EVALUATION OF WIND EFFECTS AS SPRINKLER PATTERN STABILITY AND SPACING CRITERIA

by

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The information and conclusions in this report do not necessarily reflect the position of USAID or the United States Government.

Lanny R. Ptacek

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ABSTRACT

Evaluation of Wind Effects as Sprinkler Pattern Stability and Spacing Criteria

by

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The purpose of this study was to analyze the wind effects of wind velocity, nozzle size, and pressure upon pattern profiles. To develop a graphical means of presenting various sprinkler spacings expressed as a percentage of the wetted diameter vs. coefficient of uniformity for the various sprinkler pattern shapes, pattern stability indices, spacing ratios, and relative wind directions tested. Single sprinkler can-catch data were analyzed using computer programs to determine the effect of the several factors upon CU and spacing.

The findings indicated that no one wind direction, pattern shape, or spacing consistantly produced the highest CU_c values. The total effect of all factors must be considered before optimum system design can be accomplished.

(100 pages)

INTRODUCTION

About 10 percent of the irrigated land in the United States is irrigated by sprinkling, and in many other countries sprinkler irrigation has been accepted as a sound agricultural practice. In Israel for example, about 90 percent of the irrigated land is irrigated by sprinklers. In many parts of the world, new sprinkler systems are installed in large areas annually.

Jacobson (1952) and Wilcox (1953) found sprinkler irrigation in many cases to provide a more uniform distribution of water in the soil than surface methods of irrigation. This is especially true on light soils with irregular topography.

A high level of uniformity of application from irrigation by sprinkling will generally lead to greater gross returns from plant production than is received from very non-uniform applications. However, the achievement of a high level of uniformity may be at the expense of high system costs. It is thus theoretically possible to optimize a sprinkler irrigation system design with respect to uniformity of application. That is, it is possible to achieve a design which compromises in some way between the advantages of high yield with high uniformity and low costs with low uniformity.

The dictionary defines "uniformity" as "the quality or state of being uniform, unvarying, or consistent." In irrigation it means unvarying amounts of irrigation water applied over the entire area irrigated. A uniform application would apply the same depth of water everywhere in the field. A system that is operating under conditions providing a very high uniformity can be operated so as to apply very close to the exact amount of water needed by the crop. If distribution is not even, then there are places where the application is greater than desired, other portions of the field where less than the desired application is applied, and an intermediate area where the application just about matches the desired amount.

The ultimate goal of sprinkler irrigation system design is to obtain a system with optimum nozzle capacity, sprinkler spacing, lateral spacing, lateral size and main pipe size such that the irrigation system, in addition to meeting the crop and soil requirements, is the economical one. The optimization of sprinkler system design involves the prediction and control of application uniformity so that for the particular crop grown, a maximum economic return can be realized.

One of the more important features of sprinkler irrigation compared with flood and furrow methods is that a greater degree of control of the distribution and quantity of water applied can be achieved with sprinkler irrigation. However, effective control presupposes good design. Good sprinkler system design requires the ability to predict the uniformity of distribution given the nozzle size, pressure, lateral spacing, sprinkler spacing, and prevailing wind conditions. The present work is designed to determine design information that can be used to predict the coefficient of uniformity as described by Christiansen (1942) for specified system conditions.

Objectives

The objectives of this study are (a) to categorize sprinkler pattern stability as a function of wind velocity, nozzle size, and pressure for several basic (nonwind) pattern profiles, and (b) to develop a graphical means of presenting coefficient of uniformity vs. sprinkler spacings expressed as a percentage of the wetted diameter for the various sprinkler profiles, pattern stability indices, and relative wind directions tested.

Assumptions

The method used in this study for evaluating the uniformity of application was that of superimposition the validity of which has been demonstrated by Branscheid and Hart (1968). Test data from the operation of a single sprinkler head was used to generate several desired sprinkler spacing patterns.

The following set of assumptions were set in conjunction with the operational characteristics of the sprinklers:

1. All sprinklers of identical design will have identical performance characteristics.
2. In computing the can-catch of the different spacing combinations used, it is assumed that the application rate will be below the water absorption capacity of the soil. Therefore, no runoff results.
3. Evaporation losses and evaporation effects on uniformity were recorded but are not taken into consideration.

Terminology

Some of the terms used in this study are defined as follows:

Lateral spacing on main (SM): The distance the lateral line is moved between subsequent lateral settings (distance between two lateral positions on the main line).

Pattern Shape: The plot of depth of water caught in catch-can containers vs. distance from sprinkler (Figure 5).

Pattern Stability Index (K): The shift in center of mass of a single sprinkler pattern divided by the no-wind wetted diameter all multiplied by 100.

Shift in Center of Mass: The lineal distance and direction from a reference line of the center of mass of a single sprinkler test data from sprinkler location.

Spacing Ratio (SR): The sprinkler spacing on the lateral divided by the lateral spacing on the main - SL/SM.

Sprinkler Irrigation: An irrigation method whereby water is applied as a spray over an area from overhead sprinkler heads.

Sprinkler Spacing on the Lateral (SL): The distance between sprinkler heads spaced along the lateral line.

Uniformity of Distribution: The evenness with which water is distributed over an area as the lateral is moved across the area.

Wind Direction (θ): The orientation of the sprinkler spacing with respect to the wind direction ie: wind direction is parallel to lateral line etc.

REVIEW OF LITERATURE

Early analysis of sprinklers was conducted by Staebner (1931) with a series of tests on both American and German sprinklers. He judged the sprinklers on their ability to distribute water so that the maximum depth was not more than twice the minimum, except near the edges of the areas covered. He did not, however, discuss overlap or the spacing of sprinklers for best performance. He states:

> No matter how successfully they may distribute water over a circular area, they leave much to be desired, because if circles just touch one another a considerable area is left unwatered, and if they overlap, a great amount of double coverage results.

He further states:

> More uniform distribution over a large area can be obtained with the overhead pipe system (nozzle lines) than with any other type of spray irrigation equipment now available.

Evaluation of Sprinkler Distribution

Christiansen (1942) conducted a series of extensive and detailed experiments on sprinkler irrigation between 1935 and 1940 at the University of California at Davis. He presented the results of the research in a detailed form in 1942. About 200 sprinkler tests were made on sprinklers of the types used on portable sprinkler systems to determine the uniformity of distribution for various spacings, and to determine the most desirable geometrical patterns and their relationship to spacing.

Christiansen introduced a numerical expression, which is called the uniformity coefficient, CU_c, for the purpose of comparing sprinkler patterns and determining the effect of various spacings on water distribution. The uniformity coefficient expressed as a percentage is defined by the equation:

$$CU_c = 100 \left(1 - \frac{\text{Sum } d}{m \times n}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where

d = absolute deviation of each observation from the mean

m = mean of observations

n = number of observations

A CU_c of 100 percent will represent an absolutely uniform application; a lower percentage will represent a less uniform application.

To determine the CU_c the depth of application must first be determined at uniformly spaced points over the net area covered by a sprinkler. Sufficient points must be used so that the depth at any particular point may be considered the mean for the unit area represented by that point. For actual sprinkler patterns Christiansen (1942) took the amount of water caught in each of the cans spaced 5 or 10 feet apart in parallel rows as an individual observation. This pattern was then overlapped on itself to correspond to any desired spacing, and the total amount of catch for each point from all the overlapping sprinklers within the net area covered by one sprinkler was determined and tabulated.

The mean depth of application was next determined, and the deviation from the mean at each point calculated. These deviations were then totaled and the CU_c determined using Equation 1. From each sprinkler test pattern, a different value of the uniformity coefficient was obtained for each spacing; and since the spacing may be different in the two directions, many calculations were required to analyze one sprinkler pattern completely and determine what spacing would give the most uniform results and how uniform the distribution would be.

Christiansen (1942) determined a short cut method to obtain the optimum spacings in analyzing all the sprinkler tests. This method is equivalent to spacing the sprinklers closely along the pipe line and then determining the CU_c's for different spacings between lines. (S_L is used to denote the spacing between sprinklers along the line, and S_M the spacing between the lines.)

When sprinklers are close together (S_L is 5 or 10 feet), a strip of ground will be wet so that there will be little variation in depths applied along the line of sprinklers. The profile of water distribution across the wetted strip can be determined by overlapping a sprinkler pattern upon itself corresponding to the designated sprinkler spacing (S_L). This is done by summing up the water caught in the cans in each of the parallel rows. The tabulated sums are then combined corresponding to various spacings (S_M) between lines and the CU_c is calculated. The CU_c's thus determined represent a measure of uniformity in only one direction, not a measure of the uniformity for the net area covered by sprinklers spaced normal distances along the line. Figure 1 shows curves determined by this analysis.

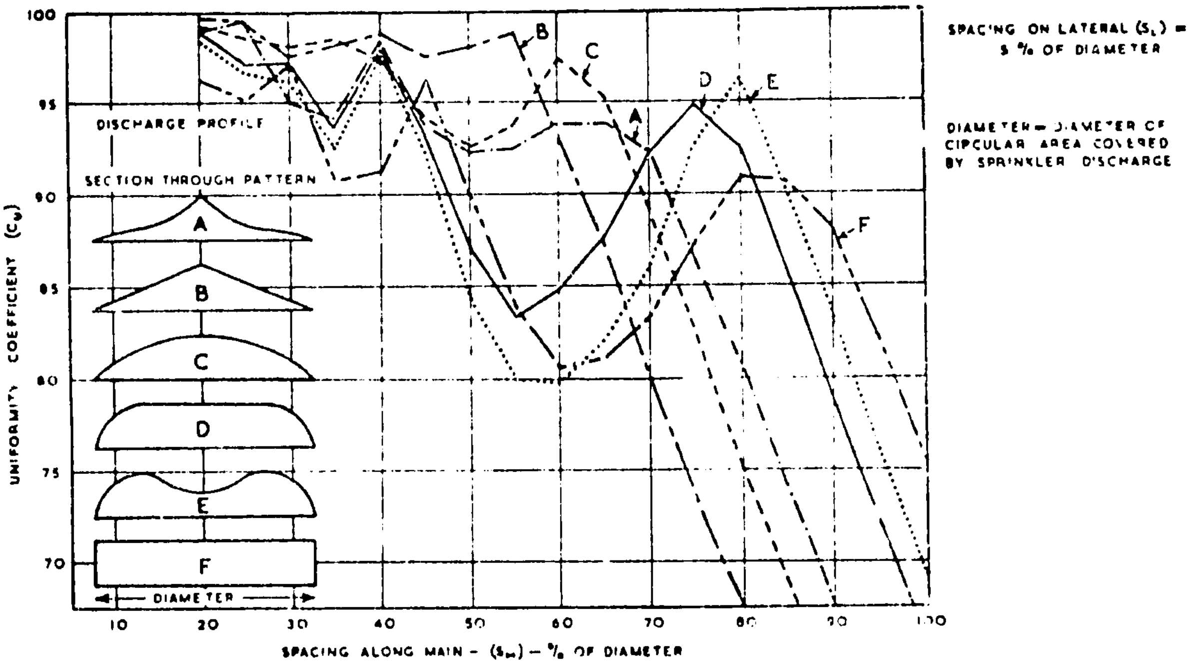


Figure 1. Christiansen's basic UC curves.

Christiansen (1942) defined six general cross - sections of patterns for water distribution. The patterns were designated by the letters shown in Figure 1. The patterns shown can be divided into two general groups: A, B, and C for which the application decreases gradually toward the edge of the area wetted, and D, E, and F for which the application is fairly uniform over most of the area covered. Optimum spacings for the first group are from about 0 to 60 percent of wetted diameter while for the second group they are from about 0 to 40 percent of wetted diameter and then again from 70 to 85 percent of wetted diameter.

A summarization of the results of the Christiansen (1942) study are:

1. The uniformity of distribution of water from sprinklers varies greatly, depending upon pressure, wind, rotation of sprinklers, spacing and many other factors.
2. A nearly uniform application is possible with proper sprinkler patterns and with proper spacing of sprinklers.
3. Approximately conical sprinkler patterns where a maximum application occurs near the sprinkler and decreases gradually to the edge of the area covered, produce a uniform application when sprinklers are not farther apart than 55 to 60 percent of the wetted diameter. See Figure 1.
4. For wider spacings a pattern in which the application is uniform some distance from the sprinkler, and then tapers off gradually is better. However, the maximum uniformity obtainable decreases with the spacing for all spacings greater than 50 percent of the wetted diameter.
5. With a portable system having sprinklers producing desirable patterns, good distribution can be obtained when the lateral is moved not farther than 50 to 70 percent of the diameter covered by a single sprinkler, and when the sprinkler spacing along the lateral is not more than 35 percent of

the diameter covered.

Wilcox and McDougald (1955) in looking for a shorter method for uniformity design than Christiansen's method developed the concepts of range coefficient and spacing coefficient. The range coefficient (R) is defined by the equation:

$$R = \frac{200\ (H-L)}{H+L} \quad \dots\dots\dots\dots\dots\dots (2)$$

where

H = highest value of grid pattern data

L = lowest value of grid pattern data

The spacing coefficient (S) is defined by the equation:

$$S = \frac{100\ (\text{square root } (SL \times SM))}{\text{wetted diameter}} \quad \dots\dots\dots (3)$$

where

SL = spacing on lateral line

SM = spacing on main line

By this formula, the same spacing coefficient was obtained irrespective of whether the spacing was square or rectangular, as long as the area represented was the same. This spacing coefficient did not prove to be a useful index for optimum spacing in that it does not differentiate between square or rectangular spacings nor does it allow for orientation of the spacing with respect to the wind direction.

Wilcox and McDougald (1955) used 8 theoretical curves to analyze their equations and determined that the best type of distribution curve for general application is one showing a steady decrease in rate of water application from the sprinkler outward. Square spacings, on the average, gave the more uniform distributions if the spacing was not greater than 60 percent of the wetted diameter. However, under windy conditions the best distribution is obtained by a rectangular spacing with sprinklers spaced more closely together perpendicular to the direction of the wind.

Measures of Sprinkler Uniformity

Christiansen (1942) first presented the concept of CU_c in sprinkler distribution for the purpose of comparing sprinkler patterns and determining the effect of various spacings on water distribution (See Equation 1). The CU_c may be rewritten as:

$$CU_c = 100\left(1 - \frac{\text{Sum}\,|X_i - \overline{X}|}{n\,\overline{X}}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where

Sum $|X_i - \overline{X}|$ = Sum of the absolute deviation of individual pattern observation from the average of the pattern observations.

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

n = number of observations

Hart (1961) demonstrated that if the distribution of the observations in an overlapped pattern is considered to be normally distributed about the mean, it can be shown that:

$$\frac{\text{Sum } |X_i - u|}{n} = \sigma (2/\pi)^{1/2} = 0.798\sigma$$

u = arithmetic mean of the universe

σ = standard deviation of the universe

Then

$$\frac{\text{Sum } |X_i - \bar{X}|}{n} = 0.798 \text{ S (Approximately)}$$

and

$$UC_H = 100 \left(1 - 0.798 \frac{S}{\bar{X}} \right) \quad \ldots\ldots\ldots\ldots \quad (5)$$

where

S = standard deviation of the sample

UC_H = HSPA uniformity coefficient

Wilcox and Swailes (1947) used a modified procedure for determining the uniformity coefficient:

$$U = 100 - \frac{100 \text{ SD}}{M} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where

SD = standard deviation of depths of water in catch cans

M = mean depth of water in catch cans

They suggest that a value of at least 70 percent for the modified uniformity coefficient would be desirable. Woodward and the United States Sprinkler Irrigation Association (1959) suggested a uniformity coefficient of 84 percent according to Christiansen's formula, as the criterion of adequate sprinkler performance.

Criddle et al. (1956) recommends the following parameter for the evaluation of sprinkler patterns:

$$PE_u = 100 \left(\frac{\text{Average 25\% minimum can catch}}{\text{Average of all can catch}}\right) \quad . \; . \; . \; . \; . \quad (7)$$

where

PE_u = USDA pattern efficiency

Another uniformity measure sometimes used is the New Coefficient by Benami and Hore (1964).

Beale and Howell (1966) related several measures of uniformity; Christiansen's CU_c, coefficient of variability, Wilcox-Swailes coefficient of uniformity, and USDA's pattern efficiency. By using graphs and equations to relate the coefficients, their results indicated that a visual examination of graphically presented data showed that regression lines relating pairs of measures of uniformity can be approximated quite well by lines the equations to which are derived as if precipitation were normally distributed.

Culver and Sinker (1966) from their research suggested that the CU_c is often maligned as an insensitive representation of the variation of water distribution. The coefficient of variation (ratio of standard deviation to the mean) is often suggested as a much more sensitive measure of the variability of the precipitation. The coefficient of variation is expressed in the same form as the CU_c , ie. as 100(1 - coefficient of variation). The relationship is then linear and the slope, indicating the sensitivity, is almost unity.

Senewongse and Reynolds (1970) analyzed the effects of skewness and kurtosis on the CU_c and concluded that for a sprinkler system which has a CU_c larger than 75 percent, the effects of skewness and kurtosis are insignificant. The distribution pattern can be considered as normal distribution and the water storage efficiency and availability factors can be estimated quite accurately from a knowledge of CU_c.

They also concluded that for sprinkler data having Christiansen's CU_c higher than 70 percent, the difference between using Christiansen's and HSPA's coefficient of uniformity is insignificant.

Factors Affecting Sprinkler Uniformity

Redditt (1965) grouped the conditions affecting sprinkler pattern uniformity into eight major factors. They are:

1. Wind Speed
2. Wind Direction
3. Spray loss
4. Spacing
5. Riser Height
6. Sprinkler Design
7. Pressure
8. Set Time

The items of greatest concern to system design are wind speed, spacing and pressure. He concluded from his tests that the uniformity of the patterns decreases as the wind speed increases. For some sprinklers and spacings the uniformity reaches a peak at about 3 to 5 miles per hours, and then gets slightly less uniform as the wind speed approaches 0. The effect of wind speed is small at very close spacings and becomes more pronounced as spacings are increased.

His analysis indicated that the loss of uniformity at high wind speeds is primarily the result of the quicker breakup of the jet. This results in a shorter cross-wind throw from the major nozzle of the sprinkler. The shortening on the upwind side is usually matched by a corresponding lengthening downwind of the sprinkler. A sprinkler system spaced for a high CU_c at low wind speeds would probably result in a considerably lower value of CU_c with high winds. Uniformity is also slightly affected by the variability in wind speed. The greater the gustiness, the more smoothing effect there would be and a resulting higher CU_c.

Redditt (1965) concluded that variability in wind direction would effect the uniformity similarily and that the actual wind direction may also have an effect on pattern stability. For square spacings it is negligible. For areas with relatively constant trade wind direction, rectangular spacings are frequently used with the long side of the rectangle parallel to the wind.

His tests indicated generally that the farther apart the sprinklers, the poorer the uniformity; the closer together, the better and that there is an optimum pressure for each set of conditions. A pressure too high or too low could reduce the uniformity. He concluded that the optimum pressure is different for each sprinkler, nozzle size and wind conditions, and must be developed by field testing.

Several researchers including Bilanski and Kidder (1958), Chu and Allred (1968), Seginer (1963), and Umback and Lemke (1966) have dealt with the problem of field performance from a theoretical basis. While a knowledge of the aerodynamic aspects of sprinkler jets may be helpful in the mechanical design of sprinklers and for a better understanding of the general interactions between wind speed, trajectory angle, pressure, and nozzle size, this information has not been successfully applied to predicting sprinkler uniformity under field conditions.

Wiersma (1950) analyzed wind direction by dividing the relative angle of the wind with respect to the lateral line into three directions. He concluded from his analysis that a wind angle between 15 degrees and 45 degrees will give a better pattern uniformity than the other wind directions. He found, however, little difference between a wind direction parallel and a wind direction perpendicular to the lateral line.

His wind velocity analysis showed that there is a definite breaking point between a 50 foot lateral move and a 60 foot lateral move using a 13/64 inch by 5/32 inch nozzle combination. Using spacings of 40 by 40 and 40 by 50 feet, and a nozzle size of 13/64 inch by 5/32 inch, Wiersma (1950) found the coefficient of uniformity at 56 psi nearly equal to that at 48 psi and coefficient of uniformity at 40 psi nearly equal to that at 28 psi. However, there is a definite breaking point of uniformity between the higher pressures and lower pressures and the higher pressures produced more uniform pattern distribution. His tests showed that under high wind conditions, larger nozzle sizes produced higher coefficients of uniformity.

Seginer (1963) analyzed several factors that effect sprinkler pattern distribution. Within actual sprinkling pressures, the wetted diameter increased with pressure, the intensity decreased, and the distribution uniformity improved. He conducted several tests to determine the effect of the oscillating arm on rotation. He found that neither the scattering by the jet arm or the angular acceleration of the body of the sprinkler have a significant effect on the distribution characteristics. There was no influence on the distribution by using the flow straightening device or the plastic nozzle, and the different sprinkler bodies performed similarly. He concluded that minor differences in the body of the sprinkler and nozzle construction do not result in major variations in performance as sometimes claimed.

Seginer (1969) tested the effects of wind speed and wind direction on sprinkler water distribution. Generally two trends occurred with increased wind speeds; an elongation of the depth contours in the direction of the wind and the reduction in the amount of water arriving at the surface. He discussed lateral orientation with average wind direction and lateral orientation when wind direction changes between two sets. His results indicated that on the average, the lateral should be perpendicular to the average wind direction. If, however, there was a definite direction change between two sets, then it would be best to orient the lateral parallel to the difference vector of the two wind directions. His analysis indicated that a longer set time improved the distribution of water.

Allison and Hesse (1969), and Pair (1968) show from their investigations that the net seasonal uniformity will be higher than most of the individual irrigations. Keller, et al. (1967) and Merriam (1968) suggest management techniques, such as alternate sets, to overcome variations in uniformity between two irrigations in order to improve the net seasonal uniformity.

Molenaar et al., (1954) studied the effects of pressure on CU_c and concluded that there was no significant change in CU_c with change in pressure. Their analysis shows the CU_c for their tests to decrease approximately three units for each one mile per hour increase in wind velocity. They suggested that there was a need for a relationship to be developed between the CU_c and the distortion of the distribution pattern due to wind. They concluded that the pronounced effect of wind on the CU_c could largely be overcome by correct spacings of sprinklers. What contributed correct spacings was not discussed.

Hart (1959) conducted many tests using small sprinklers to analyze some of the effects on pattern distribution in wind speeds ranging from 0 to 20 miles per hour. Results of his study are summarized as follows:

1. No variation in coefficient of uniformity could be attributed to sprinkler make and model.
2. Generally coefficient of uniformity increases with riser height and increases as the area covered by a single

sprinkler decreases.

3. Coefficient of uniformity increases with nozzle pressure, but is only slightly effected by nozzle size.
4. Generally increase in wind speed decreases the coefficient of uniformity and a wind direction perpendicular to the short dimension of the sprinkler spacing gives a more uniform pattern distribution than wind directions parallel to it.

Measuring Water Distribution from Sprinklers

Davis (1966) presented an analysis of three parameters used for describing sprinkler pattern uniformity and an analysis of the required can catch density for maximum allowable errors. In his experiment he used a three inch lateral line, 30 by 50 foot sprinkler spacing, and eight 11/64 inch single nozzled rotating sprinklers. His catch cans were set up with 2 and 5 foot grid spacings, so that 2, 4, 5, 6, 8, and 10 foot grid spacings could be analyzed. He concluded that for sprinkler systems that have marginal uniformity and acceptability, the density of sampling stations (representing sampling areas between 0.25 to 6.7 percent of the pattern area) had little effect on the calculated mean depth of application. The maximum error observed for the 10 foot grid was 2.3 percent of the true mean. He found the standard error of the mean approached ±5 percent for the 10 foot grid spacing and is inversely related to the square root of the number of stations.

For reasonably uniform distribution patterns, sampling station densities between 0.25 to 6.7 percent of the pattern area did not affect values of Christiansen's CU_c, statistical uniformity coefficient, or pattern efficiency. For poorer distributions, however, decreased sampling station density, resulted in increased values for all distribution parameters. Pattern efficiency was especially effected. For the poorer distribution patterns, the sampling station grid spacing should be close enough such that each sample point represents no more than 2.5 percent of the pattern area.

Branscheid and Hart (1968) described experiments conducted to determine the correct methods for utilizing single sprinkler pattern test data in the prediction of field performance and whether or not using a single sprinkler test to simulate actual spacings is a valid assumption. They used single sprinkler can test data and lateral (made up of 13 sprinklers at 30 feet) can catch data which was collected simultaneously under the exact same wind conditions. This data was collected under average wind speeds of 1.5, 5.5, 6.8, 9.9, and 14.0 miles per hour. By overlapping the single sprinkler data of a specific wind condition, they were able to construct a simulated lateral which could be then compared to the actual lateral test data. They then took the synthesized lateral data, overlapped it and compared it with the actual overlapped lateral data by using the CU_c. To synthesize different wind speeds and direction during different lateral settings, they used the lateral data (both actual and synthesized) from the different wind conditions to overlap with the previous data. The maximum error of the single overlapped sprinkler data compared to the actual overlapped lateral data, properly sequenced and lapped, was 2.35 percent and minimum error was 0.15 percent. From this analysis it was concluded that the procedure using the single sprinkler test data is a valid one.

METHODS AND PROCEDURE

The single sprinkler pattern test data analyzed in this thesis was collected from experiments carried on at the Agricultural Experimental Station of Zopatitan in El Salvador, Central America. The project was financed by USAID's 211-d fund through Utah State University. These tests were carried on in El Salvador to gather local wind data for further work in El Salvador and for this data analysis.

Apparatus

An underground source of water was used to supply the experiment and was pumped into a small field ditch. A ten horse power portable gasoline powered pump delivered water from the ditch into a 200 foot long 3 inch aluminum irrigation pipe. A 75 gallon per minute capacity pressure regulator and a bypass valve was installed between the pump outlet and the 3 inch pipe. The pressure regulator aided in controlling and stabilizing the inlet pressure at the sprinkler head. The bypass valve returned excess water produced by the pump into the field ditch. This installation prevented overloading of the pump, provided a concise control of the pressure and volume of water at the sprinkler head, and allowed the pump to run at a fairly efficient level.

The sprinkler assembly was located at the end of the irrigation pipe line in the center of the test sight (Figure 2). The riser

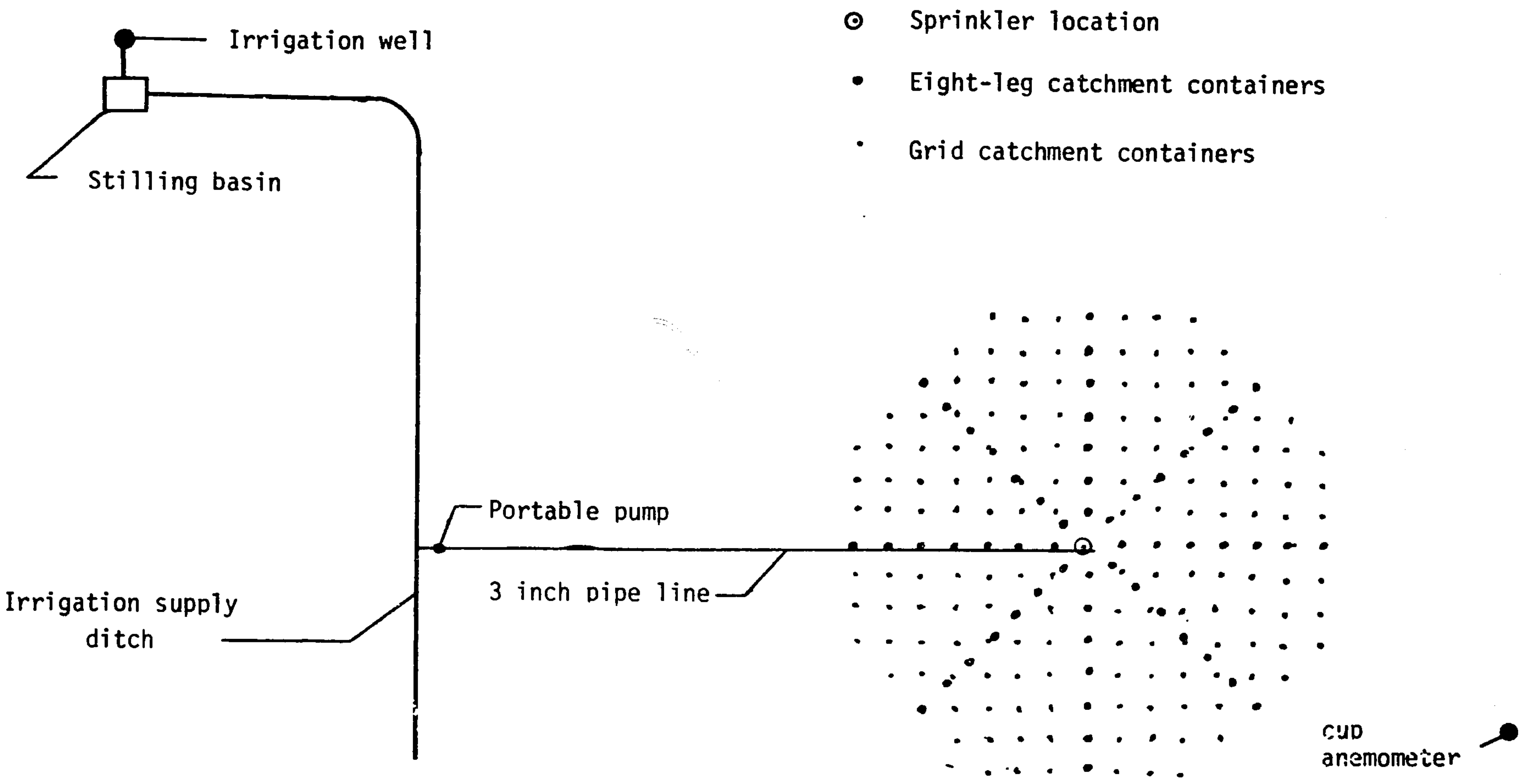


Figure 2. Schematic layout of well, ditch, pipeline, catchment containers, sprinkler location and cup anemometer.

consisted of a 3/4 inch inside diameter iron pipe of sufficient length such that the center of the main nozzle of the sprinkler was located 2.0 feet above the average elevation of the tops of the four nearest precipitation collectors (ASAE Recommendations, 1970, included in Appendix A).

The test site deviated from the ASAE recommended as follows: (1) The collectors were only 6 inches above the ground instead of 12 inches. (2) At times only 50 to 60 collectors received water instead of a minimum of 80. (3) The sprinkler was located at a collector point on the grid instead of midway between four collectors at the center. Four collectors were used at a three foot spacing surrounding the sprinkler to estimate the catch at the sprinkler. In addition to the grid collector setup, four additional radial legs set at 45 degree angles to the grid orientation were utilized for pattern shape analysis.

A pressure gage with a range of 0 - 100 pounds per square inch and an accuracy of ±2.0 percent, was incorporated into the riser 1.5 feet below the sprinkler head to measure the base pressure. It was located approximately 6 riser pipe diameters above the riser inlet. Another pressure gage, identical to the base pressure gage, and a pitot tube was used to measure the pitot - static pressure at the vena-contracta of the jet at the main (largest) nozzle. Prior tests comparing the two gages indicated pressure reading variations between the two gages less than the accuracy of the gages (ASAE Recommendations, 1970).

Several sprinkler models and a variety of nozzle size combinations were tested to gather sprinkler pattern data. Sprinkler heads were limited to one manufacturer due to the hydraulic and physical differences between different manufacturer's sprinkler heads. These differences may effect the sprinklers performance under various environmental conditions. Rainbird sprinklers were presently being used in El Salvador, C.A. where the testing was to be done. Also the Rainbird Sprinkler Company offered some of their test data that correlated with this work. All sprinkler heads were Rainbird full circle sprinklers.

Six model 30 W with a 3/4 inch male TNT bearing and brass spreader nozzle plug and six model 30 EW TNT with a 3/4 inch male TNT bearing and non clog plastic vane were the sprinkler heads tested. Brass nozzle sizes of 9/64 inch, 11/64 inch, 3/16 inch, 7/32 inch, 9/64 x 3/32 inch 7 degree, 11/64 x 3/32 inch 7 degree, and 7/32 x 1/8 inch 20 degree were used with the 30 W head while only the single nozzles were tested with the model 30 EW TNT head. These combinations were tested at several pressures and wind velocities to determine their effect on the sprinkler pattern and sprinkler spacing.

Wind speed and direction were measured using a rotating cup totalizing anemoneter and a wind vane attached to the anemometer stand. The cup anemometer was placed 13 feet (4 meters) above the surface of the test site and about 140 feet (42 meters) from the sprinkler head. Accurate minimum wind velocity measurements of 2.0 miles per hour could be determined. The anemometer was fabricated to U.S. Weather Bureau specification #450.6104, was calibrated in kilometers and could be read to the nearest .10 kilometer. Dry and wet bulb temperature measurements were made near the outside edge of the sprinkler pattern using a sling psychrometer read to the nearest degree.

Approximately 250 white styrofoam 32 ounce cups were used as precipitation catchment containers. They were made such that they could be stacked together with the top inside diameter of 4.35 inches (110.5 mm) and a container depth of 5.47 inches (139.0 mm). These particular containers were selected because of convenience in storing and transporting them, their steep sides which repelled water, depth, and their insulation properties which reduced evaporation. Because of the cup's surface properties, precipitation formed beaded water drops which reduced the amount of water remaining in the cups when emptied. Smooth, well-rounded 2 inch diameter stones were placed in the cups during the test to prevent the cups from tipping in the wind or floating in pools of water which accumulated during testing.

The precipitation collectors were spaced in a square grid pattern with spacing between containers of 10 feet. The sprinkler was located at a grid point or collector location. Four catchment containers were placed 3 feet on each of four sides of the sprinkler. This data was averaged to acquire the precipitation amount at the sprinkler grid point. Precipitation measurements were also made using an eight leg radial catchment pattern arrangement in which four legs were included in the square grid pattern. These containers were spaced 10 feet apart with the sprinkler at the center of the pattern (Figure 3). Two 50 and 100 milliliter graduated cylinders along with small polyethylene funnels were used to measure the volume of water received in the precipitation catchment containers A stop watch calibrated in minutes, tenths of minutes, and hundredths of minutes was used to determine the length of test, for computing sprinkler discharge, and to determine when wind and temperature data were to be taken.

Test Procedure

The test site was located in an area which conformed to the ASAE Recommendations (1970). A transit and woven cloth tape were used to locate the grid and radial leg catchment containers. Preliminary tests, prior to actual field testing, were run to test the variability of the six sprinkler heads for each model sprinkler. Tests were run in a laboratory with absolute zero wind conditions. Sprinkler rotation and discharge variability was analyzed to determine sprinkler heads with performance characteristics which represented the average of the 6 sampled sprinklers selected for testing. Only these "typical" sprinkler heads were used in subsequent field testing.

Approximate wind conditions were estimated prior to initiation of a test to select a nozzle size-sprinkler head-pressure combination that had not been previously tested under the particular conditions.

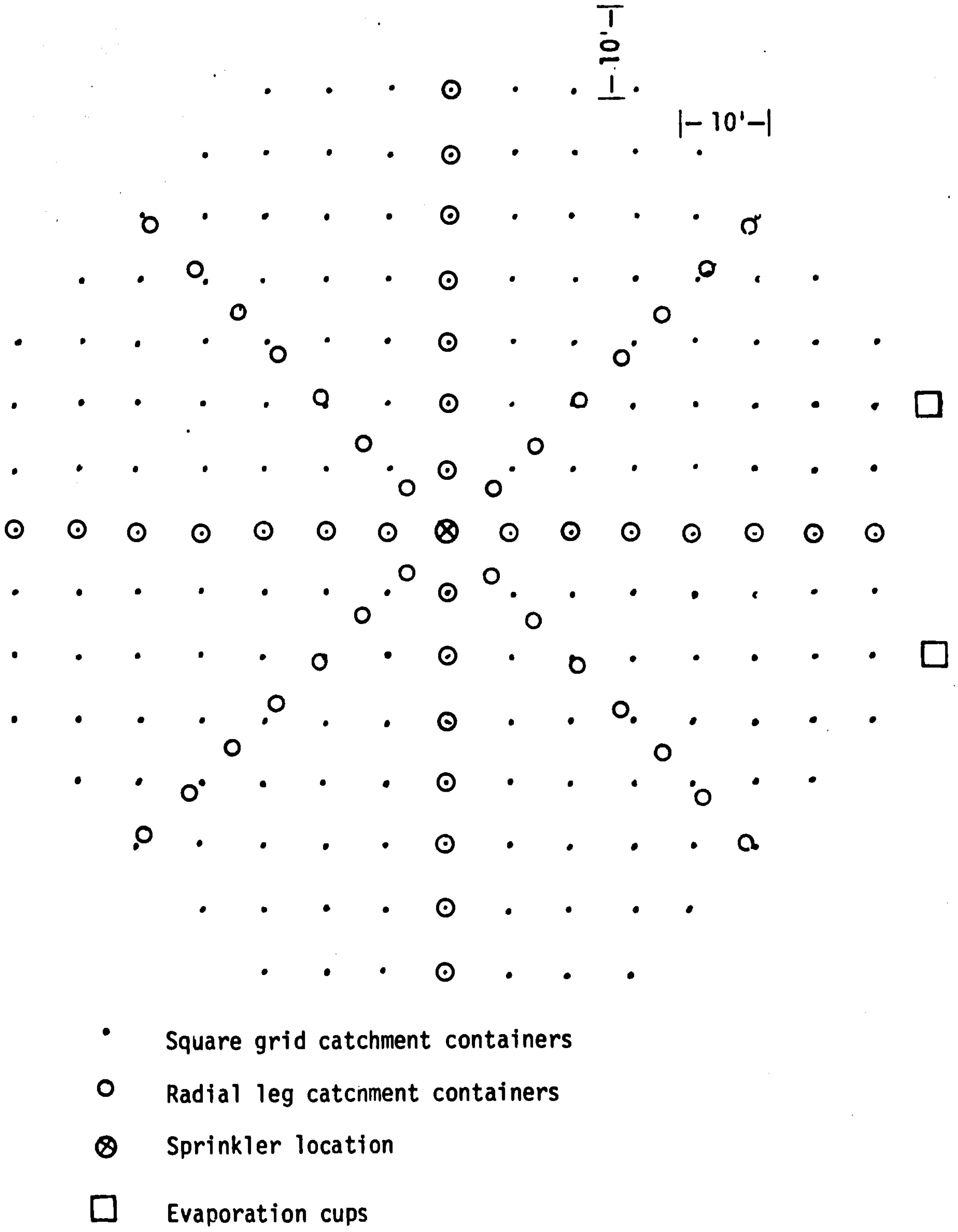


Figure 3. Test sight layout and catchment container arrangement for all tests. Grid spacing - 10 ft. x 10 ft.

The sprinkler assembly was mounted on the riser pipe and a 5 gallon container placed over the sprinkler head to prevent water from filling the catchment containers prior to initiation of the test. The pump was started and the pressure regulator and bypass valve adjusted to the desired testing pressure and flow rate. Sprinkler discharge was determined using a 2 inch plastic hose, a 5 gallon container, and the stop watch. (The relatively large diameter plastic hose allows aeration of the jet, preventing a "Venturi effect" from occurring which would cause the measured discharge to be greater than the true discharge.) Two readings were taken at the beginning and two at the termination of each test which were averaged to determine sprinkler discharge. Nozzle pressure was measured at the beginning and end of each test using the pitot tube and pressure gage. All data was recorded on the sample test data form presented in Appendix A.

The test time began when the container was removed from the sprinkler and the initial anemometer reading and wind direction was recorded. Wet and dry bulb temperature measurements were immediately taken. Evaporation losses during sprinkling were measured by placing 30 milliliters of water in a styrofoam cup placed outside the sprinkler wetted diameter just prior to initiation of the test. At the completion of the test, the water remaining in the cup was measured and the difference between the initial and final readings was recorded as evaporation. At intervals of 15 minutes throughout the duration of the test, anemometer readings, wind direction, wet and dry bulb temperatures, and base pressure were measured and recorded. Measurements of sprinkler rotation rate were also taken at 15 minute intervals. Test durations of either 30 minutes or 60 minutes depending on wind conditions and sprinkler discharge generally produced adequate precipitation to make reasonably accurate measurements.

The container was again placed over the sprinkler head at the termination of the test and final measurements were taken and recorded. Thirty milliliters of water was then poured into a second evaporation cup to determine the amount of evaporation that occurred while precipitation measurements were made. Precipitation from each grid and radial leg catchment container was poured into a graduated cylinder and recorded to the nearest .50 milliliter. Evaporation cups were read and this data along with wet and dry bulb temperature data can be used to analyze evaporation losses during sprinkler testing. A summary of evaporation data is included in Table 1.

Table 1. Temperature, humidity, wind velocity, and evaporation data for tests utilized in this analysis.

Test No.	Temperature °F DB	Temperature °F WB	Relative Humidity %	Wind Velocity Km/Hr	Evaporation ml
2	78	74	83	10.8	5
3	83	75	70	13.8	10
21	75	73	90	10.0	1
23	82	75	73	11.0	2
24	80	73	72	3.7	5
27	78	75	87	13.8	3
30	84	76	70	3.9	4
32	82	77	80	19.4	2
41	84	76	70	6.2	4
43	80	74	76	3.4	5
44	82	74	70	4.2	6
45	75	72	87	5.4	3

Analysis of Data

A comprehensive study to categorize sprinkler pattern stability as a function of wind speed, nozzle size, and pressure was not possible due to a deficit of specific data. However, the concept of pattern stability was still employed to analyze the effects on spacing.

A parameter which involved the center of mass shift for the pattern was used as the pattern stability index. Theoretically, the center of mass of a single sprinkler pattern at absolute zero wind would fall on the sprinkler location at the center of the pattern. A deviation of the center of mass from this center point would be an indication of a particular wind velocity, nozzle size, and pressure condition.

The pattern stability index, K, is defined as the deviation in feet of the center of mass of the pattern from the sprinkler, divided by the no-wind wetted diameter of the pattern in feet. This value is then multiplied by 100 to convert to percent. This parameter relates the pattern size to the shift in the center mass. In other words, a shift in center of mass of 10 feet for a pattern diameter of 100 feet would have a different effect on sprinkler spacing and CU than a shift in center of mass of 10 feet for a 50 foot pattern diameter.

An integrated wind direction for the test time was determined by calculating the angular deflection from north of the center of mass of the pattern with respect to the sprinkler position. This was used as the average wind direction for subsequent analysis. A listing of the computer program used to calculate this data can be found in Appendix B.

A computer program was developed which would rotate single sprinkler pattern data with respect to the calculated wind direction. The program is designed to use any pattern size, any collector spacing and will work whether the sprinkler is located at a grid point or at the center of four grid points.

The program initially rotates the pattern so the integrated wind direction will begin at 0 degrees or parallel to the lateral line. In order to accomplish this rotation the program calculates the distance from the sprinkler and angle of each grid point with respect to a reference line passing through the sprinkler location. For clarity of explanation, values for these terms will be assumed (See Figure 4). Assume the distance of grid point A from the sprinkler is 30 feet and the angle with respect to the reference line is 90 degrees. Assume the wind direction is to be rotated 45 degrees from an initiated wind direction of 0 degrees. The value of the rotated point A' will come from a position 45 degrees from the grid point A or 45 degrees from the reference line, and 30 feet from the sprinkler. Since the position of point A' does not fall directly on an existing known point, linear interpolation is used to determine the value of the point from the four adjacent grid points, v, w, x and z.

This procedure is used with each grid point and when completed the wind direction with respect to the pattern is 45 degrees instead of 0 degrees. The computer program then overlaps the rotated grid pattern at a specified spacing and calculates the CU_c value for the spacing and wind direction. The program output consists of the test number, center of mass shift, wind angle with respect to the lateral line, spacing on lateral, spacing on main, spacing ratio, uniformity coefficient, and spacing on main as a percent of wetted diameter.

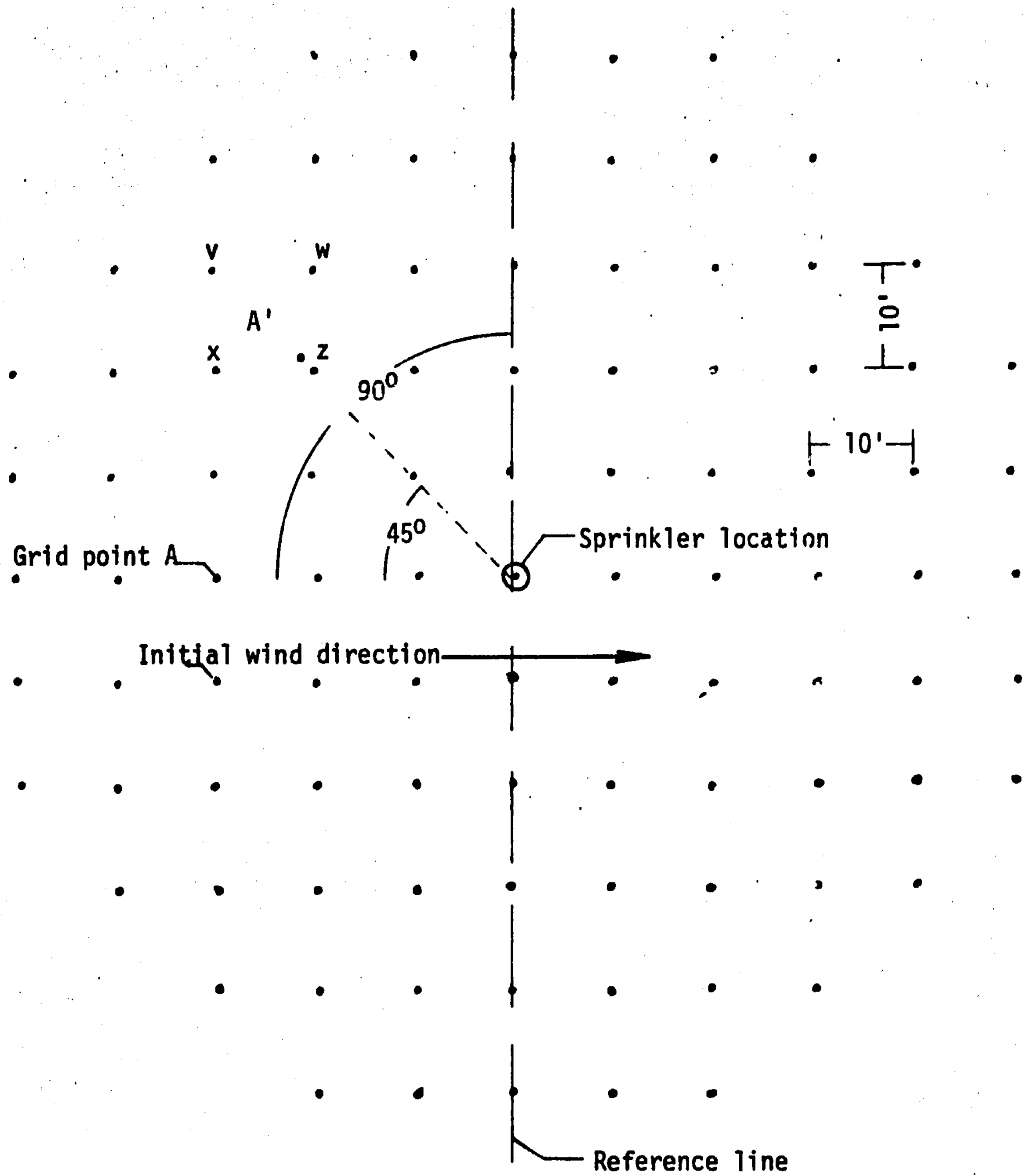


Figure 4. Location of grid points A, v, w, x, and z, and position of rotated point A' for a wind direction rotated 45° from initial wind direction of 0°.

The concept of a spacing ratio, SR, the ratio of the sprinkler spacing on the lateral to the lateral spacing on the main line was developed to combine the number of possible sprinkler spacings into four spacing ratios, 1.0, 0.8, 0.6, and 0.4. Spacings used in this analysis are presented in Table 2.

Table 2. Spacings expressed in feet used in single sprinkler pattern data analysis.

Spacing Ratio			
1.0	0.8	0.6	0.4
10 x 10	10 x 12.5	7.5 x 12.5	5 x 12.5
20 x 20	20 x 25.0	15.0 x 25.0	10 x 25.0
30 x 30	30 x 37.5	22.5 x 37.5	15 x 37.5
40 x 40	40 x 50.0	30.0 x 50.0	20 x 50.0
50 x 50	50 x 62.5	37.5 x 62.5	25 x 62.5
60 x 60	60 x 75.0	45.0 x 75.0	30 x 75.0
70 x 70	70 x 87.5	52.5 x 87.5	35 x 87.5
80 x 80	80 x 100.0	60.0 x 100.0	40 x 100.0
90 x 90	90 x 112.5	67.5 x 112.5	45 x 112.5
100 x 100	100 x 125.0	75.0 x 125.0	50 x 125.0

Three pattern shapes are used in this study (Figure 5). For each pattern shape, four single sprinkler pattern tests were selected to represent low, medium low, medium high, and high pattern stability. This information was used to analyze the effects of pattern stability and spacing. An explanation, operating instructions, and program listing for all computer programs used in this analysis are presented in Appendix B.

RESULTS AND DISCUSSION

Single sprinkler can-catch data has been analyzed to determine the effects of pattern stability, wind direction, sprinkler spacing, and pattern shape on CU_c. Only sprinkler test data where wind speed and direction did not vary significantly during the testing period were utilized in the analysis. A summary of the test data utilized in this analysis is included in Appendix C.

An attempt was made to collect single sprinkler test data for three pattern shapes. (A pattern shape is the plot of depth of application versus distance from sprinkler.) Figure 5 shows plots for the three pattern shapes analyzed. Pattern shape A is a composite of Christiansen's A and D profile (Figure 1). A single nozzled, unvaned sprinkler head was operated at or above the recommended minimum pressure to produce pattern shape A.

A single nozzled, vaned sprinkler head was operated below recommended minimum pressure to produce a "doughnut" shaped pattern B which is a composite of Christiansen's A and E pattern shapes. Pattern shape C was produced by operating a double nozzled, unvaned sprinkler head at or above minimum recommended pressures. Pattern shape C represents a shape which is a composite of Christiansen's B and C patterns. The notation used in Figure 5 will be carried through the discussion and Figures to follow.

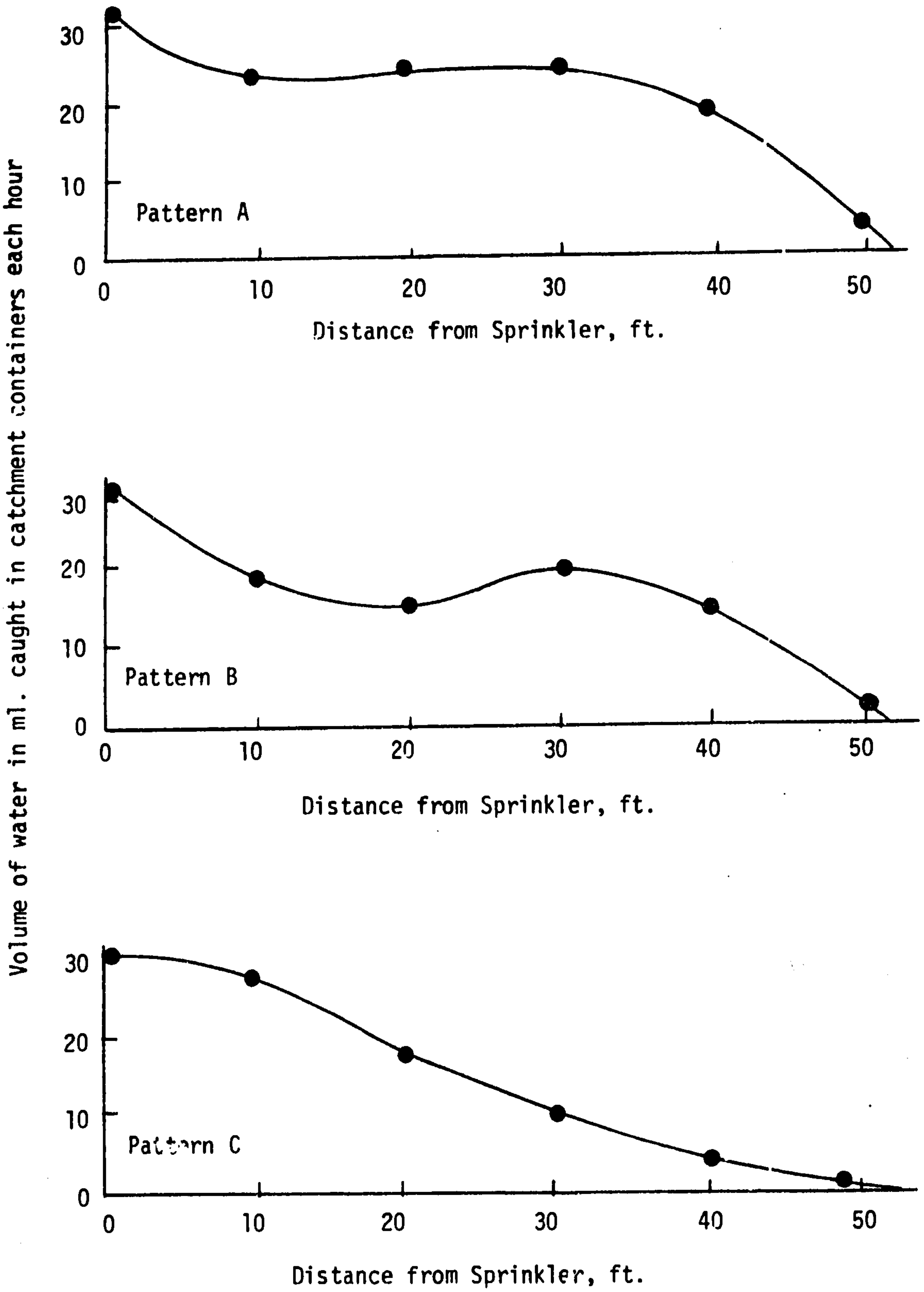


Figure 5. Pattern shapes A, B, and C plotted as volume of water caught in milliliters vs. distance from sprinkler.

Pattern Stability

Pattern stability as used in this discussion can be evaluated by determining the linear deviation of the center of mass of the test pattern can catch data from the theoretical no-wind center of mass considered to be at the sprinkler location. The concept can be used to describe not only wind speed effects, but also pressure and nozzle size effects on the pattern distribution when considering spacing regimes of sprinkler systems.

The pattern stability is a function of the hydraulic characteristics of the sprinkler head and nozzle arrangement plus the physical characteristics of the environment during the period of sprinkling. Several sprinkler characteristics that effect the pattern stability include the angle of trajectory, internal shape and roughness of the sprinkler head, the nozzle size, water pressure, double or single nozzle arrangement, and whether vaned or unvaned flow through the sprinkler head.

Four environmental conditions including wind speed, steadiness of wind speed, wind direction, and steadiness of wind direction effect the stability of the sprinkler pattern and the CU_c of the sprinkler system. Wind direction affects pattern stability only in its relationship to the actual sprinkler arrangement and resultant CU_c values. In other words, pattern stability is not dependent on wind direction when considering a single sprinkler test pattern - unless the wind direction varied during the test. Again, if the wind speed remained steady while the wind direction rotates 360 degrees uniformly during a test, theoretically the center of mass for the pattern would be at the pattern center or sprinkler location. Such a pattern would be apparently stable since the linear deviation of the center of mass of the test pattern data would be zero.

The pattern stability index, K, is a function of the deviation from the sprinkler of the center of mass of the test can catch data. The major source of this deviation is the speed of the wind. Other factors include pressure and nozzle size.

Pressure is related to wind speed with respect to pattern stability. High pressure tends to breakup the spray stream into fine water droplets whereas a lower pressure jet consists of considerably larger water droplets. Under low wind conditions the higher pressures tend to give higher CU_c values than the lower pressures (Wiersma 1950). However, under higher wind speeds, lower pressure results in greater pattern stability than high pressure. Nozzle size is similar to pattern stability in its relationship to wind speed. With a large nozzle size, breakup of the jet results in large water droplets while a small nozzle size results in small water droplets (Bilanski and Kidder 1958, Chu and Allred 1968, Seginer 1963, and Umback and Lemke 1966). The large water droplet size produces the highest pattern stability.

Pressure and nozzle size are interrelated in that the combination of each factor affects the individual droplet size and stability.

For instance, a large nozzle plus a low pressure produces a very large water droplet which is quite stable under wind conditions. The converse occurs with a small nozzle and a high pressure. This indicates that there is an interrelationship between all three factors - wind speed, pressure, and nozzle size, and that pattern stability depends upon the combination effect of each factor. The pattern stability index is a measure of the affect of the interrelationship of the three factors.

Figure 6 shows curves of CU_c vs. SM for a series of tests using pattern shape A, wind direction of 0 degrees, and spacing ratios of 1.0 for part (a) and 0.4 for part (b). Four tests with high, low and two intermediate values of K were chosen for this analysis.

Values along the abscissa in Figure 6 represent the spacing of the lateral line along the main line expressed as a percentage of the wetted diameter of the sprinkler pattern. The use of this system is convenient as it eliminates considering different pattern sizes when considering spacing for calculating CU_c. The sprinkler spacing on the lateral can be determined by multiplying the spacing ratio by the lateral spacing along the main line (SM).

Some interesting observations concerning spacing and wind effects on sprinkler performance can be seen in Figure 6. For simplicity of explanation, assume the sprinkler pattern diameter equals 100 feet. Thus the values on the abscissa will represent SM in feet.

Note the difference between parts (a) and (b) of Figure 6. The differences in shapes result from the difference in spacing ratios.

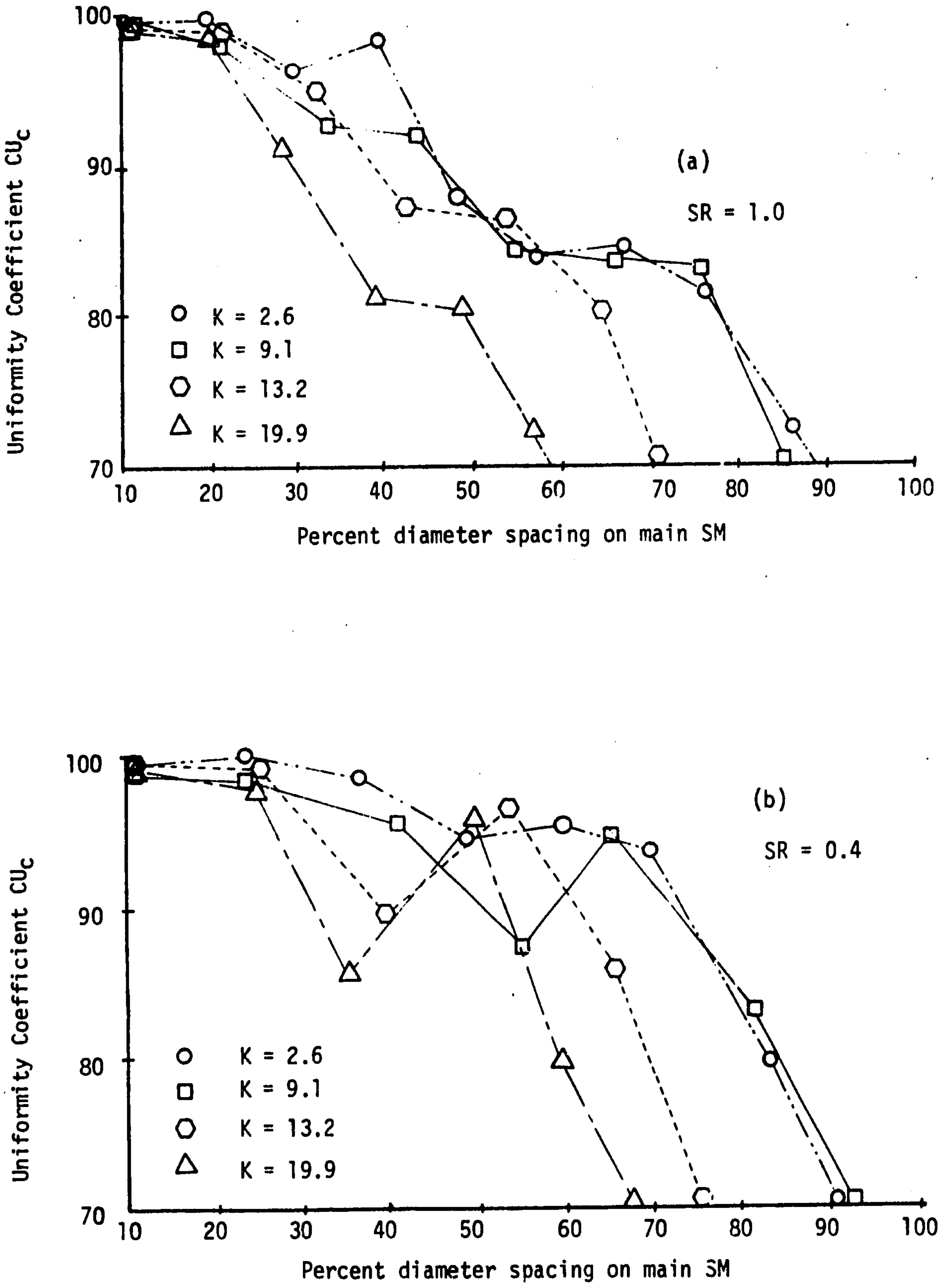


Figure 6. CU_c vs. SM for different pattern stability indices plotted for 0° wind direction and pattern shape A.

Note that as spacing increases in part (a), generally CU_c continuously decreases. However, as spacing increases in part (b), CU_c values generally decrease, increase, and then decrease again resulting in peaks of quite high CU_c values at larger spacings. Using a SR = 0.4, it is possible to increase CU_c by also increasing spacing. This is not true when SR = 1.0. A further discussion of the spacing ratio is included on page 49 of this discussion.

Note also that generally the CU_c values are higher for a particular spacing in part (b) than in part (a). For example, at SM = 1.0 and K = 19.9, CU_c = 78 for SR = 1.0 whereas CU_c = 90 for SR = 0.4. This occurs since the area covered by each sprinkler is larger for SR = 1.0 than for SR = 0.4. The area covered at SM = 50 for SR = 1.0 equals 50 feet by 50 feet or 2500 square feet.

From Figure 6, it follows with recommendations from Molenaar, et al. (1954), that a reduction in spacing is necessary with decreased pattern stability. The amount of reduction in spacing is dependent not only on a decrease in pattern stability, but also on the spacing regime of the system; ie SR = 1.0 or 0.4. As K increases the curves shift towards the left or towards smaller spacings for a given CU_c. In other words as pattern stability decreases, spacings must decrease to maintain a high value of CU_c.

Assume that a CU_c of 85 is desired, looking at part (b), note that a spacing of 32'x 80' would result in an adequate CU_c value for either K = 2.6 or K = 9.1. In this case each sprinkler covers an area of 2560 square feet. If the value of K is increased to 13.2, a sprinkler spacing of 26' x 65' would be required for a CU_c of 85. This spacing results in a 34 percent reduction in area covered to (1690 square feet) for a sprinkler with a 45 percent increase in K. When K is increased to 19.9, a spacing of 22' x 55' is required to achieve a CU_c value of 85 and results in a 53 percent reduction of area covered with a 119 percent increase in K. Note that at wider spacings there is little difference in CU_c values between K = 2.6 and K = 9.1. However, at spacings less than 70 percent of the wetted diameter, CU_c values for K = 2.6 are as much as 8 units higher than the CU_c values for K = 9.1.

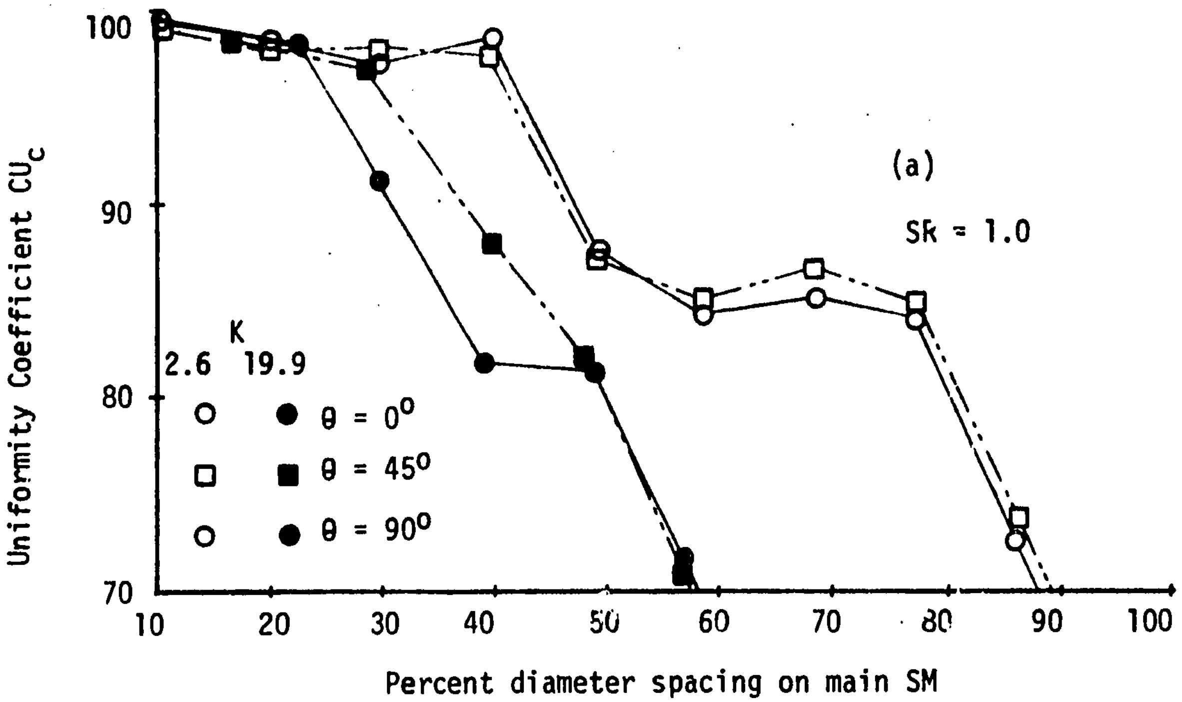
Several factors including wind speed, pressure, nozzle size, etc., effect the performance of a sprinkler. Research has been conducted which attempts to define the effects of each of these factors independently. The effects are then combined for each of these factors to simulate actual field conditions. However, it is impossible to simulate and analyze all the possible combinations along with the many spacing regimes and wind orientations available to the system designer to achieve a situation that will occur in the field.

A single term used to describe the combined effect of all these factors would be useful in system design. A term which is described as the pattern stability index in this study, includes the effects of all these factors and may be useful for the evaluation of sprinkler system design.

The pattern stability index, k, is used in this analysis to describe the total effect of all environmental and hydraulic conditions upon CU_c for various spacing regimes. Prediction of field performance by use of sprinkler profiles is analyzed in detail in a study made in conjunction with the present one (Moynahan, 1972).

Wind direction

Figure 7 shows CU_c vs. SM curves for θ plotted for pattern A, for high and low values of K, and for SR's of 1.0 for part (a) and 0.4 for part (b). Three wind directions of 0 degrees or parallel to the lateral, 45 degrees, and 90 degrees or perpendicular to the lateral, were analyzed for this disucssion. Wind directions greater than 90 degrees were not analyzed since they would produce the same results as the corresponding directions that were analyzed. For example, wind directions of 135 degrees, 225 degrees, or 315 degrees all represent a wind direction that is 45 degrees with the lateral line and would produce exactly the same results as the 45 degrees wind direction studied. The same is true with angles that are either perpendicular or parallel to the lateral line. It was found through computer analysis that wind directions between 0 degrees and 45 degrees, and 45 degrees and 90 degrees resulted in CU_c values between those of the respective directions on Figure 6. When square spacings were analyzed, CU_c values were equal for the 0 degrees and



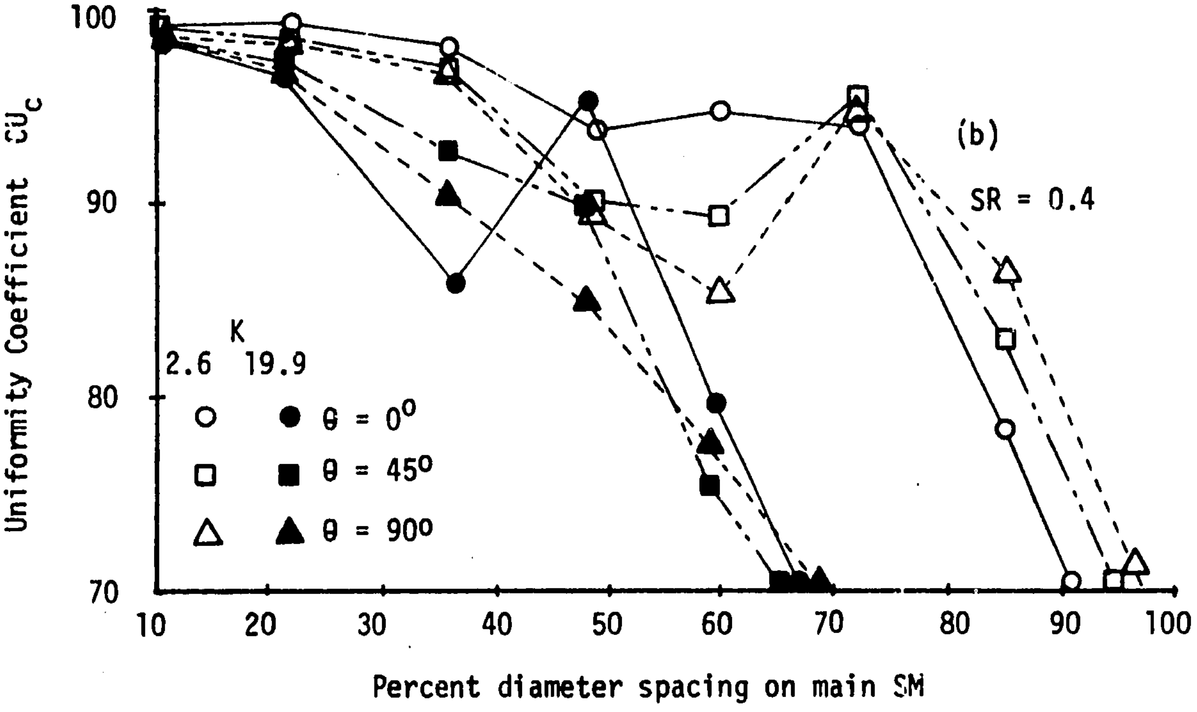


Figure 7. CU_c vs. SM for different wind directions, θ, plotted for K = 2.6 and K = 19.9, for pattern shape A.

90 degree wind directions.

In part (a) of Figure 7, low K values produced little variation in CU_c values between the three wind directions for all spacings; however, a high K value greatly shifted the curves towards smaller spacings with as much as 30 percent reduction in spacing at a CU_c of 70. At large spacings with high K values, there is little difference in CU_c values between the three wind directions analyzed. However, at smaller spacings and higher CU_c values, the 45 degree wind direction produced higher CU_c values by about 6 units over the 0 degrees and 90 degree wind directions. For square spacings and high values of K, the 45 degree wind direction produces the highest CU_c values. As would be expected wind direction has little effect on CU_c values at low values of K.

In part (b) of Figure 7 in which SR = 0.4, the CU_c values for the curve representing the 45 degree wind direction generally fall between those of the other two wind directions. The effect of high K values is similar for both the rectangular spacing and square spacing with a reduction in spacing of approximately 30 percent required at the wider spacings to produce similar CU_c values.

It is interesting to note that at certain spacings on the graph it is possible to increase values of CU_c about 10 units by increasing spacing 15 percent. However, it is also possible that at other spacings on the graph, a decrease of 10 units in CU_c values will result when an increase of 15 percent spacing occurs. It is very important in design to know the characteristic graph for the sprinkler under field conditions such that the spacing and CU_c values can be maximized.

Results from the computer spacing analysis indicate that at low winds the optimum wind direction when the SR is 0.4 is 0 degrees to the sprinkler lateral for spacings less than 70 percent of the wetted diameter, see Figure 7 (b). For instance when K = 2.6 for the spacings between 30 and 70 percent of the wetted diameter, the 0 degree wind direction gives CU_c values which are as much as 10 units over the 90 degree wind direction. However, at spacings over 70 percent, the 90 degree wind direction produced CU_c values approximately 8 units over the 0 degree direction. The curves representing K = 19.9 in Figure 7 (b), indicates that at small spacings the 45 degree and 90 degree wind directions produce higher values of CU_c than does the 0 degree wind direction. However, at intermediate spacings between a 40 percent and 65 percent wetted diameter, the 0 degree wind direction results in considerably higher CU_c values than the 90 degree direction. As spacing increases past 65 percent the CU_c values fall below 70, the directions produce slightly higher CU_c values (Allison and Hesse 1969, Seginer 1969, Wiersma 1950, and Wilcox and McDougald 1955).

With low 90 degree winds, the uniformity is reduced by the "over watering" effect at intermediate spacings in Figure 7 (b). There is a large variation in CU_c values as spacing is increased. The 0 degree wind curve, however, is smooth with little variation until the CU_c values drop off at larger spacings. Just the opposite occurs on the graphs with high K values. The 0 degree wind curve is affected most with a sharp decrease, increase, and decrease again in CU_c values as spacing increases. The 90 degree wind curve is a fairly smooth, nearly straight-lined graph with CU_c values decreasing at almost a constant rate as spacing is increased.

The patterns from the 45 degree and 90 degree wind directions are apparently affected considerably more by the "over watering" effect than the 0 degree wind direction at K = 2.6. At K = 19.9, however, the 0 degree wind seems to be affected by the "over watering" effect much more than either the 45 degree or 90 degree wind direction as observed by the dips in the curves.

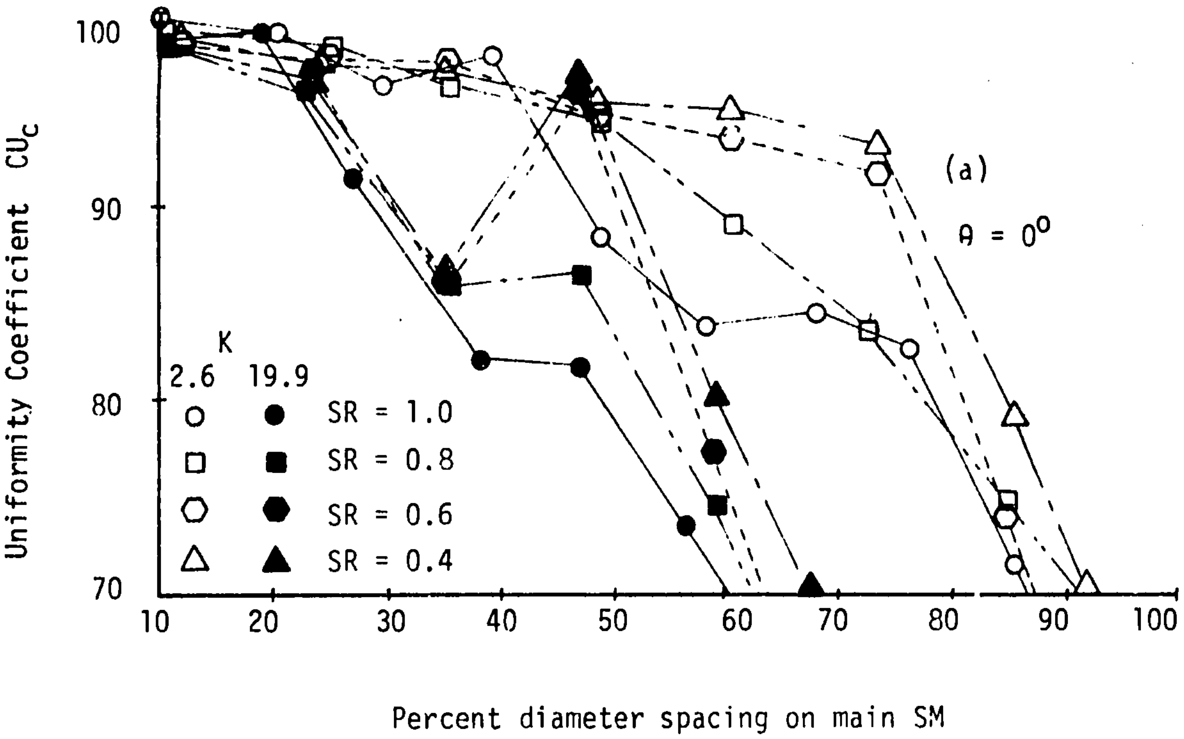
Spacing ratio

The concept of a spacing ratio was developed to eliminate the need for testing an infinite number of spacing combinations. The spacing ratio, SR, is the ratio of the sprinkler spacing on the lateral to the lateral spacing on the main; ie. a spacing of 20' x 50' results in a spacing ratio of 0.4. Each spacing ratio is a grouping of all possible spacing combinations from very small to very large that result in the particular ratio discussed. For example, assume a SR of 0.5. Spacings of 5' x 10', 10' x 20', 20' x 40', 30' x 60', 40' x 80', 50' x 100', and all other spacings that result in a SR value of 0.5 are combined into one grouping. A series of 4 or 5 spacing ratios is adequate to analyze most spacings utilized in sprinkler design (Table 2).

This concept becomes very useful in analyzing a general spacing orientation and how that orientation is affected by large or small spacings, wind direction, and K values. Figure 8 shows plots of CU_c vs. SM for various spacing ratios at low and high K values for pattern shape A with a wind direction of 0 degrees (a), and a wind direction of 90 degrees (b) to the lateral.

Generally for a specific spacing CU_c increases as the SR decreases. Basically this is due to an increase in area covered by the sprinkler as the spacing ratio increases. For example, in Figure 8 (a), at SM = 60, the CU_c at SR = 1.0 is 84; at SR = 0.8, CU_c = 89; at SR = 0.6, CU_c = 93; and at SR = 0.4, CU_c = 95. The area covered by one sprinkler decreases respectively from 3600 square feet to 1440 square feet.

The "over watering" effect was discussed in its relationship to K and θ in the section on wind direction. This effect is further demonstrated in Figure 8 (a). For example, the K = 2.6 curves are relatively smooth. However, when K is increased to 19.9, the curves for SR = 0.4 and SR = 0.6 becomes very irregular with large variations in CU_c as spacing increases. The effect θ has on the shape of the curves can also be seen. For example at K = 2.6, the 0 degree wind direction produces fairly smooth curves, part (a), however, the 90 degree wind direction part (b), produces curves that are quite irregular. At K = 19.9, the 0 degrees wind direction produces irregular curves, whereas the 90 degree wind produces relatively smooth curves.



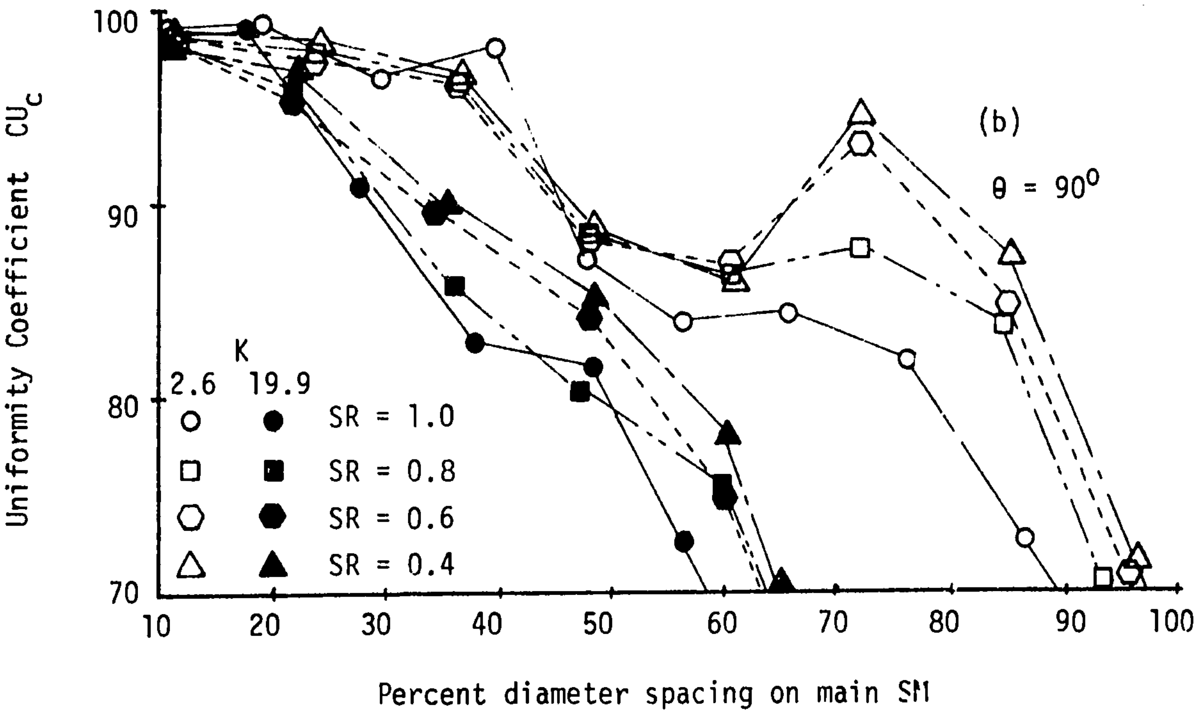


Figure 8. CU_c vs. SM for various spacing ratios plotted for pattern shape A, at K = 2.6 and K = 19.9

There is a characteristic shape of the CU_c vs. SM curve dependent upon the combination of SR, K, and θ. For example, when SR = 0.4, K = 19.9, and θ = 90 degrees, the characteristic shape of the CU_c vs. SM curve is smooth, Figure 8 (b); however, when SR = 0.4, K = 19.9 and θ = 0 degrees, the characteristic shape of the CU_c vs. SM curve is very irregular (a), i.e., has a dip.

Because of limited data analysis which deals with this occurrence, an explanation or theory is not in order. However, if this phenomena occurs throughout the spectrum of nozzle sizes, pressures, and sprinkler heads available for field use, it appears difficult to design a sprinkler system that will achieve a fairly stable uniform distribution of water under the various wind conditions.

Pattern shape

V. O. Branscheid (1971)[1] proposed using the shift in center of mass of single sprinkler test data as a good indication of the integrated wind speed and directional parameters. The concept of K was developed from this proposal. If the wind direction were stable, there would be a maximum shift in the center of mass for a given average wind speed. This could be described as an upper limit of an envelope which includes all the possible speed - K combinations.

However, even under high wind speeds, it would be possible for the center of mass shift to be zero. For example, theoretically if the wind speed remains constant, for instance at 20 mph, and

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[1] Verbal communications.

during the test time the wind direction completely and uniformly revolved 360 degrees, the value of K for this condition will be zero. At a given speed any variance in wind direction will reduce the value of K, a minimum value of which would be zero. A variable wind direction during sprinkling generally will increase the CU_c value. However, Branscheid and Hart (1968) and Allison and Hesse (1969) point out that a change in wind direction between two sets usually decreases uniformity.

Figure 9 shows the patterns stability index K plotted against the wind speed for the three pattern shapes A, B, and C. Each of the curves represent the upper limit of the envelope, or maximum K values of the respective speed for each pattern shape. These tests represent relatively steady winds such that if direction or speed changes during the test, the test was terminated and a new test begun. However, it is almost impossible without a wind tunnel to obtain test data with absolute steady winds.

It is evident from Figure 9 that in addition to wind speed, pressure, nozzle size, and pattern shape should also be included in the concept of K. For one wind speed, three different values of K result with each of the three pattern shapes. For example, a wind speed of 5.0 mph results in K values of 10.0, 12.2, and 15.2 from pattern shapes B, A, and C respectively. These values represent the approximate maximum K values under stable conditions. The actual K value for the particular wind speed and pattern shape may be

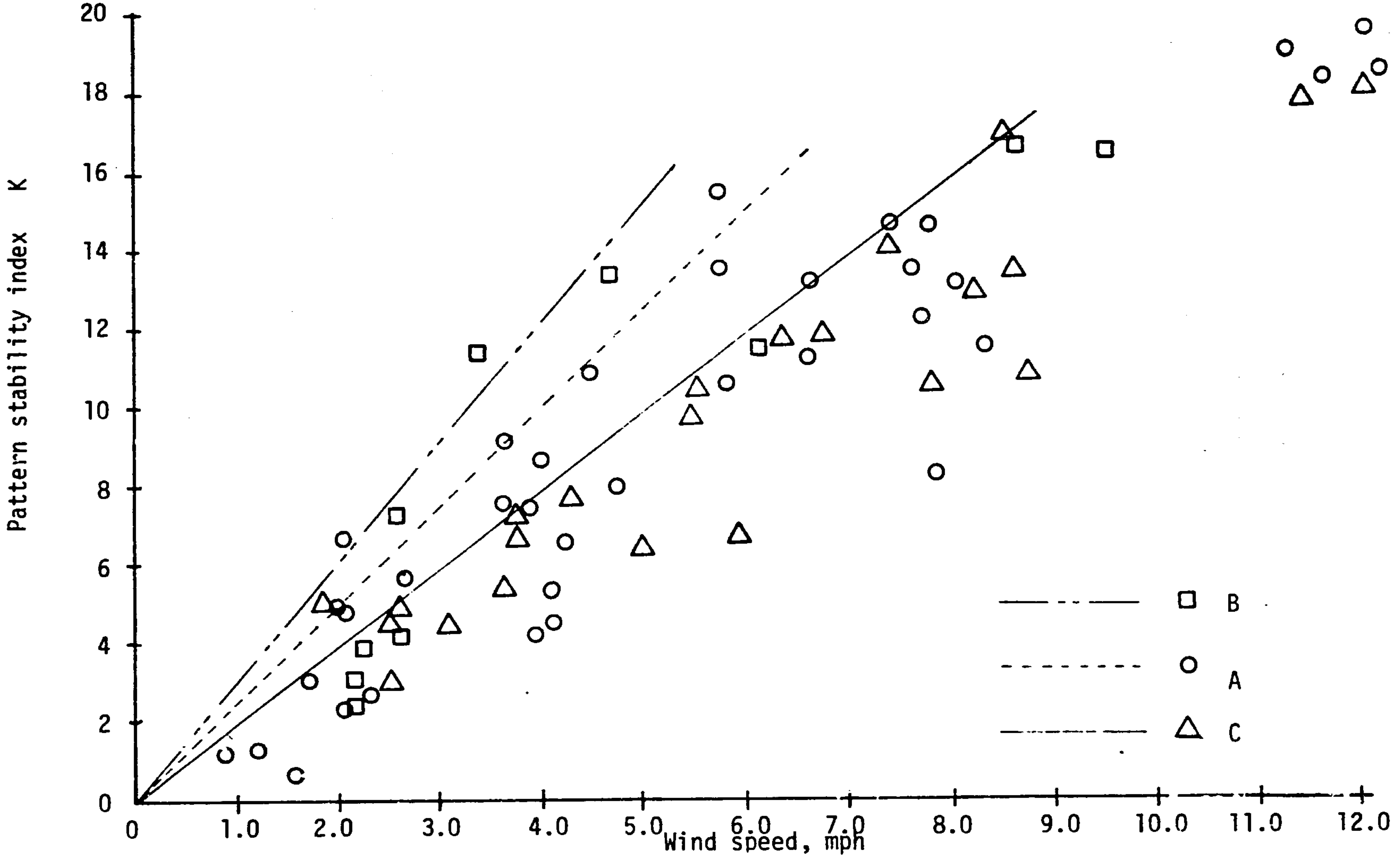

Figure 9. Pattern stability indices plotted against wind speed for single sprinkler test data for the three pattern shapes A, B. and C.

calculated using some wind variability factor times the maximum value of K.

This undefined wind variability factor would be dependent upon the regularity and duration of a particular wind speed and direction during the irrigation season. For example, where trade winds or ocean winds are prevalent, the factor may be nearly 1.0 resulting in an estimated K value very near the maximum. Conversely, if the wind direction and velocity variability is quite high, the factor would be lower and an estimated K value would be expected to be somewhat less than the maximum.

Pattern shape is a term used to describe the shape of the distribution pattern of a sprinkler for the depth of water applied versus the distance from sprinkler (Figure 5). The basic factors affecting the shape of the pattern consist of the type of sprinkler head, water pressure, nozzle orientation and angle, and whether vaned or unvaned flow through the head, as discussed earlier.

Figure 10 shows curves of CU_c vs. SM for the three pattern shapes with $K = 2.6$ and $K = 19.9$, $SR = 0.4$, for a 0 degree wind direction (a) and a 90 degree wind direction (b). It is interesting to note that the wind direction affects all of the pattern shapes in a similar manner. In part (a), note that the curves of all three pattern shapes for a small K are fairly smooth and horizontal until a spacing is reached at which the CU_c falls off sharply. However, with $\theta = 90$ degrees for a small K, the curves exhibit a decrease in CU_c values into low dips, then increase to peaks before falling sharply. A

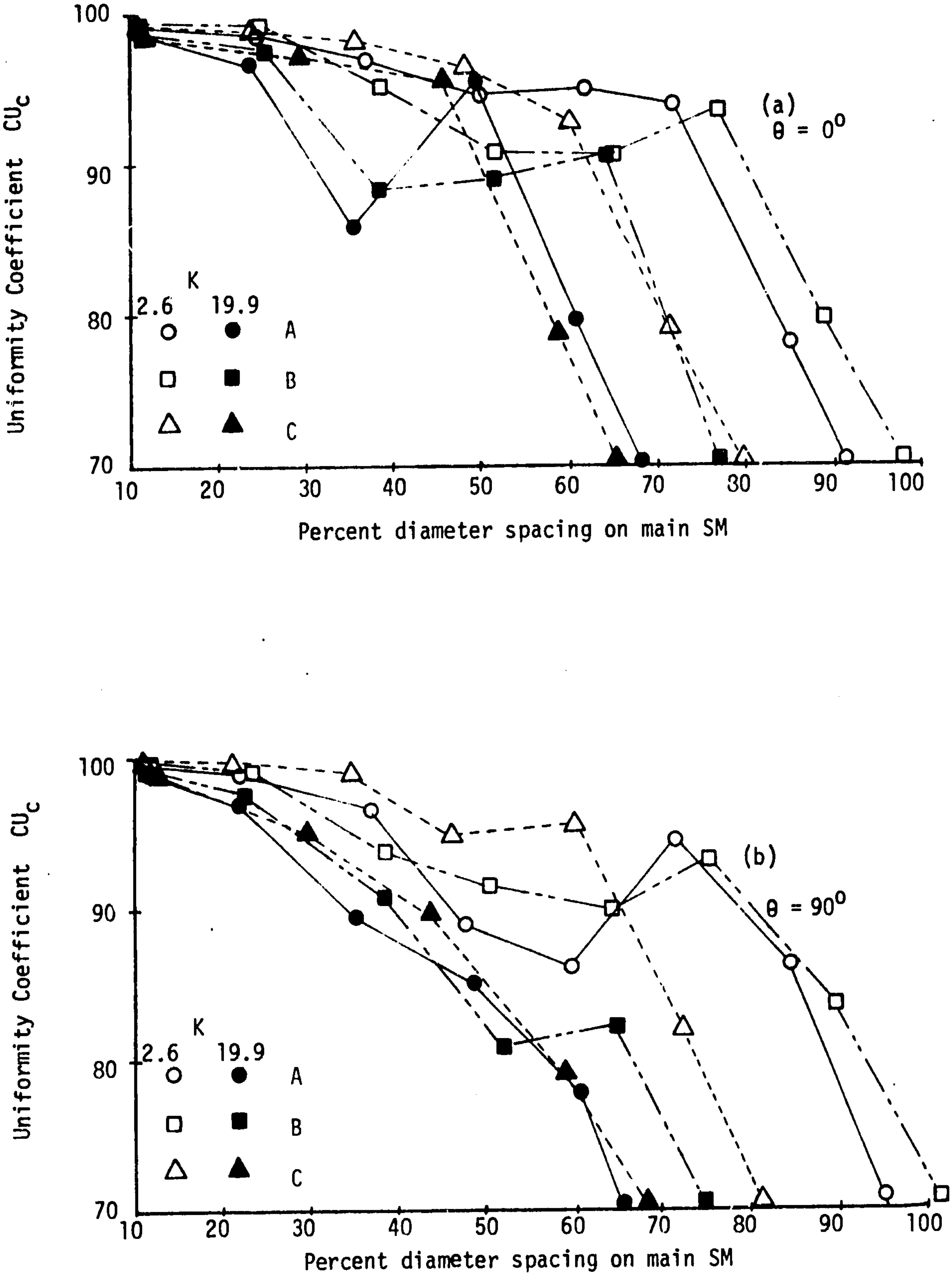

Figure 10. CU_c vs. SM plotted for pattern shape at a spacing ratio of 0.4.

similar but reversed pattern occurs when the value of K is large. The 0 degree wind direction produces irregular shaped curves with dips, peaks, and then decreasing values of CU_c as spacing increases. The 90 degree wind direction produces fairly smooth, steadily decreasing curves.

In all cases the pattern shape producing the highest values of CU_c depends upon the spacing of the overlapped pattern. Generally at small spacings, pattern shape C produced the highest values of CU_c; at intermediate spacings, pattern shape A produced the highest values of CU_c; and at larger spacings pattern shape B resulted in the highest values of CU_c. The order of these happenings may vary with different conditions, however, it does express the effect pattern shape has on sprinkler spacing. For example, for an SM of 80 percent wetted diameter, the CU_c value for pattern B is 92 while the CU_c for pattern C is 70. At SM of 50 percent, the CU_c for pattern C is 95, while that for pattern B is 91.

SUMMARY AND CONCLUSIONS

Objectives

The two main obejctives of this study were: 1. To categorize sprinkler pattern stability as a function of wind velocity, nozzle size, and pressure for several basic (no-wind) pattern profiles. 2. To develop a graphical means of presenting coefficient of uniformity, CU_c, vs. various sprinkler spacings expressed as a percentage of the wetted diameter, SM, for the various sprinkler profiles, pattern stability indices, and relative wind directions tested.

Procedure and Analysis

Single sprinkler test data for various wind conditions, nozzle sizes, and pressures were gathered from field tests. A computer program was developed to calculate the magnitude and direction of the shift in center of mass of the can catch data from the sprinkler location for the single sprinkler test data. The magnitude and directional parameters were used to describe the sprinkler pattern stability and wind direction respectively. The pattern stability was used to describe the total effect of wind speed, pressure, and nozzle size on Christensen's Coefficient of Uniformity (1942).

A computer program was developed to overlap the single sprinkler test data at various spacings to simulate the effect of a fixed solid set sprinkler system. CU_c values were calculated at each of a number of spacings. The test data was then rotated with respect to the wind direction. Overlapping and CU_c calculations were repeated to simulate different wind directional effects and spacing on CU_c.

Findings

The pattern stability index, K, utilized is the linear deviation of the center of mass of the pattern from the sprinkler location divided by the no-wind pattern diameter and multiplied by 100 to convert to a percent. A spacing ratio, SR, defined as the sprinkler spacing on the lateral divided by the lateral spacing on the main line was also used. A SR of 1.0 represents a square spacing. A wind direction of $\theta = 90$ degrees represents a wind that is perpendicular to the lateral and $\theta = 0$ degrees represents a wind parallel to the sprinkler lateral.

It was found that for a high K and a SR = 1.0, the $\theta = 45$ degrees produces the highest value of CU_c for any SM. As would be expected, at low K values, CU_c was affected very little by θ. When $\theta = 0$ degrees the highest values of CU_c was produced when K was small and with spacings less than 70 percent of the wetted diameter $SM < 70$. At $SM > 70$, $\theta = 90$ degrees was found to give the highest values of CU_c. When K is large and $SM < 40$, both $\theta = 45$ degrees and $\theta = 90$ degrees directions produce higher values of CU_c than the 0 degree wind. However, at $40 < SM < 65$, the 0 degree wind results in as much as 12 units higher CU_c than the 90 degree direction. When

SM>65 and CU_c values fall below 70, the θ = 90 degrees and θ = 45 degrees direction produces slightly higher values of CU_c.

It was found that at equal mainline spacings, the SR = 0.4 generally produced higher CU_c values than SR = 1.0. However, the area covered by one sprinkler is considerably less for a SR = 0.4 spacing than a SR = 1.0 spacing. For instance, the area of 20 feet x 50 feet is 1000 square feet compared to 2500 square feet with 50 feet x 50 feet.

The shape of the CU_c vs. SM curve, whether smooth or irregular, is dependent upon SR, K and θ. The combination of all factors determines the shape and must be considered for optimizing the CU_c as a function of spacing in system design.

In all cases the pattern shape, as shown in Figure 5, producing the highest values of CU_c depends upon the spacing of the overlapped pattern. Generally at close spacings (low SM values), pattern shape C produced the highest values of CU_c; at intermediate spacings, pattern A produced the highest values of CU_c; and at wide spacings, pattern shape B resulted in the highest CU_c values.

Conclusions

It is evident from this study that no one relative wind direction will consistently produce the best uniformity. Generally the optimum wind direction depends on the spacing and spacing regime utilized in the system design. For square spacings, a wind direction 45 degrees to the lateral line proved to produce the highest CU_c values.

Contrary to generally accepted recommendations, a wird direction parallel to the lateral line will produce the highest values of CU_c when spacing is less than 65 to 70 percent wetted diameter. At wider spacings, a wind direction perpendicular to the lateral line will produce higher CU_c values; however, at these spacings, CU_c values are often below those desired to meet system requirements.

This study shows that each pattern shape has a spacing range which will produce the highest uniformity of distribution. The specific spacing range will depend upon wind speed, nozzle size, and pressure and should be considered when designing the overall sprinkler system for these factors.

It was found that the effects of wind speed, nozzle size, and pressure on sprinkler uniformity are interrelated and that a measure of pattern stability will effectively describe the combined effect of these factors on sprinkler performance. This study shows that a reduction in spacing is necessary with decreased pattern stability. The amount of reduction is dependent not only on a decrease in pattern stability but also on the spacing regime of the system; ie, whether square or rectangular.

The shape of the CU_c-spacing curve is an important consideration for sprinkler spacing design. If it is assumed that a curve shape is a characteristic of one specific factor, pattern shape for example, spacing design for this factor becomes quite simple. It was found, however, that the shape of the CU_c-spacing curve is dependent upon wind direction, pattern stability, spacing ratio, and pattern shape.

A change in one or more of these design factors may radically change the shape of the CU_c-spacing curve. Therefore, all factors affecting the shape of the CU_c-spacing curve must be considered in sprinkler system design if high uniformity of distribution is important.

Additional work is needed for wind velocities greater than 12 miles per hour. Medium range nozzle sizes were tested for this analysis; nozzle sizes greater than 1/2 inch and smaller than 7/64 inch should be tested and analyzed to determine if the same trends follow throughout all nozzle sizes. More study is also needed to determine the effects of K, wind direction, spacing ratio, and pattern shape upon the shape of the CU_c vs. SM graph.

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APPENDICES

Appendix A

ASAE Recommendations and Data Forms

ASAE Recommendation: ASAE R330

PROCEDURE FOR SPRINKLER DISTRIBUTION TESTING FOR RESEARCH PURPOSES

Developed by the Sprinkler Irrigation Committee, approved by ASAE Soil and Water Division
Standards Committee, adopted by ASAE December 1969.

SECTION 1—PURPOSE AND SCOPE

1.1 This Recommendation has the following two purposes:

1.1.1 To provide a basis for the accumulation of data on the distribution characteristics of sprinklers.

1.1.2 To provide a uniform method for the presentation of the data described in paragraph 1.1.1.

1.2 The data collected are to be of such extent and accuracy as to assist sprinkler system designers in making rational decisions regarding the water distribution pattern of sprinklers.

1.3 This Recommendation describes the types and methods of obtaining and recording pertinent climatic data There must be a sufficient amount of data so that apparent conflicts between results of different investigators can be resolved.

1.4 No attempt is made here to define analysis procedures.

SECTION 2—SPRINKLER DESCRIPTION AND SELECTION

2.1 Number of sprinklers. Single sprinkler tests only are covered in these procedural recommendations. It is generally desirable to perform more than one test under ostensibly the same sprinkler operating and climatic conditions. Each test shall be reported separately and not combined with others in any way.

2.2 Selection of sprinklers. Any sprinkler used in these tests shall be chosen at random from normal production runs.

2.3 Description of sprinkler. The sprinkler shall be described in such a way that a completely unambiguous reference can be made to it at a future date. This description shall include, but not necessarily be limited to, the following:

Make
Model name and number
Serial number or other identifying mark
Nozzle diameter(s) and description(s)
Entrance fitting description (size, type, etc.)
Type of bearing
Other identifying information (e.g., straightening vanes, type of drive, etc.)

SECTION 3—TESTING INSTALLATION

3.1 Sprinkler location and installation.

3.1.1 The sprinkler shall be located in an area which has either a bare surface or less than 3 in. (8 mm) of vegetative growth. The land shall have a maximum slope of 1 percent for sprinklers discharging less than 35 gpm (2.21 liters per sec) and 2 percent for other sprinklers. The site shall be located such that there is a minimum clear distance upwind of the pattern area of 6 heights for each mile per hour (0.45 meter per sec) of wind speed up to a maximum of 30 heights for winds of 5 mph (2.23 meters per sec) or greater, and a minimum clear distance downwind of the pattern area equal to 5 heights of any downwind windbreak. A map showing location and height of windbreaks shall be included on the Standard Data Presentation Form. Tests shall not be run when these conditions are not satisfied.

3.1.2 The center of the main nozzle of the sprinkler shall be 2 ft (0.6m) above the average elevation of the tops of the 4 nearest collectors on land slopes of 1 percent or less, or 2 ft (0.6m) higher than the top of the highest collector on land slopes greater than 1 percent.

3.1.3 The sprinkler riser shall be vertical within 1 deg.

3.2 Collector description and location.

3.2.1 All collectors used to measure distribution shall be the same. They shall be designed such that the water does not splash out and such that evaporation is kept to a minimum. The collector shall be completely described on the data sheet. If an evaporation suppressant is used, its type and method of application shall be reported.

3.2.2 A square grid pattern of collectors shall be used, with the spacing between collectors being any whole number. The sprinkler shall be located in the center of a grid square (midway between 4 adjacent collectors). A minimum of 80 collectors shall receive water during a test. The position of the collectors shall be maintained such that the entrance portion is horizontal, as estimated by visual means.

3.2.3 The average above-ground height of the tops of the 4 collectors nearest the sprinkler shall be either 3 ft (0.9 m) above the ground, or, as an alternative, 1 ft (0.3 m) above the ground. This distance shall be reported as "collector height." For land slopes of 1 percent or less, the collectors shall be in a horizontal plane. For land slopes greater than 1 percent, the collectors shall be in a plane parallel to the average land slope.

3.3 Climatic measuring equipment and location.

3.3.1 The wind movement during the test period shall be measured with a rotating-cup totalizing anemometer, or a device of equal or better accuracy. Floating ball type devices are not satisfactory. The wind direction shall be measured with a wind vane on the basis of 8 points of the compass

3.3.2 Wind measuring equipment shall be located within the clear area as described in paragraph 3.1 but outside the sprinkler pattern, and at a height of 13 ft (4m).

3.3.3 Dry and wet bulb temperature measurements shall be made at a location where the microclimate is essentially unaffected by the operation of the sprinkler. This will normally be upwind of the pattern area.

SECTION 4—MEASUREMENTS

4.1 Sprinkler pressure.

4.1.1 The nozzle pressure is defined as the pitot-static pressure at the vena-contracta of the jet from the main (largest) nozzle. It shall be measured with a pitot tube and a pressure-indicating device accurate to within ±2 percent (at the sprinkler pressure) and reported.

4.1.2 The base pressure is defined as the pressure head at the sprinkler. This shall be measured at a point on the riser at least 2 riser diameters from any change of direction of flow or change in pipe cross-sectional area. Position shall be recorded. The base pressure shall vary not more than ±3 percent during a test.

4.2 Sprinkler flow. The flow through the sprinkler shall be measured and reported to an accuracy of ±3 percent. Volumetric measurements under the test pressure, made with a stop-watch and a container, or with a calibrated water meter, are satisfactory.

4.3 Sprinkler rotation. The rate of rotation of the sprinkler shall be measured and reported. The uniformity of rotation through the 4 quadrants shall be measured and reported.

4.4 Climatic data.

4.4.1 Wind measurements shall be taken at 15 maximum intervals of minutes. Distance shall be recorded to the nearest 0.1 mile (0.16 kilometer) of movement and directions to the nearest octant. Direction shall be keyed to one of the principal axes of the Standard Data Presentation Form.

4.4.2 Wet and dry bulb temperatures shall be measured at maximum intervals of 15 minutes.

4.5 Depth of application. The depth of application in each collector shall be determined to an accuracy of ±2 percent of the average application depth and reported in a table showing the location of the collector relative to the sprinkler (see Standard Data Presentation Form).

SECTION 5—TEST DURATION

5.1 Test duration. The preferable test duration is 1 hour. Other test durations may be used, but the circumstances and time must be clearly stated on the test sheet. Sprinklers shall be started and stopped at the same position and true total time recorded.

SECTION 6—REPORTING

6.1 Information to be recorded. The data outlined in Sections 2, 3, 4 and 5 shall be recorded on forms similar to those shown in Figs. 1 and 2. A separate set of sheets shall be prepared for each sprinkler test.

6.2 Deviations from recommended procedure. Deviations from the recommended procedure shall be indicated on the Standard Data Presentation Form for Sprinkler Distribution Tests.

6.3 Additional data. Additional data on the conduct of a test should be included if it will benefit the system designer or help explain vagaries in results.

Test Conditions

Testing Agency ______________________ Date ______________ Test No. ________

Sprinkler Specifications (Par. 2.3) ______________________________________

____

Test Location ______________________ Weather ______________________

1. Vertical distance from riser cap to nozzle, in. (Par. 4.1.2) ______________
2. Inside diameter of riser, in. ______________
3. Collector height, ft. (Par. 3.2.3) ______________
4. Collector entrance diameter, in. (Par. 3.2.1) ______________
5. Sprinkler height, ft. (Par. 3.1.2) ______________
6. Flow rate, gpm (Par. 4.2) ______________
7. Description of collector (Par. 3.2.1) ______________

____

____

____

8. Evaporation suppressant used ______________ Volume/collector ______________
9. Data during test:

Time	Wind		Temp.	°F	RH, %	Rotation rate, sec per full rev					Pres. psi	
	Mile	Dir.	DB	WB		Full	1st Q	2nd Q	3rd Q	4th Q	Nut	Base

10. Map of test area. Give the following:
    - a. Location of sprinkler.
    - b. Location of climatic measurement equipment.
    - c. Wind direction during test period.
    - d. Distance from sprinkler to all windbreaks (upwind, downwind, and to side).
    - e. Heights of all windbreaks.

This test ______ does ______ does not meet the criteria for sprinkler testing set forth in ASAE R330, Procedure for Sprinkler Distribution Testing for Research Purposes.

FIG. 1—STANDARD DATA PRESENTATION FORM, Test Conditions

Testing Agency ______________________ Date ______________________ Test. No. __________

Sprinkler Specifications ____

____

Test Location ______________________ Weather ______________________

___	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___
___	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___
___	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___
___	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___
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___	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___
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___	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___
___	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___

Above depths in inches x 100. Mark locations of sprinkler with plus (+) sign. Indicate prevailing wind direction by an arrow and give its least angle of deviation from a line parallel to one of the principal axes of this sheet. Grid spacing is_______ft.

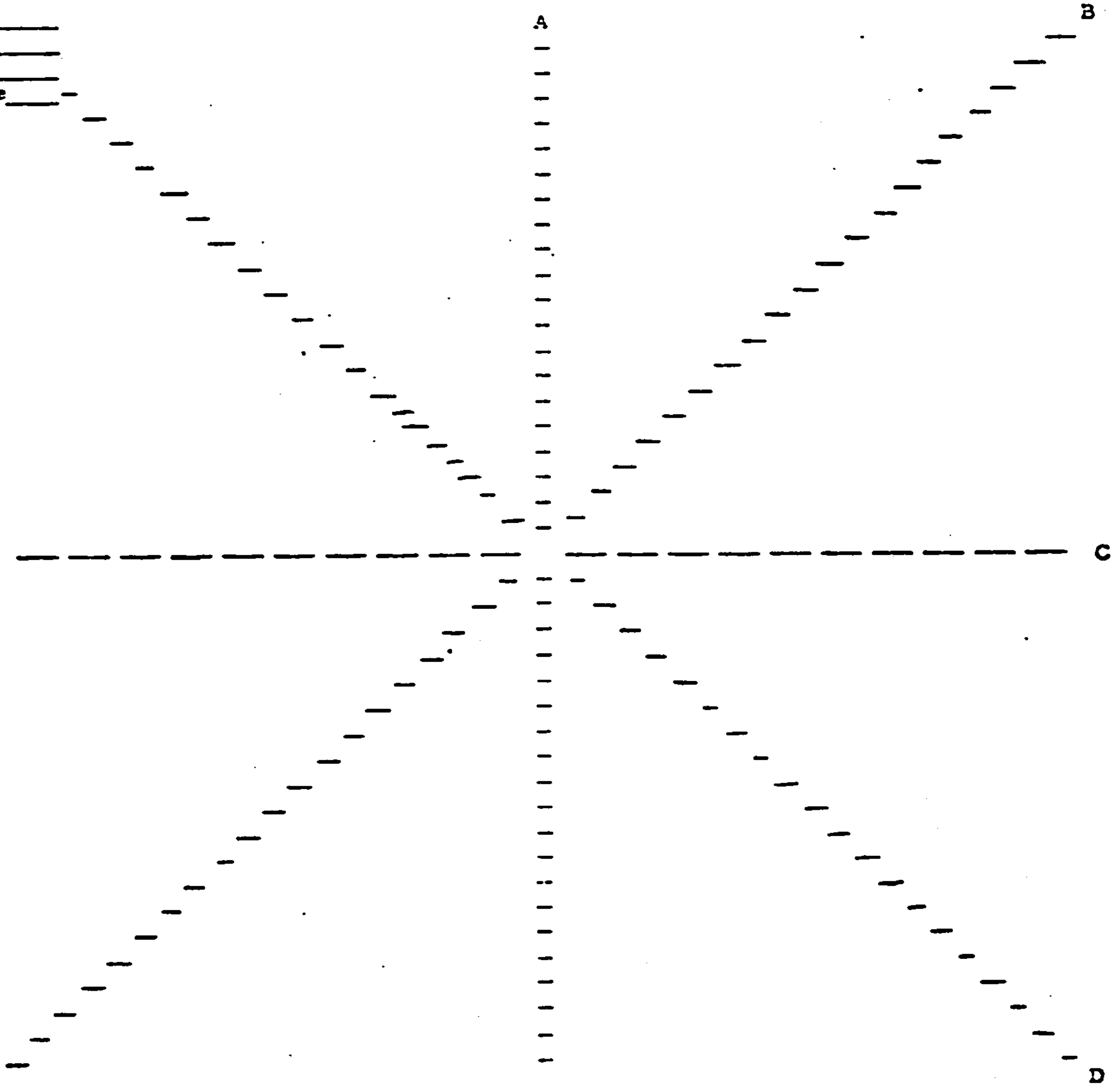
FIG. 2—STANDARD DATA PRESENTATION FORM, Map

1. Test No.__________
2. Sprinkler No.______
3. Sprinkler Model__________
4. Nozzle Sizes: Range_______ Spreader__________
5. Vane_______
6. Riser Height_______

7. Date__________
8. Time__________
9. Location______
10. Weather______
11. Evaporation: Begin Test______ End Test______
Begin Read______ End Read______

Cum. Test Time	Wind			Temp °F		RH,%	Rotation		RPM	Flow Rate Range Noz.			Flow Rate Spr. Noz.			Total Q	Pressure Psi	
	Direct.	Anem. Read.	Speed KM/HR	DB	WB		Time	No.Rev.		Time	Gal.	Q	Time	Gal.	Q		Noz.	Base

1. Test No. __________
2. Sprinkler No. ______
3. Range Nozzle ______
4. Spreader Nozzle____



Appendix B

Computer Programs

Shift in Center of Mass Calculation

Input Procedure

Data Cards

First Card: A Format

Column	
0-5	Test Number
16-21	Sprinkler Model
28-42	Nozzle Size
51-55	Nozzle Pressure
66-72	Wind Velocity

Second Card: F Format

Column	
1-5	Number of cans in the rows and columns of the sprinkler test. The cans must be symetrical about the sprinkler and the cans per row must equal the cans per column.
6-10	Catch-can spacing

The rest of the data cards are can-catch values. There are 20 can-catch readings per card. Where can-catch data was 0, this must be represented by placing a 0 or leaving a blank for this position on the data cards.

This computer program calculates the shift in center of mass with respect to the center of a no-wind sprinkler pattern. Theoretically, this point on the no-wind pattern will be located at the sprinkler with an equal distribution of water in all directions from the sprinkler.

Calculation of the center of mass is accomplished by setting up two perpendicular reference lines, x and y which are parallel to the lines made by the grid pattern of the catchment containers. The mass of water caught in each container on the grid pattern is multiplied times its linear distance in feet from each reference line. These values are summed for each reference line and this sum is divided by the sum of the masses of water in all the catchment containers. This calculation locates the center of mass with respect to the x-y reference lines. The location of the sprinkler with respect to the reference lines is a known value and is read into the program initially. By trigonometry the linear distance between the center of mass of the test pattern and the sprinkler point can be calculated which value represents the shift in center of mass of the particular sprinkler pattern.

When the center of mass for the sprinkler pattern has been located and the distance from sprinkler calculated, the program calculates the angular shift in center of mass with respect to the positive portion of the y axis. A plus angle indicates an angle measured counter-clockwise from this axis.

The shift in center of mass is dependent on the pressure, wind velocity, and nozzle size combination at the time of testing. A value defined as K in this study is calculated by dividing the shift in center of mass by the no-wind wetted diameter of the sprinkler pattern. This value is multiplied times 100 to achieve the shift in center of mass as a percent of the wetted diameter.

This program can be used either when the sprinkler is located at a grid point, or when the sprinkler is located midway between four adjacent grid points. A value, N, is read into the program. The value of N is even if the sprinkler location is midway between four adjacent grid points. If the sprinkler is located at a grid point the value of N is odd.

The Dimension statement includes two arrays. The C array consists of the sprinkler pattern to be read into the program with the sprinkler at the center of the array. The HED array consists of a heading card for each sprinkler pattern. This consists of the sprinkler number, nozzle pressure, and wind speed.

The second read statement reads the N value and a value for SPACE into the program. The SPACE value is the spacing of the catchment containers in the grid pattern. A third read statement reads the C array into the program. The C array consists of the masses or volumes of each catchment container beginning in the upper left corner of a square array.

The output of this program consists of the values read in on the HED statement plus the distance shift in center of mass and the angular shift in center of mass for the particular pattern.

Grid Rotation and Uniformity Coefficient Program

Input Procedure

Data Cards

First Card:

Column	
1-5	Number of spacing combinations to be investigated.

Second Card:

Column	
1-4	Spacing on the lateral as a proportion of the effective diameter.
5-8	Spacing of the Mainline as a proportion of the effective diameter.

There must be the same number of spacing combinations read in as indicated on the first card. The spacing combinations are read consecutively starting at the beginning of the second card using a 20 F 4.2 Format, 10 spacing combinations per card.

Third Card:

Column	
1-5	Number of cans in the rows and columns of the sprinkler test. The cans must be symetrical about the sprinkler. When the sprinkler is midway between four cans the number of cans is even. If the sprinkler is located on a grid point the number of cans in a row or column will be odd.
6-10	Catch can spacing.

Fourth Card:

Column	
1-5	Test Number
6-15	Shift in Center of Mass
16-25	Wind angle measured from North (plus angle counter-clockwise direction)
26-35	Effective Diameter. The effective diameter can be set at 100 so the proportion used on the 2nd card can be multiplied by 100 to equal the sprinkler spacing.
36-45	Desired grid spacing after interpolation for intermediate grid points. This spacing must be divisionable evenly into the can spacing for the sprinkler test.

The rest of the data cards are can-catch values. There are 20 can-catch readings per card. Where can-catch values are 0, these must be represented by placing a 0 or leaving a blank for this position on the data cards.

This computer program consists of three basic parts. Part A is a rotation of the grid points with respect to the wind direction, which essentially accomplishes a shift in wind direction - sprinkler spacing orientation.

Part B calculates, by interpolation, intermediate values between grid points of .25, .50, and .75 times the grid spacing. If the grid spacing were 10 feet, this would allow sprinkler spacings for CU_c calculations in intervals of 2.5 feet. Part C of the program superimposes the sprinkler patterns upon one another at the desired spacing and then calculates the value of CU_c.

The first read statment reads into the program a value called NSR. This stands for the number of spacing combinations to be used in the computation of the CU_c values. This value would be punched in the first 5 spaces of the first data card. The second read statement reads in values for SL and SM. These values represent the spacing on the lateral line and the spacing on the main line respectively. SL and SM values would be punched on subsequent data cards in the deck.

Input of the third read statement involves values for N and SPACE. The value for N will be either even or odd. An even value would be read in if the catchment grid pattern were arranged such that the sprinkler is located midway between 4 adjacent grid points. An odd value of N would be read in if the sprinkler is located at a grid point. The input for SPACE is the distance between the grid collectors. These values would be punched on a computer card with the format shown in the program.

Test number (ITEST), shift in center of mass (CG), wind direction (ANGLE), and the desired grid spacing after interpolation of intermediate grid points (S_2) are the input data of the fourth read statement. The S_2 value depends upon the desired spacings of SL and SM. If values of SL and SM are desired in multiples of 10, then S_2 = 10. If SL and SM are desired in multiples of 2.5, then S_2 = 2.5. The final input data involves reading in the sprinkler test pattern data. This data must be in a square array arrangement with the sprinkler located at the center of the pattern.

The initial output of the program consists of the readout of the rotated grid pattern data. The program is designed to initially rotate each grid data point such that the wind is initially from the same direction for all test data, ie. parallel to the x reference axis. When the pattern data is initially rotated the program calculates the intermediate points and then the CU_c values at all the desired spacings. The program will then rotate the data 45 degrees and make the intermediate points and CU_c calculations, and will then repeat this procedure for the 90 degree wind direction.

The final output consists of the test number, the shift in center of mass, the orientation of the wind (0 degrees = parallel to the x reference axis.), sprinkler spacing on lateral line, and lateral spacing on the main line. Outpout calculations of this program include the spacing ratio - SL/SM, CU_c, sprinkler spacing on the lateral and lateral spacing on main line expressed as a percentage of the no-wind wetted diameter of the sprinkler pattern.

```
C      SHIFT IN CENTER MASS CALCULATION
C
       DIMENSION C(24,24),HED(20)
       WRITE(6,101)
  101  FORMAT(1H1)
       WRITE (6,106)
  106  FORMAT(10X,'TEST NO.',4X,'SPRINKLER NO.',4X,'NOZZLE SIZE',4X,
      $'NOZZLE PRESSURE',4X,'WIND VELOCITY',4X,'SHIFT OF C. G.',4X,
      $'WIND ANGLE'/59X,'PSI',15X,'KM/HOUR',13X,'FEET',11X,'DEGREES'//)
    2  READ (5,104,END=3) (HED(I),I=1,20)
  104  FORMAT(20A4)
       READ (5,103) N,SPACE
C      N=DEMENSION OF THE SPRINKLER PATTERN TO BE READ IN
C        (NOTE=MUST BE SYMETRICAL ABOUT THE SPRINKLER)
C      IF N IS EVEN THE SPRINKLER IS MIDWAY BETWEEN 4 ADJACENT
C         COLLECTORS
C      IF N IS ODD THE SPRINKLER US LOCATED ON COLLECTOR POINT
C      SPACE=SPACING BETWEEN COLLECTOR POINTS
       IT=N/2*2-N
  103  FORMAT(I5,F5.1)
       READ (5,100)((C(I,J),J=1,N),I=1,N)
  100  FORMAT(20F4.1)
       XS=0.
       XM=0.
       YS=0.
       YM=0.
       DO 1 I=1,N
       DO 1 J=1,N
       CC=C(I,J)
       XM=XM+SPACE*FLOAT(J  )*CC
       YM=YM+SPACE*FLOAT(I  )*CC
       XS=XS+CC
    1  YS=YS+CC
       XC=XM/XS
       YC=YM/YS
       IF (IT .LT. 0) XG=FLOAT(N/2+1)*SPACE
       IF (IT .EQ. 0) XG=(FLOAT((N/2)+0.5))*SPACE
       YG=XG
       XD=XG-XC
       YD=YG-YC
       ALPHA=ATAN2(YD,XD)
       ALPHA=ALPHA*57.296-90.
       D=SQRT(XD**2+YD**2)
       WRITE (6,105) (HED(I),I=1,20),D,ALPHA
  105  FORMAT(10X,20A4, 5X,F6.2,10X,F7.2)
       GO TO 2
    3  WRITE (6,200)
  200  FORMAT(///20X,'NOTE--PLUS ANGLE IS CLOCKWISE MEASURED FROM NORTH')
       STOP
       END
```

```
C     CALCULATION OF GRID ROTATION
C
      DIMENSION C(24,24), CR(24,24),A(100,60),B(60,60),
     $CE(100,100),ILS(60),IMS(60),SL(60),SM(60)
      READ(5,100) NSR
C     NSR=NUMBER OF SPACING COMBINATIONS TO BE INVESTIGATED
10    FORMAT(I5)
      READ (5,908) (SL(N),SM(N),N=1,NSR)
C     SL(M)=SPACING ON THE LATERAL AS PERCENT OF EFFECTIVE
C           DIAMETER
C     SM(M)=SPACING ON THE MAIN AS PERCENT OF EFFECTIVE
C           DIAMETER
  9 8 FORMAT(20F4.2)
2     READ(5,101,END=3) N,SPACE
C     N=DEMENSION OF THE SPRINKLER PATTERN TO BE READ IN
C       (NOTE=MUST BE SYMETRICAL ABOUT THE SPRINKLER)
C     IF N IS EVEN THE SPRINKLER IS MIDWAY BETWEEN 4 ADJACENT
C        COLLECTORS
C     IF N IS ODD THE SPRINKLER US LOCATED ON COLLECTOR POINT
C     SPACE=SPACING BETWEEN COLLECTOR POINTS
10    FORMAT(I5,F5.1)
      IT=N/2*2-N
      NN=N
      ISPACE=SPACE
      READ(5,1001) ITEST,CG,ANGLE,DIA,S2
C     ITEST=TEST NUMBER OF DATA (FOR IDENTIFICATION PURPOSES)
C     CG=SHIFT IN CENTER OF MASS
C     ANGLE=DIRECTION FROM WHICH WIND IS BLOWING,PLUS ANGLE IS
C           CLOCKWISE MEASURED FROM NORTH
C     DIA=EFFECTIVE DIAMETER OF SPRINKLER (ZERO WIND)
C     S2=DESIRED GRID SPACING AFTER INTERPOLATION FOR
C        INTERMEDIATE POINTS
1001  FORMAT(I5, 4F10.0)
      DO 85 I=1,NSR
      ASPM=SM(I)*DIA/S2
      ASPL=SL(I)*DIA/S2
      ISPL=ASPL
      ISPM=ASPM
      ASPL2=ISPL
      ASPM2=ISPM
      RM=ASPM-ASPM2
      RL=ASPL-ASPL2
      IF(RM .GE. 0.5) ISPM=ISPM+1
      IF (RL .GE. 0.5) ISPL=ISPL+1
      ILS(I)=ISPL
    5 IMS(I)=ISPM
      READ(5,102) ((C(I,J),J=1,N),I=1,N)
C     C(I,J)=SINGLE SPRINKLER TEST PATTERN DATA
```

```
   12 FORMAT(20F4.1)
      DO 2010 I=1,6
      ANG1=15
      ALPHA=ANGLE-FLOAT(I-1)*ANG1
      ND=N/2+1
      IF(IT.EQ.0) RAD=(FLOAT(N/2)-0.5)*SPACE
      IF(IT.LT.0) RAD=(N/2)*SPACE
      ALPHA=ALPHA/57.29578
      N1=N+1
      DO 4 I=1,N
      DO 4 J=1,N
      IF(IT.EQ.0) GO TO 12
      IF ( I.EQ.ND .AND. J .EQ. ND)   GO TO 6
12    X=FLOAT(J-1)*SPACE-RAD
      Y=RAD-FLOAT(I-1)*SPACE
      XL=SQRT(X*X+Y*Y)
      IF(IT.EQ.0) GO TO 9
      IF (J .NE. ND) GO TO 9
      IF (I .GT. ND) BETA=-1.570795
      IF (I .LT. ND) BETA=1.570795
      GO TO 10
    9 BETA=ATAN2(Y,X)
   10 SA=SIN(BETA+ALPHA)
      CA=COS(BETA+ALPHA)
      X=XL*CA+RAD
      Y=RAD-XL*SA
      IF (ABS(X-RAD) .LE. .01  ) GO TO 11
      IF(X.GE.0.) GO TO 70
      IX=X
      XT=FLOAT(IX/ISPACE-1)*SPACE
      GO TO 71
70    IX=X
      XT=FLOAT(IX/ISPACE)*SPACE
71    IF(Y.GE.0.) GO TO 72
      IY=Y
      YT=FLOAT(IY/ISPACE-1)*SPACE
      GO TO 73
72    IY=Y
      YT=FLOAT(IY/ISPACE)*SPACE
73    XTP=XT+SPACE
      YTP=YT+SPACE
      II=0
      T=(RAD-Y)/(X-RAD)
      IF (ABS(T) .LE. .00001) GO TO 27
    9 YL=RAD-YT
      XL=YL/T
      YL=RAD-YL
      XL=RAD+XL
      J1=1
      IF((XT-XL) .LE..0001 .AND. (XL-XTP) .LE. .0001)
     $GO TO 25
    6 YL=RAD-YTP
      XL=YL/T
      YL=RAD-YL
```

```
      XL =RAD+XL
      J1 =2
      IF ((XT-XL) .LE..0001 .AND. (XL -XTP) .LE. .0001)
     $GO TO 25
    7 XL =XT-RAD
      YL =XL*T
      XL =XL+RAD
      YL =RAD-YL
      J1 =3
      IF ((YT-YL) .LE. .0001 .AND. (YL -YTP) .LE. .0001)
     $GO TO 25
    8 XL =XTP-RAD
      YL =XL*T
      XL =XL+RAD
      YL =RAD-YL
      J1 =4
      IF ((YT-YL) .LE. .0001 .AND. (YL -YTP) .LE. .0001)
     $GO TO 25
    7 WRITE (6,120) I,J,ALPHA,X,Y
  120 FORMAT(10X,'PROGRAM FAILURE AT I=',I5,3X,'J=',I5,3X
     $,'ALPHA=',F6.2,5X,'X= ',F6.2,5X,'Y= ',F6.2)
      STOP
    5 II =II+1
      IF (J1.LE. 2) GO TO 34
      I1 =XL+.02
      I1 =I1/ISPACE+1
      I0 =YL+.02
      I0 =I0/ISPACE+1
      I3 =I1
      I2 =I0+1
      D= YL -YT
      GO TO 35
    4 I1 =XL+.02
      I1 =I1/ISPACE+1
      I0 =YL+.02
      I0 =I0/ISPACE+1
      I3 =I1+1
      I2 =I0
      D= XL -XT
    5 GO TO (29,30),II
    9 X1 =XL
      Y1 =YL
      D1 =D
      I4 =I0
      I5 =I1
      I6 =I2
      I7 =I3
    6 GO TO (26,27,28,37),J1
    0 X2 =XL
      Y2 =YL
      D2 =D
      IF (ABS(X1-X2) .GE. .01 .OR . ABS(Y1-Y2) .GE. .01)
     $GO TO 31
      II =II-1
```

```
      GO TO 36
    1 F1=0.
      F2=0.
      IF ((I4.LE. N.AND. I4.GE. 1) .AND. (I5 .LE.N .AND.
     $I5 .GE. 1)) F1=C(I4,I5)
      IF ((I6.LE. N.AND. I6.GE. 1) .AND. (I7 .LE.N .AND.
     $I7 .GE. 1)) F2=C(I6,I7)
      V1=F1+D1/SPACE*(F2-F1)
      F1=0.
      F2=0.
      IF ((I0.LE. N.AND. I0.GE. 1) .AND. (I1 .LE.N .AND.
     $I1 .GE. 1)) F1=C(I0,I1)
      IF ((I2.LE. N.AND. I2.GE. 1) .AND. (I3 .LE.N .AND.
     $I3 .GE. 1)) F2=C(I2,I3)
      V2=F1+D2/SPACE*(F2-F1)
      D=SQRT((X-X1)**2+(Y-Y1)**2)
      DT=SQRT((X2-X1)**2+(Y2-Y1)**2)
    4 CR(I,J)=V1+D/DT*(V2-V1)
      GO TO 4
    6 CR(I,J)=C(I,J)
      GO TO 4
   11 JY=Y/SPACE
      D=Y-FLOAT(JY)*SPACE
      JY=JY+1
      JY1=JY+1
      CR(I,J)=C(ND,JY)+D/SPACE*(C(ND,JY1)-C(ND,JY))
    4 CONTINUE
      WRITE(6,2040)
2040  FORMAT(1H1)
      DO 2039 I=1,N
2039  WRITE(6,105) (CR(I,J),J=1,N)
105   FOPMAT(5X,24F5.1)
      WRITE(6,2020)
2020  FORMAT(///, 6X,'TEST NO.', 7X,'CG SHIFT', 7X,
     $'WIND ANGLE',10X,'LS'
     3,10X,'MS',10X,'SR',10X,'CU',12X,'SL',10X,'SM'/)
C
C     CALCULATION OF INTERMEDIATE GRID POINTS BY LINEAR
C        INTERPOLATION
C
      L=(SPACE+.02)/S2
      IF(L.EQ.1) GO TO 804
      L1=L-1
      N1=N-1
      DO 900 I=1,N
      DO 800 J=1,N1
      F1=CR(I,J)
      F2=CR(I,J+1)
      I1=L*(I-1)+1
      J1=L*(J-1)+1
      CE(I1,J1) = CR(I,J)
      CE(I1,J1+L)=CR(I,J+1)
      DO 801 K=1,L1
801   CE(I1,J1+K)=F1+FLOAT(K)/FLOAT(L)*(F2-F1)
```

```
80       CONTINUE
         NN=L*(N-1)+1
         N4=NN-L
         DO 803 I=1,N4,L
         DO 803 J=1,NN
         F1=CE(I,J)
         F2=CE(I+L,J)
         DO 802 K=1,L1
80       CE(I+K,J)=F1+FLOAT(K)/FLOAT(L)*(F2-F1)
80       CONTINUE
C
C        SUPERIMPOSITION OF SPRINKLER PATTERN AND
C        CALCATION OF UNIFORMITY COEFFICIENT
C
         ND=NN/2+1
80       DO 64 M=1,NSP
         LS=ILS(M)
         MS=IMS(M)
         LS1 = LS + ND
         DO 51 J = ND,LS1
         JJ=J
         IF(JJ.LE.NN) GO TO 88
89       JJ=JJ-LS
         IF(JJ.GT.NN) GO TO 89
88       I1=JJ
         I2=JJ
         I3=J-ND+1
         DO 56 I=1,NN
56       A(I,I3)=CE(I,JJ)
53       I1=I1+LS
         I2=I2-LS
         IF(I1.GT.NN) GO TO 50
         DO 54 I=1,NN
54       A(I,I3)=A(I,I3)+CE(I,I1)
50       IF(I2.LT.1) GO TO 51
         DO 55 I=1,NN
55       A(I,I3)=A(I,I3)+CE(I,I2)
         GO TO 53
51       CONTINUE
         MS1=MS+ND
         LS2=LS+1
         DO 57 I=ND,MS1
         IIJ=I
         IF(IIJ.LE.NN) GO TO 90
91       IIJ=IIJ-MS
         IF(IIJ.GT.NN) GO TO 91
90       J1=IIJ
         J2=IIJ
         I3=I-ND+1
         DO 60 II=1,LS2
60       B(I3,II)=A(IIJ,II)
67       J1=J1+MS
         J2=J2-MS
         IF(J1.GT.NN) GO TO 58
```

```
      DO 61 II=1,LS2
61    B(I3,II)=B(I3,II)+A(J1,II)
58    IF(J2.LT.1) GO TO 57
      DO 63 II=1,LS2
63    B(I3,II)=B(I3,II)+A(J2,II)
      GO TO 67
57    CONTINUE
      MS2=MS+1
      SUM=0.
      DO 65 I=1,MS2
      DO 65 J=1,LS2
65    SUM=SUM+B(I,J)
      AVG =SUM/FLOAT(LS2*MS2)
      SD=0.
      DO 66 I=1,MS2
      DO 66 J=1,LS2
      DEV = ABS(B(I,J)-AVG)
66    SD=SD+DEV
      CU=100.*(1.-SD/SUM)
      AMS=SM(M)*DIA
      ALS=SL(M)*DIA
      SR=ALS/AMS
      WRITE(6,2030) ITEST,CG,ANG1,ALS,AMS,SR,CU,SL(M),SM(M)
20 3  FORMAT(1H ,5X,I5,10X,F6.2,10X,F6.2,10X,F5.1,7X,F5.1
     $,6X,F6.4,7X,F6.2, 7X,F6.2,6X,F6.2)
64    CONTINUE
20 1  CONTINUE
      GO TO 2
 3    STOP
      END
```

Appendix C

Summary of Single Sprinkler Test Data

Table 3. Pattern stability indices, wind direction angles, and test conditions for single sprinkler tests used in this study.

Test No.	Pat. Shape	Nozzle Diameter (inches)	Noz. Pres. (psi)	Wind Vel. (mph)	Wetted Diameter (feet)	Wind* Angle Degrees	K
18	A	11/64	50	1.55	95	49.82	0.40
28	A	9/64	46	2.23	84	-8.36	4.22
24	A	7/32	46	2.29	104	-19.28	2.56
45	A	11/64	42	3.35	92	-113.89	9.05
37	A	9/64	47	5.83	84	-115.08	15.35
2	A	11/64	50	6.70	95	-98.95	13.22
32	A	7/32	46	12.05	104	-215.88	19.88
1670	A	9/64	60	2.00	87	82.71	6.53
2415	A	9/64	50	2.10	85	-183.88	4.50
2608	A	9/64	40	2.60	83	-1.77	5.80
1641	A	9/64	60	4.10	87	31.23	8.72
2606	A	9/64	40	4.60	83	38.27	10.70
2349	A	9/64	50	4.80	85	4.71	7.96

*Note Plus is measured clockwise from north.

Table 3. Continued

Test No.	Pat. Shape	Nozzle Diameter (inches)	Noz. Pres. (psi)	Wind Vel. (mph)	Wetted Diameter (feet)	Wind* Angle Degrees	K
2605	A	9/64	50	5.8	85	55.71	13.70
1675	A	9/64	60	7.5	87	35.10	14.57
1677	A	9/64	40	7.8	83	36.46	12.12
2427	A	9/64	40	12.2	83	24.23	18.38
16133	A	11/64	50	1.7	95	-213.67	2.45
2420	A	11/64	50	3.7	95	26.94	7.43
2398	A	11/64	50	4.2	95	21.76	6.86
2418	A	11/64	50	5.9	95	27.94	10.29
2422	A	11/64	50	6.7	95	37.62	11.65
1659	A	3/16	50	0.9	100	-240.21	1.13
1657	A	3/16	60	1.2	102	-6.75	1.18
14792	A	3/16	40	2.0	96	-59.61	2.08
2478	A	3/16	40	4.0	96	36.80	4.16
1663	A	3/16	50	4.0	100	78.80	7.52
1687	A	3/16	60	4.1	102	-76.07	5.64

* Note Plus angle is measured clockwise from north.

Table 3. Continued

Test No.	Pat. Shape	Nozzle Diameter (inches)	Noz. Pres. (psi)	Wind Vel. (mph)	Wetted Diameter (feet)	Wind* Angle Degrees	K
1390	A	3/16	40	4.1	96	29.34	4.27
1667	A	3/16	50	7.7	100	52.81	13.80
2586	A	3/16	60	7.8	102	84.68	14.65
2561	A	3/16	40	7.9	96	73.40	8.22
2483	A	3/16	60	8.1	102	84.08	13.40
14640	A	3/16	50	8.3	100	33.53	11.79
2585	A	3/16	60	11.3	102	76.97	19.10
2559	A	3/16	50	11.5	100	55.29	18.67
43	B	11/64	44	2.11	98	-129.68	2.27
11	B	11/64	35	2.11	94	-110.35	3.15
29	B	7/32	35	2.23	104	-39.37	3.94
25	B	9/64	33	2.54	88	-103.11	4.10
44	B	9/64	44	2.61	92	-136.80	7.10
39	B	7/32	44	3.48	108	-117.54	11.05

* Note Plus angle is measured clockwise from north.

Table 3. Continued

Test No.	Pat. Shape	Nozzle Diameter (inches)		Noz. Pres. (psi)	Wind Vel. (mph)	Wetted Diameter (feet)	Wind* Angle Degrees	K
9	B	7/32		35	4.03	104	-103.31	8.18
36	B	11/64		37	4.72	95	-106.69	13.20
21	B	9/64		36	6.20	89	-222.07	11.63
3	B	11/64		45	8.55	98	-104.32	16.47
33	B	7/32		36	9.42	104	-207.21	16.36
1	C	11/64	3/32	52	1.86	95	-195.86	5.10
30	C	7/32	1/8	47	2.42	105	-231.43	3.20
17	C	9/64	3/32	50	2.42	85	17.20	4.57
6	C	7/32	1/8	47	2.61	105	-99.32	5.03
41	C	11/64	3/32	40	3.85	92	-100.75	7.46
26	C	7/32	1/8	44	4.47	104	-97.70	7.80
31	C	9/64	3/32	46	5.65	84	-102.64	9.75
23	C	11/64	3/32	47	6.82	94	-214.04	11.90

* Note Plus angle is measured clockwise from north.

Table 3. Continued

Test. No.	Pat. Shape	Nozzle Diameter (inches)		Noz. Pres. (psi)	Wind Vel. (mph)	Wetted Diameter (feet)	Wind* Angle Degrees	K
4	C	11/64	3/32	50	7.43	95	-99.00	14.15
22	C	7/32	1/8	45	8.32	104	-230.58	13.00
27	C	9/64	3/32	46	8.55	84	-211.23	17.11
5	C	7/32	1/8	46	8.62	104	-83.30	13.80
14717	C	11/64	3/32	50	3.00	95	66.85	4.58
14795	C	11/64	3/32	50	3.60	95	46.94	5.65
2569	C	11/64	3/32	50	3.80	95	39.65	6.74
14794	C	11/64	3/32	50	5.00	95	38.72	6.63
2567	C	11/64	3/32	50	5.70	95	48.83	10.25
14796	C	11/64	3/32	50	6.00	95	48.72	6.82
2570	C	11/64	3/32	50	6.40	95	16.63	11.93
1372	C	11/64	3/32	50	7.90	95	35.51	11.30
14750	C	11/64	3/32	50	8.80	95	39.08	11.00
2582	C	11/64	3/32	50	11.40	95	77.45	18.00
2574	C	11/64	3/32	50	12.00	95	69.72	18.10

* Note Plus angle is measured clockwise from north.

VITA

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