overline{\Delta P})_h}{\overline{P}}\right] \qquad \ldots II\text{-}33$$

where:

$(\overline{\Delta P})_h$ = the mean deviation of the highest 25 percent precipitation values.

$\overline{P}$ = the mean of the precipitation values.

They pointed out that if a normal distribution is assumed, due to its symmetrical shape the value of HPE and PE are the same.

Karmeli (1978) proposed using the linear regression fit based upon the dimensionless cumulative frequency curve of the infiltration depth (Y) and fractional area (X) to describe sprinkler distribution patterns (see figure 10). He demonstrated that the linear regression model may be as good as the normal model for highly uniform patterns (small $S/\overline{Y}$ values), as most of the distribution curve would tend to

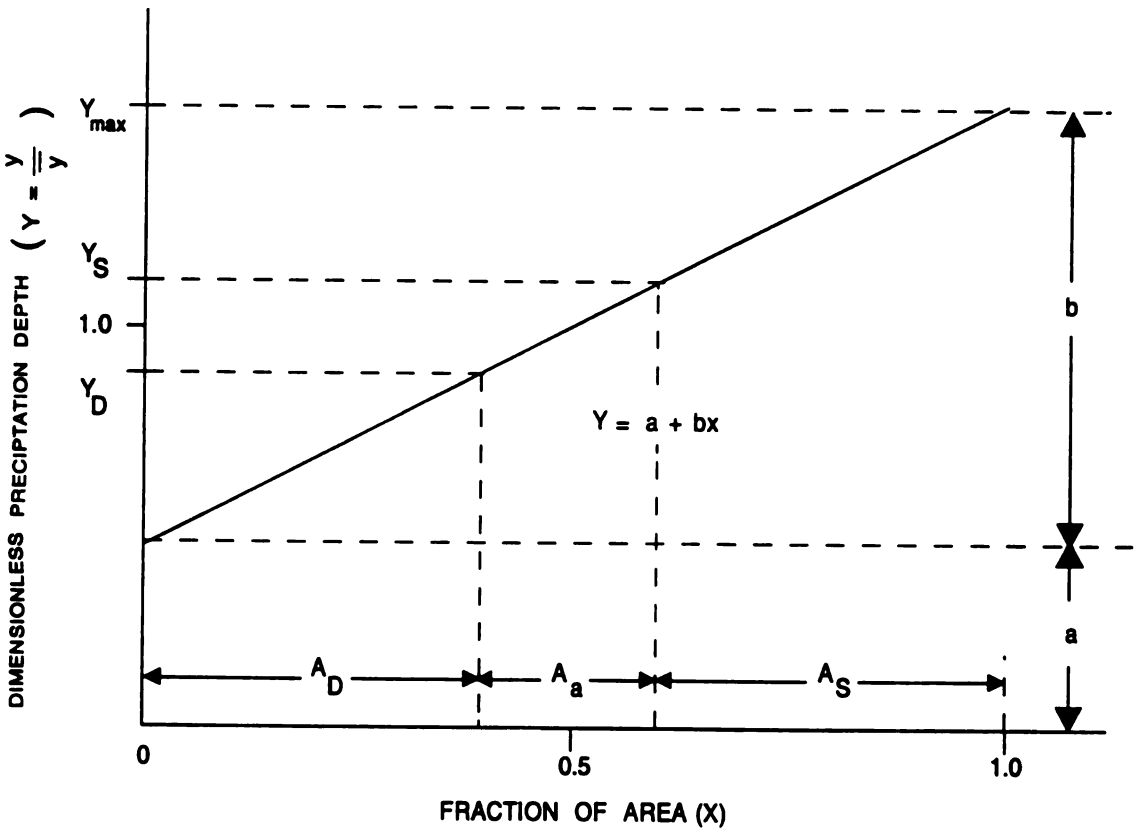

Figure 10. Linear Regression Fit of Non-Dimensional Distribution Curve for Sprinkler Patterns.

concentrate around the mean. However, for less uniform patterns (larger $S/\bar{Y}$ values), the linear fit would be better than the normal fit as the magnitude of the errors at the extremes of the curve (of actual data) would be smaller. The linear regression model has some basic properties where for $Y = 1.0$ (average precipitation depth infiltrating the soil = depth designed to replenish soil moisture deficiency), $X = 0.5$ (half of the irrigated area). The regression coefficient b (the slope of the regression line) is equal to $Y_{MAX} - Y_{MIN}$ (the difference between maximal and minimal wetting zones of the field). The regression coefficient a (the intercept) is equal to the estimated minimal precipitation depth (Y_{MIN}). With respect to figure 10, some related formulations were also written as:

1) Deficit area

$$A_D = \frac{Y_D - a}{b} \qquad ...II\text{-}34$$

where:

Y_D = the maximal depth in the deficit area.

2) Surplus area,

$$A_S = 1 - \frac{Y_S - a}{b} \qquad ...\ II\text{-}35$$

where:

Y_S = the minimal depth in the surplus area.

3) Adequate irrigated area,

$$A_A = 1 - (A_D + A_S) \qquad \text{... } II\text{-}36$$

4) Average depth in the deficient area,

$$\overline{Y_D} = \frac{Y_D + 1 - \frac{b}{2}}{2} \qquad \text{...} II\text{-}37$$

5) Average depth in the surplus area,

$$\overline{Y_S} = \frac{Y_S + 1 + \frac{b}{2}}{2} \qquad \text{...} II\text{-}38$$

A uniformity coefficient based on the linear regression model was then derived, and is given by:

$$UCL = 1 - 0.5b \qquad \text{...} II\text{-}39$$

In tests done, this coefficient showed great similarity with UCC (r^2 = 0.998).

Howell (1964), assuming a polynomial yield function and

that the same yield per area versus water depth curve would apply from irrigation to irrigation, demonstrated that the characteristics of nonuniformity necessary to completely determine its effects on yield were the moments of the distribution (of water application) to the same order as the polynomial yield function.

Varlev (1976) pointed out that the equation proposed by Howell (1964), within the set of his assumptions, is only valid for situations where irrigation water provides all the water received by the crop. Considering usable rainfall and available soil water content at planting time as the total depth of water available to the plants, he proposed the following equation for subhumid and humid zones:

$$\overline{Y} = A_0 + A_1\overline{X} + a_2\overline{X}^2 - \left(1 - \frac{1}{\overline{X}^2 w}\int_0^w X_i^2\, dX\right) a_2\overline{X}^2 \quad \ldots\ II\text{-}40$$

where:

$A_0 = a_0 + a_1\,\gamma + a_2\gamma^2$

$A_1 = a_1 + 2a_2\gamma$

where :

γ = the sum of usable rainfall and available soil water at planting time

a_0, a_1, and a_2 = constants

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w = the area integrated

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$\overline{X}$ = the average depth infiltrated

X_i= the depth infiltrated by irrigation.

Varlev noticed that the absolute yield loss, ΔY, is given by the last expression of equation 40, and that it depends only on the nonuniformity of distributed water infiltrated by irrigation. Then, a new coefficient was proposed, which he called "Coefficient of Nonuniformity", expressed as:

$$F_{NUM} = 1 - \frac{1}{\overline{X}^2 W} \int_0^W X_i^2 dX \qquad \ldots II\text{-}41$$

In this way, the absolute yield loss could be written as, $\Delta Y= a_2\overline{X}^2F_{NUM}$. The integrated form of F_{NUM} given by equation II-41 is appropriate when the equation of the distribution of infiltrated depth of water along the length of the furrows is known. For sprinkler or trickle irrigation, Varlev suggested the use of F_{NUM} expressed as:

$$F_{NUM} = \frac{1}{N} \sum_{i=1}^{N} \left(\frac{X_i}{\overline{X}} - 1 \right)^2 \qquad \ldots II\text{-}42$$

Varlev explained that because of the linear relationship between absolute yield loss and F_{NUM} , the later had a de

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definite economic significance. A reduction in F_{NUM} implies an equal reduction in the absolute yield loss. He also suggested the use of F_{NUM} not only for the comparison of different sprinkler irrigation equipment,i.e. spacing between lateral and sprinklers, but also when comparing among different irrigation methods.

Solomon (1984) demonstrated that for different hypothetical water-yield functions, the relationship between traditional irrigation uniformity and efficiency measures with expected yield, were special cases of the general yield prediction equation:

$$Y = \int_{-\infty}^{\infty} Y(\rho w)\, f(w) dw \qquad \ldots II\text{-}43$$

where:

w = W / μ, a dimensionless irrigation variable

$f(w)$ = the distribution function for the dimensionless irrigation depths,

ρ = μ / W^* , a water management parameter.

where:

μ = the average (over space) of the non-uniform seasonal irrigation application,

W = the seasonal irrigation depth,

W^* = the seasonal application depth which correspond a relative yield of $Y = 1$.

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In this way, the calculation of UCC gives the same result as calculating the expected yield using the equation II-64, with the water-yield function given by :

$$y(w) = 1 - | w - 1|$$

when the irrigator causes μ to be equal to W^*, that is ρ = 1. Therefore, a yield related uniformity coefficient (U_y) and efficiency measure (E_y) were defined as:

$$U_y = \int_{-\infty}^{\infty} y\ (\rho w)\ f(w)\ dw \qquad \ldots\ II\text{-}44$$

and

$$E_y = \left(\frac{1}{\rho}\right) \int_{-\infty}^{\infty} y\ (\rho w)\ f(w)\ dw \qquad \ldots\ II\text{-}45$$

Solomon argued that although the use of U_y or E_y requires an estimate of the appropriate water-yield function to the particular crop and site of interest, both measures assess the significance of irrigation decisions as they would affect the crop at that particular site.

With the exception of the Linear Uniformity Coefficient proposed by Karmeli (1978), all the other statistical based coefficients reviewed above were developed assuming a normal function distribution. However Chaudry (1978), Elliot et al. (1980),and Warrick (1983) have demonstrated that sprinkler application distributions can also be represented by other statistical function distributions such as log-normal, specialized power, beta and gamma distributions. Furthermore, Warrick (1983) also derived expressions for UCC and Distribution Uniformity Coefficient for all the distributions above.

E. UNIFORMITY COEFFICIENT FOR CENTER-PIVOT SYSTEMS

Heermann and Hein (1968) were the first to propose a uniformity coefficient for center-pivot systems. Based upon the fact that, the depth observed by each catch can is representative of the subarea expressed as:

$$A_s = 2\pi S_s \Delta S \qquad \ldots II\text{-}46$$

where:

S_s = the distance from the catch can to the pivot point.

ΔS = the spacing between the catch can,

and assuming that each measured observation remained constant for one revolution of the system, they modified the UCC (Christiansen uniformity coefficient) utilizing the summation of the absolute deviation of observed volumes for the subareas from the mean volume. This coefficient is expressed as:

$$UCHH = 1 - \frac{\sum_{s} | V_s - \overline{V}_s |}{V} \qquad \text{... } II\text{-}47$$

where:

V_s= the volume for the subarea A_s.

$\overline{V}_s$= the mean volume for the subarea A_s.

V = the total volume for the system.

The subarea volumes is expressed by:

$$V_s = D_s A_s = 2\pi D_s S_s \Delta S \qquad \text{... } II\text{-}48$$

where:

D_s = the observed depth at point s.

The mean volume for the subarea A_s is given by:

$$\overline{V}_s = \overline{D} A_s = \left(\frac{\sum_{s=1}^{N} V_s}{\sum_{s=1}^{N} A_s} \right) A_s \qquad \text{... } II\text{-}49$$

where:

$\overline{D}$ = the average depth for the system.

Substituting equations 48 and 49 in equation 47, noting that $V = \sum D_s A_s$, and simplifying, the UCHH can be expressed as:

$$UCHH = 1.0 - \frac{\sum_s S_s \left| D_s - \frac{\sum_s D_s S_s}{\sum_s S_s} \right|}{\sum_s D_s S_s} \quad \text{... } II\text{-}50$$

In the same way as for a stationary sprinkler systems the USDA recommends the use of the Soil Conservation Service Pattern Efficiency (1982), adapted for center-pivot systems, to evaluate the uniformity of water distribution. This coefficient compares the water application on the low one-fourth of the wetted area to the average application on the total wetted area. It is expressed by:

$$PE_{CP} = 100 \frac{WEIGHTED\ LOW\ 25\%\ AVG\ APPLICATION}{WEIGHTED\ SYSTEM\ AVG\ APPLICATION} \quad \text{... } II\text{-}51$$

where, WEIGHT LOW 25% AVG APPLICATION (WGTL25) and WEIGHTED SYSTEM AVG APPLICATION (WGTSYS):

$$WGTL25 = \frac{\sum OF\ LOW\ 25\%\ CATCH*FACTORS}{\sum OF\ LOW\ 25\%\ FACTORS} \quad \text{... } II\text{-}52$$

and

$$WGTSYS = \frac{\sum CATCH*FACTOR}{\sum FACTORS} \quad ... II\text{-}53$$

where:

FACTORS = the number of the catch can.

Marek et al. (1986) proposed the use of a new area-weighted uniformity coefficient based on the coefficient of variability (CV). This uniformity coefficient is based on the square of deviations of the volumes from the mean volume associated with each subarea. One of the advantages claimed for their coefficient is an increased sensitivity in depicting nozzle discharge deviations when compared with UCHH. This increased sensitivity is explained by the fact that the mean deviation does not emphasize the observations that are significantly different from the mean. A second advantage is the implication of better expected yield inferences when using a uniformity coefficient based on the coefficient of variability (Solomon, 1984). This coefficient is expressed as:

$$UCM = 100\left[1 - \frac{\frac{\sqrt{\sum_{i=0}^{N}[V_i - \overline{V}_i]^2}}{N - 1}}{\overline{V}}\right] \qquad \text{... } II\text{-}54$$

where :

V_i = the volume associated with subarea A_i.

$\overline{V}_i$ = the mean volume for subarea A_i.

N = the number of catch cans.

$\overline{V}$ = the average volume for the system.

The area represented by each catch can (subarea) is expressed as:

$$A_i = 2\pi\, r_i\, \Delta r \qquad \text{... } II\text{-}55$$

where :

r_i = the distance from the pivot point to catch can i

Δr = the spacing between catch can.

Assuming x_i, the depth observed at a distance r_i from the pivot, constant for one revolution, the volume associated with subarea A_i is:

$$V_i = 2\pi x_i \, r_i \, \Delta r \qquad \dots II\text{-}56$$

The mean volume for the subarea is given by:

$$\overline{V_i} = \overline{X} \, A_i \qquad \dots II\text{-}57$$

where :

$\overline{X}$ =the average depth for the system is given by:

$$\overline{X} = \frac{\sum_{i=1}^{N} V_i}{\sum_{i=1}^{N} A_i} \qquad \dots II\text{-}58$$

The average volume for the system is:

$$\overline{V} = \frac{\sum_{i=1}^{N} A_i \, x_i}{N} \qquad \dots II\text{-}59$$

Substituting equations II-55 to II-59 in equation II-54 and simplifying, this coefficient may be expressed by:

$$UCM = 100\left[1 - \frac{\dfrac{\sqrt{\sum_{i=1}^{N}\left[r_i x_i - \left(r_i \dfrac{\sum_{i=0}^{N} r_i x_i}{\sum_{i=0}^{N} r_i}\right)\right]^2}}{N-1}}{\dfrac{\sum_{i=0}^{N} r_i\, x_i}{N}}\right] \qquad ...II\text{-}55$$

F. CENTER-PIVOT EVALUATION

In the past, different test procedures for water application data collection have been recommended with the objective of evaluating center-pivot performance. For the interested reader, a short review is given by Ring and Heermann (1978). The field test procedures recommended by the American Society of Agricultural Engineers (ASAE) and by the Soil Conservation Service (SCS) have been the most accepted and used procedures in performing field evaluations of center-pivot irrigation systems. A brief summary of both procedures is given below.

In 1983, the ASAE adopted a standard (ASAE S436) test

procedure for determining the uniformity of water distribution of center-pivot and other self-moving machines. This standard was approved by the American National Standard Institute (ANSI) in 1989. Specifically for center-pivot machines, among other recommendations, the ASAE standard recommends that the catch cans must be placed in at least two radial lines with their outer end no more than 50 m (165 ft) apart. The catch cans must be spaced with a maximum spacing of 30% of the average sprinkler wetted diameter, and never more than 4.5 m (14.8 ft). The entire test shall be conducted in an representative area and during periods that the effect of evaporation will be minimized, with a wind velocity of less than 1.0 m/s (2.2 mile/h), measured at a minimum height of 2m (6.6 ft) and within 200 m of the test site. For such reasons the ASAE recommends the test to be conducted at night. For the calculation of the water application uniformity it recommends the use of UCHH (Heermann and Hein coefficient) given in previous sections as equation II-47 and II-50. In its calculation the ASAE recommends the elimination of the data on the inner 20% of the total length of the system, as well as any obviously incorrect data points that may be explained for. Other observations which are unreasonably high or low may also be eliminated from the analysis, but eliminated values should be less than 0.5% of the total number of data points.

In its evaluation test procedure, the SCS recommends the catch cans to be placed in a single radial line extending from the pivot-point to a point beyond the wetted area, at any uniform interval. Usually the spacing is of 9.1 m (30 ft). When evaluating the adequacy of the irrigation system design (at ideal conditions) the SCS recommends the use of the Pattern Efficiency coefficient defined previously as equation II-51. This coefficient has been also referred as Distribution Uniformity as well as Distribution Efficiency. For the evaluation of the irrigation application it recommends the use of the Application Efficiency Coefficient defined as:

$$ApplicationEfficiency = \frac{\frac{\Sigma CATCH * FACTOR}{\Sigma FACTOR}}{D_g} \qquad \ldots II\text{-}61$$

where:

CATCH = depth measured in the catch can,

FACTOR = the number of the can,

D_g = the gross application, the area times the average depth.

This coefficient compares the amount of water pumped to the amount of water applied in the field; therefore it is a measure of the losses due to evaporation, wind drift and leaks in the system.

G. CENTER-PIVOT SIMULATION

1- THEORETICAL DEVELOPMENT AND SYSTEM EVALUATION:

Bittinger and Logenbaugh (1962) established the theoretical basis for water distribution from moving sprinkler irrigation systems. They derived equations for the application rates and total depth of precipitation for a single sprinkler having triangular and elliptical patterns moving in a straight line and in a circular path at a constant velocity. Assuming a straight line movement, the equations for the application rate and total depth for sprinklers with triangular distribution pattern are given respectively by:

$$AR_T = h \left\{ \frac{r - (m^2 r^2 + v^2 t^2)^{\frac{1}{2}}}{r} \right\} \qquad \text{... } II\text{-62}$$

and

$$D_T = \frac{hr}{v} \left\{ (1-m^2)^{\frac{1}{2}} - m^2 \ln \frac{(1-m^2)^{\frac{1}{2}} + 1}{m} \right\} \qquad \text{... } II\text{-63}$$

And for the elliptical pattern sprinklers by:

$$AR_E = \frac{hv}{r}\left\{\frac{r^2 - m^2r^2}{v^2} - t^2\right\}^{\frac{1}{2}} \qquad \text{... } II\text{-}64$$

and

$$D_E = \frac{hr\pi\ (1 - m^2)}{2v} \qquad \text{... } II\text{-}65$$

where:

h = the application rate at the center of the sprinkler pattern,

r = the radius of sprinkler pattern,

m = the ratio of the perpendicular distance between point p and the line of travel of the sprinkler to the sprinkler pattern radius,

v = the linear velocity of the sprinkler,

t = time.

For triangular pattern sprinklers moving in a circular path, application rate is given by:

$$AR_{T(circ.)} = h - \frac{h}{r}\{(R + mr)^2 - 2R\,(R + mr)\cos\alpha + R^2\}^{\frac{1}{2}} \qquad \text{... } II\text{-}66$$

where:

R = the distance from the sprinkler to the pivot-point

α = the angle of the rotation about the pivot-point.

and the total depth of precipitation on point p with a complete pass of the sprinkler is given in the form of an elliptic integral of the second kind:

$$D_{T(circ.)} = 2hT - \frac{4h}{\omega}(2n + m)\left\{E(k, \frac{\pi}{2}) - E\,(k, \frac{\pi}{2} - \frac{\omega T}{2})\right\} \quad \ldots \; II\text{-}67$$

where:

ω = angular velocity of sprinkler (radian/T)

T = time required for one-half of sprinkler pattern to pass point p

n = the ratio of radius of rotation to pattern radius, R/r

K = $(4n(m + n)/\ (m + 2n)^2)^{1/2}$

$E(k,\phi) = \int_0^{\phi} (\ 1 - k^2 \sin^2 \phi)^{1/2}\, d\phi$, the elliptic integral.

For elliptical pattern sprinklers, also moving in a circular path, the equation for the application rate is given by:

$$AR_{E(circ.)} = \frac{h}{r}\left[r^2 - S^2 - R^2 + 2RS\cos\alpha \right]^{\frac{1}{2}} \quad \ldots II\text{-}68$$

The total depth is also given in form of an elliptical integral, which is not readily evaluated, except by numerical means:

$$D_{E(circ.)} = \frac{4h}{\omega}(1 - m^2)^{\frac{1}{2}} \int_0^{\frac{\omega T}{2}} \left\{ 1 - \frac{4n(n + m)}{1 - m^2}\sin^2\phi \right\}^{\frac{1}{2}} d\phi \quad \ldots II\text{-}69$$

where:

$\phi = \pi/2 - \alpha/2$

and

α = is the angle of rotation about the pivot-point.

Bittinger and Logenbaugh noticed that the sprinkler moving in a circular path has a skewed application rate pattern near the pivot point, and that at a distance equal to 5 times the sprinkler radius from the pivot point the pattern was nearly symmetrical. For this situation, for all practical purposes, the equations for a straight-line travel path could be used. Studying the overlapping effect of the sprinklers, they concluded that the triangular pattern sprinkler produced a more uniform distribution than the elliptical pattern sprinklers, with the best distribution being when the sprinklers were spaced a distance equal to the pattern radius. The best distribution for elliptical pattern sprinklers occurred at a spacing equal to 1.4r.

Heermann and Hein (1968), based on the work done by Bittinger and Longenbaugh (1962), wrote the equations for the total depth at any distance from the pivot point for one pass of the system for the triangular and elliptical pattern sprinklers. The equation for a triangular pattern sprinkler moving in a straight-line path travel is given by:

$$TD_T = \sum_{i=1}^{N} \frac{h_i\, r_i}{\omega R_i} \left[(1 - m_i^2)^{\frac{1}{2}} - m_i^2 \ln \left| \frac{(1 - m_i^2)^{\frac{1}{2}} + 1}{m_i} \right| \right] \quad \ldots\ II\text{-}70$$

and for the elliptical pattern sprinkler by:

$$TD_E = \frac{\pi}{2\omega} \sum_{i=1}^{N} \frac{h_i r_i}{R_i} (1 - m_i^2) \quad \ldots\ II\text{-}71$$

where:

N = is the total number of sprinklers contributing to the depth at the given point.

For sprinklers moving in a circular path, the equations for the triangular and elliptic pattern sprinklers respectively are:

$$TD_{T(circ.)} = 2\sum_{i=1}^{N}\left\{h_i T_i - \frac{h_i}{r_i\omega}\int_0^{\omega T_i}\left[S^2 + R_i^2 - 2R_i S\cos\alpha\right]^{\frac{1}{2}} d\alpha\right\} \quad \ldots\ II\text{-}72$$

and

$$TD_{E(circ.)} = \frac{4}{\omega}\sum_{i=1}^{N} h_i(1 - m_i)^{\frac{1}{2}}\int_0^{\frac{\omega T_i}{2}}\left[1 - \frac{4n_i\,(n_i + m_i)}{1 - m_i^2}\sin^2\phi\right]^{\frac{1}{2}} d\phi \quad \ldots\ II\text{-}73$$

Using the sprinkler discharges and the pattern radius taken from the manufacturer's handbook corresponding to the sprinkler orifice size and pressure, Heermann and Hein performed simulations of two different center-pivot systems. The theoretical depth distribution compared favorably with field data, validating the adequacy of the mathematical model. The uniformities expressed by UCHH , calculated from the theoretical distribution and field data were, for all practical purposes, the same.

James (1982) developed a model combining generalized versions of Heermann and Hein (1968) and Kincaid and Heermann (1970) models to study the performance of center-pivot irrigation systems operating on variable topography. In this model, radially symmetric individual sprinkler distribution patterns as well as a part circle pattern for a sprinkler mounted in the end of the lateral could also be simulated. When comparing model predictions with field data, James concluded that, for the systems and conditions considered, the model was accurate and precise in predicting the pressure along the lateral. However, while the model accurately predicted the depth of application along the lateral, average depth of application, flow rate at the pivot and uniformity of application, its precision was not as good. He also noticed that the accuracy and precision of model predictions were not significantly improved by the use of a radially symmetric individual sprinkler pattern rather than a triangular pattern.

James (1984) also used computer simulations to study the effect of pump selection and terrain on center-pivot system performance. His results showed that the amount of water applied, energy use and adequacy of irrigation (the % of irrigated area receiving at least 90% of design application depth) were significantly influenced by the selection of the proper size rather than type of pump (centrifugal or turbine). However, when constant discharge nozzle sprinklers (or sprinklers with pressure regulators) were used, pump size had little effect on the adequacy of irrigation. The type or the pump size did not influence significantly the uniformity of application. The effect of terrain (zero to $\pm$ 5%) was more pronounced in center-pivot systems with conventional fixed nozzle impact sprinklers rather than on systems with constant discharge nozzle sprinklers. The effect of terrain on uniformity of application was small and practically insignificant when changing pump types.

James and Blair (1984) used computer simulations to evaluate the theoretical performance of different low pressure center-pivot configurations (conventional sprinklers, low pressure impact sprinklers, fixed head spray sprinklers mounted above the lateral, on drop tubes, and on booms). The model was also used to study the effect of terrain (slope) and sprinkler spacing on the performance of the systems. The performance variables considered were: uniformity of application, adequacy of irrigation (as defined as in James, 1984), and energy use. Results from simulations (288) showed that the systems with conventional sprinklers, spray nozzle mounted on the lateral, and low impact sprinklers had the highest overall uniformities. Systems with conventional and low pressure impact sprinklers had the highest uniformities and adequacies (of irrigation) when spaced 12 m along the lateral. Systems with fixed head spray nozzles had the highest uniformities and adequacies when spaced 1.5 m. Terrain affected system energy use more than uniformity or adequacy of irrigation. Systems with low pressure impact sprinklers used 82% of the energy used by systems with conventional sprinklers, while systems with fixed head spray nozzles used only 68%.

Heermann and Swedensky (1984) derived equations for the application rate of a polynomial pattern sprinkler, which was believed to be more representative of the distribution of fixed head spray nozzles. These equations are expressed as:

$$AR_p = h\left[C_1 + \frac{m}{C_2}(1 - C_1)\right] \qquad \text{... II-74}$$

for $m \leq C_2$

and

$$AR_p = \frac{h}{1-C_2}(1 - m) \qquad \text{... II-75}$$

for $m > C_2$

where:

C_1 = the fraction of the maximum application rate at the sprinkler location,

C_2 = the fraction of the pattern radius from the sprinkler to the radius at which the maximum application rate occurs,

m = the ratio of the perpendicular distance between point p and the sprinkler line of travel to the sprinkler pattern radius.

h = the maximum application rate

They also modified the Heermann and Hein (1968) model to allow the simulation of part circle pattern sprinklers, which is necessary for modeling systems with an end gun. The computer model was then used to evaluate the effect of the catch can spacing on the calculated uniformity and application efficiency of both high pressure (impact sprinkler) and low pressure (spray nozzle) center-pivot systems. The catch can spacing used varied from 15 cm to 12 m for the low pressure system and from 30 cm to 27 m, for the high pressure systems. Application efficiency was defined as the ratio of the integrated discharge for the selected can spacing to the integrated discharge with the smallest can spacing for the system. Simulations of systems with high pressure sprinklers were performed assuming both a triangular and elliptical distribution pattern for the sprinklers. The change from triangular to a elliptical pattern had very little effect on the uniformity until the catch can spacing approached the SCS recommended spacing of 9.1 m (30 ft). Variation in collector spacing showed little influence in the uniformity on low pressure systems. However, water application efficiencies, for both systems, were quite variable when the catch can spacing changed.

2- UNIFORMITY ALONG THE PATH OF TRAVEL

Traditionally, when evaluating center-pivot irrigation systems, the uniformity of water distribution is measured radially from the pivot point extending to the end of the wetted area as discussed in the previous section.

Hanson and Wallender (1986) were one of the first researchers to study the uniformity along the travel path for moving sprinkler machines. Because these machines (center-pivot and linear-move systems) move in a series of start and stop sequences and not continuously, tests were performed with the objective of determining the uniformity along the path of travel, and also of any possible uniformity-movement relationship. In their test procedure for center-pivot systems, the catch can were placed in transects along the travel path installed inside towers No.10 (the guide tower) and No.5. The spacing chosen was 0.3 m. Both transects were installed at a position approximately underneath a nozzle. Additional transects along the lateral and across the span of towers No.2, 5 and 9 were also installed. The cans were installed with a spacing of 3 m for the transect along the lateral and 0.6 m for the transects across the towers' span. Besides the catch can data, the distance per move, the on/off-times of the tower nearest to the transects, and all nozzles pressures and discharges were recorded. Their results showed that the uniformity along the travel path for the transect inside tower No.10 span was much higher than for the transect inside tower No.5 span (UCC=90% and 75% respectively). Results of distance per move, on-times and off-times were almost constant for the transect inside tower No.10 span, but the results for the span inside tower No.5 were more variable. Spectral Analysis (analysis in the frequency domain) was used in the analysis of the catch can data. The analysis showed that a direct correlation existed between tower No.5 movement and catch can variance. Their explanation for such behavior was that the distances per move of tower No.5 were large compared to the sprinklers' wetted diameter, resulting in a reduced overlapping. However, no similar behavior was identified for the other towers, and as stated by the authors ".... *the difficulty in clearly relating nonuniformity in the can data with the tower movement is apparently caused by a complex interaction between the tower movement and overlapping of the spray patterns along both the travel path and lateral ...* ". Can data of the transect along the lateral showed strong periodic behavior starting at about 174 m from the pivot point, however this behavior appeared to be independent of the nozzle discharge. For such reason the authors

hypothesized that this long range variability along the lateral is also related to the tower movement. Sample spectrums of the transects across the span of towers No.2, 5 and 9 showed that much of the nonuniformity in the catch can data was related to the nozzle spacing. Also of great importance was the finding that, in contrast with a linear-move system, the nonuniformity along the path of travel of the center-pivot occurred over large distances, therefore with the potential of reducing yield.

Heermann and Stahl (1986) modified the Heermann and Swedensky (1984) model to be able to simulate the start-stop movement of the towers with the objective of evaluating the uniformity along the travel direction of a high and low pressure center-pivot systems. For the simulation of the high-pressure system a triangular distribution pattern was assumed for the sprinklers. For the simulation of the low-pressure system, equations for the application rate for a "doughnut" distribution pattern were derived. This distribution pattern is similar to the polynomial pattern developed by Heermann and Swedensky (1984) differing only in the fact that the shape of the pattern from points of maximum application rate to the end of the pattern is parabolic instead of linear. The two systems were simulated first assuming a constant velocity (1.22 m/min) for all towers, and then by decreasing the tower velocities toward the pivot point. Simulations of the lower-pressure system were performed for two different settings of the guide tower, 60% and 100% , the later being the common setting when doing chemigation. Results showed that the radial uniformity (alignment angle ± 1°) did not vary from the one calculated when the system moved continuously. However, results for the low-pressure system showed an almost 10% reduction (from UCC= 98.9 to 89.0%) in the radial uniformity. A slight improvement in the radial uniformity was observed for the variable speed low-pressure system as compared with the constant speed system. The UCC along the travel path was calculated from depth measurements at a radius of 230 m and with the spaced 2 m. The uniformity was calculated for simulations performed with alignment angles of 2, 1, 0.5 and 0.25°. Although the UCC increased with a decrease of the alignment angles for both systems, more pronounced changes were observed in the low-pressure system. Increasing the setting of the guide tower from 60% to 100% increased the uniformity of the low-pressure system (alignment angle of 1°) from UCC= 82.0 to 95.6%. Reducing the time step from 1.2 to 0.6 sec in generating the start-stop time series also resulted in a slight increase of the UCC. Such increase was due to the more randomness of nonuniformity for time step equal to 1.2 sec, and not to the magnitude of deviations from the average depth, which to the

authors' surprise were not reduced with the smaller time interval. After performing the spectral analysis of the results in a similar way as Hanson and Wallender (1986), Heermann and Stahl concluded that the UCC along the travel path is more a function of the sprinkler pattern radius and of the magnitude of the arc lengths (the relative trajectory of the can position on the sprinkler pattern) than the magnitude of the alignment angle.

III- METHODOLOGY

A. FIELD EXPERIMENTATION

Field experiments to generate data for validation of the computer model presented in the next section were conducted during the summers of 1991 and 1992, at the farm property owned by Chris Rajzer located at 76301 M-51, Decatur, Michigan. The center-pivot evaluated was a Valley 6000 three tower electrical system with a total length of 192.3 m (631.0 ft) and a capacity of 1514 L/min (400 gpm) at a pivot-point pressure of 262 kPa (38 psi). All three spans had the same length of 55.7 m (182.9 ft). The system also had an overhang of 25.1 m (82.4 ft) beyond the last tower adding to its total length. The system was equipped with pressure regulating nozzles and with Valmont Spray sprinklers mounted at the top of the lateral and at a uniform spacing of 9.1 ft. An end-gun (model SR100) was mounted at the end of the lateral.

The field procedure adopted was kept very simple so it could be performed by anyone. The procedure consisted of placing a series of catch cans spaced 0.6 m (2 ft) apart in the travel path (in a circular arc) of the last sprinkler of each lateral span. The last sprinkler of each span was chosen because it was believed that any influence of the intermittent movement of a tower would be more pronounced closer to it. Every catch can had the same shape (section of cone), same dimensions and conformed with ANSI/ASAE S330.1 standard. Each catch can was mounted on stakes made of 1/2 in PVC pipe at a height of 1.7 m (5.5 ft). The position of each tower at each stop point was marked with wire flags from the moment the first droplets started falling in the first catch can of each transect until the moment water stopped wetting the last can of the same transect. The time a tower was moving (on-times) and the time a tower stopped (off-times) in a given position were measured using a stop watch. Immediately after the water stopped wetting the last can in each transect the volume (ml) of water deposited in each catch can was measured using a 100 ml (± 0.5 ml) volumetric cylinder. At last, the alignment angles between tower No.1 (the guiding tower) and tower No.2 and between tower No.2 and tower No.3 were measured using a theodolite. The procedure was, to mark with a wire flag the position of tower No. X each time tower No. X+1 stopped and when it resumed movement. In cases when tower No. X+2 moved within the time interval, the measurements were discarded. Every time tower No. X+2 moved within the time interval, it would move the lateral span between it and tower No. X+1 which would cause an error in the angle measurement. It would cause the angle measured to be larger or smaller depending on whether tower No. X was lagging or leading tower No. X+1. The results of the field experimentation is presented in the Computer Validation section.

B. COMPUTER MODEL

1. MODEL DEVELOPMENT

A computer model was developed to perform the simulation of an electrical driven center-pivot system considering its intermittent movement (the series of starts and stops of the towers) with the towers operating in a level terrain at constant velocities. That is, the velocity of each tower is constant when the tower is moving. However, the velocities of the towers may or may not be different. The computer model was based on the mathematical model developed by Bittinger and Logenbaugh (1962) presented in chapter II as equations II-62 to equations II-69. With exception of equation II-67 all other equations can be readily evaluated when the assumption of continuous movement and constant velocities is made. However, when the intermittent movement of a center-pivot system is considered and with sprinkler pattern profiles other than triangular or elliptical, a mathematical model does not exist. When considering the intermittent movement of a center-pivot system, the contribution of an individual sprinkler to the total depth at any given point p, is equal to the integral of the sprinkler application rate over the interval of time necessary for the sprinkler pattern to pass through point p, and is given by:

$$d_p = \int_0^T A(t)dt \qquad \ldots III\text{-}1$$

where:

d_p = depth of application at point p by an individual sprinkler,

A(t) = the application rate function.

Considering the overlapping of different sprinklers contributing to the total depth at any point p, we have:

$$D_p = \sum_{i=1}^{T_i} \int_0^{T_i} A_i(t)\, dt \qquad \ldots III\text{-}2$$

In order to carry out the evaluation of the above equation it is necessary to know not only the individual time it takes for each sprinkler profile to move through point p but also to know at each instant in time (or at each time iteration) the exact distance from each contributing sprinkler to the point being wetted. These calculations as well as the solution of equations above are performed by the computer model developed in this study. The flowchart of the computer model is given below and the computer code is presented in the appendix.

2. MODEL DESCRIPTION

a. INPUT REQUIREMENTS

The required inputs to initiate the simulation are:

1) the system's total number of towers,
2) the length of the spans between towers (it is assumed that all spans are of the same length), ft
3) the sprinkler spacing (assumed the same throughout the system), ft
4) the angle of alignment between towers (different angles between different towers are allowed), degrees
5) the number of rows of catch cans

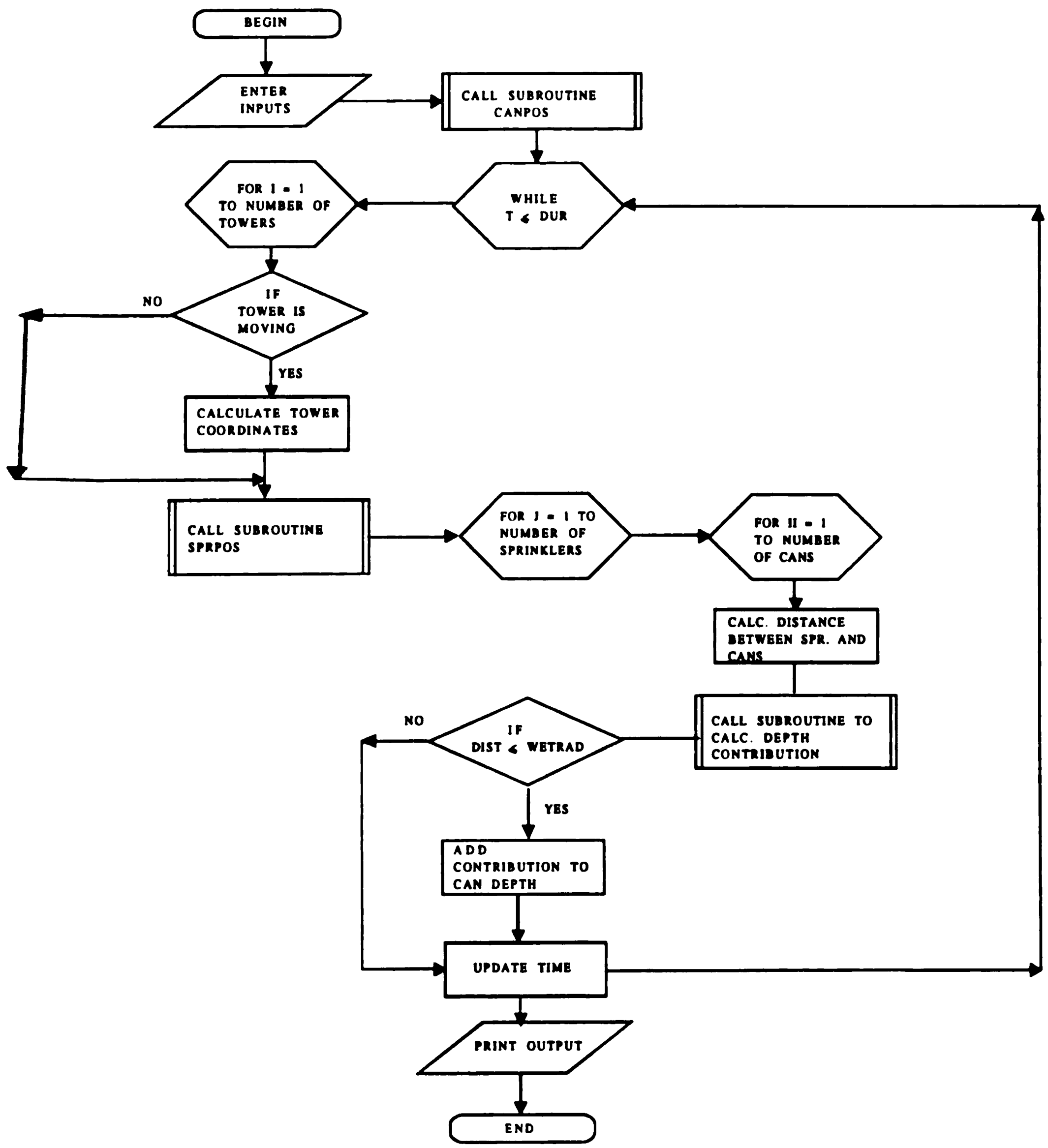

Figure 11. Computer Model Flowchart

6) the number of catch cans per row

7) the polar coordinates of the first can of farthest transect from the pivot-point, radian

8) the distance from each row of catch cans to the pivot-point, ft

9) the spacing between catch cans of the farthest row from the pivot-point, ft

10) the setting of the guide tower timer, in %

11) the duration of the simulation, hours

12) the time between iterations, ΔT, seconds

13) choice of lateral spans where the sprinkler that contribute to the depth in cans are located

14) the number of sprinklers and the sprinkler number to be initialized in a chosen lateral span

15) the sprinkler pattern, triangular, elliptical, polygonal or any of the actual patterns built in

16) the flow rate (gpm) and wetted radius (ft) if triangular or elliptical pattern sprinklers were chosen

17) the peak instantaneous application rate (in/h), the distance (ft) from the sprinkler to the point of maximum application rate and the application rate directly under the sprinkler (in/h) if polygonal pattern sprinkler were chosen

18) the wetted radius (ft) for each sprinkler if a

actual pattern sprinkler were chosen.

b. MODEL EXECUTION PHASE

After the inputs are entered, the coordinates of the catch cans are computed (SUBROUTINE CANPOS) in each transect. The spacings between the cans are computed in such way that the cans of same number in different transect are positioned radially. If spacing between cans of different rows are desired to be equal it is necessary to run different simulations for each row. The coordinates of the sprinklers chosen to perform the simulation are computed (SUBROUTINE SPRPOS). At the beginning of the simulation all towers with the exception of the guide tower are not moving, "OFF" state. The state of the guide tower is controlled by its setting while the state of the other towers is controlled by their alignment angle. A tower state remains "ON" or "OFF" as long the angle formed by the adjacent lateral spans do not equal or exceed the pre-set alignment angle for that tower. At each time iteration the positions of the towers are updated if their state is "ON", and the new sprinklers coordinates are calculated along the lateral span(s) (SUBROUTINE SPRPOS) chosen, keeping the predetermined space between them. The distances between every sprinkler and all the catch can is computed at each iteration and if it is smaller or equal to the wetted radius of the sprinkler considered, the sprinkler contribution to the total depth caught in that can is calculated and added. The computation to the depth of water caught in a can by a contributing sprinkler is done according to its pattern (subroutines DEPTRIPAT, POLIPAT, ACTPAT).

c. SPRINKLER PATTERNS

The model allows a choice of different sprinkler profiles to perform the simulation. The profiles available are:

1- Triangular profile

2- Elliptical profile

3- Polygonal profile

4- Actual profile from distribution can data

1- GEOMETRICAL PATTERNS

The triangular and elliptical patterns are more appropriate when simulating high and low impact sprinklers, while the polygonal pattern is believed to give a better representation of spray nozzles.

For the triangular and elliptical profiles the maximum application rate occurs underneath the sprinkler position in the middle of the profile. The application rate decreases linearly towards the end of the triangular profile and it follows the ellipse equation for the elliptical profile. Figure 11 illustrates these profiles. The polygonal profile available in the model is the profile derived by Heermann and Swedensky (1984) and presented in chapter II by equations II-74 and II-75 and rewritten here as:

$$A=h\left[c_1+\frac{m}{c_2}(1-c_1)\right] \qquad \ldots\ III\text{-}3$$

for $m \leq c_2$

and

$$A=\frac{h}{(1-c_2)}(1-m) \qquad \ldots\ III\text{-}4$$

for $m > c_2$

where:

c_1 = the ratio between the application rate underneath the sprinkler and the maximum application rate,

c_2 = the ratio between the distance from the sprinkler to the point of maximum application rate and the pattern wetted radius

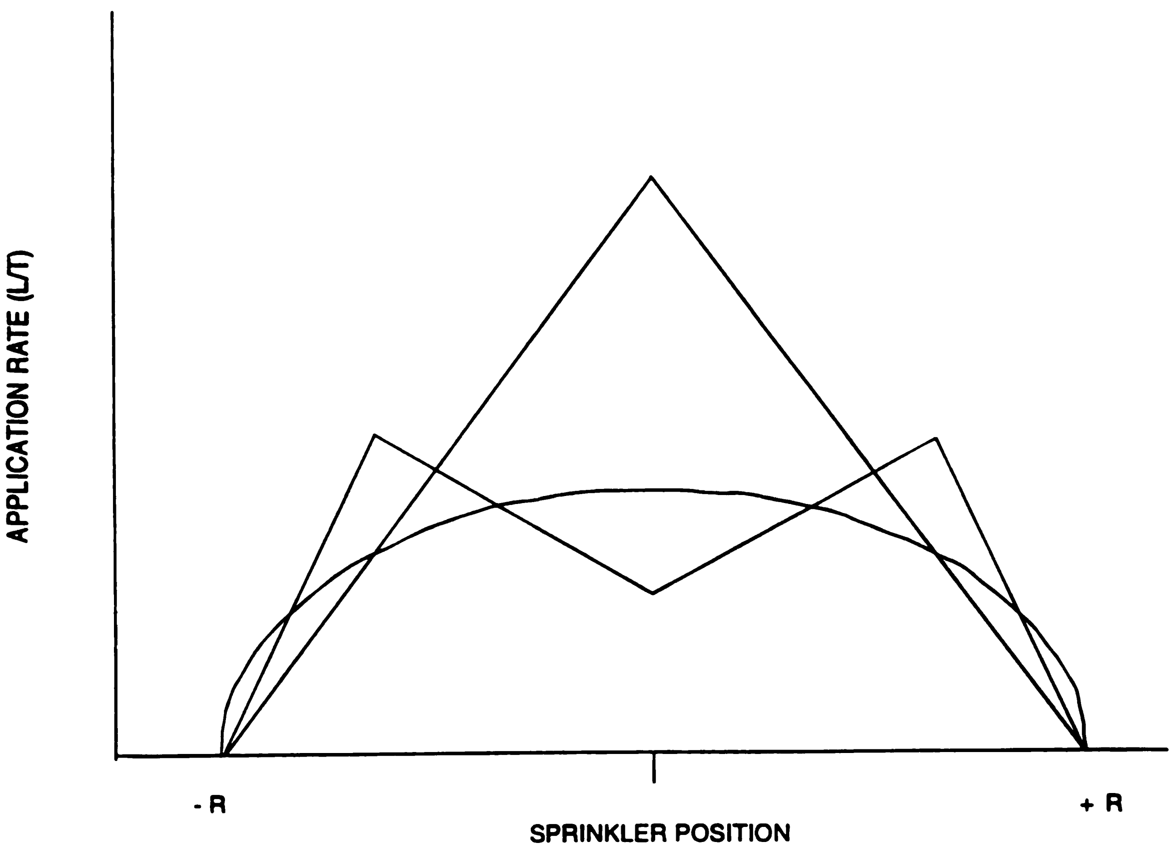

Figure 12. Geometrical Sprinkler Patterns.

m = the ratio between the perpendicular distance between point p and the sprinkler line of travel to the sprinkler pattern radius.

h = the maximum application rate

However, the inputs required in the model are h, c_1h, c_2R therefore being necessary to modify the above equations, as:

$$A = \frac{h}{R - c_2R}(R - L) \qquad \ldots III\text{-}5$$

for $R \geq L > c_2R$

and

$$A = \frac{h(1 - c_1)}{c_2R}L + c_1h \qquad \ldots III\text{-}6$$

for $L \leq c_2R$

where:

R = the pattern radius,

c_2R = the distance from the sprinkler to the point of maximum application rate,

c_1h = the application rate underneath the sprinkler,

L = the distance between the catch can and the sprinkler.

2- ACTUAL PATTERNS

The actual profiles available in the computer model are:

1) Nelson R30 - U4 nozzle #20 (5/32) 3RN at 30 PSI
2) Nelson R30 - U4 nozzle #30 (15/64) 3RN at 30 PSI
3) Nelson R30 - U4 nozzle #40 (5/16) 3RN at 30 PSI
4) Nelson R30 - D6 nozzle #20 (5/32) 3RN at 30 PSI
5) Nelson R30 - D6 nozzle #30 (15/64) 3RN at 30 PSI
6) Nelson R30 - D6 nozzle #40 (5/16) 3RN at 30 PSI
7) Nelson R30 - D6C nozzle #18 (9/64) 3RN at 30 PSI
8) Nelson R30 - D6C nozzle #32 (1/4) 3RN at 30 PSI
9) Nelson R30 - D4 nozzle #20 (5/32) 3RN at 30 PSI
10) Nelson R30 - D4 nozzle #30 (15/64) 3RN at 30 PSI
11) Nelson R30 - D4 nozzle #40 (5/16) 3RN at 30 PSI

The actual profiles were obtained directly from the manufacturer[1] and were expressed by one or more higher order polynomials fitted to the total or partial data by using nonlinear regression (procedure NLIN - SAS/STAT ver. 6.03 by SAS Institute Inc., Cary, NC USA.). Figure 13 shows the actual profile, the profile recreated using the higher

[1] The exclusive use of NELSON sprinklers does not necessary implies any superiority of their products over the products of other manufacturers.

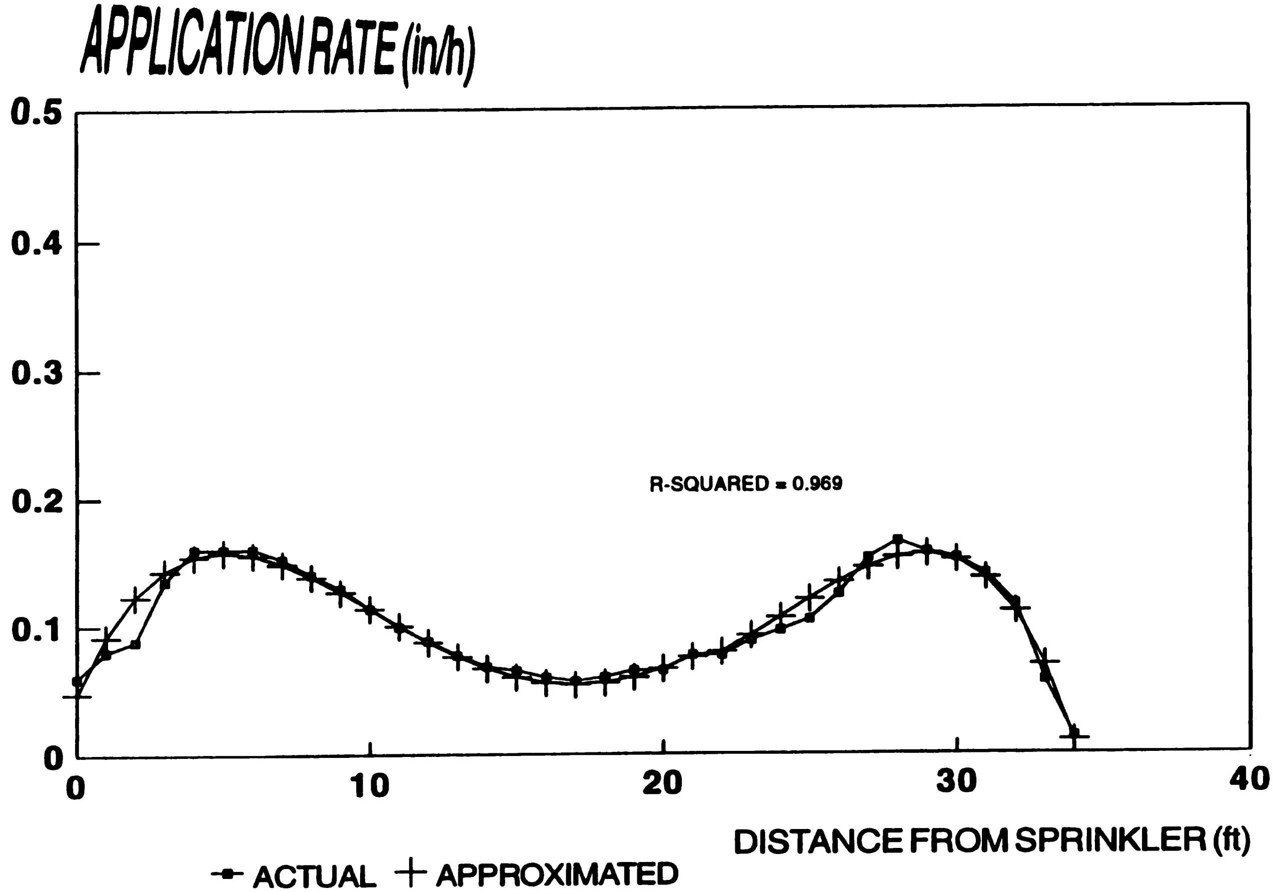

Figure 13. Nelson R-30 U4 No.20 3RN approximated pattern operating at 30 psi.

order polynomials as well as their R-Squared values for spray Nelson R-30-U4 nozzle #20 3RN operating at 30.0 psi. The figures for the other actual pattern sprays as well as the order and coefficients of each polynomial used to reconstruct the pattern are presented in the appendix.

3. Model ΔT SENSITIVITY

When performing a computer simulation, there is generally a trade-off between accuracy and computation time. As the time step shrinks greater accuracy is obtained until a point that further shrinking results in no more evident gain in accuracy. Usually the choice of the most adequate time step to perform any computer simulation depends on the application, that is, how important the accuracy of the results will be. Studying the effect of different time steps in the proposed model showed that the choice of the time step, due to the nature of the model, influenced the synchronization of the towers as well as the number of cycles per time interval and the times the towers changed state. Tables 3 and 4 illustrate the last two concepts. It is clear by examining these two tables that when using the results of the simulation in applications where accurate positions of the towers are required, a smaller time step is recommended. Other parameters (design or management variables) should also be considered when choosing the time step for the simulation. The choice of the time step is sensitive to the magnitude of the angle of alignment. By increasing the angle of alignment from 1.0 to 2.0 degrees in a simulation of a three tower system, the time step could be increased four fold (from 0.0125 sec. to 0.05 sec) without affecting the accuracy of the results (towers positions, on and off-times). The choice of the time step, however, was not sensitive to the magnitude of the velocity of the towers. An increase of 50% in the velocity of the interior towers (tower No.2 and No.3) of the same three tower systems, did not affect the accuracy of the results. The magnitude of the time step, however, had a much smaller effect on the simulation of the depth of application especially for systems equipped with larger wetted radius sprinkler patterns.

4. MODEL VALIDATION

The computer model developed was validated with the lateral operating in both a continuous and intermittent mode. Continuous mode is defined as the idealized state of

Table 3. Tower no.2 starting times for different ΔT's, guide tower timer setting equal to 100% and alignment angle equal to 1.0 degrees.

	TIME "ON", SEC. (TOWER NO. 2)				
	TIME STEP, ΔT (sec.)				
	0.01	0.0125	0.025	0.05	0.1
	16.19	16.19	16.20	16.20	16.200
	88.16	88.14	88.15	88.10	88.000
	188.67	188.65	188.63	188.55	188.500
	253.41	253.40	253.38	253.35	242.100
	343.91	343.93	343.83	343.80	341.300
	445.62	445.64	445.50	445.45	406.000
	510.36	510.38	510.25	510.25	496.300
	600.87	600.88	600.75	600.75	597.900
	702.55	702.55	702.45	702.40	662.900
	767.27	767.26	767.15	767.10	753.200
	857.77	857.74	857.63	857.55	854.900
	959.46	959.40	959.32	959.25	908.600
	1024.19	1024.14	1024.10	1024.10	1007.800
	1114.69	1114.63	1114.60	1114.65	1072.500
	1216.40	1216.33	1216.28	1216.50	1162.700
	1281.14	1281.05	1281.05	1270.05	1264.500
	1371.65	1371.55	1371.55	1369.30	1318.200
	1473.34	1473.20	1473.15	1434.05	1417.300
	1538.06	1537.90	1537.85	1524.35	1482.100
	1628.54	1628.38	1628.33	1626.00	1572.700
CTD20[2]	0.00	1.05	2.14	70.72	528.57

[2]The cumulative time difference of the first twenty time "On" referred to ΔT = 0.01 sec..

Table 4. Number of cycles/hr as function of time step, guide tower timer setting equal to 100% and alignment angle equal to 1.0 degrees.

	NUMBER OF CYCLES/HOUR					
	TIME STEP, ΔT (SEC)					
TOWER No.	0.01	0.0125	0.05	1.0	1.25	5.0
2	43	43	44	43	45	40
3	15	15	17	18	21	19

all lateral spans moving continuously at the same angular velocity, resulting in the perfect alignment of the lateral. It should not be confused with the lateral movement when the guide tower timer is set at 100%. Performing the validation in a continuous mode had the objective of testing the adequacy of the model, that is the adequacy of the integration formula (Euler Integration) used by the subroutines in computing the depth of application. The simulation of a center-pivot system operating in a continuous mode can be accomplished simply by choosing the number of the towers of the system to be equal to one, i.e. a long span. The objective of the validation of the model operating intermittently was to test the adequacy of the model in simulating the movement of the towers (on-times and off-times) as well as the depth of application.

a. CONTINUOUS MODE OPERATION

The simulation of the depth of water application by a center-pivot system (system F, Kincaid (1968)) operating in a continuous mode was performed. The system had a 3470 L/min (917 gpm) capacity covering an area of 54.4 ha (134.3 acres) with an angular velocity of 0.118 rad/hr. Simulations were performed for triangular and elliptical sprinkler patterns. The simulation results were then compared with the mathematical solution obtained by Kincaid using equations II-70 and II-71. The simulation results and the respective results found by Kincaid are presented in Table 5 . A Linear Regression Analysis of these results was also performed and it is summarized in Figures 14 and 15.

b. INTERMITTENT MODE OPERATION

The simulation of the three tower electrical center-pivot system described in a previous section (field experimentation) was performed. The angle of alignment between towers used in the simulation was the average value of the angles measured in the field experimentation. These

Table 5. Depth of application, mathematical solution and simulation results with model operating in a continuous mode for triangular and elliptical patterns.

	DEPTH (IN)			
DISTANCE FROM PIVOT, FT	MATHEMATICAL SOL.		SIMULATION RESULTS	
	TRIANGULAR	ELLIPTICAL	TRIANGULAR	ELLIPTICAL
440	0.945	0.873	0.925	0.889
450	0.916	0.886	0.900	0.911
460	0.907	0.866	0.893	0.898
470	0.917	0.856	0.907	0.876
480	0.890	0.882	0.984	0.911
490	0.884	0.881	0.878	0.917
500	0.893	0.843	0.889	0.866
540	0.900	0.842	0.888	0.861
550	0.890	0.876	0.893	0.904
560	0.884	0.841	0.876	0.872
570	0.891	0.848	0.879	0.868
580	0.893	0.891	0.879	0.917
590	0.888	0.866	0.873	0.893
600	0.892	0.922	0.872	0.833
740	0.931	0.943	0.942	0.949
750	0.925	0.939	0.937	0.948
760	0.909	0.870	0.917	0.882
770	0.909	0.913	0.914	0.917
780	0.901	0.922	0.906	0.927
790	0.882	0.866	0.884	0.873
900	0.876	0.883	0.873	0.880
910	0.868	0.885	0.865	0.883

Table 5 (cont'd)

920	0.846	0.828	0.843	0.825
960	0.843	0.805	0.851	0.808
970	0.828	0.821	0.837	0.826
980	0.801	0.781	0.810	0.789
990	0763	0.706	0.767	0.707
1000	0.705	0.693	0.707	0.695
1010	0.641	0.654	0.642	0.656
1060	0.586	0.614	0.594	0.619
1070	0.645	0.661	0.654	0.669
1080	0.712	0.695	0.712	0.706
1090	0.788	0.773	0.793	0.779
1100	0.826	0.803	0.829	0.808
1160	0.838	0.840	0.847	0.846
1170	0.824	0.817	0.833	0.824
1180	0.814	0.792	0.823	0.808
1190	0.827	0.804	0.836	0.811
1200	0.821	0.806	0.829	0.813

values are presented below in table 6. The velocity of the towers in a system is dependent on the speed of the motor, the gear box ratio and the type of tires. The system simulated was equipped with a 1.5 hp motor (high speed drive) on towers No.1 (the guide tower) and tower No.2 and with a 1 hp motor (normal speed drive) on tower No.3. All three towers had the same type of tires, retread 11 X 24.5

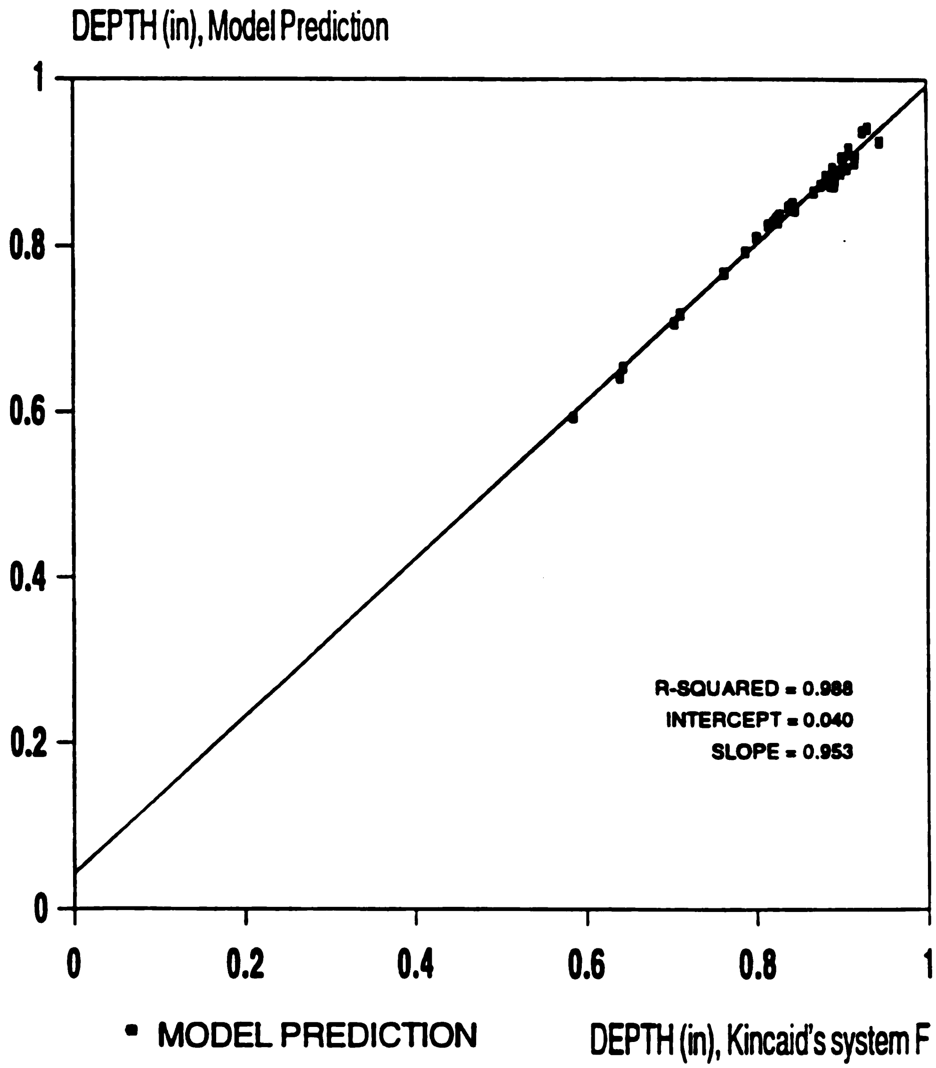

Figure 14. Linear Regression Fit, model vs. Kincaid's system F results for triangular pattern sprinklers.

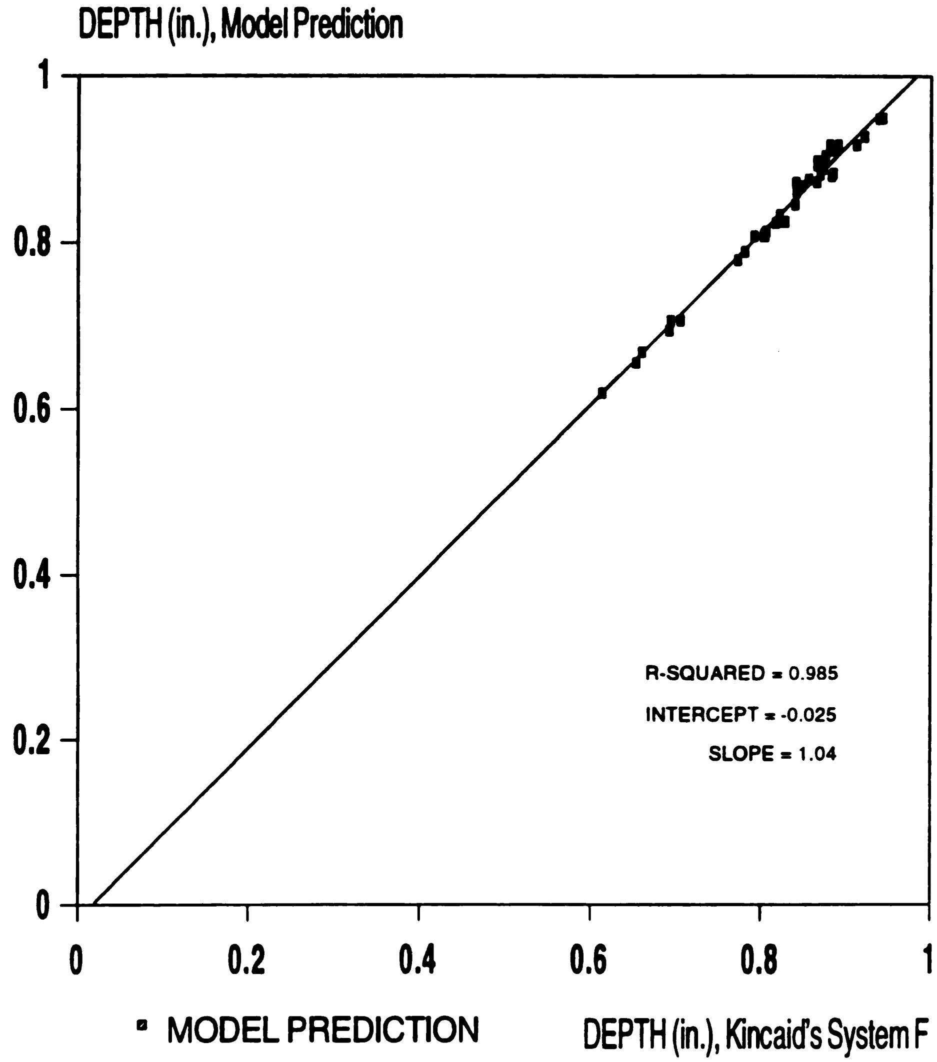

Figure 15. Linear Regression Fit, model vs. Kincaid's system F results for elliptical pattern sprinklers.

Table 6. Alignment angle between towers, field measurements.

	ALIGNMENT ANGLE (DEGREES):	
	TOWER No.1 & No.2	TOWER No.2 & No.3
	0.285	0.250
	0.237	0.318
	0.280	0.422
	0.256	0.387
	0.225	0.365
	0.269	0.418
	0.279	0.385
	0.303	0.398
	0.227	0.420
	0.224	0.351
	0.280	0.330
	0.226	0.410
	-----	0.380
	-----	0.363
AVERAGE	0.258	0.371

Table 7. Tower velocities used in the simulations.

	ANGULAR VELOCITY, rad/sec
TOWER No.1	0.0003595
TOWER No.2	0.0005395
TOWER No.3	0.0005767

tires. The tower velocities used in the simulation were the velocities given by the manufacturer (Valmont Industries, Inc.) for the description above and are given in Table 7. Simulations were performed for three different guide tower percentage timer settings, 50, 37 and 25%. The results of the simulations as well as the field data (on and off-times for tower No.1 and No.2 only) and the water depth applied in transect inside span No.1, 2 and 3, for the three percentage timer settings of the guide tower are given in figures 16 through 36. As can be seen, the simulations resulted in periodic behavior similar to the field data. The differences found could be due to the influence of several factors, the most obvious being: slippage of tires, non alignment of towers on beginning of the field experimentation, experimental error, small variations on the alignment angle depending on if tower is leading or lagging the adjacent outer tower and terrain effects.

5. MODEL APPLICATION

Simulations using the center-pivot computer model developed in this work were performed to make the analysis of a traditional center-pivot and a LEPA system. Simulations were performed with the objective of determining how the

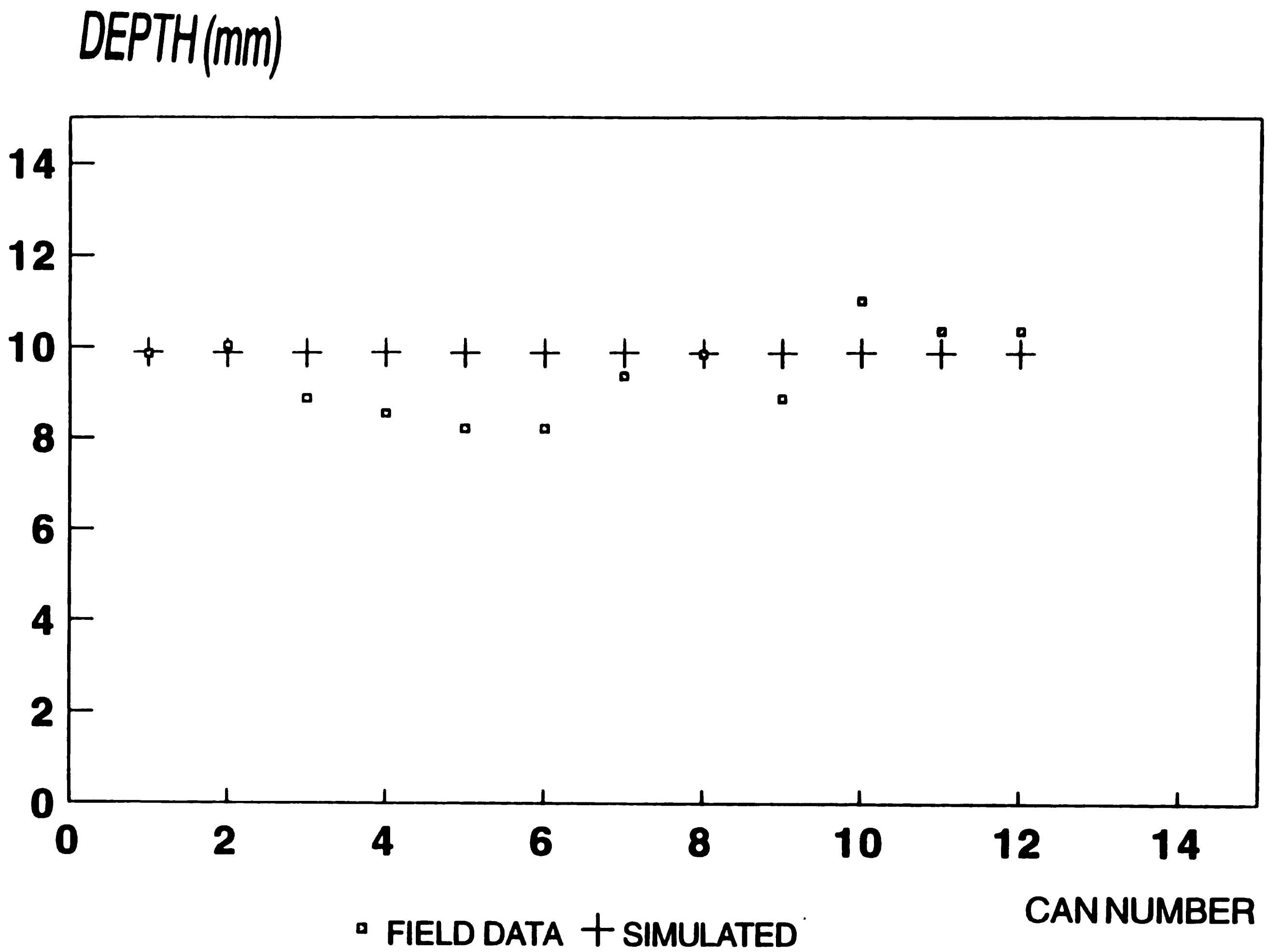

Figure 16. Depth of application on transect no.1, guide tower timer set at 25%.

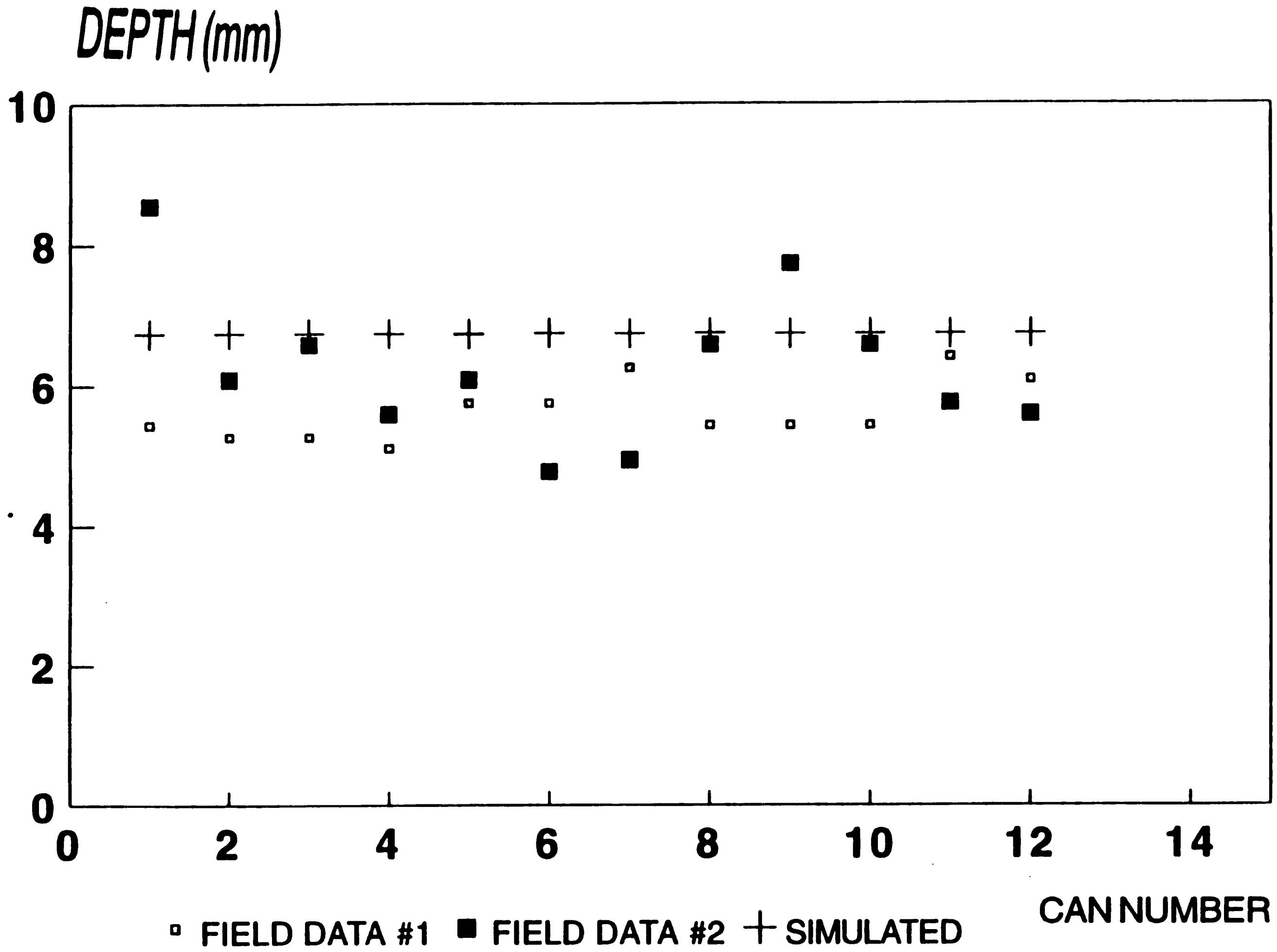

Figure 17. Depth of application on transect no.1, guide tower timer set at 37%.

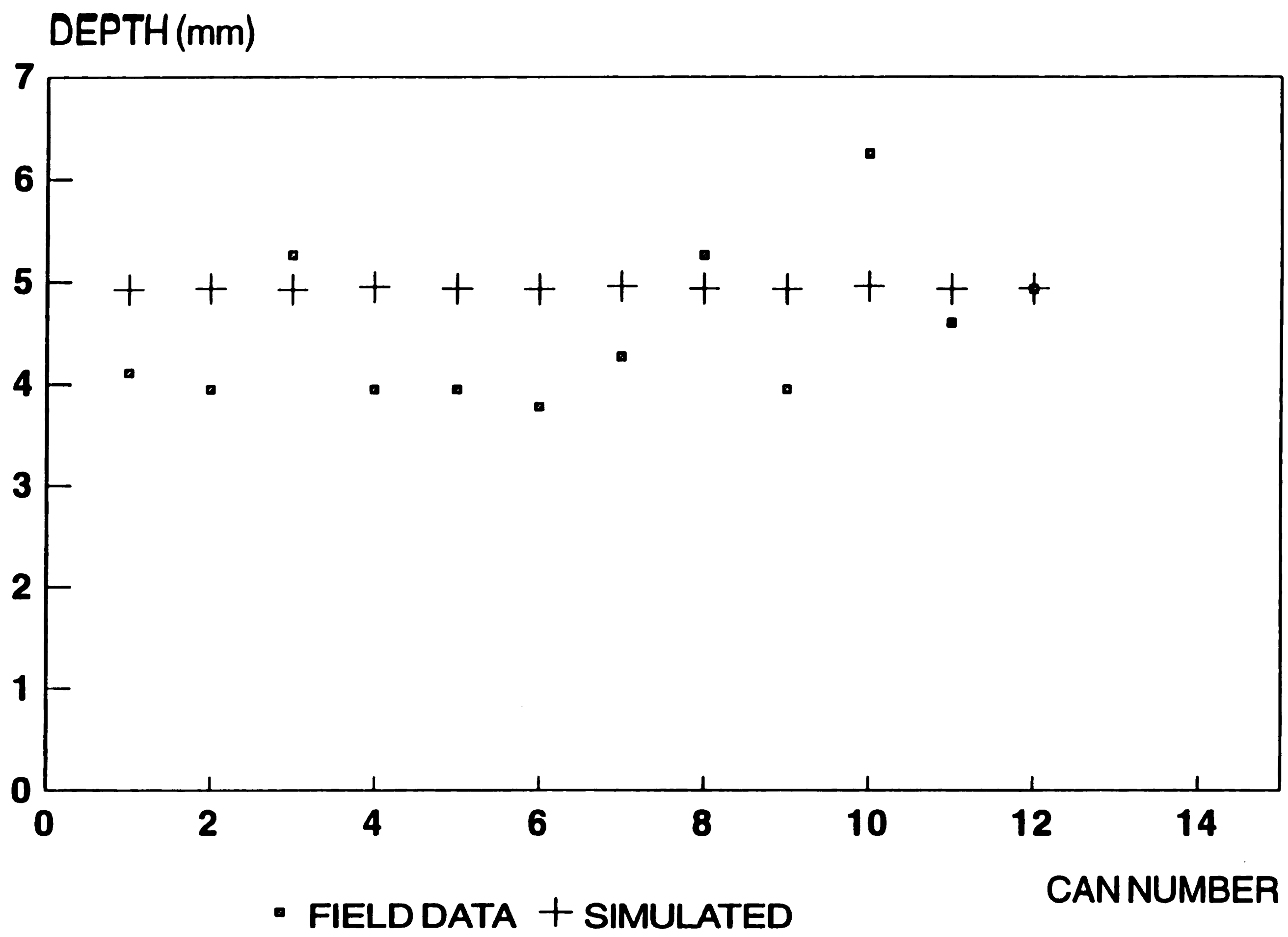

Figure 18. Depth of application on transect no.1, guide tower timer set at 50%.

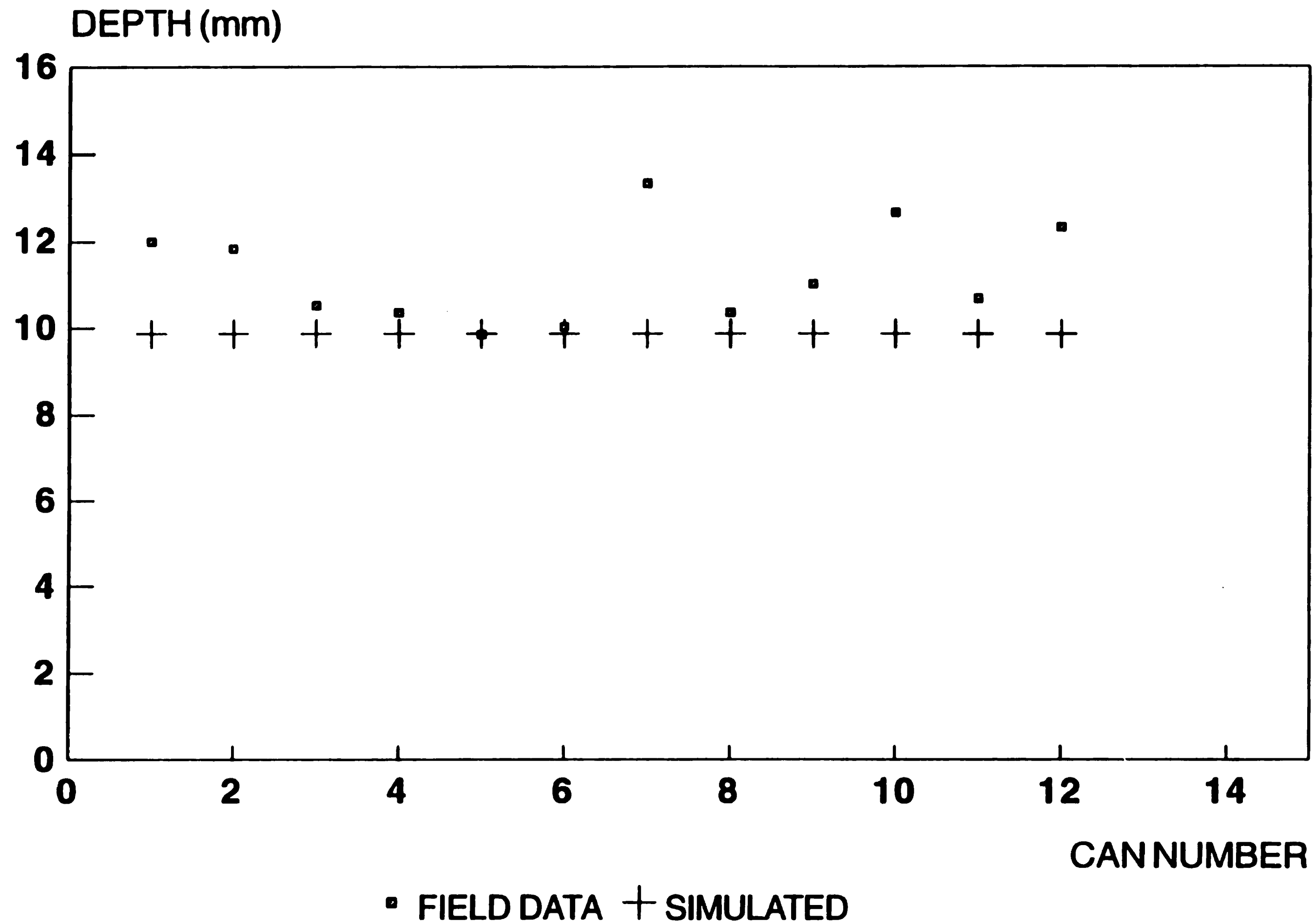

Figure 19. Depth of application on transect no.2, guide tower timer set at 25%.

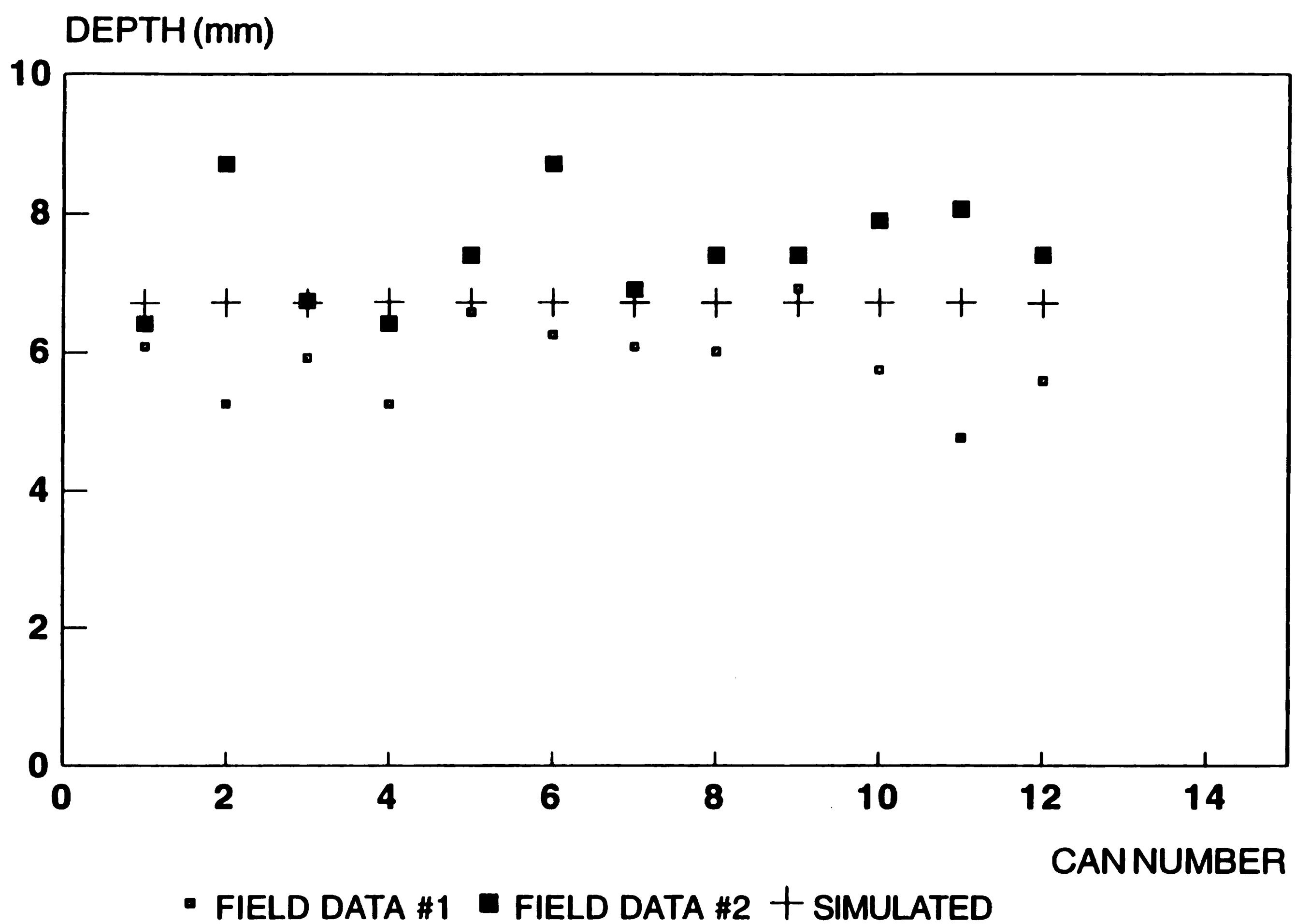

Figure 20. Depth of application on transect no.2, guide tower timer set at 37%.

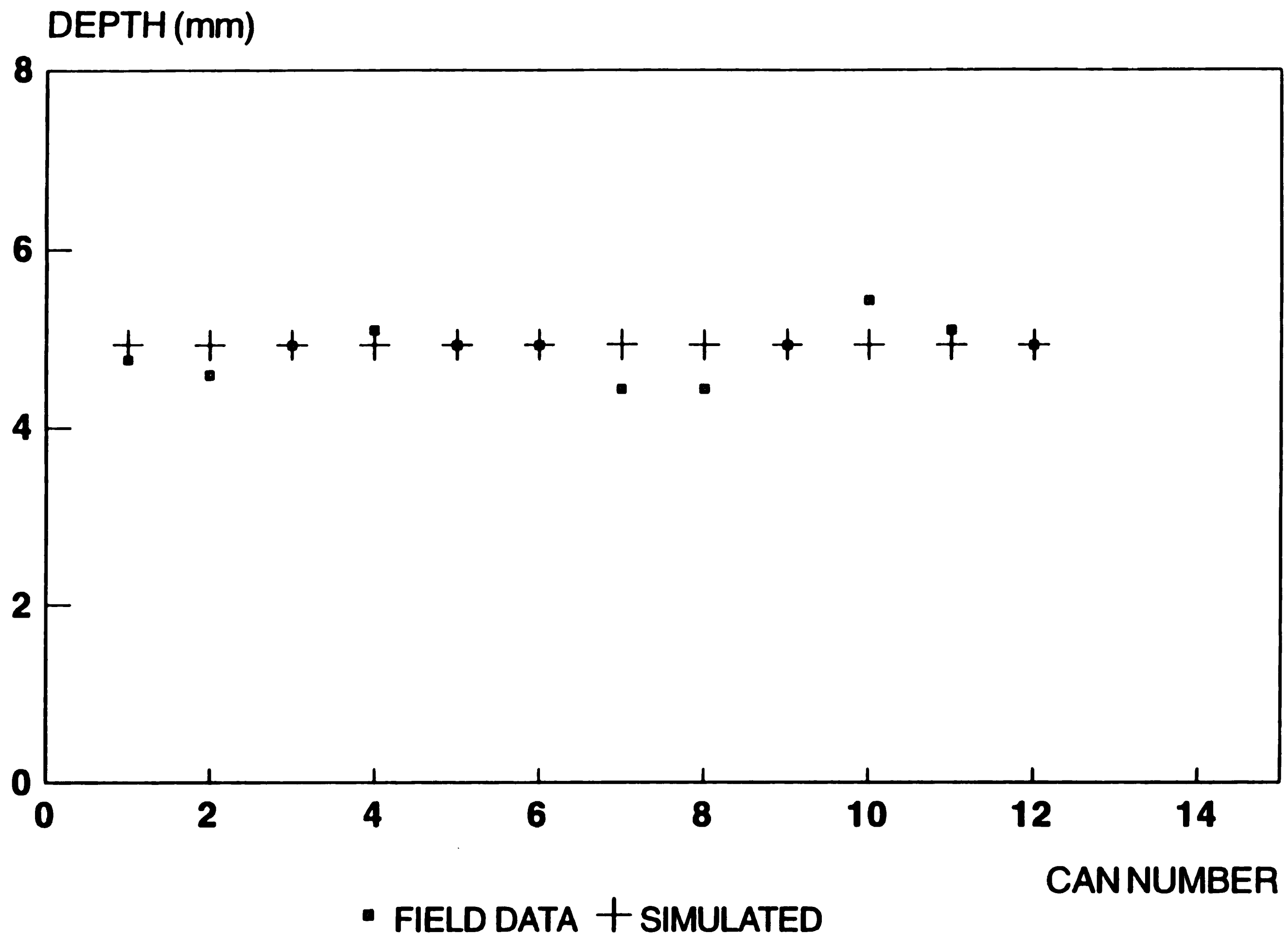

Figure 21. Depth of application on transect no.2, guide tower timer set at 50%.

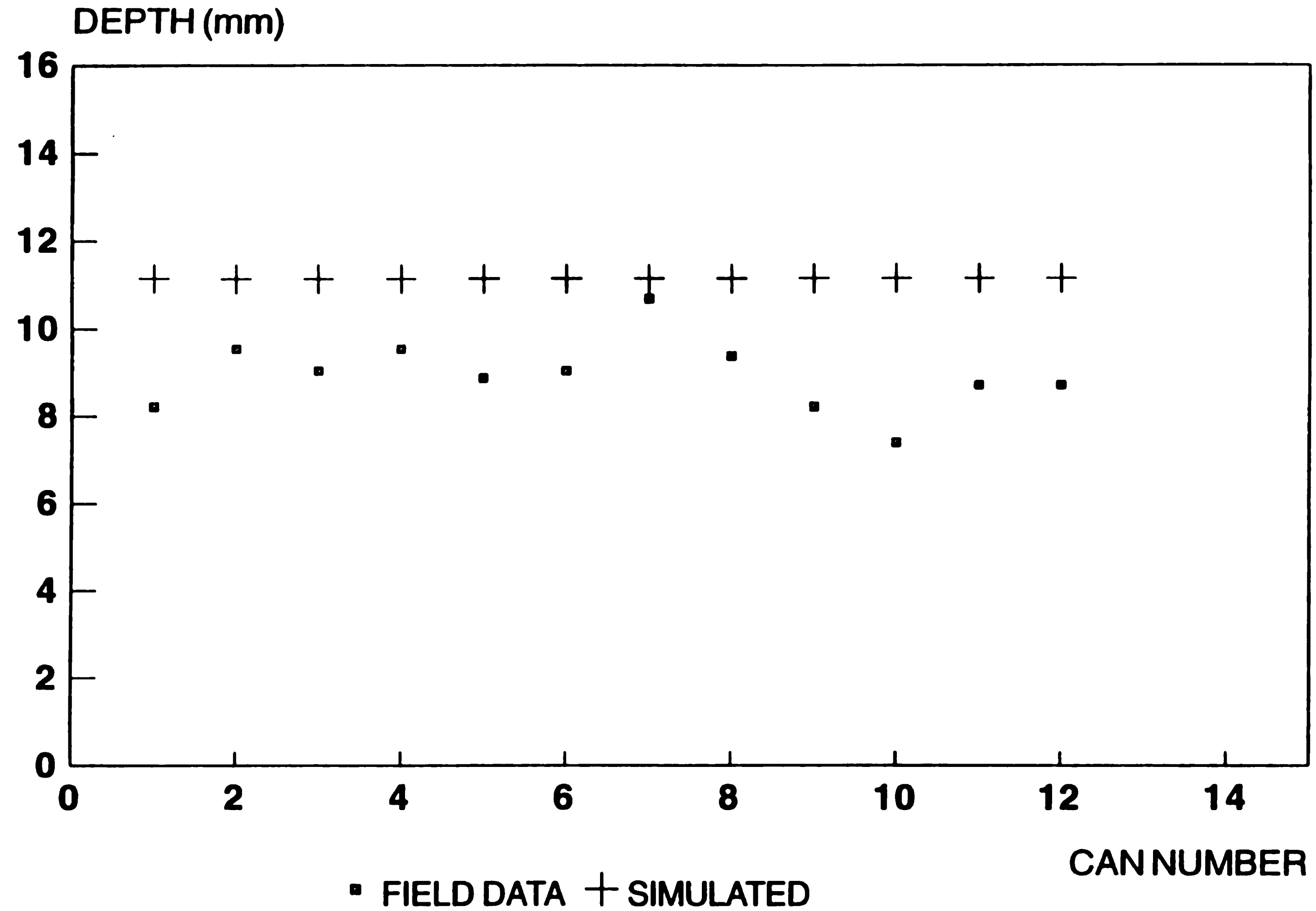

Figure 22. Depth of application on transect no.3, guide tower timer set at 25%.

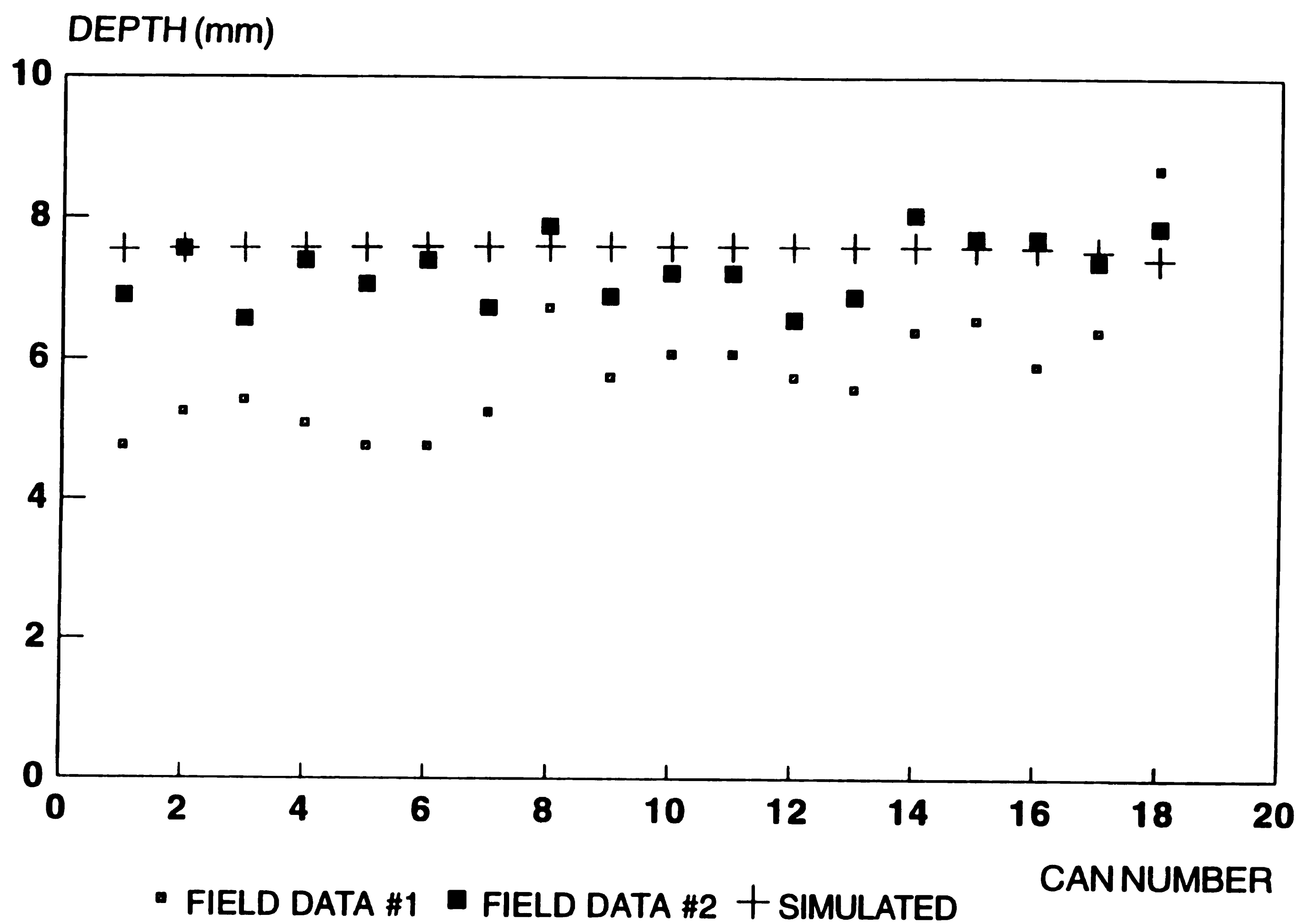

Figure 23. Depth of application on transect no.3, guide tower timer set at 37%.

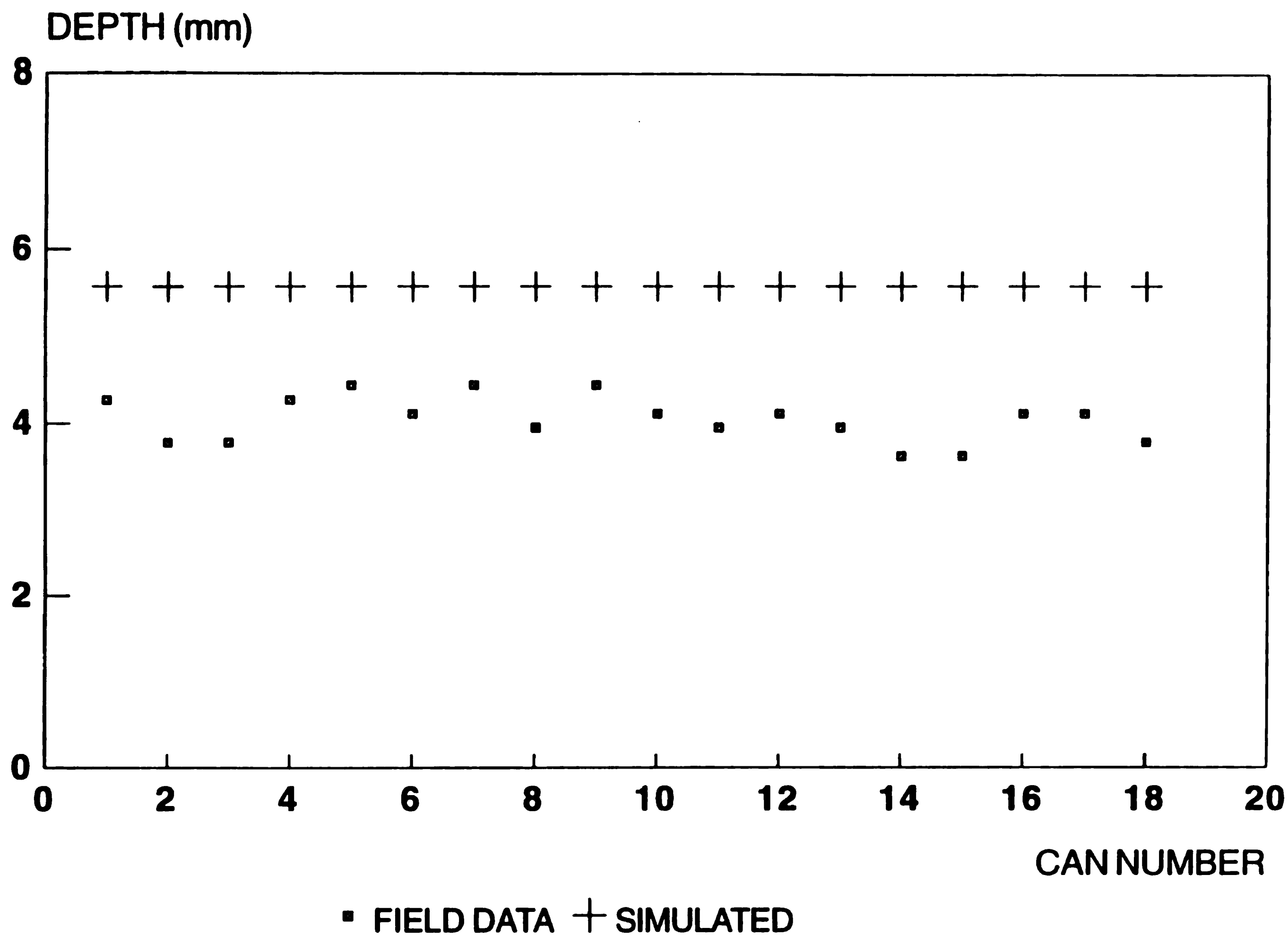

Figure 24. Depth of application on transect no.3, guide tower timer set at 50%.

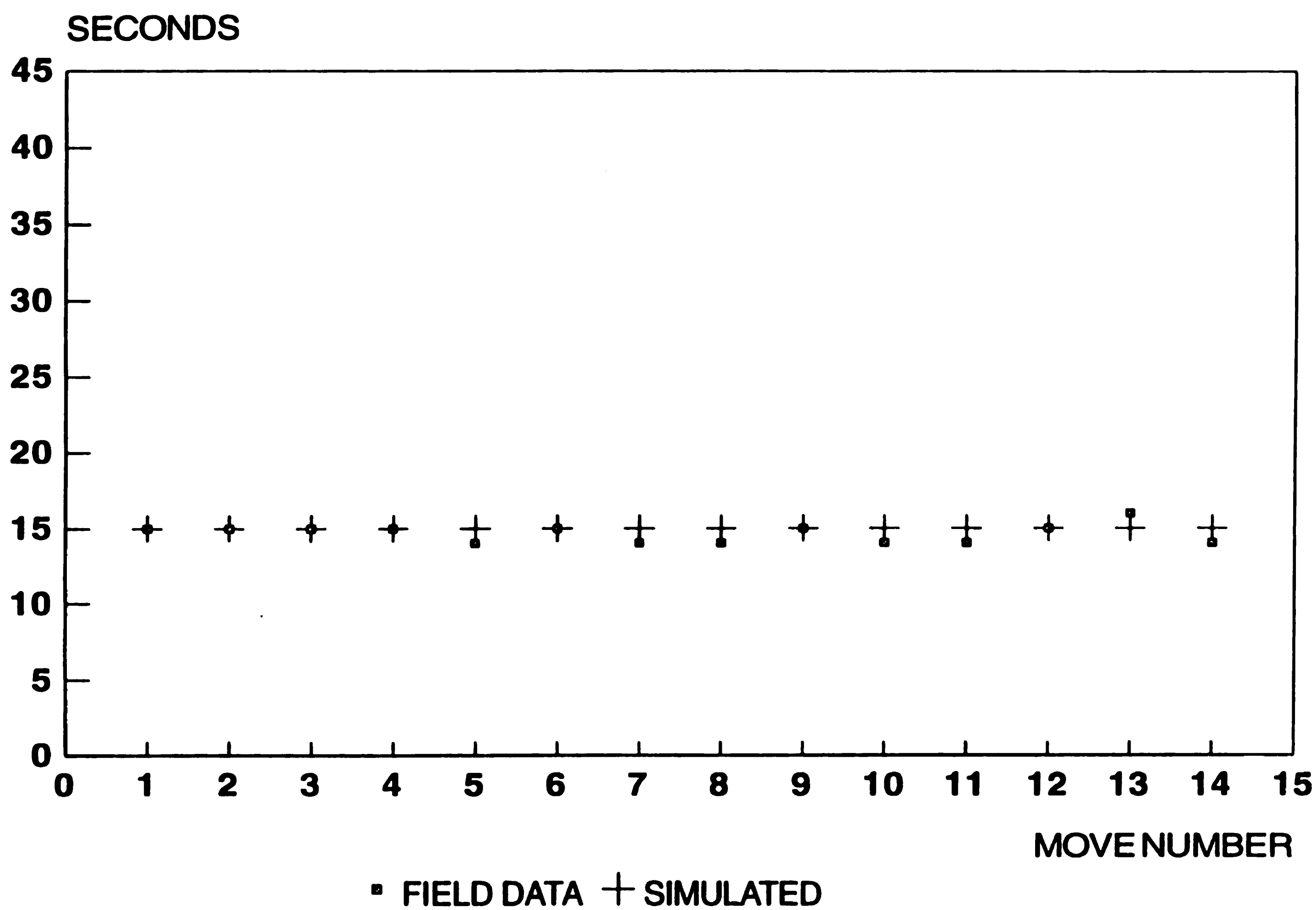

Figure 25. Tower no.1 on-times, guide tower timer set at 25%.

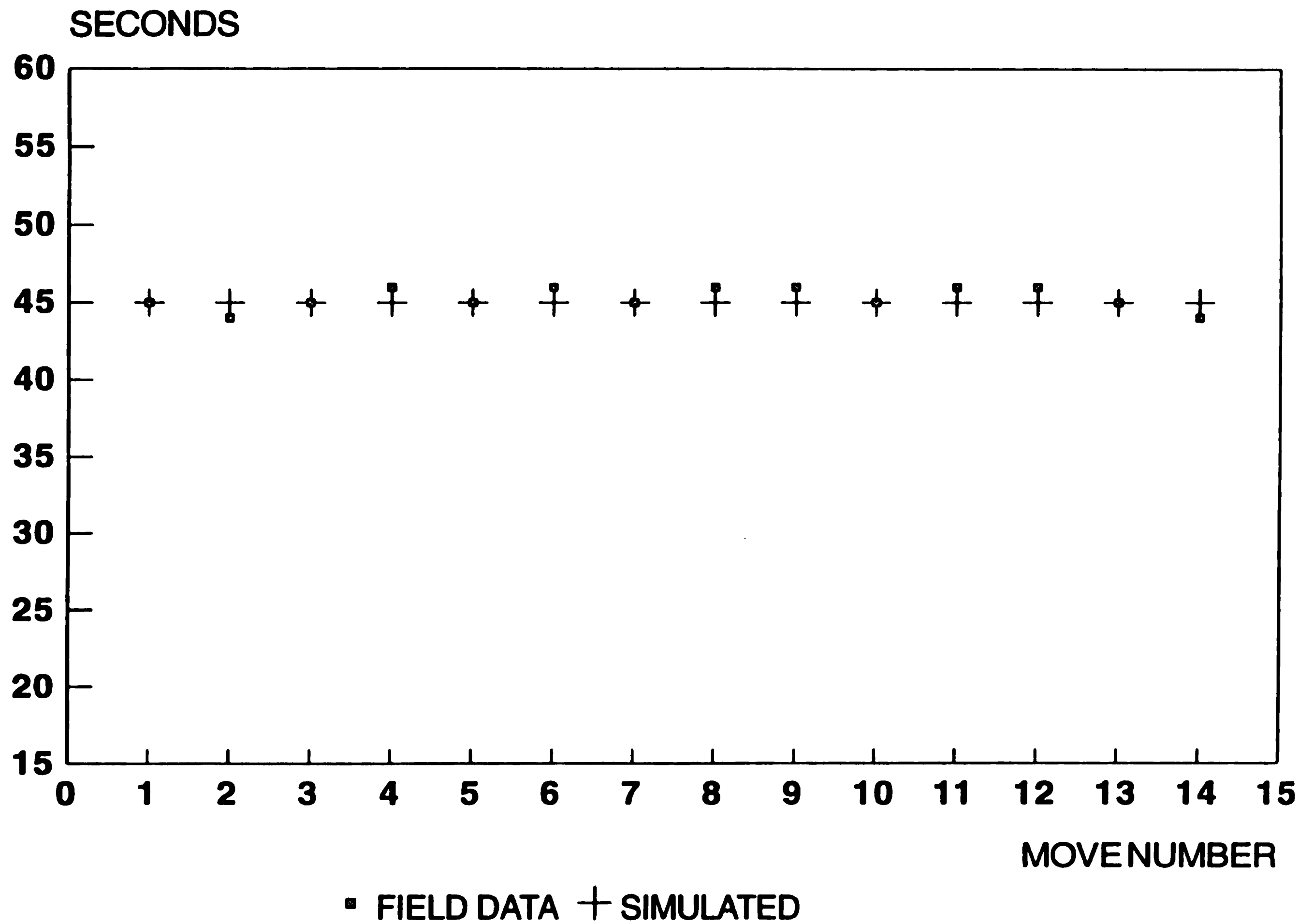

Figure 26. Tower no.1 off-times, guide tower timer set at 25%.

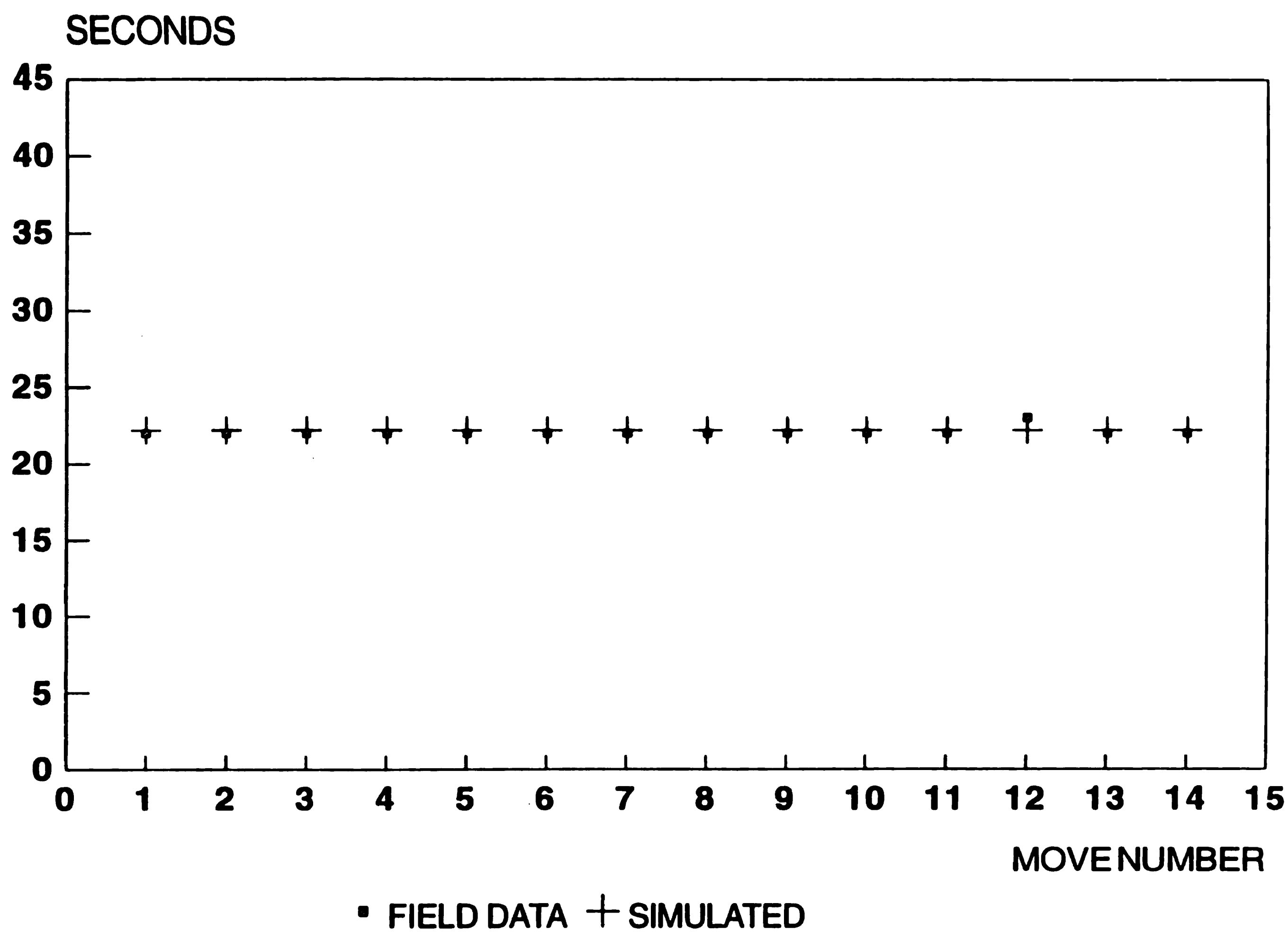

Figure 27. Tower no.1 on-times, guide tower timer set at 37%.

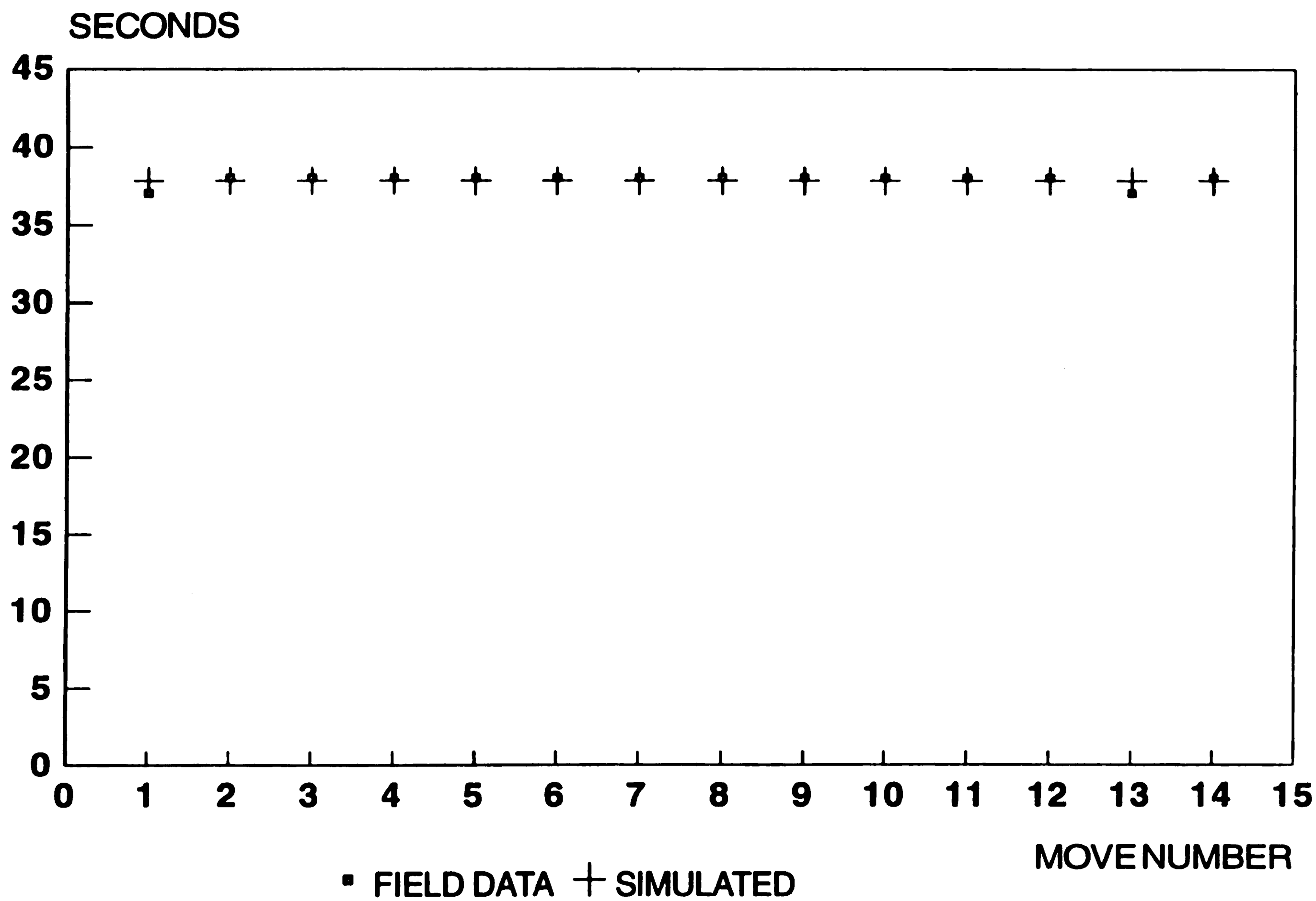

Figure 28. Tower no,1 off-times, guide tower timer set at 37%.

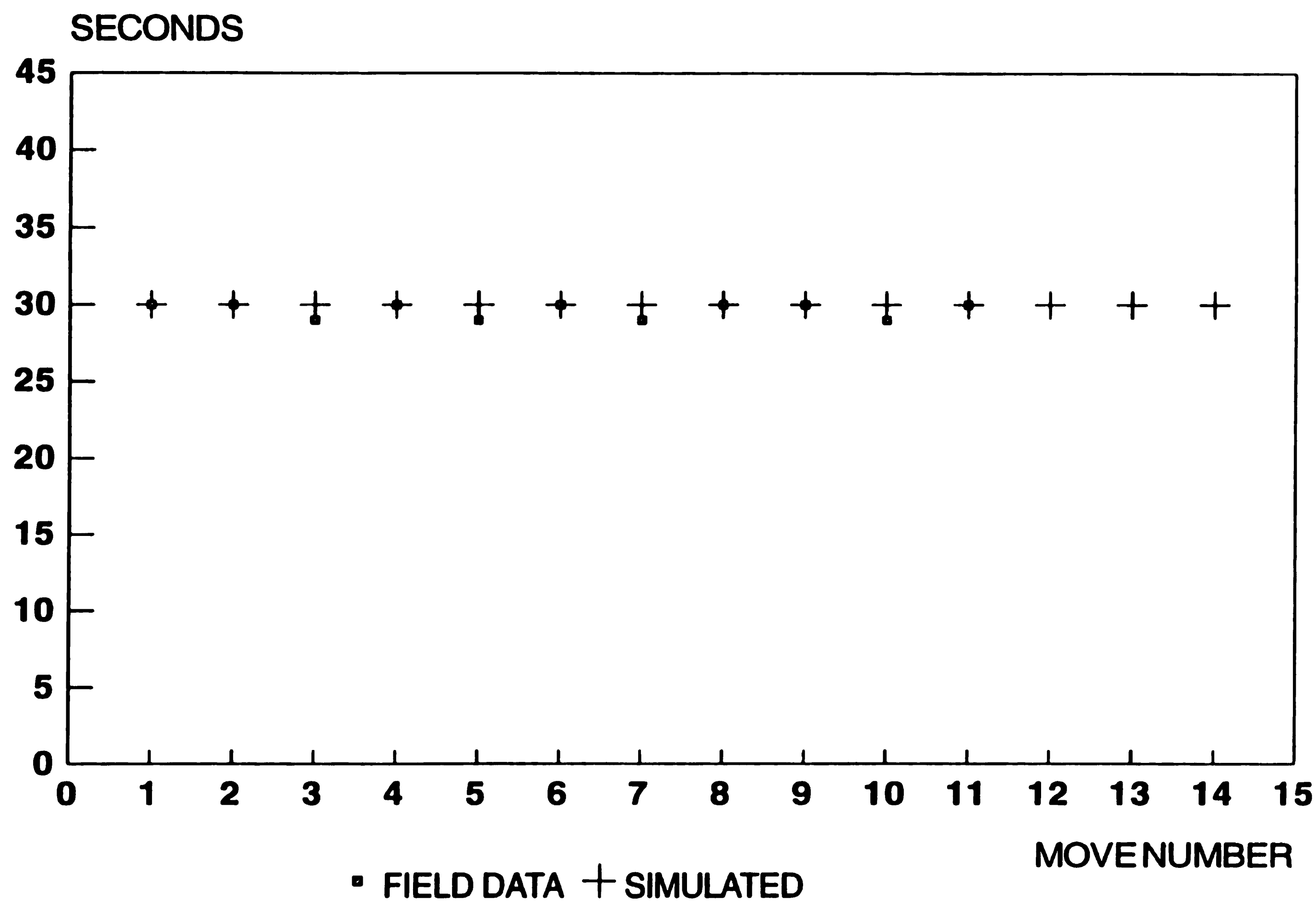

Figure 29. Tower no.1 on-times, guide tower timer set at 50%.

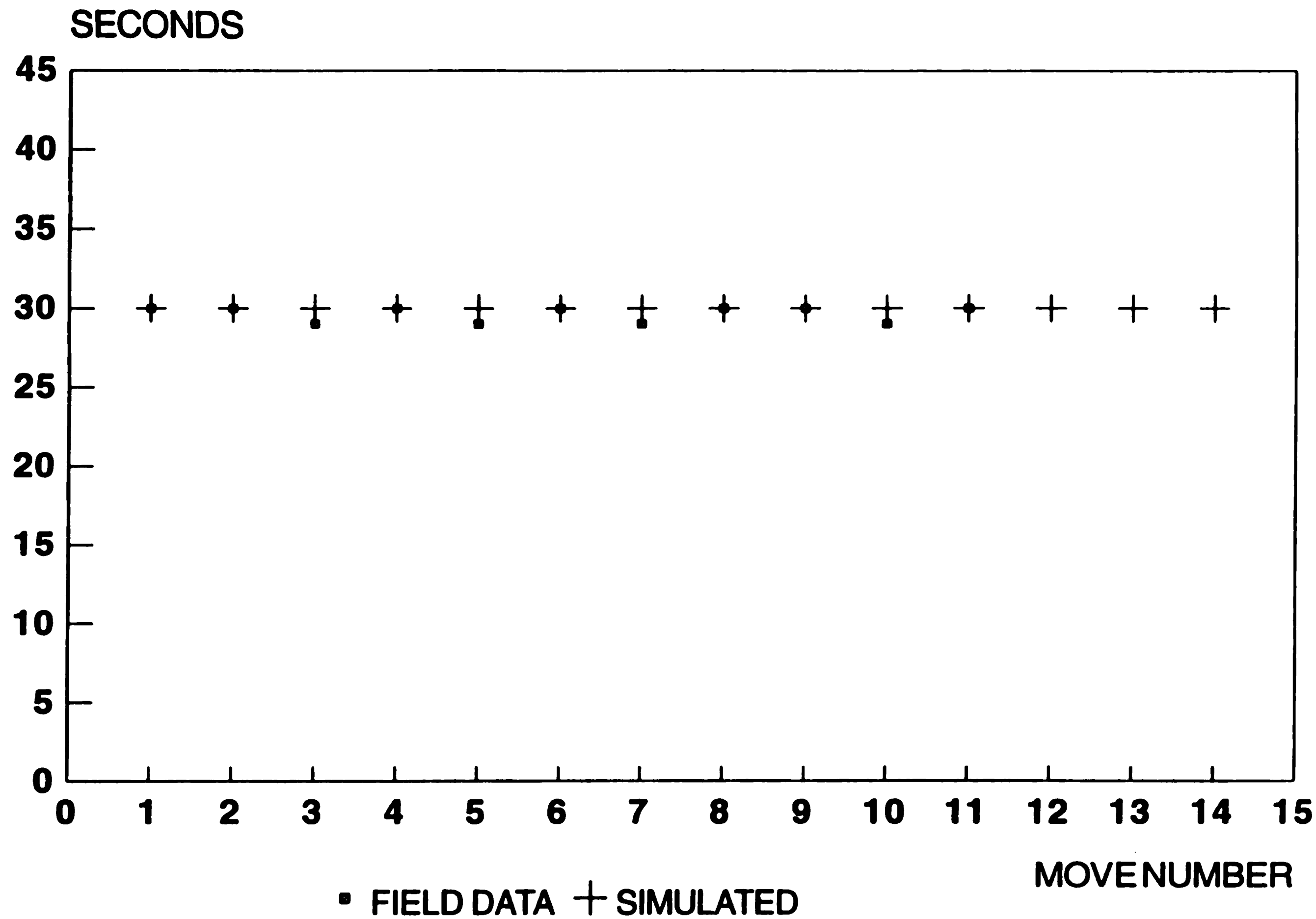

Figure 30. Tower no.1 off-times, guide tower timer set at 50%.

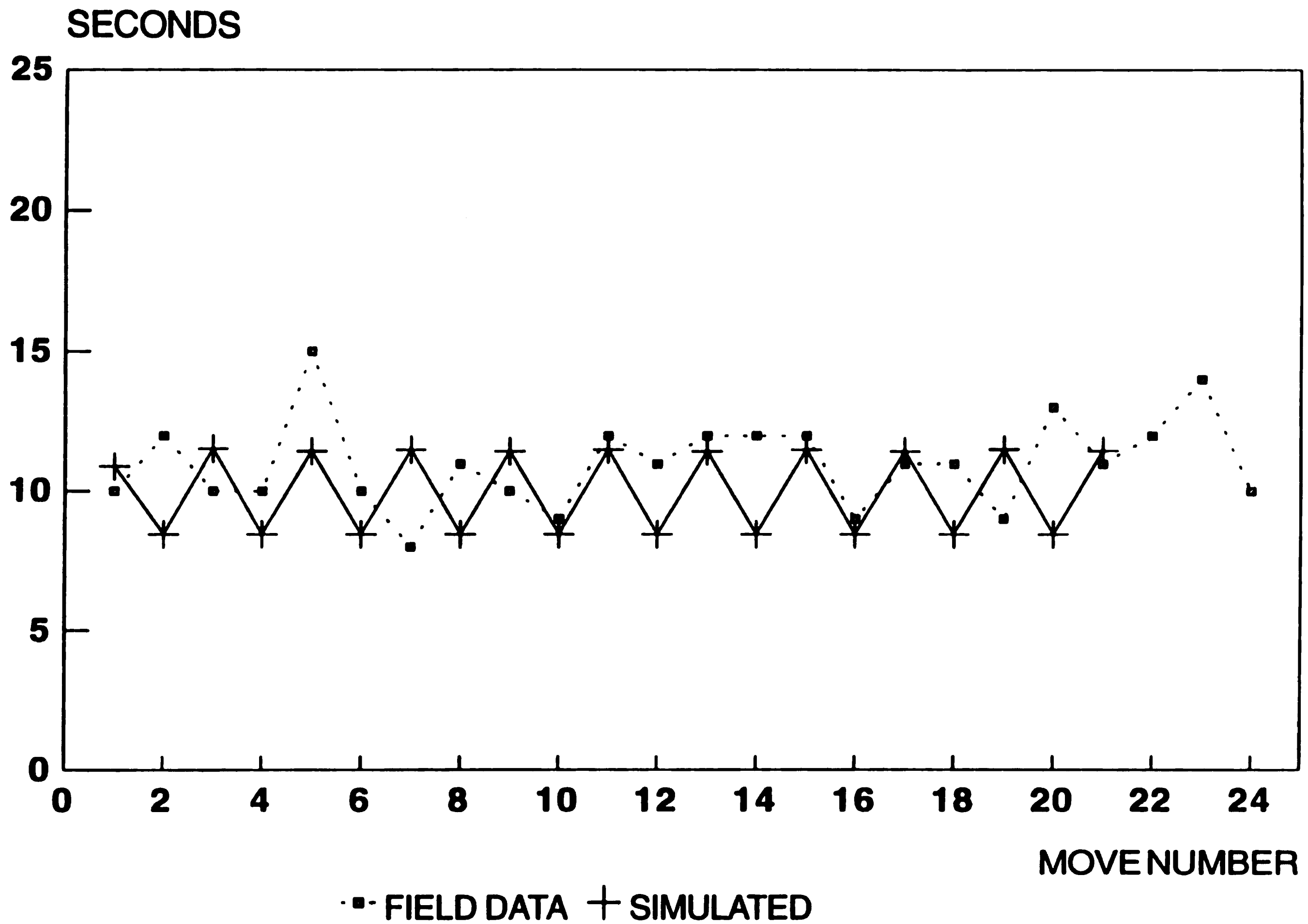

Figure 31. Tower no.2 on-times, guide tower timer set at 25%.

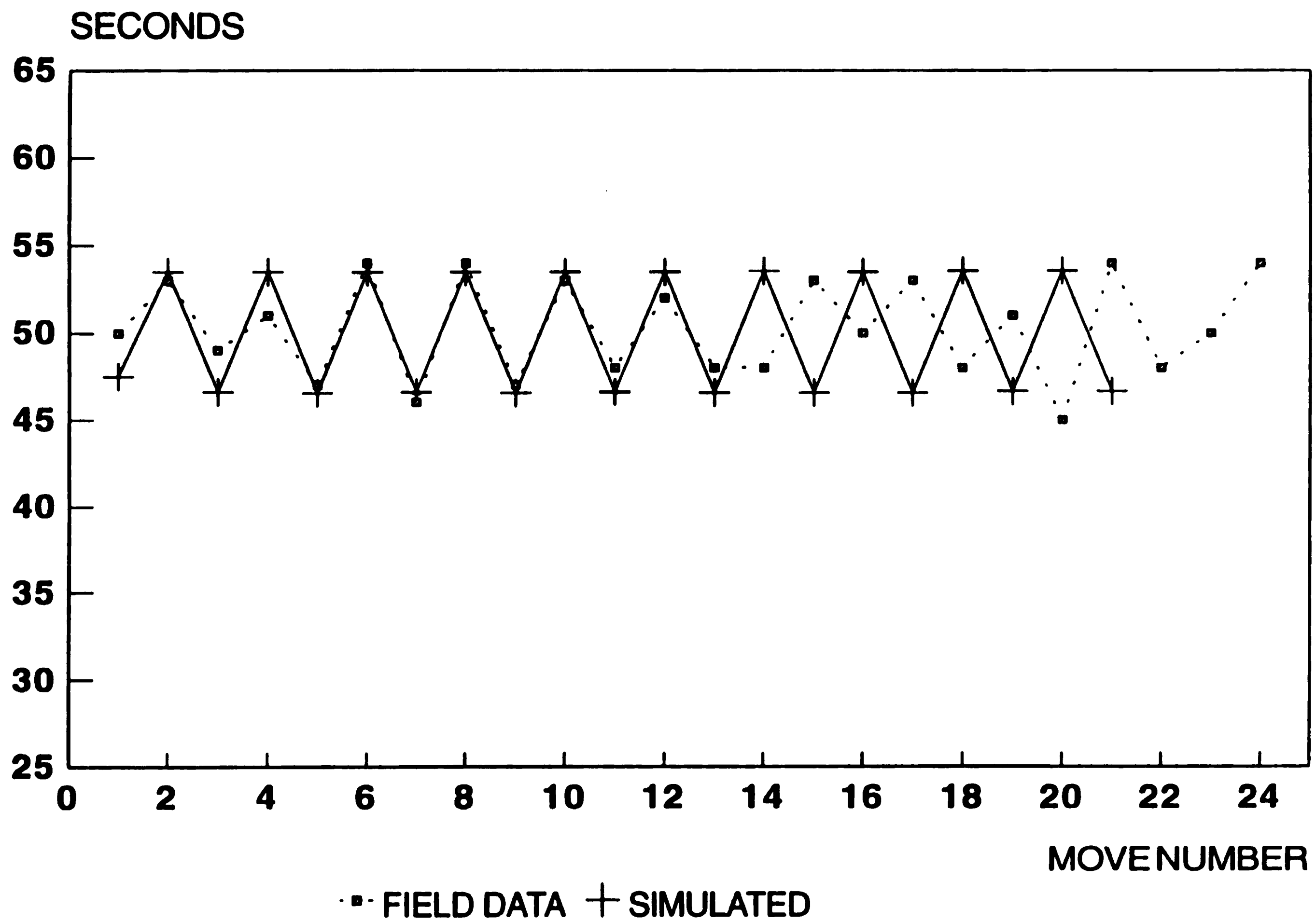

Figure 32. Tower no.2 off-times, guide tower timer set at 25%.

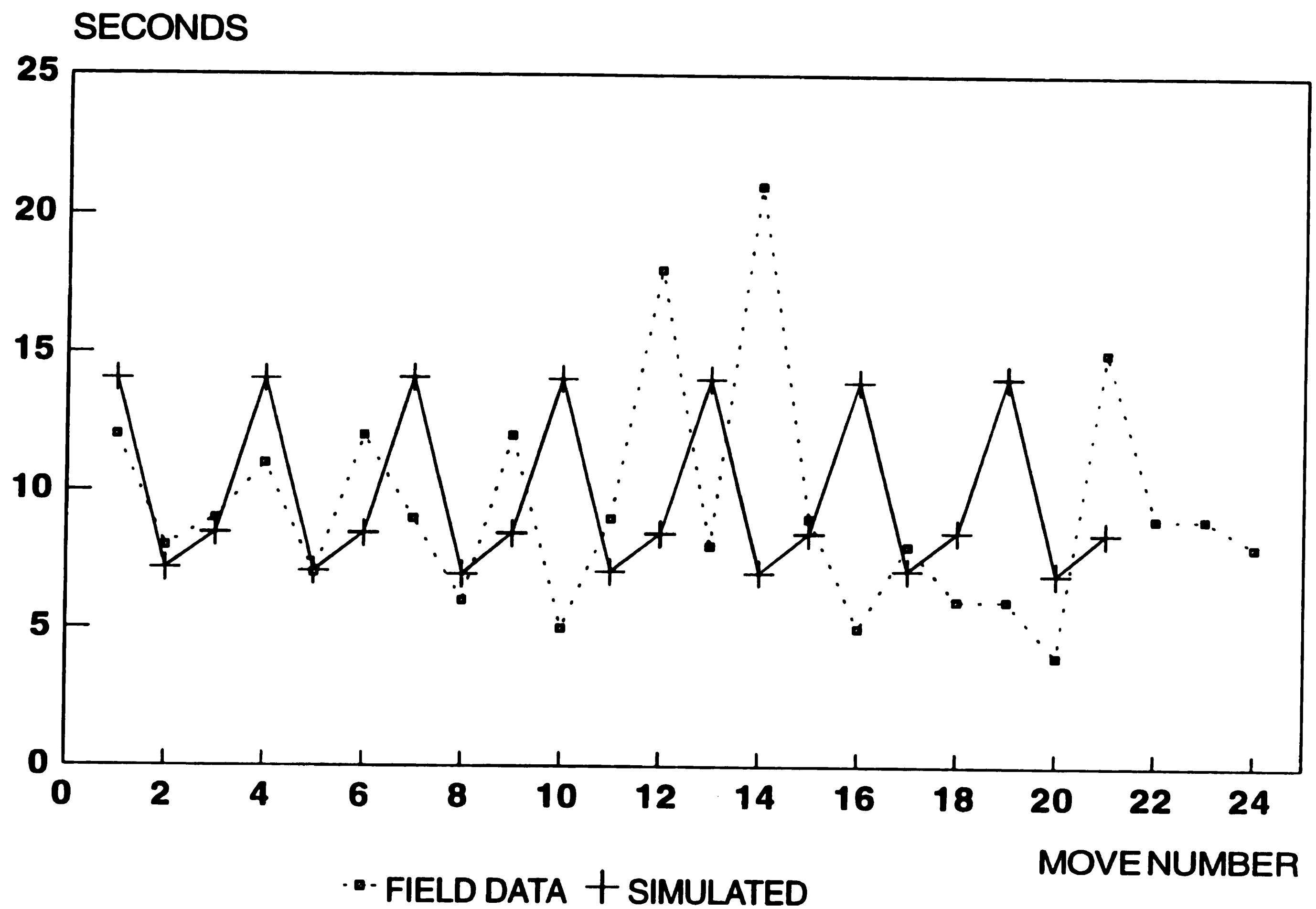

Figure 33. Tower no.2 on-times, guide tower set at 37%.

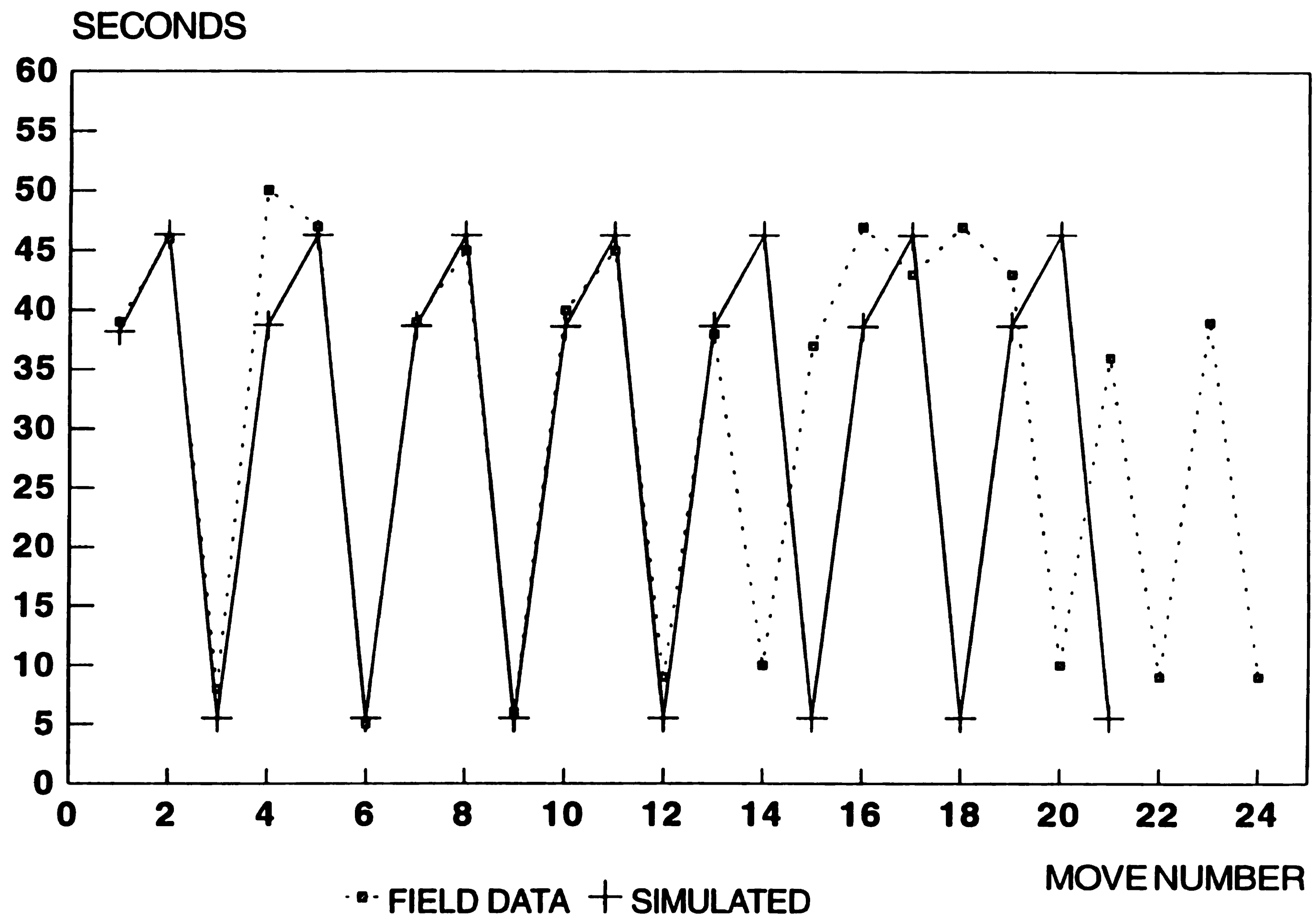

Figure 34. Tower no.2 off-times, guide tower timer set at 37%.

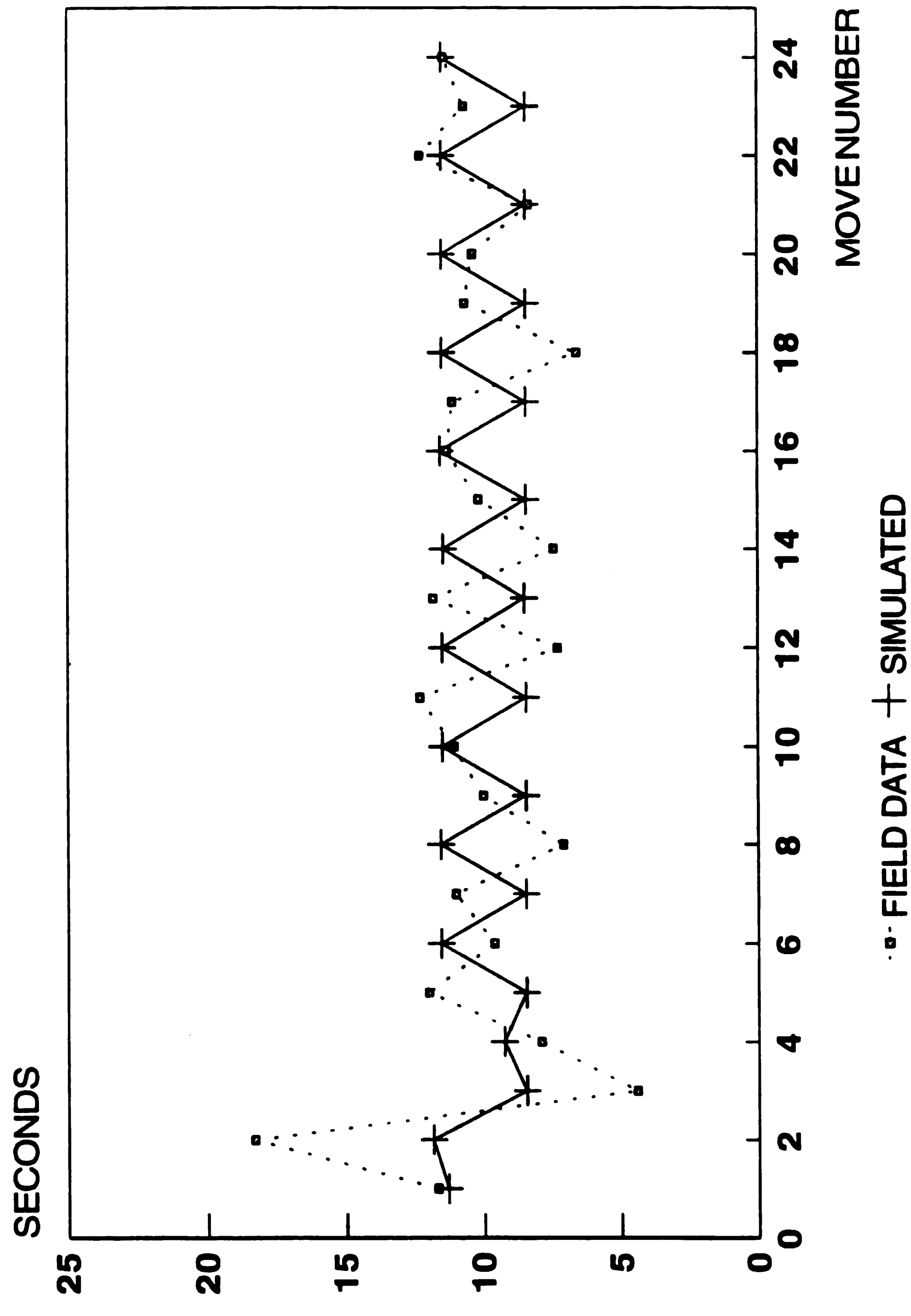

Figure 35. Tower no.2 on-times, guide tower timer set at 50%.

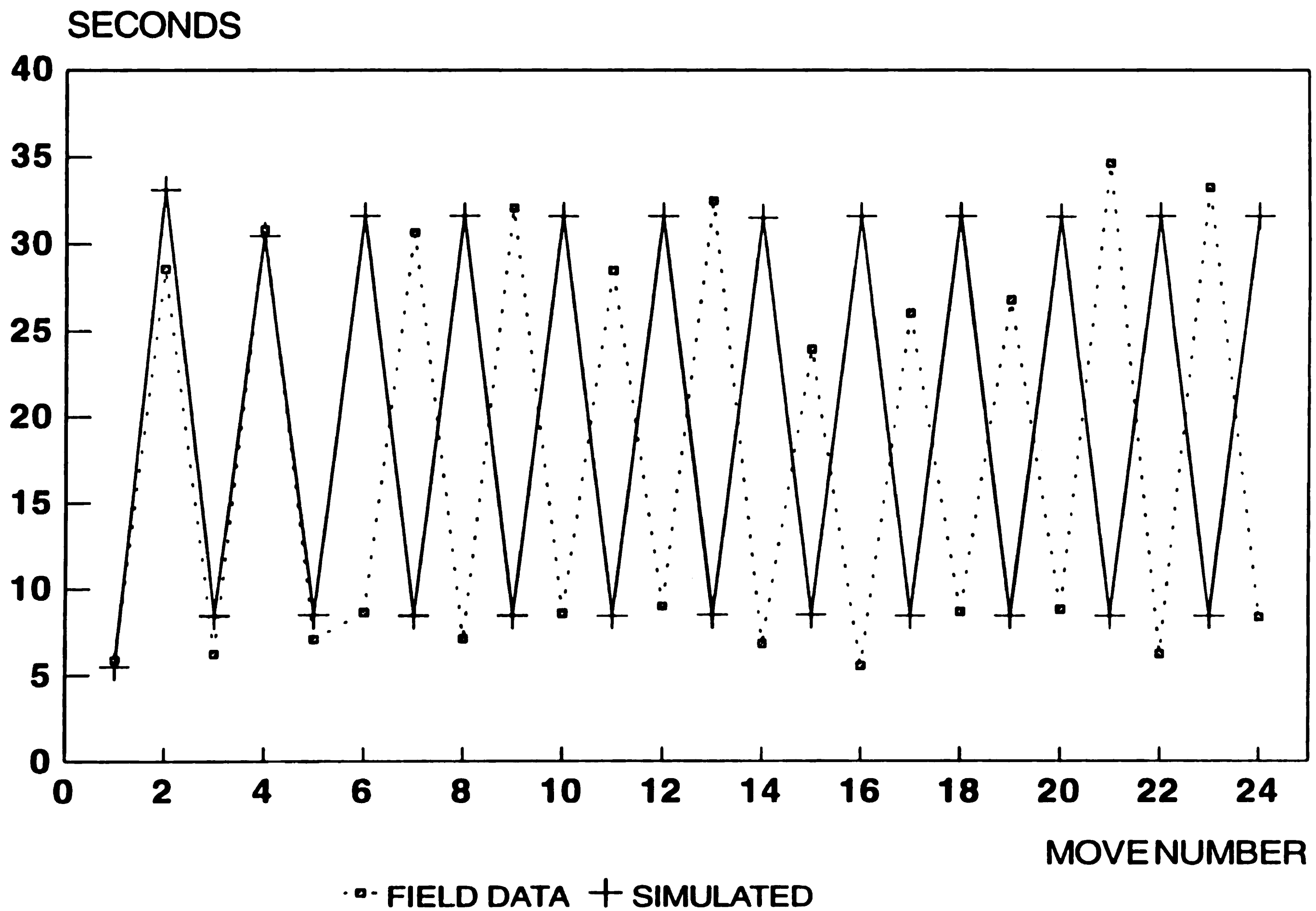

Figure 36. Tower no.2 off-times, guide tower timer set at 50%.

sprinkler application pattern, the magnitude of the sprinkler wetted diameter, the magnitude of the tower alignment angle and the guide tower timer percentage setting affect the uniformity along the path of travel.

Triangular, elliptical and polygonal pattern sprinklers as well as "actual" pattern sprinklers were compared. The wetted diameters chosen to perform the simulations were the wetted diameter of the "actual" pattern sprinklers and a typical value for spray nozzles used for chemigation with a LEPA system (Buchleiter, 1992). The simulations were performed with the towers moving continuously (for triangular pattern sprinklers and LEPA spray nozzles) as well as moving intermittently (all patterns). In the later case three different tower alignment angles were used: 2, 1 and 0.5 degrees. Simulations of the LEPA system were only performed with a guide tower timer set of 100%. All other simulations were performed with the guide tower timer set at 100% and 50%. The simulations generated application data at different distances from the pivot-point as shown in tables 8 and 9. In all simulations the depth of application was determined at 40 positions along the travel path with a 0.3 m (1 ft) spacing. The flowrate of the sprinklers contributing to the depth at each distance from the pivot-point for the traditional center-pivot and LEPA system are also given in the tables 8 and 9.

Table 8. Flowrates and wetted radii for sprinklers contributing to the depth of water applied at different distances from the pivot-point for a traditional center-pivot system.

DISTANCE FROM PIVOT-POINT (m)	SPRINKLER FLOWRATE (L/min)	SPRINKLER WETTED RADIUS (m)
292.7	56.0	10.7
	56.0	9.8
	56.0	8.8
189.1	36.3	10.1
170.8	32.2	11.0
	32.2	9.4
	32.2	8.8
73.2	14.4	10.7
	14.4	8.5
	14.4	7.6
55.0	11.7	6.4

Table 9. Flowrates and wetted radii for sprinklers contributing to the depth of water applied at different distances from the pivot-point for a LEPA system.

DISTANCE FROM PIVOT-POINT (m)	SPRINKLER FLOWRATE (L/min)	SPRINKLER WETTED RADIUS (m)
196.7	9.35	1.0
140.3	6.67	1.0
85.4	4.05	1.0

All complementary information needed to perform the simulations, are presented in the summary of the system specifications given below and in table 10.

NUMBER OF TOWERS: 7

SPAN LENGTH: 55.7 m (182.9 ft)

TOTAL SYSTEM LENGTH: 390.2 m (1280.3 ft)

SYSTEM CAPACITY: 2270.0 L/min (600 gpm)

SPRINKLER OPERATING PRESSURE: 206.8 Kpa (30 psi))

Table 10. Tower velocities used in center-pivot simulation.

TOWER NUMBER	ANGULAR VELOCITY (RAD/SEC)
1	0.000153
2	0.000179
3	0.000215
4	0.000268
5	0.000179
6	0.000268
7	0.000537

The system was designed to apply a net depth of application equal to 3.8 mm (0.15 in) per revolution with the guide tower timer set at 100%. Each revolution of the system is completed in a 12 hr period at a guide tower timer set at 100% .

VI- RESULTS AND DISCUSSION:

The results and discussion of the data generated by the simulations performed in the previous section, Model Application, are presented in this section.

A. TRADITIONAL CENTER-PIVOT SYSTEMS

The Uniformity Coefficient (UCW) and depth of application averages of simulations performed are presented in this section. The Swaile-Wilcox Uniformity Coefficient (UCW) was chosen over the widely used Christiansen Uniformity Coefficient (UCC) for reasons presented in chapter II, that is it gives greater weight to the deviates far from the average.

Simulations were performed with different sprinkler patterns: triangular, elliptical, polygonal and actual patterns for R-30 Nelson Spray Nozzles equipped with U4, D4, D6, and D6C rotary plates. Application data were generated at 5 different distances from the pivot-point, with the system towers moving intermittently but for the triangular sprinkler pattern it was also performed with the lateral moving continuously. Simulations were performed for three different angles of alignment, 2, 1, and 0.5 degrees. All simulations were performed with the guide tower set at 100% and at 50%. The results of the simulations are given in tables 11 through 19. The simulated UCW ranged between 76.3% to 99.7% when the towers moved intermittently. UCW for simulations with the lateral moving continuously (only for the triangular sprinkler pattern) were for all practical purposes equal to 100%. For that reason, simulations with the lateral moving continuously and using other sprinkler patterns were not performed. The same response would be found. It is important to remember that these are the highest values possible for each set of parameters. In field conditions, the two most important factors responsible for these values not being reached are probably distortions in the sprinkler pattern caused by wind and slippage of the tower tires.

Contrary to results found by other researchers (Wallender and Hansen, 1986; Heermann and Stahl, 1988), the uniformity coefficient did not always decrease toward the center of the system, the area believed to present the most irregular movement pattern. This finding is of extreme importance because it raises the hypothesis that such irregularity can be particular to the systems studied, and that it may be a function of the towers' velocities and the alignment angles between towers.

TABLE 11. Uniformity Coefficient (UCW)* and Average Depths (mm)** for Triangular Pattern Sprinklers with guide tower set at 100%.

DISTANCE FROM PIVOT-POINT(m)	WETTED RADIUS (m)	ALIGNMENT ANGLE		
		2.0	1.0	0.5
292.7	10.7	88.6*	96.5	98.7
		3.78**	3.43	3.53
	9.8	85.9	95.4	98.5
		3.87	3.47	3.57
	8.8	82.9	94.6	98.3
		3.91	3.45	3.56
189.0	10.1	99.1	99.4	98.3
		3.21	3.33	3.52
170.8	11.0	94.9	99.0	97.6
		3.16	3.31	3.55
	9.4	94.0	99.0	96.7
		3.21	3.37	3.64
	8.8	93.6	98.7	96.4
		3.19	3.36	3.64
73.2	10.7	98.7	98.9	99.5
		3.39	3.62	3.59
	8.5	98.3	98.7	99.2
		3.38	3.65	3.61
	7.6	97.9	98.6	98.8
		3.31	3.63	3.54
55.0	7.0	97.0	98.4	98.3
		3.41	3.44	3.65

TABLE 12. Uniformity Coefficient (UCW)* and Average Depths (mm)** for Triangular Pattern Sprinklers with guide tower set at 50%.

DISTANCE FROM PIVOT-POINT(m)	WETTED RADIUS (m)	ALIGNMENT ANGLE		
		2.0	1.0	0.5
292.7	10.7	88.8	99.3	99.7
		6.65	7.16	7.01
	9.8	85.8	98.4	99.7
		6.88	7.26	7.09
	8.8	83.2	96.3	99.7
		6.88	7.26	7.09
189.0	10.1	95.6	96.5	98.1
		7.92	6.68	6.71
170.8	11.0	89.7	92.7	97.6
		7.57	5.36	6.07
	9.4	89.6	91.4	95.6
		7.95	5.28	6.02
	8.8	89.7	90.8	94.5
		8.03	5.21	5.94
73.2	10.7	91.5	99.2	99.3
		6.15	6.96	7.09
	8.5	89.8	97.4	98.3
		6.12	7.06	7.16
	7.6	88.9	97.3	97.8
		6.20	7.16	7.11
55.0	7.0	85.8	93.0	97.6
		6.81	6.35	7.39

TABLE 13. Uniformity Coefficients (UCW)* and Average Depths (mm)** for Triangular Pattern Sprinklers and lateral moving continuously with guide tower timer set at 100 and 50%.

DISTANCE FROM PIVOT-POINT (m)	WETTED RADIUS (M)	TIMER SET PERCENTAGE, %	
		100	50
292.7	10.7	100.0	99.95
		3.51	7.04
	9.8	100.0	99.92
		3.56	7.11
	8.8	100.0	99.90
		3.56	7.09
189.0	10.1	100.0	99.88
		3.56	6.86
170.8	11.0	100.0	99.37
		3.43	6.93
	9.4	100.0	99.44
		3.51	7.24
	8.8	100.0	99.50
		3.48	7.34
73.2	10.7	100.0	99.85
		2.79	6.83
	8.5	100.0	99.94
		3.02	7.01
	7.6	100.0	99.91
		3.12	7.09
55.0	7.0	100.0	99.79
		3.45	7.47

TABLE 14. Uniformity Coefficients (UCW)* and Average Depths (mm)** for Elliptical Pattern Sprinklers with guide tower timer set at 100%.

DISTANCE FROM PIVOT-POINT(m)	WETTED RADIUS (m)	ALIGNMENT ANGLE (DEGREES)		
		2.0	1.0	0.5
292.7	10.7	94.3 *	98.5	98.8
		3.61 **	3.38	3.45
	9.8	91.2	96.3	98.6
		3.78	3.51	3.58
	8.8	87.8	94.7	98.3
		3.91	3.56	3.63
189.0	10.1	98.1	99.2	99.0
		3.15	3.23	3.40
170.8	11.0	95.6	98.3	98.4
		3.09	3.22	3.41
	9.4	94.6	98.4	97.6
		3.25	3.39	3.64
	8.8	94.1	98.7	97.2
		3.28	3.42	3.69
73.2	10.7	97.9	98.3	99.0
		3.39	3.62	3.55
	8.5	97.9	98.4	99.2
		3.55	3.84	3.74
	7.6	96.4	98.8	98.6
		3.46	3.75	3.64
55.0	7.0	95.8	97.9	98.1
		3.40	3.45	3.68

TABLE 15. Uniformity coefficients (UCW)* and Average Depths (mm)** for Elliptical Pattern Sprinklers with guide tower set at 50%.

DISTANCE FROM PIVOT-POINT(m)	WETTED RADIUS (m)	ALIGNMENT ANGLE (DEGREES) 2.0	1.0	0.5
292.7	10.7	93.2 *	96.5	99.5
		6.68 **	7.01	6.88
	9.8	90.3	97.1	99.3
		6.86	7.24	7.11
	8.8	86.4	98.4	98.7
		6.99	7.39	7.24
189.0	10.1	91.1	96.7	97.9
		7.72	6.43	6.63
170.8	11.0	92.5	96.6	98.9
		7.25	6.64	6.60
	9.4	89.6	96.7	98.9
		7.82	6.99	6.93
	8.8	89.7	97.4	98.7
		8.00	7.06	6.99
73.2	10.7	94.2	99.3	99.3
		6.40	7.15	7.12
	8.5	91.0	98.8	98.9
		6.62	7.53	7.51
	7.6	89.3	98.4	98.9
		6.47	7.36	7.33
55.0	7.0	88.0	93.4	97.4
		6.76	6.76	7.39

TABLE 16. Uniformity Coefficients (UCW)* and Average Depths (mm)** for Polygonal Pattern Sprinklers with guide tower timer set at 100% .

DISTANCE FROM PIVOT-POINT(m)	WETTED RADIUS (m)	ALIGNMENT ANGLE (DEGREES)		
		2.0	1.0	0.5
292.7	10.7	92.1 *	96.5	98.7
		3.40 **	3.18	3.23
	9.8	89.5	94.8	98.5
		3.43	3.15	3.20
	8.8	86.7	96.7	98.2
		3.35	3.05	3.10
189.0	10.1	97.5	98.4	98.8
		2.92	3.05	3.20
170.8	11.0	95.1	98.2	98.2
		2.91	3.02	3.23
	9.4	94.0	98.3	97.5
		2.87	2.99	3.23
	8.8	93.5	98.7	97.1
		2.79	2.91	3.15
73.2	10.7	97.9	98.1	99.3
		3.15	3.38	3.30
	8.5	98.3	98.2	98.8
		2.94	3.19	3.10
	7.6	97.4	98.6	98.2
		2.72	2.96	2.86
55.0	7.0	96.1	97.2	97.2
		2.97	3.18	3.07

TABLE 17. Uniformity Coefficients (UCW)* and Average Depths (mm)** for polygonal pattern sprinklers with guide tower timer set at 50% .

DISTANCE FROM PIVOT-POINT(m)	WETTED RADIUS (m)	ALIGNMENT ANGLE (DEGREES)		
		2.0	1.0	0.5
292.7	10.7	91.2 *	96.7	99.2
		6.22 **	6.55	6.43
	9.8	88.1	97.6	98.5
		6.15	6.50	6.38
	8.8	84.7	98.4	98.0
		5.92	6.30	6.17
189.0	10.1	90.0	97.2	98.1
		7.14	6.10	6.20
170.8	11.0	90.2	96.3	99.0
		6.88	6.23	6.20
	9.4	88.2	96.9	98.8
		6.95	6.16	6.12
	8.8	88.4	97.3	98.6
		6.83	6.01	5.95
73.2	10.7	93.9	99.2	99.0
		5.91	6.65	6.63
	8.5	90.1	98.6	98.6
		5.48	6.26	6.24
	7.6	88.7	98.7	98.7
		5.06	5.79	5.77
55.0	7.0	92.2	94.9	98.0
		6.48	6.45	6.63

TABLE 18. Uniformity Coefficients (UCW)* and Average Depths (mm)** for Actual Pattern Sprinklers with guide tower timer set at 100%.

DISTANCE FROM PIVOT-POINT(m)	SPRINKLER TYPE	ALIGNMENT ANGLE (DEGREES)		
		2.0	1.0	0.5
292.7	R30-U4 NOZZLE #40	94.6*	97.3	98.6
		4.01**	3.81	3.86
	R30-D4 NOZZLE #40	90.7	93.1	96.6
		3.51	3.43	3.43
	R30-D6 NOZZLE #40	86.8	92.3	97.5
		3.96	3.63	3.68
189.0	R30-D6C NOZZLE #32	97.8	99.0	98.2
		3.61	3.75	4.00
170.8	R30-U4 NOZZLE #30	95.9	97.5	98.6
		3.61	3.73	3.91
	R30-D4 NOZZLE #30	94.0	94.0	97.3
		3.35	3.42	3.64
	R30-D6 NOZZLE #30	93.7	98.5	97.2
		3.40	3.54	3.82
73.2	R30-U4 NOZZLE #20	95.3	97.1	97.5
		3.45	3.63	3.57
	R30-D4 NOZZLE #20	93.0	95.9	97.9
		4.05	4.37	4.27
	R30-D6 NOZZLE #20	97.3	98.8	98.3
		3.22	3.51	3.40
55.0	R30-D6C NOZZLE #18	92.3	95.4	97.9
		3.67	3.98	3.85

TABLE 19. Uniformity Coefficients (UCW)* and Average Depths (mm)** for Actual Pattern Sprinklers with guide tower timer set at 50%.

DISTANCE FROM PIVOT-POINT(m)	SPRINKLER TYPE	ALIGNMENT ANGLE (DEGREES)		
		2.0	1.0	0.5
292.7	R30-U4 NOZZLE #40	94.1 *	94.4	99.2
		7.44 **	7.82	7.70
	R30-D4 NOZZLE #40	92.5	90.7	97.2
		6.53	6.91	6.83
	R30-D6 NOZZLE #40	83.4	95.9	96.6
		6.99	7.49	7.32
189.0	R30-D6C NOZZLE #32	95.6	96.9	98.9
		8.69	7.82	7.62
170.8	R30-U4 NOZZLE #30	91.2	95.3	98.0
		8.14	7.72	7.68
	R30-D4 NOZZLE #30	76.3	90.7	93.0
		7.52	7.04	7.06
	R30-D6 NOZZLE #30	88.3	96.9	98.4
		8.27	7.30	7.24
73.2	R30-U4 NOZZLE #20	91.9	97.3	98.7
		6.55	7.20	7.16
	R30-D4 NOZZLE #20	89.4	96.3	97.1
		7.55	8.57	8.55
	R30-D6 NOZZLE #20	88.6	98.3	98.8
		6.02	6.87	6.85
55.0	R30-D6C NOZZLE #18	83.1	995.4	98.0
		6.73	7.76	7.79

1- ANALYSIS OF VARIANCE RESULTS

An Analysis of Variance (ANOVA) was done for the results of the geometrical sprinkler patterns (triangular, elliptical and polygonal) at distances equal to 292.7, 170.8 and 73.2 m from the pivot-point. Results of simulations using the actual sprinkler pattern were not included in the ANOVA because the sprinkler pattern is not the same at different distances from the pivot-point. A split-plot design was used with the distances from the pivot-point as blocks, and the other parameters: alignment angle (AA); guide tower setting (GT); sprinkler profile (SS); and wetted radius (WR) as factors. The level of each factor is given in the ANOVA results below. The dependent variable was the coefficient of uniformity, UCW.

ANOVA RESULTS

Analysis of Variance Procedure
Class Level Information

Class	Levels	Values
BLOCK	3	1 2 3
AA	3	1 2 3
SS	3	1 2 3
WR	3	1 2 3
GT	2	1 2

number of observations in data set = 162

ANOVA RESULTS (cont'd)

Dependent Variable: UCW

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	97	2482.358704	25.591327	69.86	0.0001
Error	64	23.446296	0.366348		
Corrected Total	161	2505.805000			

R-Square	C.V.	Root MSE	UCW Mean
0.990643	0.630304	0.605267	96.0277778

Analysis of Variance Procedure

Dependent Variable: UCW

Source	DF	Anova SS	Mean Square	F Value	Pr > F
BLOCK	2	185.300370	92.650185	252.90	0.0001
AA	2	1539.917037	769.958519	2101.71	0.0001
BLOCK*AA	4	181.745926	45.436481	124.03	0.0001
SS	2	7.002593	3.501296	9.56	0.0002
BLOCK*SS	4	17.747037	4.436759	12.11	0.0001
AA*SS	4	15.319259	3.829815	10.45	0.0001
BLOCK*AA*SS	8	39.891111	4.986389	13.61	0.0001
WR	2	56.934444	28.467222	77.71	0.0001
BLOCK*WR	4	17.292963	4.323241	11.80	0.0001
AA*WR	4	56.505185	14.126296	38.56	0.0001
BLOCK*AA*WR	8	20.950741	2.618843	7.15	0.0001
SS*WR	4	1.202963	0.300741	0.82	0.5166
BLOCK*SS*WR	8	1.452963	0.181620	0.50	0.8548
AA*SS*WR	8	4.348519	0.543565	1.48	0.1808
GT	1	39.803025	39.803025	108.65	0.0001
BLOCK*GT	2	47.743086	23.871543	65.16	0.0001
AA*GT	2	165.751605	82.875802	226.22	0.0001
BLOCK*AA*GT	4	57.641728	14.410432	39.34	0.0001
SS*GT	2	3.857160	1.928580	5.26	0.0076
BLOCK*SS*GT	4	6.229506	1.557377	4.25	0.0041
AA*SS*GT	4	1.418765	0.354691	0.97	0.4312
WR*GT	2	0.686790	0.343395	0.94	0.3970
BLOCK*WR*GT	4	6.342099	1.585525	4.33	0.0037
AA*WR*GT	4	6.933580	1.733395	4.73	0.0021
SS*WR*GT	4	0.340247	0.085062	0.23	0.9193

Among the factors included in this experiment, the alignment angle and the guide tower timer setting affect the tower movement which in turn affects the uniformity of water distribution along the path of travel. Sprinkler pattern and magnitude of wetted radius each affect the uniformity along the path of travel directly by determining the instantaneous application rate at any given point and the time required for the sprinkler pattern to move through the transect. The ANOVA showed all two and three factor interactions to be significant at $\alpha = 0.01$, with the exception of the interactions where sprinkler pattern and wetted radius factor appear together. The reason for the interactions being significant is due to the response of one factor in the presence of another factor (or combination of factors) being not constant for all factor levels. Although meaningful observations on the main effects can be difficult to make in face of the interactions among factors being significant, an attempt is made in the following pages.

2- MAIN EFFECTS

a. ALIGNMENT ANGLE:

If no interactions involving the alignment angle were

existent, it would be logical to assume that the smaller the alignment angle between towers, the higher the coefficient of uniformity along the path of travel. Because the interactions were significant the results showed this was not always the case. At 292.7 m from the pivot-point all results but one, the UCW increased when decreasing the alignment angle from 2 to 0.5 degrees, independent of the guide-tower setting, sprinkler pattern and magnitude of wetted radius. Figures 37 to 39 show the relative position of the lateral, time-off of closest tower and depth of application for the transect at 292.7 m from the pivot-point for triangular pattern sprinklers. However, at 170.8 m from the pivot-point and particularly when the guide-tower was set at 100% and for a smaller wetted radius, the coefficient of uniformity was in many instances higher for the distributions generated with the alignment angle equal to 1 degree than for 0.5 degrees. It is hypothesized that due to interactions, the movement of the lateral over the transect was more irregular (irregular start-stop cycles and variable off-times) when the alignment angle was equal to 0.5 degrees. The movement of the lateral (or sprinkler) over any given point is a function of the state of its adjacent towers. Four combinations are possible, which are: (1) both towers are stopped; (2) both towers are moving; (3) outer tower is moving and inner tower is stopped; and (4) outer

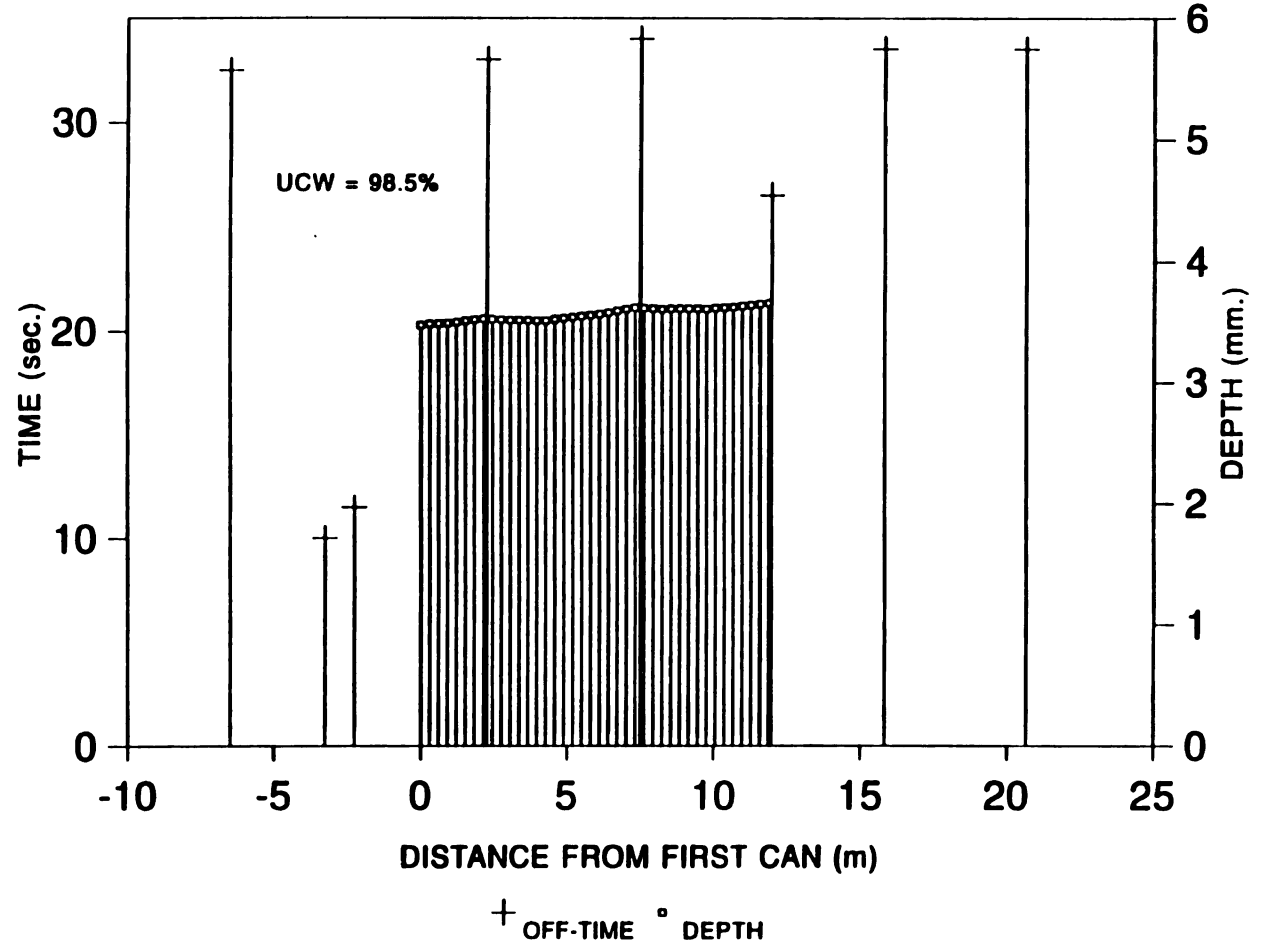

Figure 37. Span No.3 Positions and Off-Times, and Depth of Application on Transect located at 292.7 m from the pivot-point for Triangular Pattern Sprinklers (WR=9.8 m, guide tower timer = 100%) and Alignment Angle equal to 0.5°.

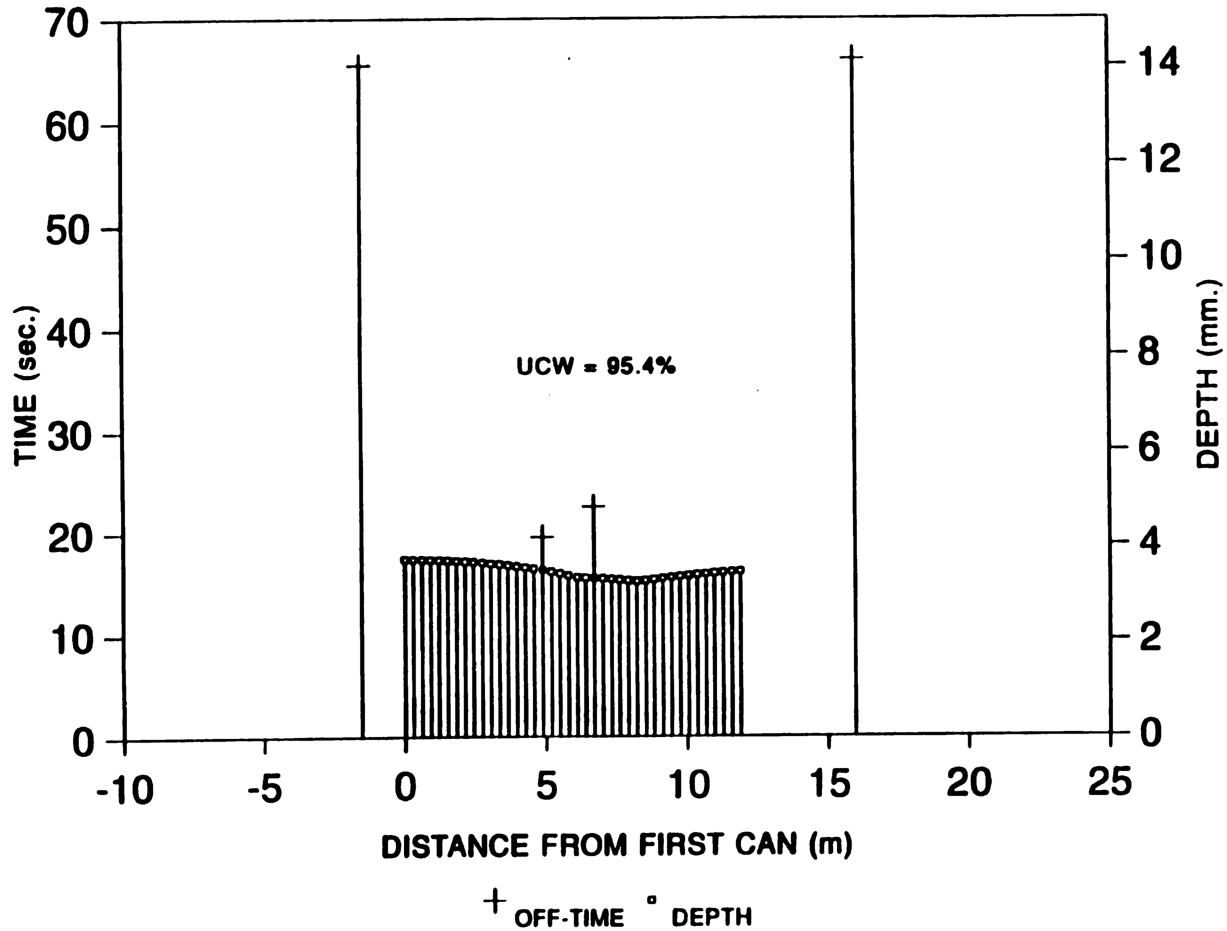

Figure 38. Span No.3 Position and Off-Times and Depth of Application on Transect located at 292.7 m from the pivot-point for Triangular Pattern Sprinklers (WR = 9.8 m, guide tower timer = 100%) and Alignment Angle equal to 1.0°.

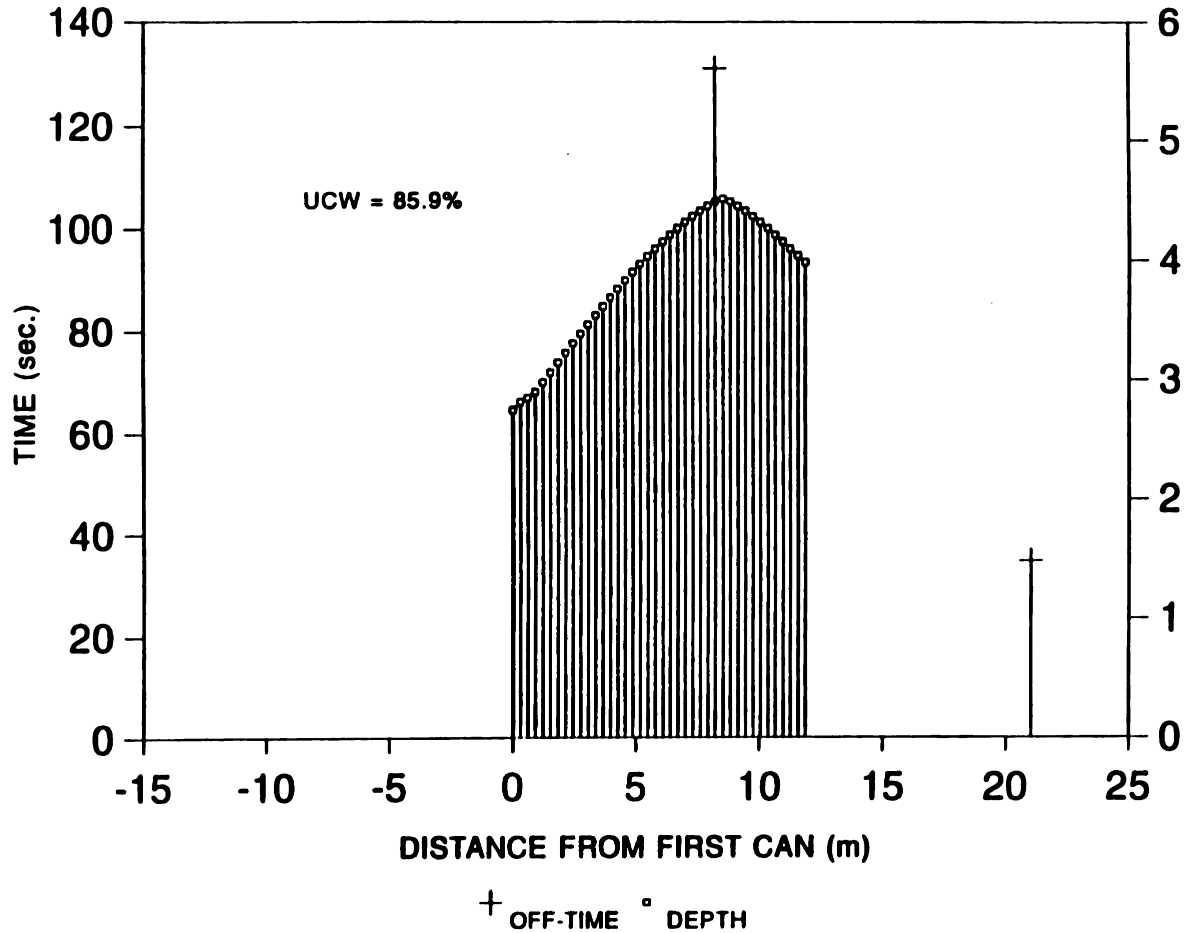

Figure 39. Span No.3 Positions and Off-Times, and Depth of Application on Transect located at 292.2 m from the pivot-point, for Triangular Pattern Sprinklers (WR = 9.8 m, guide tower timer = 100%) and Alignment Angle equal to 2.0°.

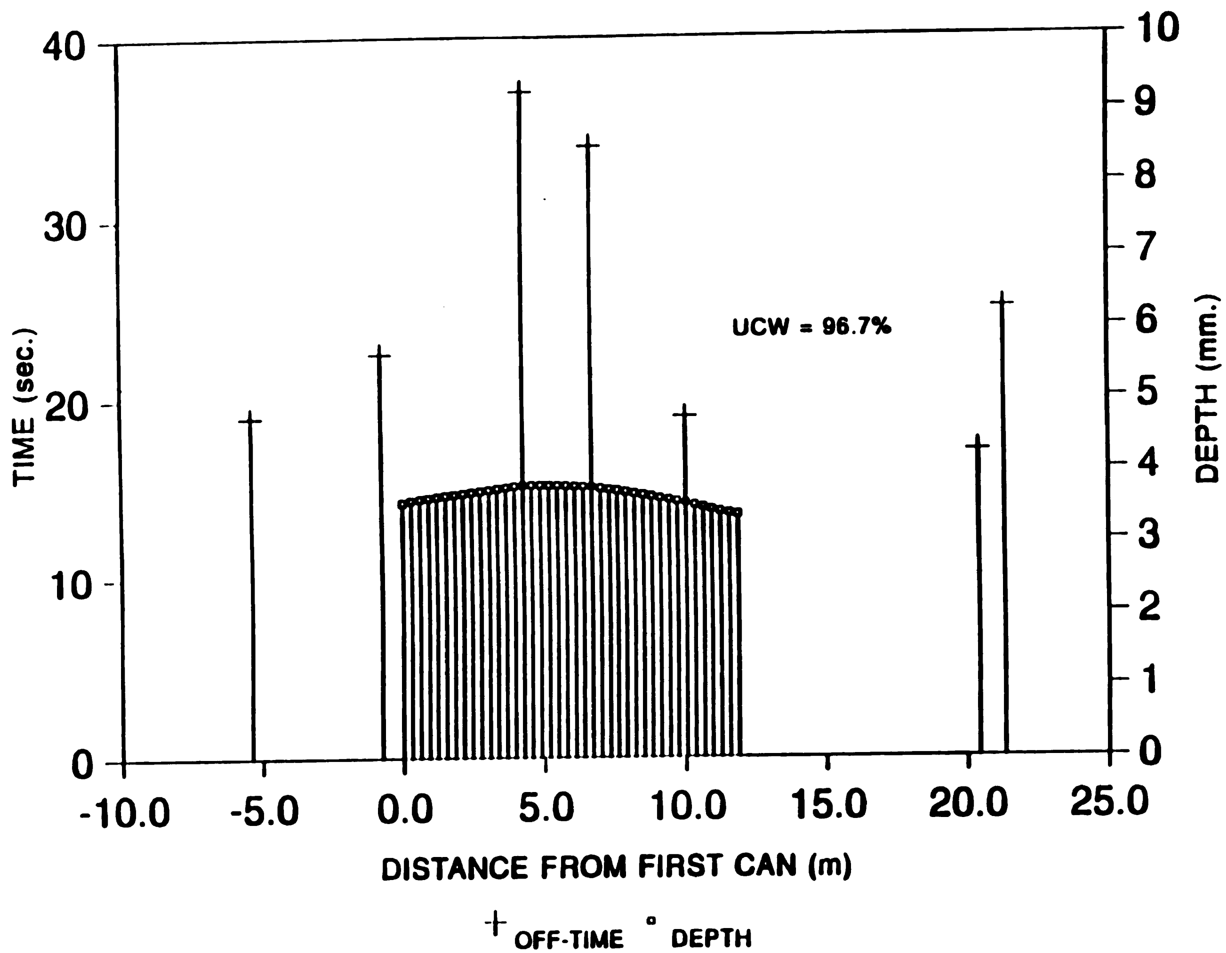

Figure 40. Span No.5 Positions and OFF-Times, and Depth of Application on Transect located at 170.8 m, from the pivot-point for Triangular Pattern Sprinklers (WR = 9.4 m, guide tower timer = 100%) and Alignment Angle equal to 0.5°.

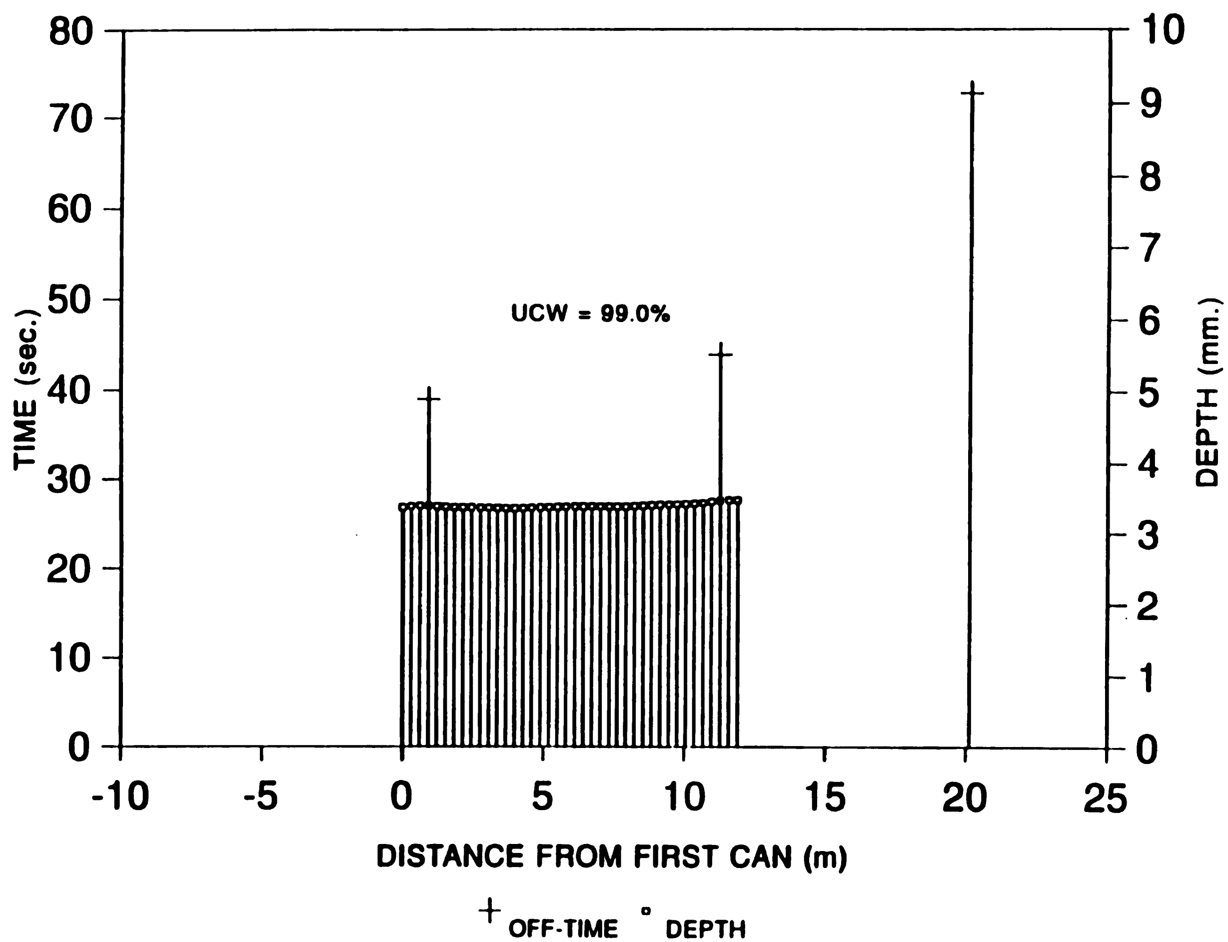

Figure 41. Tower No.5 Positions and Off-Times, and Depth of Application on Transect located at 170.8 m from the pivot-point for Triangular Pattern Sprinklers (WR = 9.4 m, guide tower timer = 100%) and Alignment Angle equal to 1.0°.

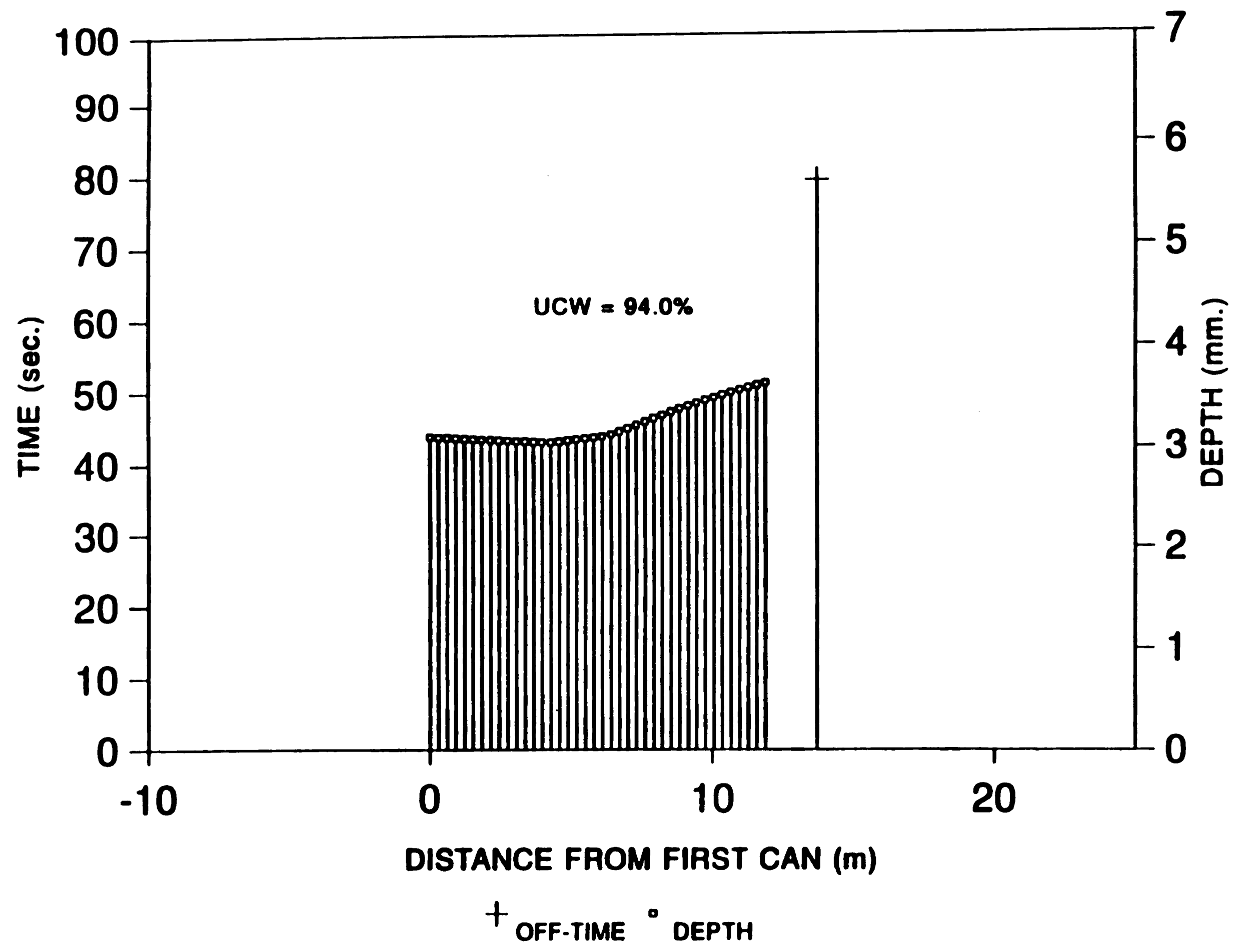

Figure 42. Tower No.5 Position and Off-Times, and Depth of Application on Transect located at 170.8 m from the pivot-point, for Triangular Pattern Sprinklers (WR = 9.4 m, guide tower timer = 100%) and Alignment Angle equal to 2.0°.

tower is stopped and inner tower is moving (Heermann and Sthal, 1986). Unless a sprinkler is mounted exactly at a tower position, the sprinkler is always moving except for the first combination above. It is also clear that the closer a sprinkler is to a tower, the more its movement and velocity will be influenced by the state and velocity of the tower. Figures 40 through 42 show the relative lateral position, off-times of closest tower at each of its stops and the depth of application distributions for some cases where the coefficient of uniformity was higher for an alignment angle equal to 1 degree than 0.5 degrees.

b. GUIDE-TOWER SETTING:

Decreasing the guide-tower setting from 100% to 50% had the effect of doubling the depth of application as expected. Theoretically, the time for the lateral to move over a set of catch cans at any given transect would also be doubled. Usually, the longer time to complete a pass, the higher the number of start-stop cycles, resulting in better overlapping of the sprinkler patterns and a more uniform distribution. No general trend was identified by examining the data presented. However, when examining the averages (see table No.20) for each sprinkler pattern and alignment angle at each transect some observations can be made. For any sprinkler pattern and alignment angle equal to 2 degrees, the average of the coefficient of uniformity at any distance from the pivot-point decreased when the guide-tower setting was changed from 100% to 50%. For alignment angles equal to 1 and 0.5 degrees, with one exception (see table 21), the averages of the coefficient of uniformity increased when the guide-tower setting was changed from 100% to 50%. This confirms the importance of the interaction involving the alignment angle, guide-tower setting and distance from the pivot-point.

c. SPRINKLER PATTERN:

1- GEOMETRICAL PATTERNS

Even though the overall UCW average for the elliptical sprinkler pattern (96.3%) was slightly higher than for the triangular (95.8%) and polygonal (95.9%) sprinkler patterns, at smaller alignment angles the averages were practically the same (98.3, 98.2, and 98.1%). The lowest and highest UCW averages were for the triangular sprinkler pattern with alignment angles equal to 2 and 0.5 degrees respectively. A possible reason for the similarity in the results is

TABLE 20. Uniformity Coefficient Averages for different Alignment angles and guide tower settings at different distances from the pivot-point.

SPRINKLER PATTERN	GUIDE TOWER %	A.ANGLE (DEGREES)	DISTANCE FROM PIVOT-POINT (m)		
			292.7	170.8	73.2
TRIANGULAR	100	2.0	85.8	94.2	97.7
		1.0	95.5	98.9	98.7
		0.5	98.5	96.9	98.8
	50	2.0	85.9	92.2	90.0
		1.0	98.0	97.6	98.8
		0.5	99.7	98.7	99.2
ELLIPTICAL	100	2.0	91.1	94.8	97.4
		1.0	96.5	98.5	98.5
		0.5	98.6	97.7	98.9
	50	2.0	90.0	90.6	91.5
		1.0	97.3	96.8	98.8
		0.5	99.2	98.8	99.0
POLYGONAL	100	2.0	89.4	94.2	97.9
		1.0	96.0	98.4	98.3
		0.5	98.5	97.6	98.8
	50	2.0	88.0	88.9	90.9
		1 .0	97.6	96.8	98.8
		0.5	98.6	98.8	98.8

probably due to the equalizing effect of the overlapping of different sprinklers. More will be said with respect to the geometrical sprinkler pattern when discussing the results of simulations of the LEPA center-pivot system.

2- ACTUAL SPRINKLER PATTERNS

The UCW results of simulations performed using the actual sprinkler patterns of R-30 NELSON SPRAY NOZZLES equipped with U4, D4, D6, and D6C rotary plates operating at 207 kPa (30 psi) were in most cases lower than those obtained with geometrical sprinkler patterns. They ranged between 76.3 and 99.2%. Different rotary plates showed different responses, i.e, the results of the D6 pattern were lower than the geometrical patterns only at 292.7 m from the pivot-point while the results of U4 and D4 patterns were lower at all distances from it. With few exceptions, results for D6C patterns were more like those obtained with geometrical patterns. The actual sprinkler pattern results can also be compared among themselves; however, when doing so, it is necessary to remember that the wetted radius varies from one pattern to another. Therefore, in this sprinkler pattern comparison an implicit comparison of the wetted radii is also being made. When comparing different sprinkler patterns it would be possible for one to be superior to another, based solely in its shape, but it might not produce a better distribution along the path of travel because of its smaller wetted radius. In tables 18 and 19 at distances of 73.2 m and 170.8 m from the pivot-point, the results of D6 patterns were higher than those of U4 and D4 patterns specially at smaller alignment angles (1 and 0.5 degrees). However, at 292.7 m from the pivot-point, with one exception (guide tower setting = 50%, alignment angle = 1.0 degree), the highest values were for the U4 pattern. Despite the higher uniformities obtained by simulation with U4 rotary plates as compared to the ones with D4 plates, under field conditions this may not be so. Spray nozzles equipped with U4 rotary plates are mounted on the lateral at a height approximately equal to 3.7 m (12 ft) while spray nozzles with D4 plates are mounted on drop tubes much closer to the ground making their pattern less susceptible to wind distortion.

d. WETTED RADIUS:

In general, the results found showed that larger wetted radii sprinkler patterns resulted in more overlapping (with itself in the direction of travel and with other sprinklers) and more uniform distribution along the path of travel. Exceptions were found where UCW decreased with an increase in the magnitude of the wetted radius when the alignment angle was equal to 1.0 degree and at distances equal to 170.8 and 73.2 m from the pivot-point.

e. DISTANCE FROM PIVOT-POINT:

The data did not show a trend in UCW values with distance from the pivot-point. However, higher values of UCW were found for the transect located at 189.0 m from the pivot-point than for the one at 170.8 m, specially with the guide tower timer set at 100% and alignment angles equal to 2 and 1 degrees. One possible explanation is that the transect located at 189.0 m from the pivot-point is positioned about the middle of the span between towers no.4 and no.5. The movement of the lateral going through this transect would be equally affected by the state and movement of both towers. The lateral would be moving, unless both towers were off. The transect at 170.8 m from the pivot-point is positioned only at 11.6 m from tower no.5, and the movement of the lateral at that point is largely influenced by the state of that tower . The lateral would be stopped or moving very slowly if the tower no.5 were off, depending on the state of tower no.6.

B. LEPA SYSTEMS

The simulation results using LEPA sprinkler packages are presented in table 21. The spacing between sprinklers was kept constant along the lateral and equal to 1.52 m (5 ft). The uniformity of water distribution was determined at three distances from the pivot-point, 196.7, 140.3 and 85.4 m (645.3, 460.3 and 280.3 ft), just underneath a sprinkler. Each transect contained 40 collector cans spaced at 0.305 m (1 ft) in the same way as the simulations for the traditional center-pivot system. The wetted radii of the sprinklers at the three different distances from the pivot-point were equal to 1.0 m (3.3 ft). Simulations were performed with the lateral moving continuously and intermittently. The alignment angles used when the lateral moved intermittently were, 2, 1, and 0.5 degrees. The simulations were only performed with the guide-tower set at 100%, which is the case when application of chemicals (chemigation) is done with irrigation water.

The results showed clearly that the difference between the continuous and intermittent moving systems becomes much

TABLE 21. Uniformity Coefficients (UCW)* and Average Depths (mm)** for Triangular, Elliptical and Polygonal Pattern LEPA sprinklers moving intermittently and continuously with guide tower timer set at 100%.

DISTANCE FROM PIVOT-POINT(m)	SPRINKLER PATTERN	ALIGNMENT ANGLE (DEGREES)			
		2.0	1.0	0.5	CONT.
196.7	TRIANGULAR	52.2 *	70.2	80.1	100.0
		4.76 **	4.77	4.76	4.45
	ELLIPTICAL	54.2	74.5	83.9	100.0
		3.74	3.76	3.76	3.73
	POLYGONAL	54.0	73.9	82.5	100.0
		3.40	3.43	3.43	3.51
140.3	TRIANGULAR	74.5	67.8	75.2	100.0
		4.06	4.63	5.19	4.90
	ELLIPTICAL	75.7	71.9	80.0	100.0
		3.19	3.63	4.06	3.86
	POLYGONAL	75.6	71.3	78.7	100.0
		2.91	3.31	3.70	3.51
85.4	TRIANGULAR	15.3	48.3	74.6	100.0
		4.58	4.60	4.77	4.90
	ELLIPTICAL	25.3	58.0	78.6	100.0
		3.60	3.62	3.74	3.84
	POLYGONAL	22.9	55.3	77.6	100.0
		3.27	3.34	3.43	3.51

more striking as the sprinkler wetted radius is reduced and no overlapping between different sprinklers occurs. As mentioned before, the lateral of the continuous moving system moves at a constant angular velocity, which is not the case with hydraulic moving systems. In such systems the velocity of any given tower varies according to its alignment with adjacent towers (proportional control).

The results for the continuous moving system showed a perfect distribution (UCW = 100%) along the path of travel for all transects, independent of the sprinkler pattern. In the same way as the traditional center-pivot systems the results of the LEPA system moving intermittently showed dependence on the distance from the pivot-point, magnitude of the alignment angle and on the shape of the sprinkler pattern.

The magnitude of the alignment angle was of greater importance for the LEPA system than for traditional systems. The range of the UCW values varied from 15.3% to 83.9%, with the smallest results obtained when the alignment angle were equal to 2 degrees. The UCW increased with a decrease in the alignment angle at distances of 196.7 and 85.4 m (645.6 and 280.3 ft) from the pivot-point. However, at 140.3 m (460.3 ft) from the pivot-point the coefficient of uniformity of the distributions generated with alignment angle equal to 2.0 degrees were higher than the ones with

1.0 degree, with no exception. This confirms the importance of the interactions existent between the distance from the pivot-point and the alignment angle.

With respect to the shape of the sprinkler pattern, the UCW of the distributions obtained with the elliptical pattern sprinkler were the highest. They were followed by the ones obtained with the polygonal pattern and then by the triangular pattern. Such findings should cause no big surprise since these patterns are more like the uniform pattern. The lower the pattern maximum application rate the less it will be its influence on the depth of application of collector cans closer to it, at each lateral stop.

V- CONCLUSION AND RECOMMENDATIONS

The objectives stated in the introductory chapter were fully addressed. An easy to use computer model for the simulation of center-pivot systems was developed. The computer model developed in this study differs from the model proposed by Heermann & Sthal (1986) for not having a modular structure. The sequences of "on-time" and "off-time" of the towers are not necessary prior running the model. This feature makes it simpler to run, and more importantly makes it suitable for optimization. Another advantage is that it also allows the user to run simulations using actual sprinkler profiles. The results of the simulations ("on-times" and "off-times") performed using the model showed a periodic behavior similar to the results obtained in the field. The model also showed good accuracy in predicting the depth of water application. However, good accuracy in predicting tower position was not found, mainly because of tower velocity variability due to tire slippage in field conditions.

The uniformity coefficient for the distributions obtained with the lateral moving continuously were higher than for the lateral moving intermittently. For both, traditional and LEPA systems the Wilcox and Swailes

Uniformity Coefficient (UCW), were for all practical purposes equal to 100%, when the lateral moved continuously. With the lateral moving intermittently, UCW values as low as 82.9% and 15.3% were found for traditional and LEPA system respectively. These results showed the necessity of considering the uniformity along the path of travel when determining a center-pivot system uniformity, specially for LEPA systems. Among the factors that influence the uniformity along the path of travel in an intermittently moving lateral systems, the magnitudes of the wetted radius and of the alignment angle are the most important. In general, smaller alignment angles and larger wetted radii reflect a higher uniformity. The sprinkler pattern shape proved to be of little importance when in combination with large wetted radii. However, in LEPA systems where the magnitude of the wetted radius is smaller than in traditional system the differences among the pattern shapes were more evident. Distributions generated with sprinkler pattern shapes approximating uniform distribution resulted in higher uniformity. The importance of the sprinkler pattern should not be overlooked when designing the system. In general, systems operating at reasonable alignment theoretically produced high distribution uniformities making them suitable to chemigation. Therefore, the choice of the sprinkler should be made based on their field performance.

RECOMMENDATIONS

Recommendations for further research include:

1) Field Tests of hydraulically driven center-pivot systems to determine how well the lateral movement of these systems approximates a truly continuous movement.

2) Use of the model developed to perform optimization of the system, that is, find the set of design and management parameters that will maximize the uniformity of water application.

3) Development of new procedures to determine an overall system uniformity coefficient considering both the uniformity of application along the lateral and along the path of travel, mainly in LEPA systems.

4) Field work to assess the importance of uniformity of application along the path of travel when performing chemigation.

APPENDIX A

Coefficient values of the high order polynomials used to represent the actual sprinkler patterns used in the simulations.

Each pattern of the spray nozzle R-30 used in the simulations were represented by a high order polynomial of the form:

$$Y = C_1 + C_2X + C_3X^2 + \ldots + C_nX^{(n-1)}$$

where: Y = the application rate (in/hr) at distance X from the sprinkler position ($X \leq$ wetted radius)

C_1 to C_n = coefficients which values are function of the sprinkler type and height, nozzle size and operating pressure.

COEFFICIENTS VALUES OF SPRINKLERS USED IN SIMULATIONS:

A- NELSON R-30 - U4 / NOZZLE #20 (5/32") 3RN - 30 PSI

FOR $0 \leq X \leq 21$

C_1 = 4.7638212E-02
C_2 = 5.1125734E-02
C_3 = -7.4459446E-03
C_4 = 3.5068430E-04
C_5 = -5.1924000E-06

FOR $21 < X \leq 35$

C_1 = 4.8786940E-02
C_2 = 4.2022900E-02
C_3 = -5.0463800E-03
C_4 = 1.4360890E-04
C_5 = 1.9898665E-06
C_6 = -8.6626120E-08

B- NELSON R-30 - U4 / NOZZLE #30 (15/64") 3RN - 30 PSI

FOR $0 \leq X < 20$

C_1 = 5.136180E-02
C_2 = -4.177242E-03
C_3 = 1.610852E-02

C_4 = -1.699431E-03
C_5 = -7.972334E-06
C_6 = 6.439168E-06
C_7 = -1.866352E-07

FOR $20 \leq X < 28$
C_1 = 2.514501
C_2 = -9.3118970E-02
C_3 = -1.1540330E-02
C_4 = 7.6955680E-04
C_5 = -1.210340E-05

FOR $28 \leq X \leq 35$
C_1 = 8.467767
C_2 = -1.013946
C_3 = 4.093127E-02
C_4 = -5.397946E-04

C- NELSON R-30 - U4 / NOZZLE #40 (5/16") 3RN - 30 PSI

FOR $0 \leq X < 4$
C_1 = 0.23
C_2 = -4.0E-03

FOR $4 \leq X \leq 9$
C_1 = 1.20E-03
C_2 = 5.32E-02

FOR $9 < X \leq 35$
C_1 = 1.498498
C_2 = -2.312978E-01
C_3 = 1.727711E-02
C_4 = -4.834677E-04
C_5 = 4.060102E-06

D- NELSON R-30 - D6 / NOZZLE #20 (5/32") 3RN - 30 PSI

FOR $0 \leq X < 4$
C_1 = 0.23
C_2 = -4.0E-03

FOR $4 \leq X \leq 9$
C_1 = 1.20E-03
C_2 = 5.32E-02

FOR $9 < X \leq 35$
C_1 = 1.498498
C_2 = -2.312978E-01

C_3 = 1.727711E-02
C_4 = -4.834677E-04
C_5 = 4.060102E-06

E- NELSON R-30 - D6 / NOZZLE #30 (15/64") 3RN - 30 PSI

FOR $0 \leq X \leq 2$

C_1 = 6.0E-01
C_2 = -1.08E-01

FOR $2 < X \leq 29$

C_1 = 3.698215E-01
C_2 = -2.576273E-03
C_3 = 1.659467E-03
C_4 = -1.919641E-04
C_5 = 8.080694E-05
C_6 = -1.168070E-06

F- NELSON R-30 - D6 / NOZZLE #40 (5/16") 3RN - 30 PSI

FOR $0 \leq X \leq 4$

C_1 = 2.35E-01
C_2 = 5.73E-02

FOR $4 < X \leq 13$

C_1 = 1.008953E-01
C_2 = 1.237290E-01
C_3 = -6.829177E-03
C_4 = 2.585948E-04

FOR $13 < X \leq 19$

C_1 = -28.43676
C_2 = 5.672495
C_3 = -3.554213E-01
C_4 = 7.221505E-03

FOR $19 < X \leq 29$

C_1 = -20.75859
C_2 = 2.5904332
C_3 = -1.014985E-01
C_4 = 1.269538E-03

G- NELSON R-30 - D6C / NOZZLE #18 (9/64") 3RN - 30 PSI

FOR $0 \le X < 2$

$C_1 = 3.00E-01$
$C_2 = 1.81E-01$

FOR $2 \le X \le 12$

$C_1 = 7.498E-01$
$C_2 = -4.390E-02$

FOR $12 < X \le 23$

$C_1 = 4.66276E-01$
$C_2 = -2.02730E-02$

H- NELSON R-30 - D6C / NOZZLE #32 (1/4") 3RN - 30 PSI

FOR $0 \le X \le 15$

$C_1 = 8.199914E-01$
$C_2 = 1.498167E-01$
$C_3 = -3.699838E-02$
$C_4 = 2.809597E-03$
$C_5 = -7.711797E-05$

FOR $15 < X \le 33$

$C_1 = 2.243668E-04$
$C_2 = 1.721536E-01$
$C_3 = -1.946300E-02$
$C_4 = 7.877457E-04$
$C_5 = -1.079675E-05$

I- NELSON R-30 - D4 / NOZZLE #20 (5/32") 3RN - 30 PSI

FOR $0 \le X \le 16$

$C_1 = 1.638221E-01$
$C_2 = -4.995140E-02$
$C_3 = 1.498470E-02$
$C_4 = -1.701006E-03$
$C_5 = 7.898698E-05$
$C_6 = -1.260777E-06$

FOR $16 < X \le 28$

$C_1 = -29.17034$
$C_2 = 5.167176$
$C_3 = -3.043008E-01$
$C_4 = 4.963067E-03$
$C_5 = 1.170825E-04$
$C_6 = -3.361771E-06$

J- NELSON R-30 - D4 / NOZZLE #30 (15/64") 3RN - 30 PSI

FOR $0 \le X \le 7$

$C_1 = 6.828395E-02$
$C_2 = 1.954686E-01$
$C_3 = -1.883152E-01$
$C_4 = 6.517420E-02$
$C_5 = -9.101001E-03$
$C_6 = 4.505710E-04$

FOR $7 < X \le 16$

$C_1 = 1.033247E-03$
$C_2 = 1.922724E-02$
$C_3 = 5.280385E-03$
$C_4 = -3.770389E-04$

FOR $16 < X \le 26$

$C_1 = -2.822429E-04$
$C_2 = 1.191840E-01$
$C_3 = -1.211325E-02$
$C_4 = 3.244428E-04$

FOR $26 < X \le 31$

$C_1 = -1.035154E-03$
$C_2 = 1.072518$
$C_3 = -6.707106E-02$
$C_4 = 1.046970E-03$

K- NELSON R-30 - D4 / NOZZLE #40 (5/16") 3RN - 30 PSI

FOR $0 \le X < 16$

$C_1 = 2.739339E-01$
$C_2 = -8.035340E-02$
$C_3 = 1.476606E-02$
$C_4 = -4.742017E-04$

FOR $16 \le X \le 26$

$C_1 = 2.128959E-03$
$C_2 = 1.2881754$
$C_3 = -1.608466E-01$
$C_4 = 6.713171E-03$
$C_5 = -9.210217E-05$

FOR $26 < X \leq 32$

$$C_1 = -188.0355$$
$$C_2 = 19.50391$$
$$C_3 = -6.668486E-01$$
$$C_4 = 7.530886E-03$$

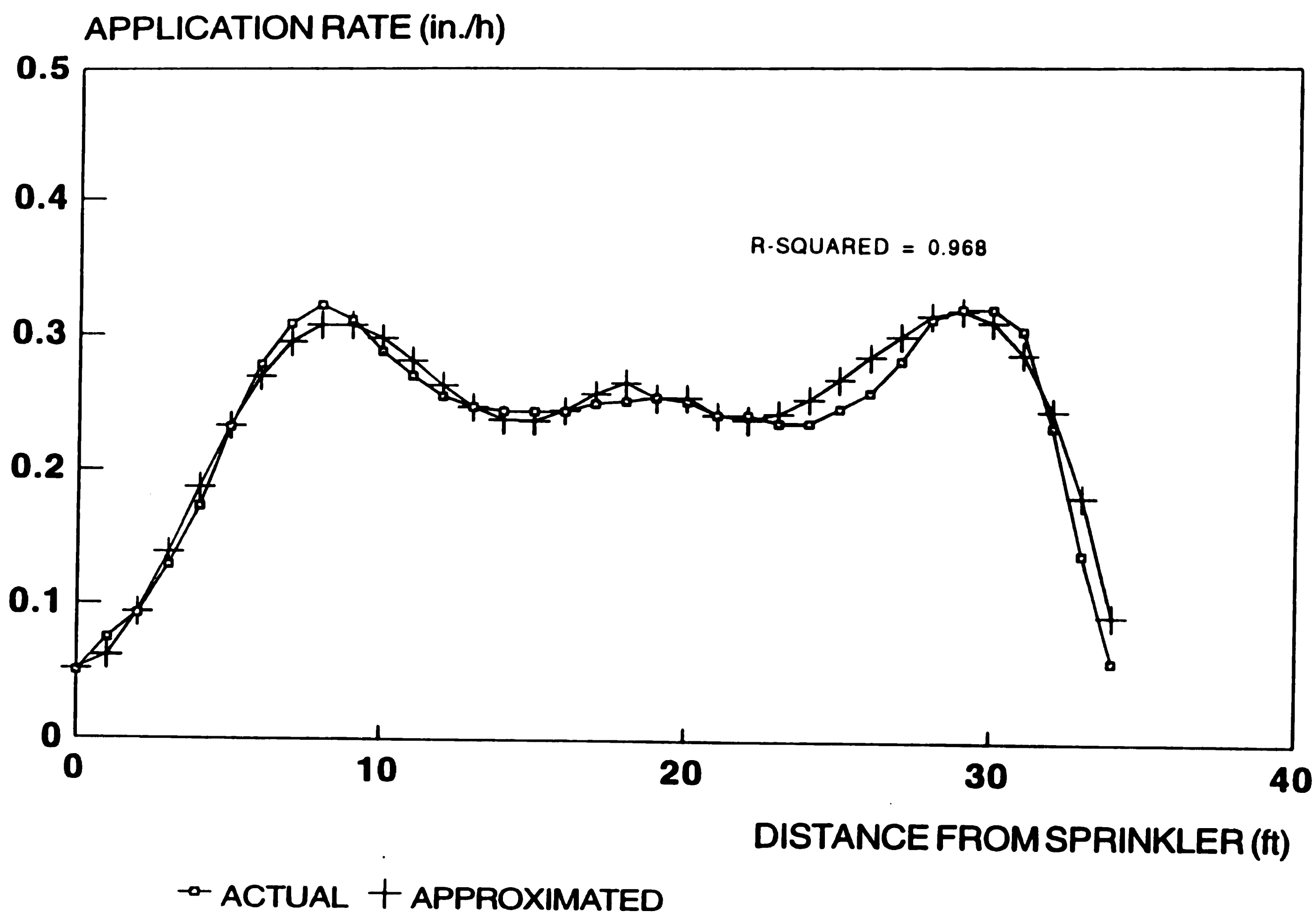

Figure A1. Nelson R-30 U4 No.30 3RN approximated pattern operating at 30 psi.

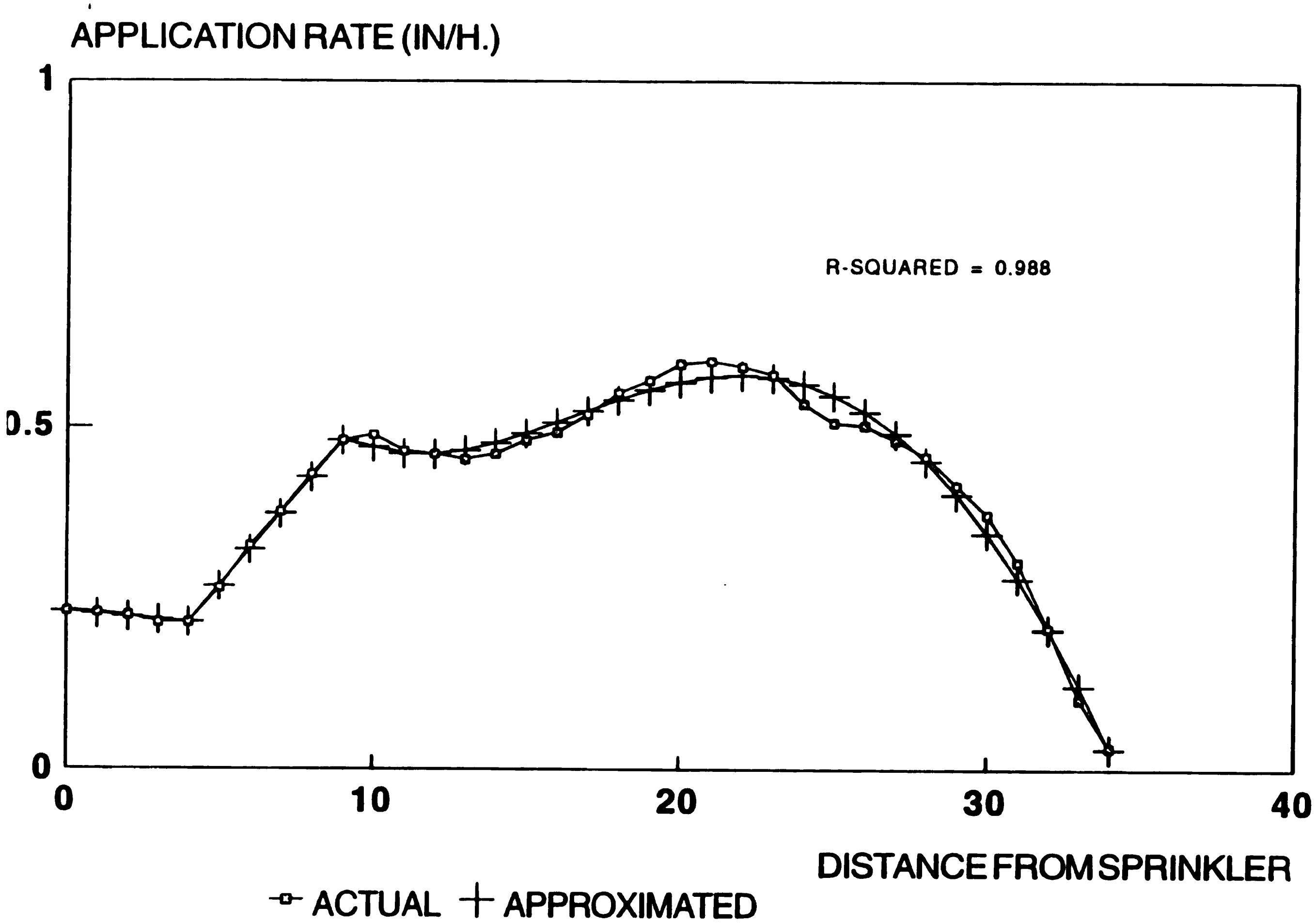

Figure A2. Nelson R-30 U4 No.40 3RN approximated pattern operating at 30 psi.

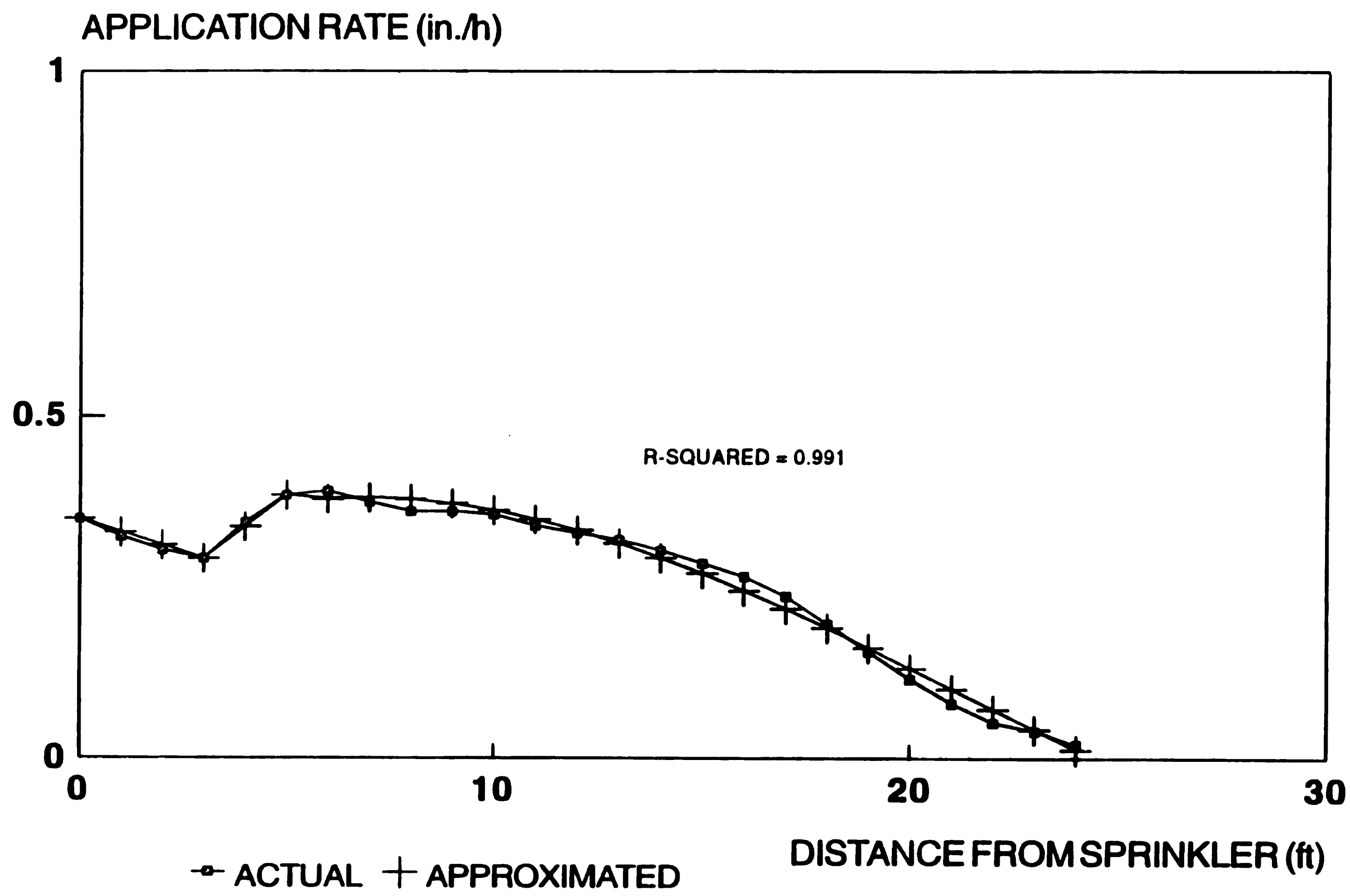

Figure A3. Nelson R-30 D6 No.20 3RN approximated pattern operating at 30 psi.

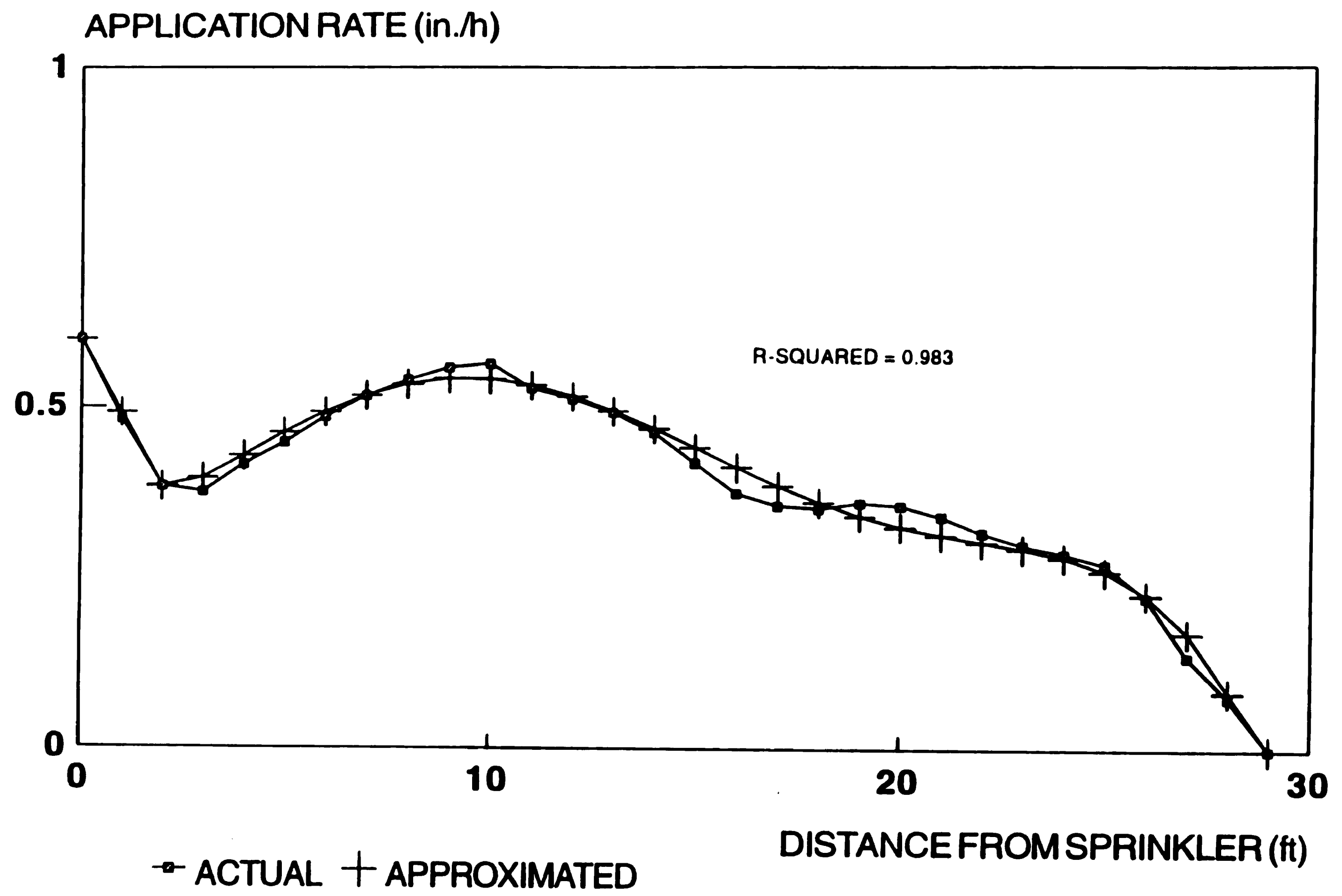

Figure A4. Nelson R-30 D6 No.30 3RN approximated pattern operating at 30 psi.

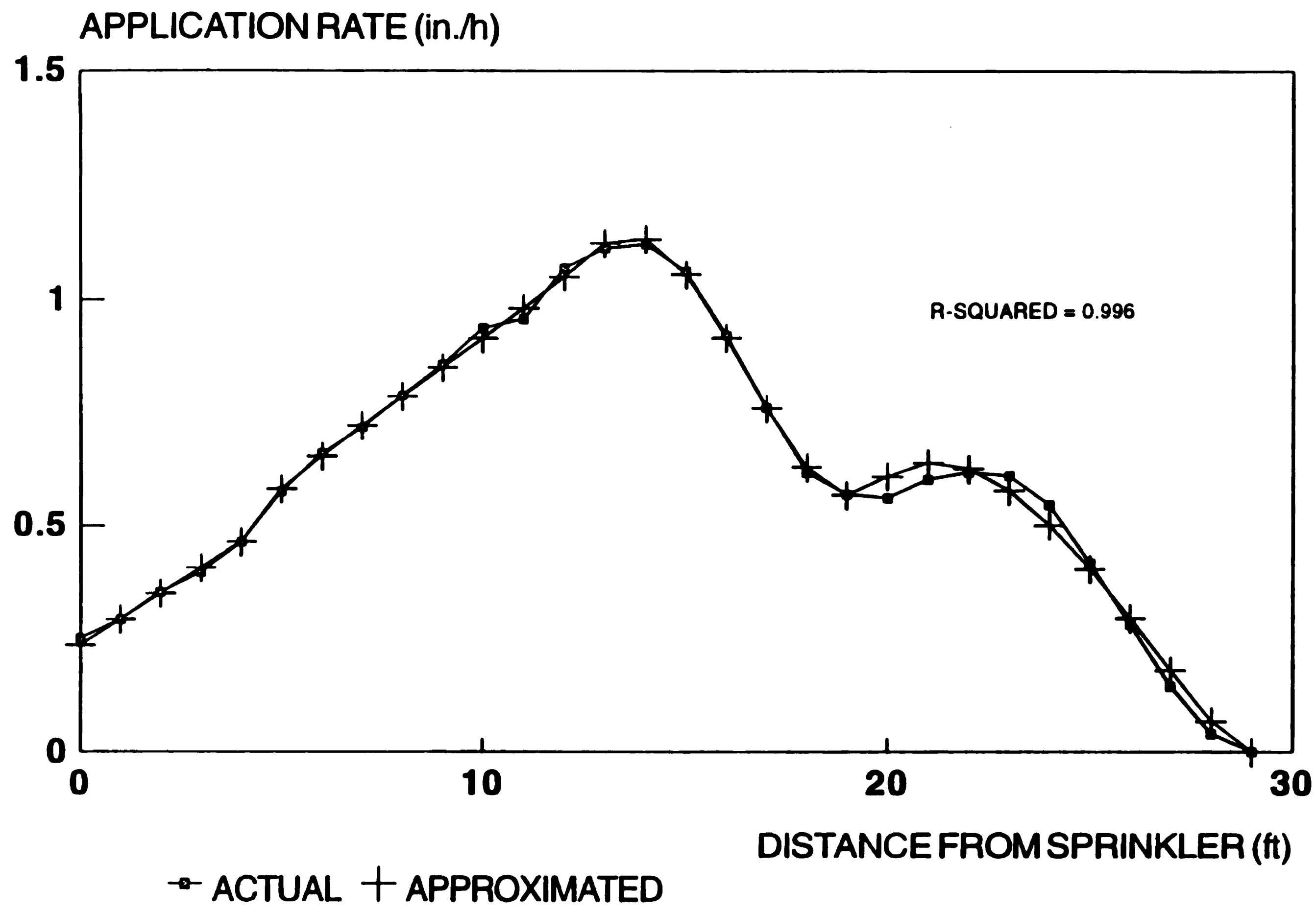

Figure A5. Nelson R-30 D6 No.40 3RN approximated pattern operating at 30 psi.

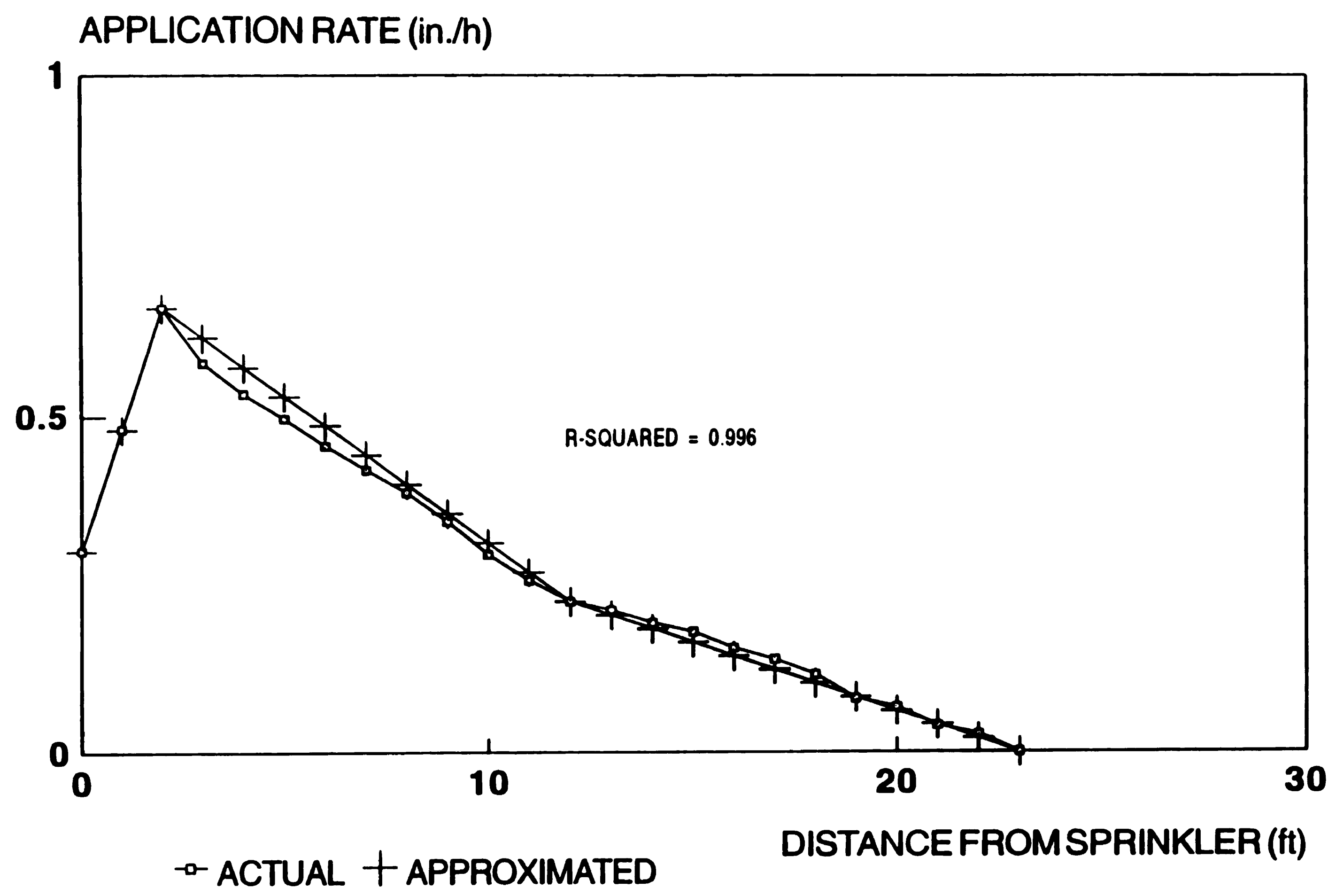

Figure A6. Nelson R-30 D6C No.18 3RN approximated pattern operating at 30 psi.

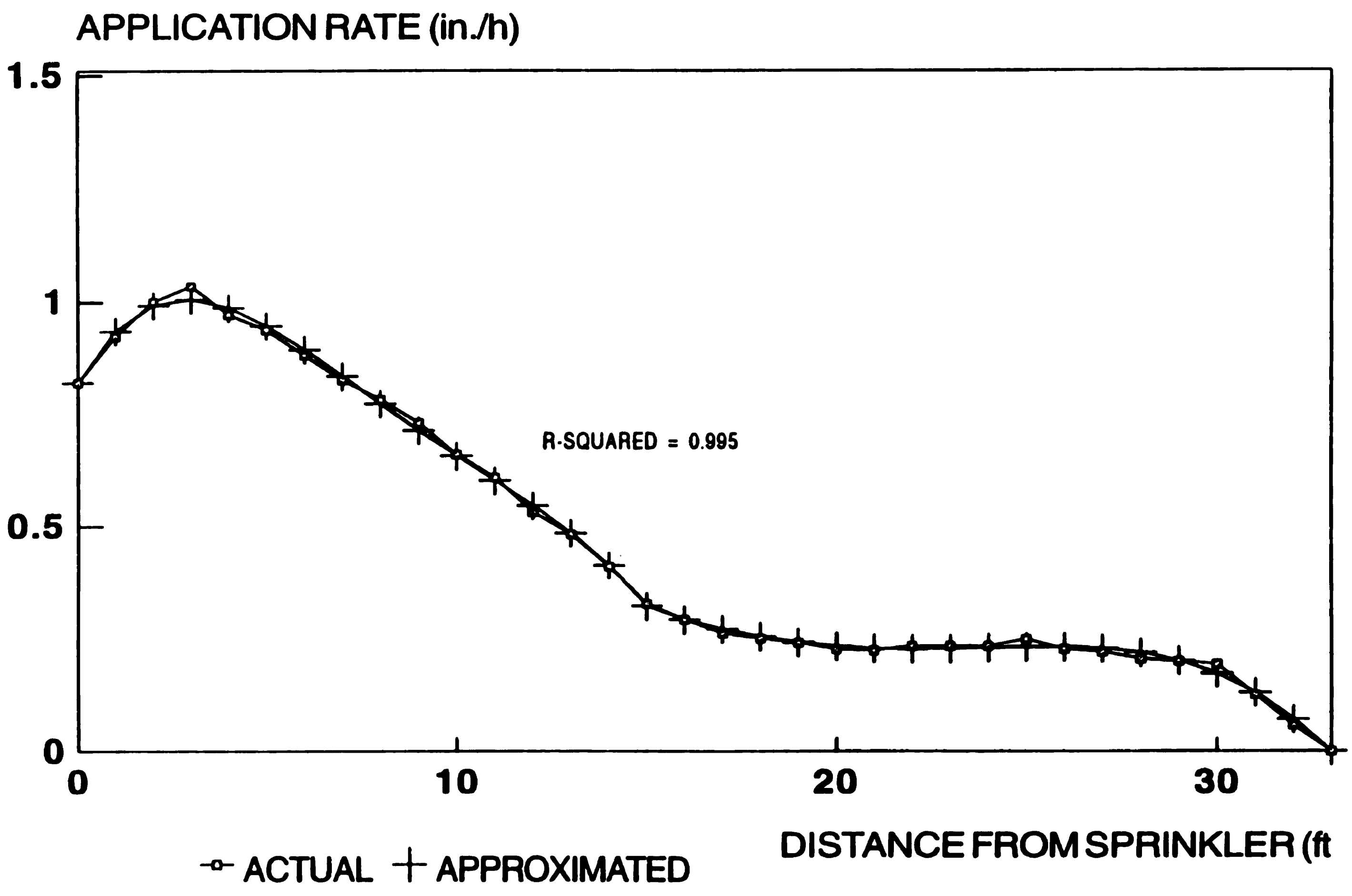

Figure A7. Nelson R-30 D6C No. 32 3RN approximated pattern operating at 30 psi.

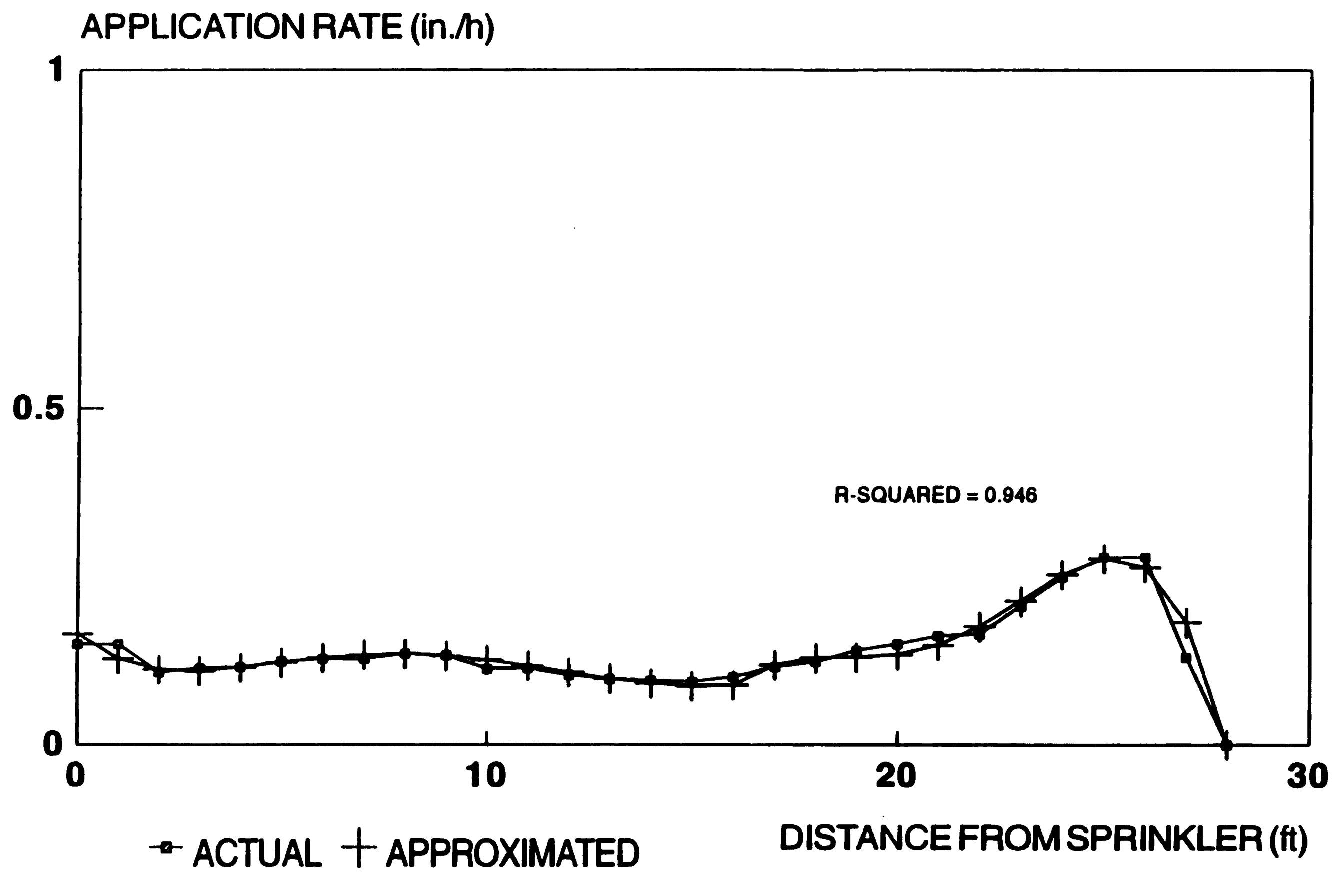

Figure A8. Nelson R-30 D4 No.20 3RN approximated pattern operating at 30 psi.

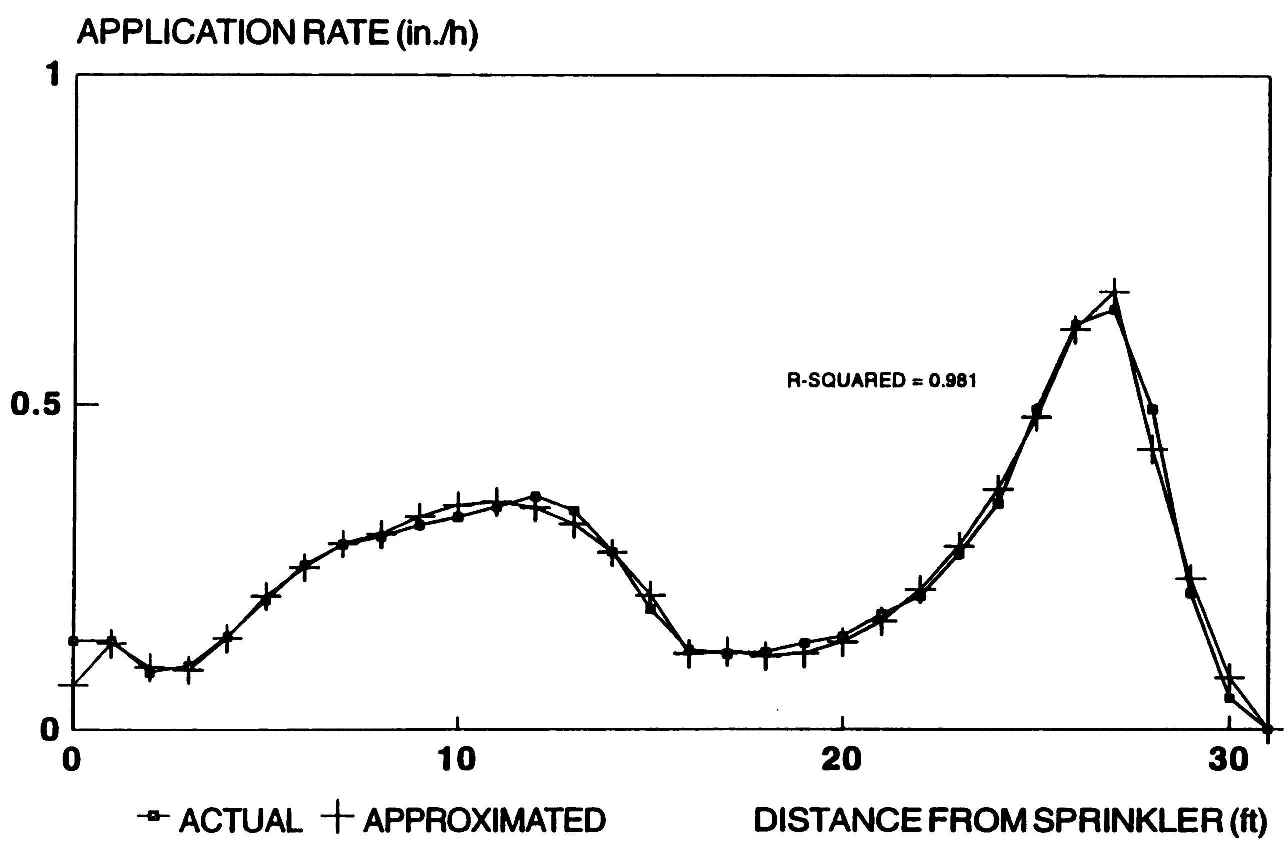

Figure A9. Nelson R-30 D4 No.30 3RN approximated pattern operating at 30 psi

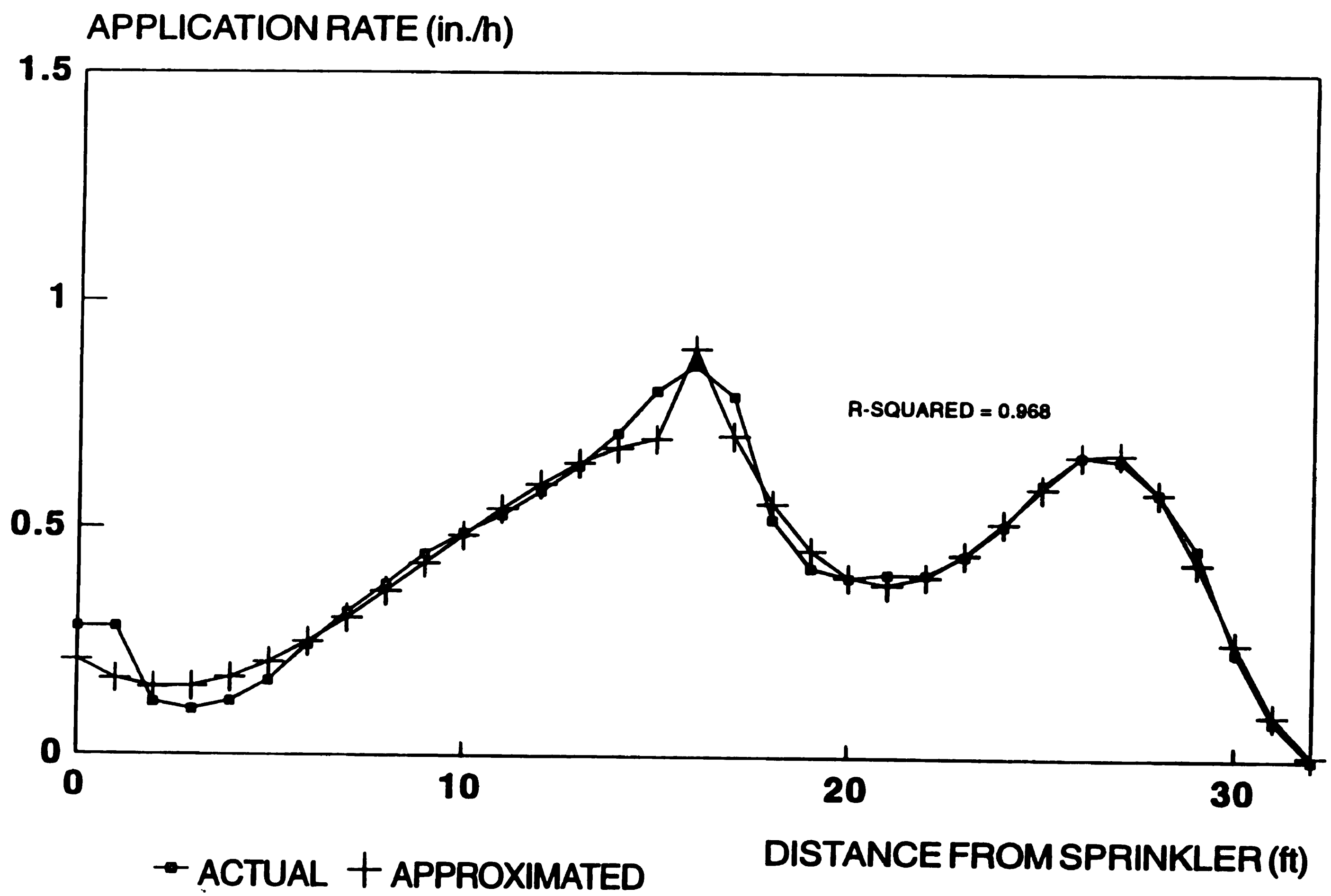

Figure A10. Nelson R-30 D4 No.40 3RN approximated pattern operating at 30 psi.

APPENDIX B

Center-Pivot Model Computer Code

MAIN PROGRAM

```
REM
REM  Program to simulate the intermittent movement of the towers of
REM  a Center pivot system, and compute the depth of application
REM  for System  Equipped with Geometrical Sprinkler Patterns or
REM  Nelson R-30 series operating at 30.0 psi.
REM
REM WRITTEN BY: MARIO FUSCO JR.
REM LAST REVIEW: JAN 12, 1993.
REM LAST USE:  JAN 13,1993.
REM
DEFDBL N
REM declare arrays dynamic so they can be bigger than 64k
REM
REM $DYNAMIC
REM
    DIM RADTW(20), NANGTW(20), NXTW(20), NYTW(20), TOWER(20),
        W(20), DIST(20)
    DIM DANGTW(20), ACLEN(20), SPACCAN(10), RADCAN(100),
        XCAN(20, 200)
    DIM YCAN(20, 200), YSPR(10, 100), XSPR(10, 100),
        WETRAD(20, 100)
    DIM FLOWRATE(20, 100), DEPTH(100, 100), TOWINI(40),
               TNUMSPR(200)
    DIM NINISPR(100), TSPRNUM(20, 100), LINANG(10), ALPHA(10)
    DIM MAXRAT(20, 100), C1H(20, 100), C2RAD(20, 100)
REM
REM OPEN OUTPUT FILES
REM
     OPEN "A:\STATE.DAT" FOR OUTPUT AS #1
     OPEN "A:\ANGALIGN.DAT" FOR OUTPUT AS #2
     OPEN "A:\CORDTOW.DAT" FOR OUTPUT AS #3
     OPEN "A:\COORDSPR.DAT" FOR OUTPUT AS #4
     OPEN "A:\CANPOS.DAT" FOR OUTPUT AS #5
     OPEN "A:\DEPTH.DAT" FOR OUTPUT AS #6
REM
      PRINT #1, "TIME", "TOWER NUMBER", "TOWER STATE"
      PRINT #1, "----", "------------", "-----------"
      PRINT #2, TAB(4); "T"; TAB(14); "ANGTW(1)"; TAB(24);
                "ANGTW(2)"; TAB(34); "ANGTW(3)"; TAB(44); "
                 BETA(1)"; TAB(54); "BETA(2)"
      PRINT #2, TAB(2);"-----"; TAB(14);"----"; TAB(24); " ---- ";
                TAB(34); " ---- "; TAB(44); " ---- "; TAB(54);
                "---- "
      PRINT #3, "TIME", "TOWER NUMBER", "X-COORD", "Y-COORD"
      PRINT #3, "----", "------------", "-------", "-------"
      PRINT #4, "TOWER", "  SPRINKLER", "   XSPR", "   YSPR"
      PRINT #4, "-----", "  ---------", "   ----", "   ----"
      PRINT #5, "NUMROW", "NUMCAN", "   XCAN", "   YCAN"
      PRINT #5, "------", "------", "-------", "-------"
      PRINT #6, "NUMROW", "NUMCAN", "  DEPTH(in)"
```

```
        PRINT #6, "------", "------", "-----------"
   REM
   REM  INPUTS
   REM
       CLS
       SCREEN 9
       COLOR 2, 1
   REM
       PRINT "ENTER NUMBER OF TOWERS"
       INPUT NTOWERS
       PRINT "ENTER THE LENGTH OF THE TOWERS"
       INPUT LENG
       PRINT "ENTER THE SPACING BETWEEN SPRINKLERS"
       INPUT SPRSPAC
       FOR I = 1 TO NTOWERS - 1
       PRINT "ENTER THE ANGLE OF ALIGMENT BETWEEN TOWER #", I,
             "AND TOWER #", I + 1
       INPUT LINANG(I)
       NEXT I
       PRINT "ENTER THE NUMBER OF ROWS ALONG THE PATH OF TRAVEL"
       INPUT NUMROW
       PRINT "ENTER THE NUMBER OF CANS"
       INPUT NUMCAN
       PRINT "ENTER THE ANGLE OF THE RADIAL LINE WHERE FIRST CAN
              WILL BE"
       INPUT CANANG
       PRINT "ENTER THE LINEAR SPACING OF CANS OF THE OUT MOST
              ROW"
       PRINT "THE COMPUTER WILL COMPUTE SPACING FOR OTHER ROWS"
       INPUT SPACCAN(1)
       PRINT "ENTER THE %  SETTING TIME GUIDING TOWER WILL BE
              ON,  PER CYCLE."
       INPUT SETTG
       PRINT "ENTER THE DURATION OF THE SIMULATION, IN HOURS"
       INPUT DUR
       PRINT "ENTER THE TIME STEP, DT, THE SIMULATION WILL BE
              RUN, IN  SECONDS"
       INPUT DT
 REM
 REM TRANSECT DISTANCES FROM THE PIVOT-POINT
 REM
       I = 2
       WHILE I <= NUMROW + 1
         PRINT "ENTER THE DISTANCE FROM ROW", I - 1, "TO THE
           PIVOT POINT"
         INPUT RADCAN(I - 1)
         IF I > 2 AND RADCAN(I - 1) >= RADCAN(I - 2) THEN I = 1:
         PRINT "ERROR, RESTART THE PROGRAM!"
         I = I + 1
       WEND
REM
REM
          CLS
          SCREEN 9
```

```
        COLOR 2, 1
        PRINT TAB(18); "MENU"
        PRINT
        PRINT
        PRINT TAB(10); "CHOOSE HOW MANY TOWERS YOU WANT THE
 SPRINKLERS TO BE INITIALIZED"
        PRINT : PRINT TAB(10); "1. INITIALIZE SPRINKLERS ON
 EVERY TOWER"
        PRINT : PRINT TAB(10); "2. INITIALIZE SPRINKLERS ON
 CHOSEN TOWERS"
        PRINT
        PRINT
        INPUT "ENTER THE NUMBER OF YOUR CHOICE", CHOICE
        IF CHOICE = 1 THEN
 REM
        FOR I = 1 TO NTOWERS
                TOWINI(I) = 1
        NEXT I
        END IF
 REM
        IF CHOICE = 2 THEN
        PRINT
        INPUT "ENTER THE NUMBER OF TOWERS TO BE INITIALIZED",
           NUTWINI
 REM
        FOR I = 1 TO NTOWERS
            TOWINI(I) = 0
        NEXT I
 REM
        FOR I = 1 TO NUTWINI
             INPUT "ENTER THE TOWER NUMBER", II
             TOWINI(II) = 1
        NEXT I
        END IF
        FOR I = 1 TO NTOWERS
           PRINT TOWINI(I)
        NEXT I
REM
REM  CALL SUBROUTINE TO INITIALIZE CAN POSITIONS.
REM
     CALL CANPOS(NUMROW, NUMCAN, SPACCAN(), RADCAN(), XCAN(),
                 YCAN(), CANANG)
REM
REM PRINT THE COORDINATES OF THE CAN POSITIONS
    FOR I = 1 TO NUMROW
        FOR J = 1 TO NUMCAN
         PRINT #5, I, J, XCAN(I, J), YCAN(I, J)
        NEXT J
    NEXT I
REM COMPUTE THE TOWERS DISTANCES FROM THE PIVOT-POINT.
REM
    FOR I = 0 TO NTOWERS - 1
        RADTW(I + 1) = (NTOWERS - I) * LENG
    NEXT I
```

```
REM
REM INITIALIZE THE TOWER POSITIONS (POLAR COORDINATES)
REM First the angles and then the "X's"
REM and finally the state (on/off) of each tower to be off.
REM
    FOR I = 1 TO NTOWERS
      NANGTW(I) = 3.1415927# / 2
      NXTW(I) = 0!
      NYTW(I) = (NTOWERS - (I - 1)) * LENG
      TOWER(I) = 2                             '  1 = ON; 2= OFF '
      ALENG(I) = LENG
    NEXT I
REM
REM CALL SUBROUTINE SPRPOS TO INITIALIZE SPRIKLER POSITIONS
REM  AT T = 0
REM
    CALL SPRPOS(LENG, SPRSPAC, NTOWERS, TNUMSPR(), NYTW(),
                NXTW(), YSPR(), XSPR(), TOWER(), T)
REM
    FOR I = 1 TO NTOWERS
     PRINT "TOWER=", I, "NUMBER OF SPRINKLERS=", TNUMSPR(I)
        FOR J = 1 TO TNUMSPR(I)
          PRINT #6, I, J, XSPR(I, J), YSPR(I, J)
        NEXT J
    NEXT I
REM
REM CHOICE OF SPRINKLER PROFILES.
REM
    CLS
    PRINT TAB(10); "CHOOSE THE BEST CHOICE FOR THE SPRINKLER
                PATTERN IN THE SYSTEM"
    PRINT
    PRINT TAB(10); "1. TRIANGULAR"
    PRINT TAB(10); "2. ELLIPTICAL"
    PRINT TAB(10); "3. POLIGONAL "
    PRINT TAB(10); "4. ACTUAL PROFILE"
    PRINT
    INPUT "ENTER THE NUMBER OF YOUR CHOICE", PATCHOICE
    PRINT
REM
          IF PATCHOICE = 1 THEN
             PATSPR$ = "TRIANGULAR"
          ELSEIF PATCHOICE = 2 THEN
             PATSPR$ = "ELLIPTICAL"
          ELSEIF PATCHOICE = 3 THEN
             PATSPR$ = "POLIGONAL"
          ELSEIF PATCHOICE = 4 THEN
             PATSPR$ = "ACTUAL"
          END IF
REM
REM ENTER WETTED RADIUS AND FLOWRATES.
REM
    FOR I = 1 TO NTOWERS
       SPRNUM = 1
REM
```

```
        IF TOWINI(I) = 1 THEN
           PRINT "ENTER THE NUMBER OF SPRINKLERS TO BE
INITIALIZED IN TOWER"
           PRINT "NUMBER", I, ".THESE ARE THE SPRINKLERS THAT
WILL CONTRIBUTE"
           PRINT "TO THE DEPTH IN THE ROW OF CANS"
           INPUT NINISPR(I)
           FOR K = 1 TO NINISPR(I)
                PRINT "ENTER THE SPRINKLER NUMBERS OF THE
NUMBER", K, "SPRINKLER"
                INPUT TSPRNUM(I, K)
           NEXT K
REM
           FOR II = 1 TO TNUMSPR(I)
             FOR JJ = 1 TO NINISPR(I)
               IF II = TSPRNUM(I, JJ) THEN
                 IF PATSPR$ = "TRIANGULAR" OR PATSPR$ ="ELLIPTICAL"
THEN
                     PRINT "ENTER THE WETTED RADIUS IN (ft)
AND THE FLOW RATE (GPM)"
                     PRINT "FOR THE SPRINKLER NUMBER",
TSPRNUM(I, JJ), "STARTING AT OUT MOST"
                     PRINT "END OF THE TOWER", I
                     INPUT WETRAD(I, II), FLOWRATE(I, II)
                 ELSEIF PATSPR$ = "POLIGONAL" THEN
                     PRINT "ENTER THE WETTED RADIUS IN FT,
THEN THE MAXIMUM APPLICATION RATE"
                     PRINT "AND APPLICATION RATE UNDERNEATH
THE SPRINKLER AND FINALY THE DISTANCE FROM THE POINT OF
MAXIMUM APPLICATION RATE TO THE SPRINKLER"
                INPUT WETRAD(I, II), MAXRAT(I, II), C1H(I,II)
, C2RAD(I, II)
               ELSEIF PATSPR$ = "ACTUAL" THEN
                   CLS
               PRINT TAB(10); "ENTER THE WETTED RADIUS, IN FT"
INPUT WETRAD(I, II)
                PRINT TAB(10); "SPRINKLER LIBRARY"
                PRINT
PRINT TAB(10); " 1. R30 - U4 /NOZZLE #20 (5/32)  3RN - 30 PSI"
PRINT TAB(10); " 2. R30 - U4 /NOZZLE #30 (15/64) 3RN - 30 PSI"
PRINT TAB(10); " 3. R30 - U4 /NOZZLE #40 (5/16)  3RN - 30 PSI"
PRINT TAB(10); " 4. R30 - D6 /NOZZLE #20 (5/32)  3RN - 30 PSI"
PRINT TAB(10); " 5. R30 - D6 /NOZZLE #30 (15/64) 3RN - 30 PSI"
PRINT TAB(10); " 6. R30 - D6 /NOZZLE #40 (5/32)  3RN - 30 PSI"
PRINT TAB(10); " 7. R30 - D6C /NOZZLE #18 (9/64) 3RN - 30 PSI"
PRINT TAB(10); " 8. R30 - D6C /NOZZLE #32 (1/4)  3RN - 30 PSI"
PRINT TAB(10); " 9. R30 - D4  /NOZZLE #20 (5/32) 3RN - 30 PSI"
PRINT TAB(10); "10. R30 - D4 /NOZZLE #30 (15/64) 3RN - 30 PSI"
PRINT TAB(10); "11. R30 - D4 /NOZZLE #40 (5/32)  3RN - 30 PSI"
PRINT
INPUT "ENTER THE NUMBER OF YOUR CHOICE", SPRTYPE(I, II)
END IF
REM
        END IF
```

```
        NEXT JJ
            SPRNUM = SPRNUM + 1
      NEXT II
         END IF
     NEXT I
REM
REM To complete initialization phase all other variables
REM should be initialized here
REM
         PI = 3.1415927#
        DUR = 30/3600     'duration of the simulation, in hours
         DT = 1           'time increment in seconds
         T = 0!           'initial time
       NIT = (DUR * 3600 / DT)       'number of iterations
      NIPP = 1                  'number of iterations per print
      NIOL = NIT / NIPP   'number of iterations on outside loop
REM
     FOR I = 1 TO NTOWERS - 1
     ALPHA(I) = LINANG(I) * 3.1415927# / 180  'alignment angle in
radians
     NEXT I
REM
REM also initialize  angular velocities
REM
     FOR J = 1 TO NTOWERS
     PRINT"ENTER THE ANGULAR VELOCITY OF TOWER",J,"IN RAD/SEC"
        INPUT W(J)
     NEXT J
REM
REM print initial values
REM
       PRINT #1, T, TOWER(1), TOWER(2), TOWER(3)
       PRINT #2, USING "###.###          "; NANGTW(1); NANGTW(2);
NANGTW(3); BETA(1); BETA(2)
       PRINT #3, USING "###.####     "; NXTW(1); NYTW(1); NXTW(2);
NYTW(2);  NXTW(3); NYTW(3)
REM
REM Print the time of begining of simulation
REM
     T1$ = TIME$
     PRINT "THE TIME AT THE BEGINING OF THE SIMULATION IS", T1$
REM
REM START EXECUTION PHASE
REM
FOR M = 1 TO NIOL
     FOR N = 1 TO NIPP
REM
REM initialize the distance moved and increment angle to zero
REM like a default value that will change if tower is "on"
REM
          FOR I = 1 TO NTOWERS
           DIST(I) = 0!
           DANGTW(I) = 0!
          NEXT I
```

```
        T = T + DT
        COUNT = COUNT + 1
REM
REM
REM Set tower1 ON depending on value of COUNT
REM
        IF COUNT <= (SETTG * 60! / (100 * DT)) THEN
           TOWER(1) = 1
        ELSE TOWER(1) = 2
        END IF
REM
REM Print the time tower #1 changes state, also the tower
REM coordinates. First when tower #1 becomes on, and then when  it
REM becomes off.
REM
        TWN1 = 1
        IF COUNT = CINT(SETTG * 60 / (100 * DT)) + 1 THEN
             PRINT #1, T, TWN1, TOWER(1)
        END IF
REM
        IF TOWER(1) = 1 THEN
           DIST(1) = W(1) * NTOWERS * LENG * DT
           XIN = ((DIST(1) / 2) / (NTOWERS * LENG))
           DANGTW(1) = 2 * ASIN(XIN)
           NANGTW(1) = NANGTW(1) + DANGTW(1)
           NXTW(1) = NTOWERS * LENG * COS(NANGTW(1))
           NYTW(1) = NTOWERS * LENG * SIN(NANGTW(1))
        END IF
REM
REM Compute new coordinates if towers are "ON"
REM
        FOR I = 2 TO NTOWERS
         IF TOWER(I) = 1 THEN
            DIST(I) = W(I) * (NTOWERS - (I - 1)) * LENG * DT
            XIN = ((DIST(I) / 2)/((NTOWERS -(I - 1)) * LENG))
            DANGTW(I) = 2 * ASIN(XIN)
            NANGTW(I) = NANGTW(I) + DANGTW(I)
            NXTW(I) = (NTOWERS - (I - 1))*LENG * COS(NANGTW(I))
            NYTW(I) = (NTOWERS - (I - 1)) * LENG * SIN(NANGTW(I))
         ELSE
            NXTW(I) = (NTOWERS - (I - 1)) * LENG * COS(NANGTW(I))
            NYTW(I) = (NTOWERS - (I - 1)) * LENG * SIN(NANGTW(I))
         END IF
        NEXT I
REM Determine the angle between towers and compare with
REM alignment angle
REM
        FOR I = 1 TO NTOWERS - 1
REM
           S1MINOR = ABS(NXTW(I + 1) - NXTW(I + 2))
           S2MINOR = ABS(NYTW(I + 1) - NYTW(I + 2))
           TETA = ATN(S2MINOR / S1MINOR)
              IF NANGTW(I + 1) > PI/2 AND NANGTW(I + 1) < 3 * PI/2
```

```
                THEN
                   S1MINOR = -S1MINOR
                END IF
              NXDUM = 2 * S1MINOR + NXTW(I + 2)
                IF NANGTW(I + 1) > PI AND NANGTW(I + 1) < 2 *PI THEN
                   S2MINOR = -S2MINOR
                END IF
              NYDUM = NYTW(I + 2) + 2 * S2MINOR
          DISPT = SQR((NYTW(I) - NYDUM)^2 + ((NXTW(I) - NXDUM) ^ 2))
              SIDUM = SQR((LENG) ^ 2 - (DISPT / 2) ^ 2)
              BETA(I) = 2 * ATN((DISPT / 2) / SIDUM)
REM
                IF BETA(I) >= ALPHA(I) THEN
                 IF  (TOWER(I  +  1)  =  1)  AND  (NANGTW(I  +  1)  >
NANGTW(I)) THEN
                    TOWER(I + 1) = 2
                    PRINT #1, T, I + 1, TOWER(I + 1)
                    PRINT #3, USING "###.####         "; T; I + 1;
                              NXTW(I + 1); NYTW(I + 1)
                    PRINT #2, USING "###.####      "; T; NANGTW(1);
NANGTW(2); NANGTW(3); BETA(1); BETA(2)
                 ELSEIF  (TOWER(I + 1)  =  2)  AND  (NANGTW(I  +  1)  <
NANGTW(I))  THEN
                    TOWER(I + 1) = 1
                    PRINT #1, T, I + 1, TOWER(I + 1)
                    PRINT #3, USING "###.####         "; T; I + 1;
NXTW(I + 1); NYTW(I + 1)
                    PRINT #2, USING "###.####      "; T; NANGTW(1);
NANGTW(2); NANGTW(3); BETA(1); BETA(2)
                 ELSE
                 END IF
                END IF
         NEXT I
REM
REM
REM Reset COUNT after one minute
REM
         IF COUNT >= (60! / DT) THEN COUNT = 0!
REM
REM CALL SUBROUTINE SPRPOS TO DETERMINE THE COORDINATES OF THE
SPRINKLERS
REM ALONG THE TOWERS' SPANS.
REM
    CALL SPRPOS(LENG, SPRSPAC, NTOWERS, TNUMSPR(), NYTW(), NXTW(),
YSPR(),XSPR(), TOWER(), T)
REM
REM Print the coordinates of the sprinkler positions
     FOR I = 1 TO NTOWERS
         FOR J = 1 TO TNUMSPR(I)
          PRINT #4, I, J, XSPR(I, J), YSPR(I, J)
         NEXT J
     NEXT I
REM
REM CALL SUBROUTINE TO COMPUTE THE TOTAL DEPTH APPLIED IN EACH CAN.
```

```
REM
    IF PATSPR$ = "TRIANGULAR" OR PATSPR$ = "ELLIPTICAL" THEN
         CALL DEPTRIPAT(DT, NUMROW, NUMCAN, TNUMSPR(), NTOWERS,
              XCAN(), YCAN(), XSPR(), YSPR(), WETRAD(), FLOWRATE(),
              DEPTH(), TOWINI(), PATSPR$, NINISPR(), TSPRNUM())
REM
      ELSEIF PATSPR$ = "POLIGONAL" THEN
         CALL POLIPAT(DT, NUMROW, NUMCAN, TNUMSPR(), NTOWERS,
             XCAN(), YCAN(), XSPR(), YSPR(), WETRAD(), DEPTH(),
             TOWINI(), NINISPR(), TSPRNUM(), MAXRAT(), C1H(),
             C2RAD())
REM
      ELSEIF PATSPR$ = "ACTUAL" THEN
         CALL ACTPAT(DT, NUMROW, NUMCAN, TNUMSPR(), NTOWERS,
              XCAN(), YCAN(), XSPR(), YSPR(), WETRAD(), DEPTH(),
              TOWINI(), NINISPR(), TSPRNUM(), SPRTYPE())
    END IF
REM
    NEXT N
REM
NEXT M
REM
REM Print the time at the end of the simulation
    T2$ = TIME$
    PRINT "THE TIME AT THE END OF THE SIMULATIONS IS", T2$
REM
REM Print the total depth of water in each can
REM
    FOR I = 1 TO NUMROW
        FOR J = 1 TO NUMCAN
         PRINT #6, I, J, DEPTH(I, J)
        NEXT J
    NEXT I
REM
REM Sound alarm
        SOUND 100, 100
END
```

SUBROUTINE ACTPAT

```
REM $STATIC
      SUB ACTPAT (DT, NUMROW, NUMCAN, TNUMSPR(), NTOWERS, XCAN(),
          YCAN(), XSPR(), YSPR(), WETRAD(), DEPTH(), TOWINI(),
          NINISPR(), TSPRNUM(), SPRTYPE())
REM Subroutine to compute the depth of water in a catch can
REM from the contribution of different sprinklers.
REM
DIM DISTA(20, 100), HBAR(15, 100), H(15, 100)
REM
REM
    FOR I = 1 TO NUMROW
```

```
        FOR J = 1 TO NUMCAN
         FOR II = 1 TO NTOWERS
           IF TOWINI(II) = 1! THEN
             FOR JJ = 1 TO TNUMSPR(II)
              FOR KK = 1 TO NINISPR(II)
                IF JJ = TSPRNUM(II, KK) THEN
REM
                   DISTA(I, J) = SQR((XSPR(II, JJ) - XCAN(I,J)) ^ 2
+ (YSPR(II, JJ) - YCAN(I, J)) ^ 2)
REM
                   IF DISTA(I, J) <= WETRAD(II, JJ) THEN
                      IF SPRTYPE(II, JJ) = 1 THEN
                          DEPTH(I, J) = DEPTH(I, J) +
+(FUNC1(DISTA(), I, J)) * DT
                      ELSEIF SPRTYPE(II, JJ) = 2 THEN
                          DEPTH(I, J) = DEPTH(I, J) +
+ (FUNC2(DISTA(), I, J)) * DT
                      ELSEIF SPRTYPE(II, JJ) = 3 THEN
                          DEPTH(I, J) = DEPTH(I, J) +
+ (FUNC3(DISTA(), I, J)) * DT
                      ELSEIF SPRTYPE(II, JJ) = 4 THEN
                          DEPTH(I, J) = DEPTH(I, J) +
+ (FUNC4(DISTA(), I, J)) * DT
                      ELSEIF SPRTYPE(II, JJ) = 5 THEN
                          DEPTH(I, J) = DEPTH(I, J) +
+ (FUNC5(DISTA(), I, J)) * DT
                      ELSEIF SPRTYPE(II, JJ) = 6 THEN
                          DEPTH(I, J) = DEPTH(I, J) +
+ (FUNC6(DISTA(), I, J)) * DT
                      ELSEIF SPRTYPE(II, JJ) = 7 THEN
                          DEPTH(I, J) = DEPTH(I, J) +
+ (FUNC7(DISTA(), I, J)) * DT
                      ELSEIF SPRTYPE(II, JJ) = 8 THEN
                          DEPTH(I, J) = DEPTH(I, J) +
+ (FUNC8(DISTA(), I, J)) * DT
                      ELSEIF SPRTYPE(II, JJ) = 9 THEN
                          DEPTH(I, J) = DEPTH(I, J) +
+ (FUNC9(DISTA(), I, J)) * DT
                      ELSEIF SPRTYPE(II, JJ) = 10 THEN
                          DEPTH(I, J) = DEPTH(I, J) +
+ (FUNC10(DISTA(), I, J)) * DT
                      ELSEIF SPRTYPE(II, JJ) = 11 THEN
                          DEPTH(I, J) = DEPTH(I, J) +
+ (FUNC11(DISTA(), I, J)) * DT
REM
                    END IF
                  END IF
                END IF
              NEXT KK
             NEXT JJ
           END IF
         NEXT II
        NEXT J
      NEXT I
 END SUB
```

SUBROUTINE CAMPOS

```
DEFDBL N
SUB CANPOS (NUMROW, NUMCAN, SPACCAN(), RADCAN(), XCAN(), YCAN(),
         CANANG)
REM SUBROUTINE TO INITIALIZE THE POSITION OF THE CANS FOR A CENTER
PIVOT EVALUATION
REM  Compute the radial angle
REM
     COSA  =  (2  *  (RADCAN(1))  ^  2  -  SPACCAN(1)  ^  2)  /  (2  *
(RADCAN(1)) ^ 2)
     SINA = SQR(1 - COSA ^ 2)
     TANA = SINA / COSA
     A = ATN(TANA)
REM
REM Initialize can positions
REM
      FOR I = 1 TO NUMROW
        FOR J = 1 TO NUMCAN
            IF J = 1 THEN
                XCAN(I, J) = RADCAN(I) * COS(CANANG)
                YCAN(I, J) = RADCAN(I) * SIN(CANANG)
            ELSE
                XCAN(I, J) = RADCAN(I) * COS(CANANG + (J * A))
                YCAN(I, J) = RADCAN(I) * SIN(CANANG + (J * A))
            END IF
        NEXT J
      NEXT I
END SUB
```

SUBROUTINE DEPTRIPAT

```
SUB DEPTRIPAT (DT, NUMROW, NUMCAN, TNUMSPR(), NTOWERS, XCAN(),
               YCAN(), XSPR(), YSPR(), WETRAD(), FLOWRATE(),
               DEPTH(), TOWINI(), PATSPR$, NINISPR(), TSPRNUM())
REM Subroutine to compute the total depth of water in a catch can
REM after one pass from the contribution of different sprinklers.
DIM DISTA(20, 100), HBAR(15, 100), H(15, 100)
REM
    FOR I = 1 TO NUMROW
      FOR J = 1 TO NUMCAN
       FOR II = 1 TO NTOWERS
         IF TOWINI(II) = 1! THEN
           FOR JJ = 1 TO TNUMSPR(II)
             FOR KK = 1 TO NINISPR(II)
              IF JJ = TSPRNUM(II, KK) THEN
               IF FLOWRATE(II, JJ) = 0! OR WETRAD(II, JJ) = 0! THEN
                  HBAR(II, JJ) = 0
               ELSE
                  HBAR(II, JJ) = (.02674 * FLOWRATE(II, JJ)) /
(3.1459 * (WETRAD(II, JJ) ^ 2))
               END IF
```

```
REM
                  DISTA(I, J) = SQR((XSPR(II, JJ) - XCAN(I, J))^ 2
+ (YSPR(II, JJ) - YCAN(I, J)) ^ 2)
REM
                  IF DISTA(I, J) <= WETRAD(II, JJ) THEN
                     IF PATSPR$ = "TRIANGULAR" THEN
                      H(II, JJ) = 3 * HBAR(II, JJ)
                      DEPTH(I, J) = DEPTH(I, J) + H(II,JJ) * (1
- (DISTA(I, J) / WETRAD(II,JJ)))*DT
                     ELSEIF PATSPR$ = "ELLIPTICAL" THEN
                      H(II, JJ) = 1.5 * HBAR(II, JJ)
                      DEPTH(I, J) = DEPTH(I, J) + H(II, JJ) * SQR(1
-((DISTA(I, J) ^ 2)/(WETRAD(II,JJ)^2)))*DT
                     END IF
                    END IF
                   END IF
                 NEXT KK
             NEXT JJ
           END IF
         NEXT II
       NEXT J
     NEXT I
END SUB
```

SUBROUTINE POLIPAT

```
SUB POLIPAT (DT, NUMROW, NUMCAN, TNUMSPR(), NTOWERS, XCAN(),
            YCAN(), XSPR(), YSPR(), WETRAD(), DEPTH(), TOWINI(),
            NINISPR(), TSPRNUM(), MAXRAT(), C1H(), C2RAD())
REM Subroutine to compute the total depth of water in a catch can
REM after one pass from the contribution of different sprinklers.
DIM DISTA(20, 100), HBAR(15, 100), H(15, 100)
REM
REM
    FOR I = 1 TO NUMROW
      FOR J = 1 TO NUMCAN
        FOR II = 1 TO NTOWERS
          IF TOWINI(II) = 1! THEN
            FOR JJ = 1 TO TNUMSPR(II)
                FOR KK = 1 TO NINISPR(II)
                   IF JJ = TSPRNUM(II, KK) THEN
REM
                    DISTA(I, J) = SQR((XSPR(II, JJ) - XCAN(I, J))^2
+ (YSPR(II, JJ) - YCAN(I, J))^ 2)
REM
                    IF DISTA(I, J) <= WETRAD(II, JJ) THEN
                             IF DISTA(I, J) <= C2RAD(II, JJ) THEN
                        DEPTH(I, J) = DEPTH(I, J)+(((MAXRAT(II, JJ)
- C1H(II, JJ))/(C2RAD(II,JJ)))*DISTA(I, J)+ C1H(II, JJ)) * DT
REM
```

```
                      ELSEIF  C2RAD(II,  JJ)  <  DISTA(I,  J)  <=
WETRAD(II, JJ)   THEN
                        DEPTH(I, J) = DEPTH(I, J) + (MAXRAT(II, JJ)
*C2RAD(II, JJ) - DISTA(I, J))/(WETRAD(II, JJ) - C2RAD(II, JJ)))* DT
REM
                      END IF
                     END IF
                    END IF
                 NEXT KK
            NEXT JJ
          END IF
        NEXT II
      NEXT J
    NEXT I
END SUB
```

SUBROUTINE SPRPOS

```
SUB SPRPOS (LENG, SPRSPAC, NTOWERS, TNUMSPR(), NYTW(), NXTW(),
            YSPR(), XSPR(), TOWER(), T)
REM Subroutine to compute the rectangular coordinates of the
REM sprinkler positions along the towers keeping the same spacing
REM on the whole system.
REM
REM DATE : JANUARY 21,1993
REM BY : MARIO FUSCO JUNIOR
REM
DIM FSPRDIS(200)
REM
FOR I = 1 TO NTOWERS
    J = 1
    WHILE J <> 9999
      IF I = 1 THEN
         IF J = 1 THEN
            YSPR(I, J) = NYTW(I)
            XSPR(I, J) = NXTW(I)
            J = J + 1
         ELSE
            YSPR(I, J) = (LENG - (J - 1) * SPRSPAC) * (NYTW(I)
- NYTW(I + 1)) / LENG + NYTW(I + 1)
            XSPR(I, J) = (LENG - (J - 1) * SPRSPAC) * (NXTW(I)
- NXTW(I + 1)) / LENG + NXTW(I + 1)
            IF (LENG - (J - 1) * SPRSPAC) <= SPRSPAC THEN
                    J = 9999
            ELSE
                   J = J + 1
                   TNUMSPR(I) = J
            END IF
         END IF
REM
```

```
      ELSE
           FSPRDIS(I) = SPRSPAC - (LENG - ((TNUMSPR(I - 1) - 1) *
SPRSPAC + FSPRDIS(I - 1)))
           YSPR(I, J) = (LENG - (FSPRDIS(I) + (J - 1) * SPRSPAC))
*(NYTW(I) - NYTW(I + 1)) / LENG + NYTW(I + 1)
           XSPR(I, J) = (LENG - (FSPRDIS(I) + (J - 1) * SPRSPAC))
*(NXTW(I) - NXTW(I + 1)) / LENG + NXTW(I + 1)
           IF (LENG - ((J - 1) * SPRSPAC + FSPRDIS(I)) <= SPRSPAC)
THEN
                   J = 9999
           ELSE
                   J = J + 1: TNUMSPR(I) = J
           END IF
       END IF
    WEND
NEXT I
END SUB
```

FUNCTION ASIN (ARC SINE)

```
DEFSNG N
FUNCTION ASIN (XIN) STATIC
ASIN = XIN + XIN ^ 3 / 6 + 3 * (XIN ^ 5) / 40 + 15 * (XIN ^ 7) / 336
+ 105 * (XIN ^ 9) / 3456 + 945 * (XIN ^ 11) / 42240
END FUNCTION
```

FUNCTION FUNC1:

```
      FUNCTION FUNC1 (DISTA(), I, J) STATIC
REM   COMPUTE THE APPLICATION RATE IN INCHES PER HOUR
      IF DISTA(I, J) >= 0! AND DISTA(I, J) <= 21 THEN
          INOVHOUR = .047638212 + .0511257336# * DISTA(I, J)
- .0074459446 * (DISTA(I, J) ^2) + 3.506843E-04 * (DISTA(I, J) ^ 3)
- 5.1924E-06 * (DISTA(I, J) ^ 4)
      ELSEIF DISTA(I, J) > 21 AND DISTA(I, J) <= 35 THEN
          INOVHOUR = 4.878694E-02 + .0420229# * DISTA(I, J)
- 5.04638E-03 * (DISTA(I, J) ^ 2) + 1.436089E-04 *(DISTA(I, J) ^ 3)
+ 1.9898665E-06 *(DISTA(I, J) ^ 4) - 8.662612E-08 *(DISTA(I, J) ^5)
      END IF
REM   RETURN THE FUNCTION VALUE IN INCHES PER SEC
      VALUE1 = INOVHOUR / 3600
      IF VALUE1 <= 0! THEN
        FUNC1 = 0!
      ELSE
        FUNC1 = VALUE1
      END IF
END FUNCTION
```

FUNCTION FUNC2:

```
       FUNCTION FUNC2 (DISTA(), I, J) STATIC
REM    COMPUTE THE APPLICATION RATE IN INCHES PER HOUR
       IF DISTA(I, J) >= 0! AND DISTA(I, J) < 20 THEN
           INOVHOUR = .0513618 - 4.177242E-03 * DISTA(I, J)
+ 1.610852E-02 * (DISTA(I, J) ^ 2)- 1.699431E-03 * (DISTA(I, J)^3)
- 7.972334E-06 * (DISTA(I, J)^ 4)+ 6.439168E-06 * (DISTA(I, J) ^ 5)
- 1.866352E-07 * (DISTA(I, J) ^ 6)
       ELSEIF DISTA(I, J) >= 20 AND DISTA(I, J) < 28 THEN
           INOVHOUR = 2.514501 - 9.311897E-02 * DISTA(I, J)
- 1.154033E-02 * (DISTA(I, J) ^ 2)+ 7.695568E-04 *(DISTA(I, J) ^ 3)
- 1.21034E-05 * (DISTA(I, J) ^ 4)
       ELSEIF DISTA(I, J) >= 28 AND DISTA(I, J) <= 35 THEN
           INOVHOUR = 8.467767 - 1.013946 * DISTA(I, J)
+ 4.093127E-02 * (DISTA(I, J) ^ 2)- 5.397946E-04 *(DISTA(I, J) ^ 3)
       END IF
REM    RETURN THE FUNCTION VALUE IN INCHES PER SEC
       VALUE2 = INOVHOUR / 3600
       IF VALUE2 <= 0! THEN
         FUNC2 = 0!
       ELSE
         FUNC2 = VALUE2
       END IF
END FUNCTION
```

FUNCTION FUNC3

```
        FUNCTION FUNC3 (DISTA(), I, J) STATIC
REM    COMPUTE THE APPLICATION RATE IN INCHES PER HOUR
       IF DISTA(I, J) >= 0 AND DISTA(I, J) < 4 THEN
           INOVHOUR = .23 - .004 * DISTA(I, J)
       ELSEIF DISTA(I, J) >= 4 AND DISTA(I, J) <= 9 THEN
           INOVHOUR = .0012 + .0532 * DISTA(I, J)
       ELSEIF DISTA(I, J) > 9 AND DISTA(I, J) <= 35 THEN
           INOVHOUR = 1.498498 - .2312978 * DISTA(I, J)
+1.727711E-02 *(DISTA(I, J) ^ 2) - 4.834677E-04 * (DISTA(I, J) ^ 3)
+ 4.060102E-06 * (DISTA(I, J) ^ 4)
       END IF
REM    RETURN THE FUNCTION VALUE IN INCHES PER SEC
       VALUE3 = INOVHOUR / 3600
       IF VALUE3 <= 0! THEN
         FUNC3 = 0!
       ELSE
         FUNC3 = VALUE3
       END IF
END FUNCTION
```

FUNCTION FUNC4

```
 FUNCTION FUNC4 (DISTA(), I, J) STATIC
REM   COMPUTE THE APPLICATION RATE IN INCHES PER HOUR
      IF DISTA(I, J) >= 0! AND DISTA(I, J) < 3! THEN
          INOVHOUR = .35 - .01933 * DISTA(I, J)
      ELSEIF DISTA(I, J) >= 3! AND DISTA(I, J) <= 5! THEN
          INOVHOUR = .1525 + .0465 * DISTA(I, J)
      ELSEIF DISTA(I, J) > 5! AND DISTA(I, J) <= 25! THEN
          INOVHOUR = .2641389 + 3.626893E-02 * DISTA(I, J)
- .003135126 * (DISTA(I, J) ^ 2)+ 4.942799E-05 * (DISTA(I, J) ^ 3)
      END IF
REM   RETURN THE FUNCTION VALUE IN INCHES PER SEC
      VALUE4 = INOVHOUR / 3600
      IF VALUE4 < 0! THEN
        FUNC4 = 0!
      ELSE
        FUNC4 = VALUE4
      END IF
END FUNCTION
```

FUNCTION FUNC5

```
FUNCTION FUNC5 (DISTA(), I, J) STATIC
REM   COMPUTE THE APPLICATION RATE IN INCHES PER HOUR
      IF DISTA(I, J) >= 0! AND DISTA(I, J) <= 2! THEN
          INOVHOUR = .6 - .108 * DISTA(I, J)
      ELSEIF DISTA(I, J) > 2! AND DISTA(I, J) <= 29! THEN
          INOVHOUR = .3698215 - 2.576273E-02 * DISTA(I, J)
+ 1.659467E-02 * (DISTA(I, J) ^ 2)- 1.919641E-03 *(DISTA(I, J) ^ 3)
+ 8.080694E-05 * (DISTA(I, J) ^ 4)- 1.16807E-06 * (DISTA(I, J) ^ 5)
      END IF
REM   RETURN THE FUNCTION VALUE IN INCHES PER SEC
      VALUE5 = INOVHOUR / 3600
      IF VALUE5 < 0! THEN
        FUNC5 = 0!
      ELSE
        FUNC5 = VALUE5
      END IF
END FUNCTION
```

FUNCTION FUNC6

```
FUNCTION FUNC6 (DISTA(), I, J) STATIC
REM   COMPUTE THE APPLICATION RATE IN INCHES PER HOUR
```

```
      IF DISTA(I, J) >= 0! AND DISTA(I, J) <= 4! THEN
          INOVHOUR = .235 + .0573 * DISTA(I, J)
      ELSEIF DISTA(I, J) > 4! AND DISTA(I, J) <= 13! THEN
          INOVHOUR = .1008953 + .1237291 * DISTA(I, J)
- 6.829177E-03 *(DISTA(I, J) ^ 2)+ 2.585948E-04 * (DISTA(I, J) ^ 3)
      ELSEIF DISTA(I, J) > 13! AND DISTA(I, J) <= 19! THEN
          INOVHOUR = -28.43676 + 5.672495 * DISTA(I, J)
- .3554213 * (DISTA(I, J) ^ 2)+ 7.221505E-03 * (DISTA(I, J) ^ 3)
      ELSEIF DISTA(I, J) > 19! AND DISTA(I, J) <= 29! THEN
          INOVHOUR = -20.75859 + 2.5904332 * DISTA(I, J)
- .1014985 * (DISTA(I, J) ^ 2)+ 1.269538E-03 * (DISTA(I, J) ^ 3)
      END IF
REM   RETURN THE FUNCTION VALUE IN INCHES PER SEC
      VALUE6 = INOVHOUR / 3600
      IF VALUE6 < 0! THEN
        FUNC6 = 0!
      ELSE
        FUNC6 = VALUE6
      END IF
END FUNCTION
```

FUNCTION FUNC7

```
FUNCTION FUNC7 (DISTA(), I, J) STATIC
REM   COMPUTE THE APPLICATION RATE IN INCHES PER HOUR
      IF DISTA(I, J) >= 0! AND DISTA(I, J) < 2! THEN
          INOVHOUR = .3 + .181 * DISTA(I, J)
      ELSEIF DISTA(I, J) >= 2! AND DISTA(I, J) <= 12! THEN
          INOVHOUR = .7498 - .0439 * DISTA(I, J)
      ELSEIF DISTA(I, J) > 12! AND DISTA(I, J) <= 23! THEN
          INOVHOUR = .466276 - .020273 * DISTA(I, J)
      END IF
REM   RETURN THE FUNCTION VALUE IN INCHES PER SEC
      VALUE7 = INOVHOUR / 3600
      IF VALUE7 < 0! THEN
        FUNC7 = 0!
      ELSE
        FUNC7 = VALUE7
      END IF
END FUNCTION
```

FUNCTION FUNC8

```
FUNCTION FUNC8 (DISTA(), I, J) STATIC
REM   COMPUTE THE APPLICATION RATE IN INCHES PER HOUR
      IF DISTA(I, J) >= 0! AND DISTA(I, J) <= 15! THEN
```

```
          INOVHOUR = .8199914 + .1498167# * DISTA(I, J)
- 3.699838E-02 *(DISTA(I, J) ^ 2)+ 2.809597E-03 *(DISTA(I, J) ^ 3)
- 7.711797E-05 * (DISTA(I, J) ^ 4)
      ELSEIF DISTA(I, J) > 15! AND DISTA(I, J) <= 33! THEN
          INOVHOUR = 2.243668E-04 + .1721536# * DISTA(I, J)
- .019463 * (DISTA(I, J) ^ 2)+ 7.877457E-04 * (DISTA(I, J) ^ 3)
- 1.079675E-05 * (DISTA(I, J) ^ 4)
      END IF
REM   RETURN THE FUNCTION VALUE IN INCHES PER SEC
      VALUE8 = INOVHOUR / 3600
      IF VALUE8 < 0! THEN
        FUNC8 = 0!
      ELSE
        FUNC8 = VALUE8
      END IF
END FUNCTION
```

FUNCTION FUNC9

```
       FUNCTION FUNC9 (DISTA(), I, J)
REM   COMPUTE THE APPLICATION RATE IN INCHES PER HOUR
      IF DISTA(I, J) >= 0! AND DISTA(I, J) <= 16 THEN
          INOVHOUR = .1638221 - .0499514 * DISTA(I, J)
+ 1.498472E-02 *(DISTA(I, J) ^ 2)- 1.701006E-03 *(DISTA(I, J) ^ 3)
+ 7.898698E-05 *(DISTA(I, J) ^ 4) - 1.260777E-06 *(DISTA(I, J) ^ 5)
      ELSEIF DISTA(I, J) > 16 AND DISTA(I, J) <= 28 THEN
          INOVHOUR = -29.17034 + 5.167176 * DISTA(I, J)
- .3043008 * (DISTA(I, J) ^ 2)+ 4.963067E-03 * (DISTA(I, J) ^ 3)
+ 1.170825E-04 *(DISTA(I, J) ^ 4)- 3.361771E-06 *(DISTA(I, J) ^ 5)
      END IF
REM   RETURN THE FUNCTION VALUE IN INCHES PER SEC
      VALUE9 = INOVHOUR / 3600
      IF VALUE9 < 0! THEN
        FUNC9 = 0!
      ELSE
        FUNC9 = VALUE9
      END IF
END FUNCTION
```

FUNCTION FUNC10

```
      FUNCTION FUNC10 (DISTA(), I, J) STATIC
REM   COMPUTE THE APPLICATION RATE IN INCHES PER HOUR
      IF DISTA(I, J) >= 0! AND DISTA(I, J) <= 7 THEN
          INOVHOUR = 6.828395E-02 + .1954686 * DISTA(I, J)
- .1883152 * (DISTA(I, J)) ^ 2 + .0651742 * (DISTA(I, J)) ^ 3
- 9.101001E-03 * (DISTA(I, J) ^ 4)+ 4.50571E-04 *(DISTA(I, J) ^ 5)
```

```
      ELSEIF DISTA(I, J) > 7 AND DISTA(I, J) <= 16 THEN
          INOVHOUR = 1.033247E-03 + 1.922724E-02 * DISTA(I, J)
+ 5.280385E-03 *(DISTA(I, J)) ^ 2 - 3.770389E-04 *(DISTA(I, J))^ 3
      ELSEIF DISTA(I, J) > 16 AND DISTA(I, J) <= 26 THEN
          INOVHOUR = -2.822429E-04 + .1191841# * DISTA(I, J)
- 1.211325E-02 *(DISTA(I, J))^ 2 + 3.244428E-04 *(DISTA(I, J))^ 3
      ELSEIF DISTA(I, J) > 26 AND DISTA(I, J) <= 31 THEN
          INOVHOUR = -1.035154E-03 + 1.072518# * DISTA(I, J)
- 6.707106E-02 *(DISTA(I, J))^ 2 + 1.04697E-03 * (DISTA(I, J))^ 3
      END IF
REM   RETURN THE FUNCTION VALUE IN INCHES PER SEC
      VALUE10 = INOVHOUR / 3600
      IF VALUE10 < 0! THEN
        FUNC10 = 0!
      ELSE
        FUNC10 = VALUE10
      END IF
END FUNCTION
```

FUNCTION FUNC11

```
      FUNCTION FUNC11 (DISTA(), I, J) STATIC
REM   COMPUTE THE APPLICATION RATE IN INCHES PER HOUR
      IF DISTA(I, J) >= 0! AND DISTA(I, J) < 16 THEN
          INOVHOUR = .2739339 - .0803534 * DISTA(I, J)
+ 1.476606E-02 *((DISTA(I, J))^2)- 4.742017E-04 *((DISTA(I, J))^ 3)
      ELSEIF DISTA(I, J) >= 16 AND DISTA(I, J) <= 26 THEN
          INOVHOUR = 2.128959E-03 + 1.2881745# * DISTA(I, J)
- .1608466 * (DISTA(I, J) ^ 2)+ 6.713171E-03 * (DISTA(I, J) ^ 3)
- 9.210217E-05 * (DISTA(I, J) ^ 4)
      ELSEIF DISTA(I, J) > 26 AND DISTA(I, J) <= 32 THEN
          INOVHOUR = -188.0355 + 19.50391 * DISTA(I, J)
- .6668486 * (DISTA(I, J) ^ 2) + 7.530886E-03 * (DISTA(I, J) ^ 3)
      END IF
REM   RETURN THE FUNCTION VALUE IN INCHES PER SEC
      VALUE11 = INOVHOUR / 3600
      IF VALUE11 < 0! THEN
        FUNC11 = 0!
      ELSE
        FUNC11 = VALUE11
      END IF
END FUNCTION
```

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