## Bibliographic Data Sheet

1. Subject Classification

Irrigation

2. Publication Number

PN-AAA- 440

3. Title and Subtitle

The Use of Sprinkler Profiles to Predict Field Performance

4. Author(s)

Michael D. Moynahan

5. Report Date

1972

6. Number of Pages

88p 89

7. ARC Number

ARC-No. ( 631.7072 - M938 )

8. Performance Organization Name and Address

Utah State University
Dept. of Agricultural Engineering
Logan, Utah 84321

9. Supplementary Notes: (e.g. Sponsoring Organization, Publishers, Availability)

10. Abstract

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The method utilizes the shift in the center of mass of the single sprinkler pattern to characterize wind speed. Values of UC versus spacing along the main as a percentage of the effective diameter, 100 $Sm/D_e$, were plotted for a sprinkler spacing on the lateral of 3% of $D_e$. From these plots, called "basic UC curves", functional relationships were developed to predict the field performance of a particular sprinkler nozzle pressure combination under a variety of steady state wind conditions from a knowledge of the zero wind basic UC curve for that combination.

11. Descriptors

Geometric profiles

12. Project No.

931-11-120-116

13. Contract No.

AID/csd-2459

14. Type of Report

Thesis

# THE USE OF SPRINKLER PROFILES TO PREDICT FIELD PERFORMANCE

by

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A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Agricultural and Irrigation Engineering

Approved:

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1972

# ACKNOWLEDGMENTS

For their guidance, help and encouragement, the author wishes to express his gratitude to the committee members: Dr. John R. Hanks, chairman, Dr. Komain Unhanand, and Dr. Jack Keller, thesis director.

Whole hearted thanks is expressed to Lanny Ptacek, a fellow graduate research assistant on this project and also to Bob Harris for wirting the computer programs used in the analysis.

Appreciation is expressed to the Ministry of Agriculture in El Salvador for allowing the research to be conducted in that country. Thanks is also expressed to Ing. Andres Solorzano Burgas, Director of the Dept. of Irrigation and Drainage and his staff for the assistance and equipment. A special thanks is expressed to Mr. Richard Griffin, USAID advisor, and his family for the help rendered.

The author thanks the Agricultural and Irrigation Engineering Department and contract AID/csd-2459 for financial assistance and Linda Findlay for typing assistance.

And finally to my wife and family for their understanding and encouragement.

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

Michael D. Moynahan

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# ABSTRACT

## The Use of Sprinkler Profiles to Predict Field Performance

by

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Utah State University, 1972

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A method was developed and successfully tested for predicting the field performance of sprinklers for a variety of steady state wind conditions from a limited number of single sprinkler tests. Three basic geometric profile shapes were investigated.

The method utilizes the shift in the center of mass of the single sprinkler pattern to characterize wind speed. Values of UC versus spacing along the main as a percentage of the effective diameter, $100\ Sm/D_e$, were plotted for a sprinkler spacing on the lateral of 3% of $D_e$. From these plots, called "basic UC curves," functional relationships were developed to predict the field performance of a particular sprinkler nozzle pressure combination under a variety of steady state wind conditions from a knowledge of the zero wind basic UC curve for that combination.

(88 pages)

# INTRODUCTION

Sprinkler irrigation, in recent years, has developed into a highly sophisticated method of irrigation. The ultimate goal of sprinkler system design is to optimize the potential returns from a particular irrigated area. This requires considering the interaction of the concept of system capacity, crop production versus water applied, operating costs with optimized fixed costs, spray losses, water quality, and water application distribution.

There have been procedures, such as presented by Keller (1965), developed for optimizing fixed and operational costs in the hydraulic networks of sprinkler irrigation systems.

Several investigators, such as Culver and Sinker (1966), Howell (1964), Liang and Wu (1970), and Norum (1966) have studied the interaction between these factors. The major controlling factors needed to begin the optimization precess for system design are water application distribution and crop production versus water application for given system capacities and climatic conditions.

Much of the data available at the present time concerning the crop production function, that is, the relationship between crop yield and the amount of water applied is hard to interpret and not accurate. Some studies in this area have been conducted by Hogg, and Chang (1969), Musick and Dusek (1971) and Yaron (1971), however, many researchers are active in this area and it is hoped that more adequate information will be available in the near future.

As a first step in optimizing a system design, the field performance of each sprinkler-pressure-nozzle-spacing combination selected under the anticipated field environmental conditions must be predicted. At the present time, no reliable method exists to predict field performance of a particular sprinkler design combination without actually testing the combination under similar environmental conditions.

## Objectives

The objectives of this research are to answer the following questions:

What is the effect of sprinkler nozzle-pressure interaction on the profile shape and stability under steady state winds?

Can a technique be developed for predicting the field performance of a sprinkler nozzle-pressure-spacing combination from single sprinkler test data taken under a limited number of steady state wind conditions? It is hoped that the technique will contribute to the optimization of the overall development objectives, as well as be useful in the design of less sophisticated sprinkler irrigation systems.

# REVIEW OF LITERATURE

## Factors Affecting Distribution Uniformity

There have been many studies made investigating the factors which affect the distribution uniformity of sprinkler irrigation systems, such as Christiansen (1942), Molenarr et al. (1954), Pair (1968), Pair et al. (1969), Wiersma (1950), and Redditt (1965). They can be grouped into three categories: Environmental factors (mainly wind); mechanical operating conditions of the sprinkler; and spacing along the lateral and between the lateral.

### Environmental factors

When considering the environmental effects on system distribution uniformity one must consider the wind speed and direction; wind histories as related to set time; and spray losses.

Wind speed and direction. Christiansen (1941), one of the pioneers in sprinkler irrigation research, states that the influence of wind on the distribution pattern of a single sprinkler is quite pronounced. There is generally a high concentration of water near the sprinkler on the up wind side, normal to the direction of wind, and a deficiency on the down wind side. Christiansen concludes, however, that the effect of wind on the distribution uniformity over a large area can largely be overcome by proper spacing of the sprinkler to provide an adequate overlap, because "with wind the local areas of high and low concentrations always occur at the same relative position with respect to the sprinkler and do not overlap on themselves and produce an exaggerated effect" (Christiansen, 1941, p. 85).

It has generally been concluded by investigators such as Allison and Hesse (1969), Christiansen (1941), Culver and Sinker (1966), Scott and Corry (1954); and sprinkler manufacturers such as Rain Bird and Buckner that a reduction in spacing can adequately compensate for distortions of the distribution pattern due to wind.

The general recommendation for a medium pressure rotating sprinkler is that the maximum spacing under no wind conditions should not exceed 65% of the effective diameter and as wind speed increases the spacing as a percent of the effective diameter should be reduced to a maximum of 30% of the effective diameter. However, there seems to be some confusion as to the specific amount of reduction required for a given wind speed. The confusion arises because there are several distinct profile patterns produced by sprinklers and each reacts differently to wind. Strong (1961) utilizing results from the early work of Christiansen (1941) and actual test data, has presented a performance table for selecting the proper spacing of various sprinkler profiles representing single and double nozzle sprinkler patterns under different wind conditions.

The results of studies by Hart (1959) show that the preferred wind angle is parallel to the lateral or perpendicular to the long dimension of a rectangular spacing. Fry (1969) and Seginer (1969) recommend the lateral be placed perpendicular to the wind direction. Wiersma (1950) concluded from a comprehensive study of factors effecting distribution uniformity that in no case was there found to be a significant difference in distribution uniformity due to angle of wind approach. However, he states that the trend indicates the best results are obtained when the angle of wind with respect to the lateral is between 15° and 45°. It can be concluded from these studies that there is no single wind orientation which provides a superior uniformity for all sprinkler spacings and wind conditions. This is the conclusion reached by Ptacek (1972) in a study made in conjunction with the present one.

Branscheid (1971)[1] proposed using the shift in the center of mass of the wind effected single sprinkler pattern as a good indication of the integrated wind velocity and directional parameters. If the direction were stable, there would be a maximum shift in the center of mass for a given wind velocity. However, even under very high winds, it would be possible for the velocity vectors to shift direction in such a manner that the center of mass would remain at the sprinkler.

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[1] Verbal communications.

Wind histories. There have been studies made to investigate the effect on uniformity of varying wind histories during the set, from one set to the next and the net uniformity resulting from variations in wind histories over a complete irrigation season. Intuitively, it would appear that wind variations during a single set would improve uniformity. This has been shown to be true, however, the increase is not large and may not be important in practice (Seginer, 1969).

Seginer (1969) used the concept of convergence and divergence of patterns to describe the effect of diurnal wind changes on day and night sets. He also investigated the effect on uniformity of relative direction of lateral move to the component of wind. Convergence will cause an increase in the average depth between the two lateral positions as well as an increase in uniformity. Divergence has the opposite effect. With day and night sets, alternating convergence and divergence will occur. Both Branschied and Hart (1968), and Seginer (1969) conclude that errors result when wind histories are ignored and a move system is evaluated as if it were a solid set system. In no case will wind variation between sets improve distribution uniformity (Branschied and Hart, 1968).

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.

Spray losses. The effect of spray losses on distribution uniformity has not been fully investigated. Sternberg (1967) has conducted a comprehensive study concerning the effect wind has on the amount of spray loss occurring during sprinkler irrigation and an evaluation of day versus night irrigation.

### Mechanical operating conditions of the sprinkler

Physical sprinkler design. Theoretical investigations such as Bilanski and Kidder (1958) and Seginer (1963) have been conducted to analyze the effect physical sprinkler design has on water distribution. Seginer (1963) concludes that small differences in sprinkler construction, such as in the shape of the sprinkler body or nozzle, do not cause major differences in sprinkler performance. A knowledge of the aerodynamic aspects of sprinkler jets may be useful in mechanical design, however, it has not proven successful in predicting field performance.

Nozzle size and discharge. It has been found that as the nozzle size increases for a given pressure and sprinkler spacing, the distribution uniformity also increases for conditions of moderate to high winds (Wiersma, 1950). The larger nozzles tend to produce large drops which are less subject to wind drift than smaller droplets. However, the intake characteristics of the soil usually limit the size of the nozzle which can be utilized.

Rate and uniformity of rotation. Christiansen (1941) demonstrated that high rate and non-uniformity of rotation were major contributors to the poor performance of some sprinklers. His criteria of 1-2 rpm for medium pressure sprinklers still applies today, however, new innovations in bearing materials have eliminated non-uniformity of rotation as a major factor. Bilanski and Kidder (1958) reported that an increase in the speed of rotation of sprinklers resulted in a decreased range. One explanation is that the drops use energy to accelerate air particles around them by means of friction. A change in the direction of the jet requires some additional energy to start the movement of the air in the new direction. As a result, the kinetic energy of the drops and therefore, the range decreases (Ohler, 1949).

Riser height. The findings of Wiersma (1950), later confirmed by Hart (1959) indicate that in winds of less than 4 mph riser height above the crop has little effect on uniformity, but in moderate to high winds, riser height becomes highly significant. The difference in uniformities between 6 inch and 24 inch risers is much greater than between 24 inch and 48 inch risers. This is true because a turbulent air layer exists near the surface of the crop due to crop roughness. Once the sprinkler head has reached the fringes of this layer, an increase in height has little more effect (Keller et al., 1967). Hart (1959), however, found that as riser height increased excessive water losses from wind drift increased.

Operating pressure. It is generally agreed that an optimum pressure range exists for a given nozzle size where satisfactory jet breakup and desirable pattern cross-section occur. Distribution uniformity increases with an increase in pressure until the optimum pressure range is reached, after which the uniformity may begin to decrease (Christiansen, 1941 Seginer, 1963; and Wiersma, 1950). According to Seginer (1963) operating pressure is the most important factor contributing to satisfactory sprinkler performance. The higher the pressure, the longer the range of the drops, the finer the drops and the more even the distribution of the water on the ground.

### Spacing along the lateral and between the laterals

It can generally be said that as spacing between sprinklers increases, the distribution uniformity will decrease (Hart, 1959). Many factors must be considered when selecting sprinkler spacing, such as operating pressure, nozzle size, sprinkler geometric profile and wind parameters. A more comprehensive look at sprinkler spacing can be found in the portion of the Review of Literature entitled "Predicting Field Distribution Uniformity."

## Distribution Uniformity

Distribution uniformity can be defined as the evenness with which water is applied over the area irrigated. The area of coverage of most sprinklers is circular and the spacing configuration rectangular. Therefore, a perfectly uniform water application is impossible.

Christiansen (1941) proposed a means of evaluating sprinkler distribution uniformity with a single parameter, which he called the "uniformity coefficient." The uniformity coefficient expressed as a percentage is defined by the equation,

$$UC = 100\left(1 - \frac{\Sigma d}{mn}\right) \qquad (1)$$

where d is the deviation of individual observations from the mean value, m; and n is the number of observations.

Numerous investigators, such as Beale and Howell (1966), Benami and Hore (1964), Dabbous (1962), Hart (1961), Howell (1964), and Wilcox and MacDougald (1954) have compared various means of evaluating sprinkler uniformity and have attempted to develop better indices to describe the degree of pattern uniformity. It has been generally concluded that for relatively high UC values, Christiansen's uniformity coefficient provides a good estimate of water distribution.

The lack of a clear cut relationship between the uniformity coefficient and irrigation efficiency has been a limitation in its use as an index in sprinkler system design (Allison and Hesse, 1969). A UC value of 80 is generally considered adequate or acceptable, however, it is difficult to interpret this value in a physical sense.

Hart (1961) shows that the water application distribution from closely spaced stationary sprinklers nearly approximates a normal or Gaussian distribution. Seniwongse, Wu and Reynolds (1970) supported Hart for UC values greater than 75. Hart and Reynolds (1965), assuming a normal distribution, presented a means of predicting the entire distribution function for any UC value greater than 75. In other words, for a given value of UC and average depth of water applied, the percentage of area receiving any given depth of water can be predicted.

Allison and Hesse (1969) present a method for graphically obtaining the relationships between the coefficient of uniformity and the effective use of water. The reasoning is similar to Hart's, that is, it is based on the assumption that a sprinkler pattern approaches a normal distribution.

## Predicting Field Distribution Uniformity

The purpose of most sprinkler testing is to predict the field distribution which can be anticipated under actual operating conditions.

The common practice has been to run a single sprinkler test, and by a process of superimposition, simulate various sprinkler spacings to predict the field performance of the sprinkler. Branscheid and Hart (1968) compared test results from single sprinkler tests with test data from sprinkler laterals running simultaneously and concluded the superimposition process produced reliable results.

In order to predict the field performance of a given sprinkler, it is necessary to know the expected field environmental conditions (mainly wind speed and direction) and test stand performance of the sprinkler under similar environmental conditions. Assuming the field conditions can be anticipated, a major obstacle to design is the general shortage of sprinkler test data, since such a large number of tests are necessary in order to categorize each sprinkler-nozzle-pressure combination under all possible environmental conditions.

In order to simplify sprinkler selection and anticipate performance at various spacings, Christiansen (1941) presented the geometric sprinkler profile concept. (The geometric profile is the plot of distance from the sprinkler versus depth of application.) He explored the possibility of analyzing the geometric profiles in an effort to predict UC for various sprinkler spacing situations.

In his study, Christiansen worked with six basic sprinkler geometric profiles, some of which approximated actual sprinklers, as shown in Figure 1[1]. Coefficients of uniformity were determined for various profiles with different spacing along the main and with a spacing of 5 percent of the diameter along the lateral line. Figure 1 shows Christiansen's dimensionless curves of UC plotted against spacing along the main for each of the basic profiles.

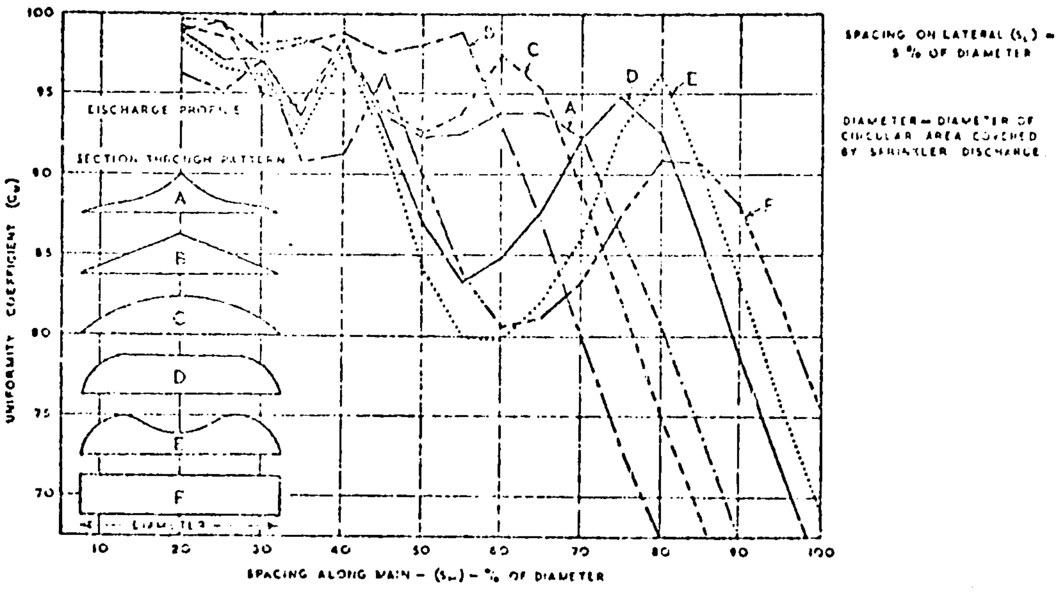

Figure 1. Christiansen's basic UC curves.

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[1] In the early stages of the research an attempt was made to categorize sprinkler geometric profiles by a single dimensionless parameter. The parameter was not used in this analysis, however, it is presented in Appendix C.

Strong (1961) realized the usefulness of Figure 1 was limited if it could only be used to predict the performance for sprinklers spaced at 5 percent of the wetted diameter along the lateral. He proposed extending the usability of the graph to include various spacings along the lateral, $S_\ell$, as well as along the main, $S_m$. He assumed the UC for a given spacing combination could be approximated by dividing 100 into the product of the UC values obtained by entering Figure 1 with both $S_m$ and $S_\ell$. Further details of this method are presented by Keller et al. (1967).

Strong (1961) indicated that he had conducted numerous tests with actual data and found the above method to be reliable and capable of producing results within 3 percent of what would be obtained through superimposition and the utilization of Equation 1. As previously mentioned, he presented a performance table for selecting the proper spacing of various single and double nozzle sprinklers under different wind conditions. He assumed that double nozzle sprinklers would fall somewhere between Christiansen's B and C profile, and the single nozzle sprinklers would produce the D profile. In developing these tables he reduced the diameter for wind prior to entering Figure 1. The reduction factor used was 2 percent for each 1 mph average wind velocity over 5 mph, i.e., 10 percent reduction in diameter was applied for a 5 to 15 mph wind.

# METHODS AND MATERIALS

Facilities were made available for testing in El Salvador, Central America. It was decided to set up a preliminary test site near Logan, Utah, in order to perfect the test procedure. This would then allow data to be gathered in a complete and systematic manner. The final test site was located in the Zopatitan Valley of El Salvador on the federally operated agricultural farm.

The test site nearly complied with Recommendation ASAE R330, entitled "Procedures for Sprinkler Testing for Research Purposes," (see Appendix A for the complete Recommendation). The test site deviated from the recommended as follows: (1) the collectors were only 6 inches above the ground instead of 12 inches; (2) the rims of the collectors were only 3 inches above the crop of grass instead of 6 inches; (3) at times only 40 to 60 collectors in the grid configuration received water instead of a minimum of 80; (4) the sprinkler was located at a collector point on the grid instead of midway between the four collectors at the center.

## Apparatus

Single nozzle sprinklers, both with and without stream straightening vanes, and double nozzle sprinklers without straightening vanes were utilized. The sprinklers had 3/4 inch inlets and range nozzle sizes from 9/64 inches to 7/32 inches. The sprinklers selected for the tests were of the model 30 series produced by Rain Bird Manufacturing Corporation and were equipped with teflon-neoprene washers. Six sprinklers of each configuration (plane single, vane single, and double nozzle) were selected "off the shelf" at a retail outlet. It was felt that these particular sprinklers were representative of medium pressure agricultural sprinklers in use throughout the world and were capable of producing a variety of geometric sprinkler profiles.

Each sprinkler was tested for uniformity of rotation and discharge with a 11/64 inch range nozzle at 40 psi. The rotation rates varied between 0.75 rpm and 1.8 rpm, and the discharges varied approximately ± 2 percent. The sprinklers having the rotation rate and discharge closest to the average for each configuration were selected for the test program.

Two pressure gages with dial indicators reading from 0-100 psi were utilized during the tests. One gage was located at the base of the riser. The other, equipped with a pitot tube, was used to measure pressure at the nozzle. The accuracy of the gages was ± 2 percent.

A bypass valve system was provided between the pumping plant and the sprinkler being tested so that a variety of sprinkler pressure-discharge combinations could be achieved by throttling the engine and/or regulating the bypass valve. The sprinkler being tested was mounted on a 3/4 inch diameter steel riser 2 feet, 3 inches in length, held in a vertical position by a tripod. This riser length was chosen in order that the sprinkler would be approximately 2 feet above the tops of the nearest four collectors.

White styrefoam cups were selected for the collectors. The cups had tapered sides so they could be nested and were 5.5 inches deep with a top diameter of 4.4 inches. The white styrefoam provided insulation capacity and repelled water which should have minimized container related losses. Smooth stones were placed in the collectors to stabilize them and prevent them from blowing over. Graduated cylinders were used to measure the precipitation caught in the collectors.

The collectors were placed on the ground in a ten foot grid pattern with the sprinkler located on a grid point. Four collectors were placed around the sprinkler at a distance of three feet in order to estimate the catch at the sprinkler. In addition to the grid layout, collectors at ten foot spacings along four additional radial legs at 45 degree angles to the grid were utilized. With the sprinkler placed on a grid point and the additional radial legs at 45 degrees, it was possible to obtain the geometric profiles for eight radial legs at intervals of 45° and with the collector points at ten foot intervals.

Figure 2 is a plan view of the test site showing the collector configuration.

## Test Procedure

The reason for testing was to gather data for a variety of geometric sprinkler patterns under different steady state wind conditions. Therefore, it was necessary to determine the approximate wind speed, and any variability in wind speed and/or direction before beginning each test. By this procedure, it was hoped that duplication of data and collection of non-steady state data could be kept to a minimum.

A five gallon can was placed over the sprinkler before the pump was started to prevent water from entering the collectors. The engine throttle and pump bypass valve were adjusted until the desired pressure at the base of the riser was reached. The operating pressure measured at the nozzle jet "vena contracta" was determined using the pressure gage equipped with the pitot tube. The discharge from both the range and spreader nozzles was then measured by placing a two inch plastic hose over the nozzle and determining the time required to fill a five gallon bucket. (The relatively large diameter hose allows aeration of the jet, preventing a "Venturi effect" from occurring. If the hose fits tightly around the nozzle, an area of negative pressure may be created causing the measured discharge to be greater than the true discharge.)

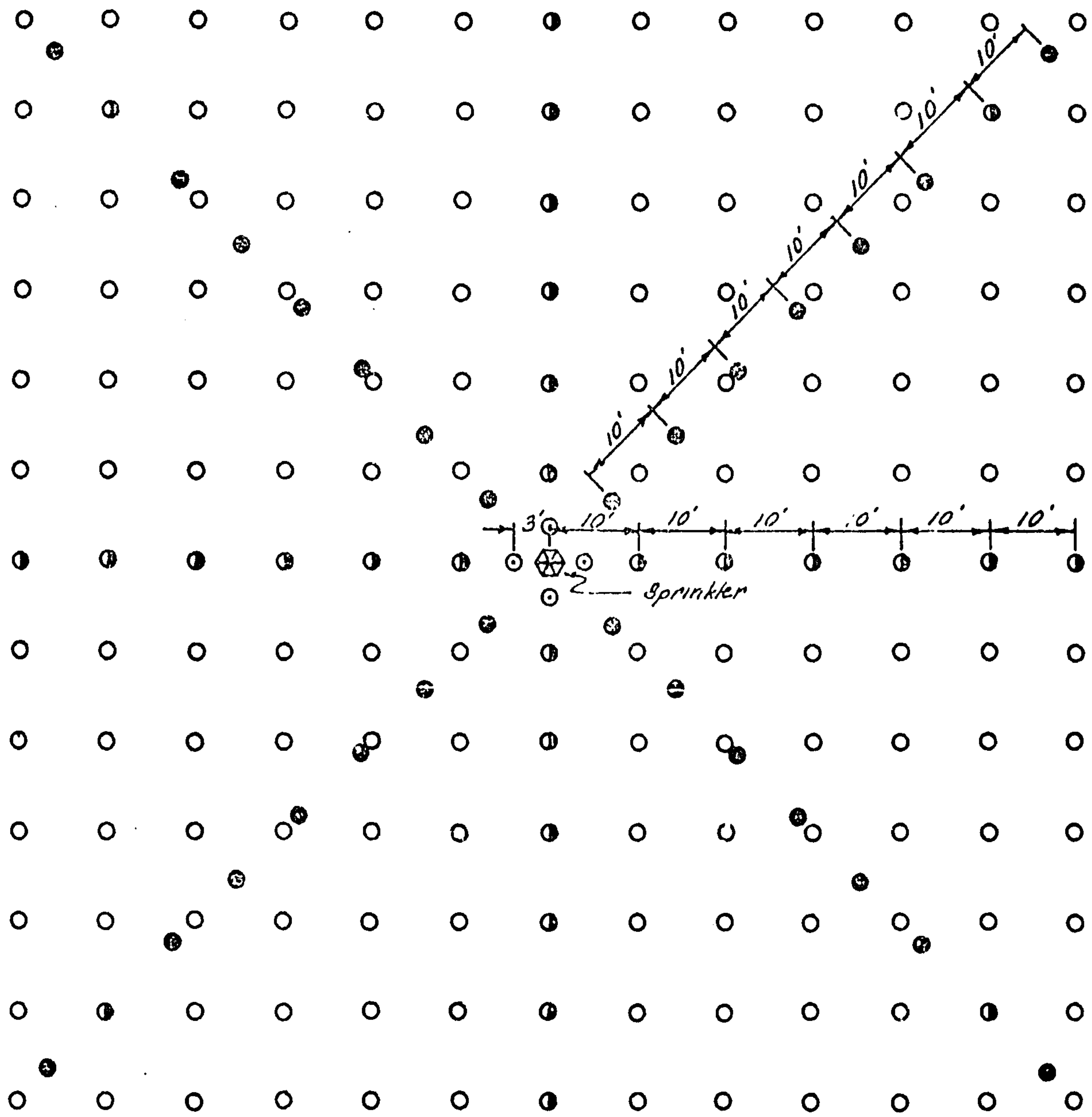

Figure 2. Catch-can configuration used in El Salvador.

A collector containing 30 mililiters of water was placed at the edge of the test area in order to evaluate evaporation losses during the test. The sprinkler was then allowed to begin rotating and the anometer reading, wind direction, riser base pressure and the wet and dry bulb temperatures were recorded initially and at fifteen minute intervals during the test. At least once during the test, the average rotation rate of the sprinkler was recorded for a fifteen minute interval. Sample data collection sheets are presented in Appendix A.

At the termination of the test, the discharge rate and nozzle pressure were again measured. Another collector containing 30 mililiters of water was placed near the edge of the test area in order to evaluate the evaporation losses that occurred while the precipitation in the collectors was measured. The precipitation caught was measured to the nearest 0.5 mililiter using a graduated cylinder. When all the collectors had been read, the evaporation readings were recorded.

Test durations were either thirty minutes or sixty minutes depending on wind conditions and sprinkler discharge. The smaller the amount of precipitation caught in a collector, the lesser the accuracy of measurement. Therefore, it was necessary to run the low discharge sprinklers for a longer period of time than the higher discharge sprinklers to achieve an equivalent degree of accuracy.

## Computer Program

A computer program was developed to aid in analyzing the data. The program first calculated the direction and magnitude of the shift in center of mass, C, of the wind affected single sprinkler pattern. The relative direction of C from the sprinkler location was taken as the effective wind direction, $W_d$, of the test. The computer program rotated the test data to a new grid configuration so that the columns of the grid were parallel and the rows perpendicular to the effective wind direction; this direction, parallel to the lateral, was then considered to be a $0^o$ wind angle. A $W_d$ perpendicular to the lateral would then be a $90^o$ wind angle. At this point in the program, the pattern could be rotated to any desired $W_d$ and superimposed to generate any desired rectangular spacing. The UC was then determined for the particular spacing combination. A listing of the computer program is presented in Appendix B.

# RESULTS AND DISCUSSION

## Data Collected

Approximately one-half of the data utilized in the analysis was produced at the test site in El Salvador. The rest of the data was provided through the courtesy of Rain Bird Manufacturing Company, Glendora, California. Ten foot grid spacings were utilized for collection of data in El Salvador. The data obtained from Rain Bird was collected on a five foot grid spacing with the sprinkler placed midway between four collectors. The sprinklers tested and the physical and environmental conditions under which they were tested can be found in Tables 1, 2 and 3. (The fact that the two sets of data were similar in overlapping areas was encouraging.)

An attempt was made to collect data for three basic geometric profiles. (A geometric profile is the plot of distance from the sprinkler versus depth of application. A sprinkler pattern will refer to the depths of catch for the entire single sprinkler test.) The double nozzle sprinklers produced a profile falling somewhere between Christiansen's B and C profile (Figure 1). The single nozzle sprinklers without vanes produced profiles similar to the D profile. The single and double nozzle sprinklers were operated at

**Table 1.** Sprinkler environmental test conditions for single nozzle sprinklers without stream straightening vanes.

Single Nozzle Sprinklers - W/O Vanes

| Nozzle Size | Pressure | Effective Radius | C | $C/R_e \times 100$ | Wind Speed MPH |
|---|---|---|---|---|---|
| 9/64 | 40 | 39 | 4.81 | 12.3 | 2.6 |
| 9/64 | 40 | 39 | 8.88 | 22.8 | 4.6 |
| 9/64 | 40 | 39 | 10.15 | 26.0 | 7.8 |
| 9/64 | 40 | 39 | 15.24 | 39.1 | 12.2 |
| 9/64 | 45 | 40 | 3.55 | 8.9 | 2.2 |
| 9/64 | 45 | 40 | 5.20 | 15.0 | 2.6 |
| 9/64 | 45 | 40 | 12.89 | 32.2 | 5.9 |
| 9/64 | 50 | 40 | 3.82 | 9.6 | 2.1 |
| 9/64 | 50 | 40 | 6.77 | 16.9 | 4.8 |
| 9/64 | 50 | 40 | 11.64 | 29.2 | 5.8 |
| 9/64 | 60 | 41 | 5.68 | 13.9 | 2.0 |
| 9/64 | 60 | 41 | 7.59 | 18.5 | 4.1 |
| 9/64 | 60 | 41 | 12.68 | 31.0 | 7.5 |
| 11/64 | 45 | 45 | 2.22 | 4.8 | 2.1 |
| 11/64 | 45 | 45 | 8.33 | 19.0 | 3.4 |
| 11/64 | 45 | 45 | 16.14 | 35.2 | 8.6 |
| 11/64 | 50 | 45 | 2.33 | 5.2 | 1.7 |
| 11/64 | 50 | 45 | 7.06 | 15.7 | 3.7 |
| 11/64 | 50 | 45 | 6.51 | 14.5 | 4.2 |
| 11/64 | 50 | 45 | 9.77 | 21.7 | 5.9 |
| 11/64 | 50 | 45 | 12.57 | 28.0 | 6.7 |
| 11/64 | 50 | 45 | 11.06 | 24.6 | 6.7 |
| 3/16 | 40 | 45 | 1.12 | 2.5 | 2.0 |
| 3/16 | 40 | 45 | 5.84 | 13.0 | 4.1 |
| 3/16 | 40 | 45 | 13.15 | 29.2 | 7.9 |
| 3/16 | 40 | 45 | 1.13 | 2.4 | 0.9 |
| 3/16 | 50 | 47 | 7.52 | 16.0 | 4.0 |
| 3/16 | 50 | 47 | 13.80 | 29.4 | 7.7 |
| 3/16 | 50 | 47 | 11.79 | 25.0 | 8.3 |
| 3/16 | 50 | 47 | 18.67 | 40.0 | 11.6 |
| 3/16 | 60 | 48 | 2.39 | 5.0 | 1.2 |
| 3/16 | 60 | 48 | 5.75 | 12.0 | 4.1 |
| 3/16 | 60 | 48 | 14.95 | 31.2 | 7.8 |
| 3/16 | 60 | 48 | 13.68 | 28.6 | 8.1 |
| 3/16 | 60 | 48 | 19.46 | 40.6 | 11.3 |
| 7/32 | 45 | 50 | 2.67 | 5.4 | 2.3 |
| 7/32 | 45 | 50 | 11.93 | 23.0 | 3.5 |
| 7/32 | 45 | 50 | 20.68 | 41.5 | 12.1 |

Table 2. Sprinkler environmental test conditions for single nozzle sprinklers with stream straightening vanes.

| Single Nozzle Sprinklers - W/Vanes | | | | | |
|---|---|---|---|---|---|
| Nozzle Size | Pressure | Effective Radius | C | $C/R_e \times 100$ | Wind Speed MPH |
| 9/64 | 33 | 42 | 3.60 | 8.6 | 2.5 |
| 9/64 | 36 | 42 | 10.35 | 24.6 | 6.2 |
| 11/64 | 35 | 44 | 2.96 | 6.7 | 2.1 |
| 11/64 | 37 | 44 | 12.54 | 28.5 | 4.7 |
| 7/32 | 35 | 50 | 4.10 | 8.2 | 2.2 |
| 7/32 | 35 | 50 | 8.51 | 17.0 | 4.0 |
| 7/32 | 36 | 50 | 17.02 | 34.0 | 9.5 |

**Table 3.** Sprinkler environmental test conditions for double nozzle sprinklers without stream straightening vanes.

Double Nozzle Sprinklers W/O Vanes

| Nozzle Size | Pressure | Effective Radius | C | $C/K_e$ x 100 | Wind Speed MPH |
|---|---|---|---|---|---|
| 9/64 x 3/32 | 50 | 40 | 3.88 | 9.7 | 2.4 |
| 9/64 x 3/32 | 46 | 40 | 8.19 | 20.5 | 5.7 |
| 9/64 x 3/32 | 46 | 40 | 14.39 | 36.0 | 8.6 |
| 11/64 x 3/32 | 40 | 44 | 6.87 | 15.7 | 3.9 |
| 11/64 x 3/32 | 47 | 45 | 11.20 | 25.0 | 6.8 |
| 11/64 x 3/32 | 52 | 45 | 4.84 | 10.7 | 1.9 |
| 11/64 x 3/32 | 50 | 45 | 4.35 | 9.7 | 3.0 |
| 11/64 x 3/32 | 50 | 45 | 5.28 | 11.8 | 3.6 |
| 11/64 x 3/32 | 50 | 45 | 6.40 | 14.2 | 3.8 |
| 11/64 x 3/32 | 50 | 45 | 6.30 | 14.0 | 5.0 |
| 11/64 x 3/32 | 50 | 45 | 9.72 | 21.6 | 5.7 |
| 11/64 x 3/32 | 50 | 45 | 11.34 | 25.2 | 6.4 |
| 11/64 x 3/32 | 50 | 45 | 13.41 | 29.8 | 7.5 |
| 11/64 x 3/32 | 50 | 45 | 17.10 | 38.0 | 11.4 |
| 11/64 x 3/32 | 50 | 45 | 17.20 | 38.2 | 12.0 |
| 7/32 x 1/8 | 44 | 49 | 8.12 | 16.6 | 4.5 |
| 7/32 x 1/8 | 47 | 50 | 5.29 | 10.6 | 2.6 |
| 7/32 x 1/8 | 47 | 50 | 3.36 | 6.7 | 2.4 |
| 7/32 x 1/8 | 46 | 49 | 14.34 | 29.4 | 8.6 |

or above recommended minimum pressures when possible. The vaned single nozzle sprinklers were operated below the recommended operating pressure to produce a profile similar to Christiansen's E profile or "doughnut" profile.

One of the objectives in data collection was to obtain information on the stability of the profile under steady state wind conditions. Therefore, only sprinkler test data where the wind speed and direction did not vary significantly during the period of the test were utilized in the analysis.

## Wind and Profile Analysis

### Wind speed

It was felt that in order to compare the relative effect wind speed had on the stability of the various sprinkler profiles produced, it would be necessary to make the comparison on a dimensionless basis. The dimensionless parameter, $C_r$, was then developed utilizing the ratio of the magnitude of the shift in center of mass, C, of the test pattern and the average effective radius (not trace radius), $R_e$, of the sprinkler under 0 to 3 mph winds; where $C_r = 100\ (C/R_e)$. An integrated effect of nozzle size and pressure is reflected in the average effective radius, $R_e$, measured in low wind conditions. The shift in center of mass, C, gives an indication of the sprinkler stability in wind. The value of $C_r$ was computed for each of the 65 test patterns utilized in the study (see Tables 1, 2, and 3).

Figure 3 is a plot of $C_r$ versus the average wind velocity, We, (i.e., total wind passing divided by the test duration) during a test. All of the data in Figure 3 was fit by a second degree quadratic function using a regression analysis which forced the function through the origin. (The analysis was performed on the IBM 360 using a statistical regression program obtained from the Applied Statistics and Computer Science Department, Utah State University.) Theoretically, under zero wind conditions, the center of mass of the sprinkler pattern should be at the sprinkler, therefore, the regression curve should pass through the origin.

The high degree of correlation ($R^2 = 0.897$) demonstrates that $C_r$ is a reasonable indicator of the magnitude of the integrated wind vector irrespective of the variations in the sprinkler-nozzle-pressure combination tested. (However, this conclusion must be qualified, because only data from 65 sprinkler tests representing a limited number of sprinkler-nozzle-pressure combinations were utilized in the analysis.) An interesting trend can be observed in the data plotted for wind speeds greater than 11 mph. It appears that for an increase in wind speed, there is not an increase in $C_r$. It is speculated that at some wind speed, $C_r$ may even possibly begin to decrease for increasing wind speeds. One possible

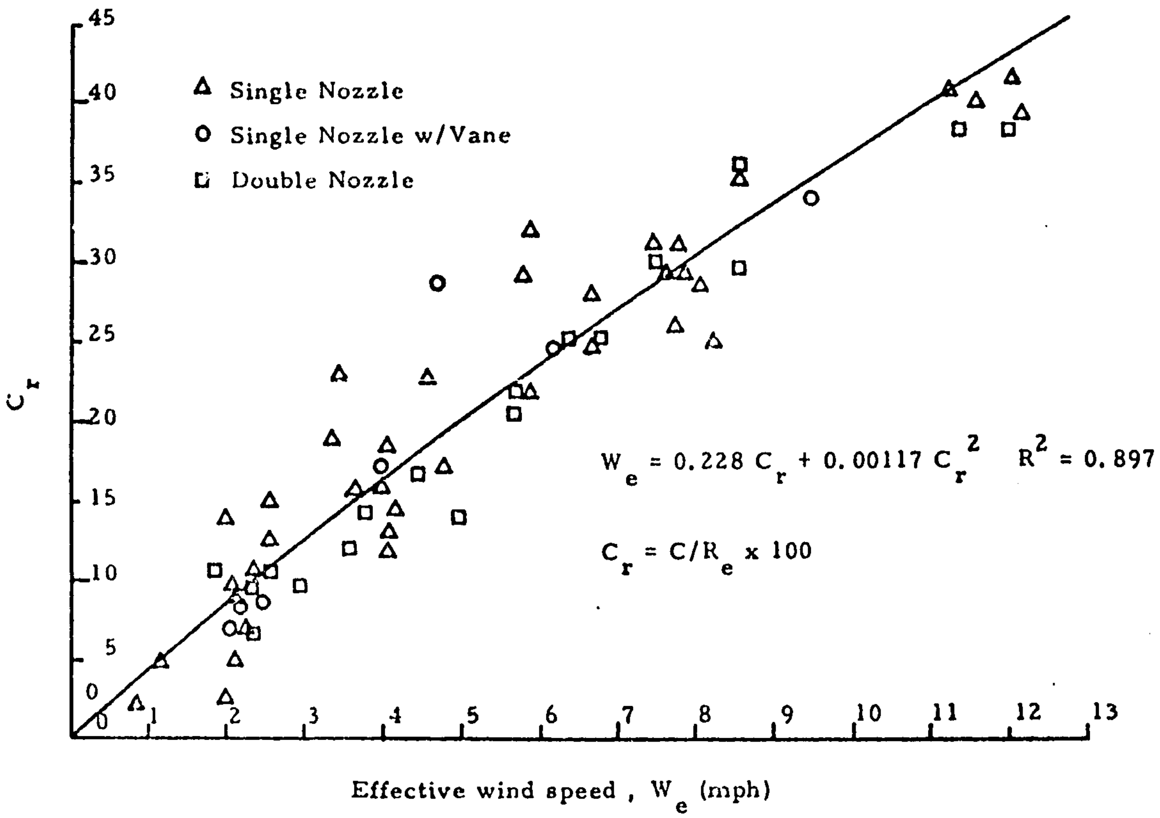

Figure 3. Shift in center of mass ratio, Cr, versus average steady state wind velocity or effective wind velocity, $W_e$.

explanation is as follows: It has been observed that in high winds, the sprinkler jet when passing upwind tends to curl down depositing water near the sprinkler. When the jet passes downwind, large quantities of water tend to be carried out of the test area completely, thus decreasing the relative magnitude of the shift in center of mass.

Because there was a high degree of correlation between $C_r$ and wind speed for the tests utilized, it was decided, for the subsequent analysis, to use the wind speed represented by the regression curve in Figure 3 for the computed $C_r$ of each test.

### Wind direction

The effect of wind angle on distribution uniformity was analyzed in detail in a study made in conjunction with the present one (Ptacek, 1972). It was therefore decided to conduct this entire study using $W_d = 45^o$.

### Profile analysis

A number of efforts were made to develop sprinkler profile indices which would be useful for design purposes. The most useful concept evolved was similar to Christiansen's suggestion (Figure 1) of plotting UC versus $S_m$ for a small $S_\ell$ value (where $S_\ell$ is the sprinkler spacing on the lateral, and $S_m$ is the lateral spacing along the main).

The test data was organized into groups. Each group consisted of a series of tests of a particular sprinkler model and nozzle size, operated at a specific pressure, under a range of wind velocities. Values of UC versus the spacing along the main as a percentage of the effective diameter, 100 $S_m/D_e$, (where $D_e$ = effective diameter), were computed for $S_\ell = 0.03\ D_e$. Plots were drawn up for each individual group. These plots or curves will be referred to as "basic UC curves." The three most complete and accurate basic UC curves obtained were chosen to represent the basic geometric profiles that were analyzed.

Figure 4 represents a series of tests using a 3/16 inch single nozzle sprinkler without a vane operated at 50 psi with effective wind speeds of 0, 0.6, 3.9, 7.7, and 11.0 mph at $W_d = 45^\circ$. The actual sprinkler profile based on an evaluation of the average depth of application along the 8 radial legs at low wind is also depicted on Figure 4. The 0 mph wind basic UC curve was synthesized by graphically determining the sprinkler pattern using the no wind profile and computing values for the basic UC curve by the method mentioned above. Figure 4 demonstrates the effect a steady wind has on the UC versus $S_m$ spacing relationship for a specific sprinkler-nozzle-pressure combination. (This particular sprinkler had a $D_e$ of approximately 100 feet, so any actual synthesized spacing selected would be equal to 3 feet by $S_m$ feet, i.e. the graph can be entered with 100 $(S_m/D_e)$ = 100 $(S_m/100)$ = $S_m$.)

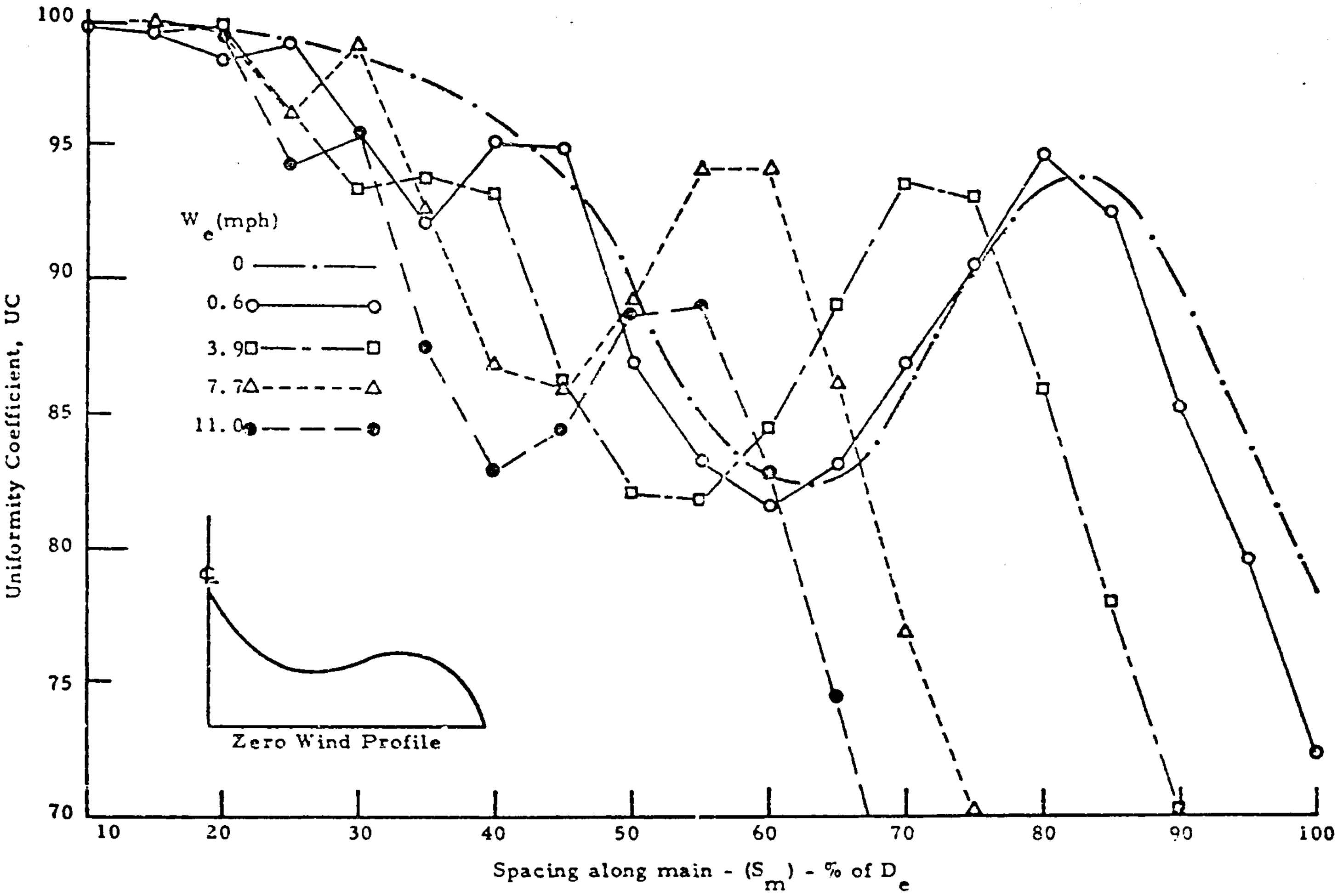

Figure 4. Basic UC curves showing UC versus the spacing along the main as a percentage of the wetted diameter for a 3/16 inch nozzle sprinkler without vane operating at 50 psi and $W_d = 45^\circ$.

Some interesting concepts concerning the effect of wind on spacing can be observed in Figure 4. For example, when $S_m$ = 80 feet and $W_e$ = 0.6 mph, UC = 95, as the wind is increased to 7.7 mph, the UC is decreased to 65. On the other hand, if the spacing were only $S_m$ = 60 feet at a wind of 0.6 mph, UC = 82, and when the wind is increased to 7.7 mph the uniformity is increased to 94.

The above example demonstrates that the effect of wind on uniformity is dependent on sprinkler spacing. The dip in each curve represents spacings where the sprinklers overlap in such a manner than a poor UC results due to over-watering midway between the laterals. (Wind decreases the effectiveness of the diameter and, thus, can reduce overlap and increase UC where spacings are selected in the dip of low wind curves and the wind increases.)

As the spacing is decreased, the applications from adjacent lateral lines completely overlaps and the UC begins to approach 100. However, as the spacing increases the excess watering created by the intermediate overlap condition is eliminated, and the uniformity also increases. Further increases in spacing result in insufficient overlap, and a poor UC results due to under-watering midway between the laterals. Since winds decrease the effectiveness of the diameter, the UC of spacings past the peak decrease rapidly as wind velocity increases. Therefore, extreme caution should be exercised when selecting such spacings based on no wind conditions.

The curves in Figure 4 indicate that as the effective wind speed increases the curves are shifted inward, with the peaks remaining approximately at the same elevation until a $W_e = 11.0$ mph is reached. The peak for the 11.0 mph wind curve has dropped from a UC = 95 to a UC = 90. This indicates that $S_m > 0.3\ D_e$ could be used in winds up to approximately 11.0 mph before an appreciable decrease in distribution uniformity occurred. (Provided the proper spacing was chosed for the wind conditions encountered.)

Figure 5 represents a series of tests using a vaned sprinkler with a 7/32 inch single nozzle operated at 36 psi with effective wind speeds of 0, 2.2, 4.0, and 9.5 mph at $W_d = 45^o$. This particular combination approximates an E or "doughnut" profile.

As wind increases, the peaks shown in Figure 5, for the E profile immediately begin to drop, indicating that this particular sprinkler combination is not very stable in wind. The sprinkler was operated considerably below the minimum recommended pressure of 65 psi in order to produce the "doughnut" effect. At a pressure of 36 psi fairly large drops were formed, however, because of the low pressure the large drops were traveling at a relatively low

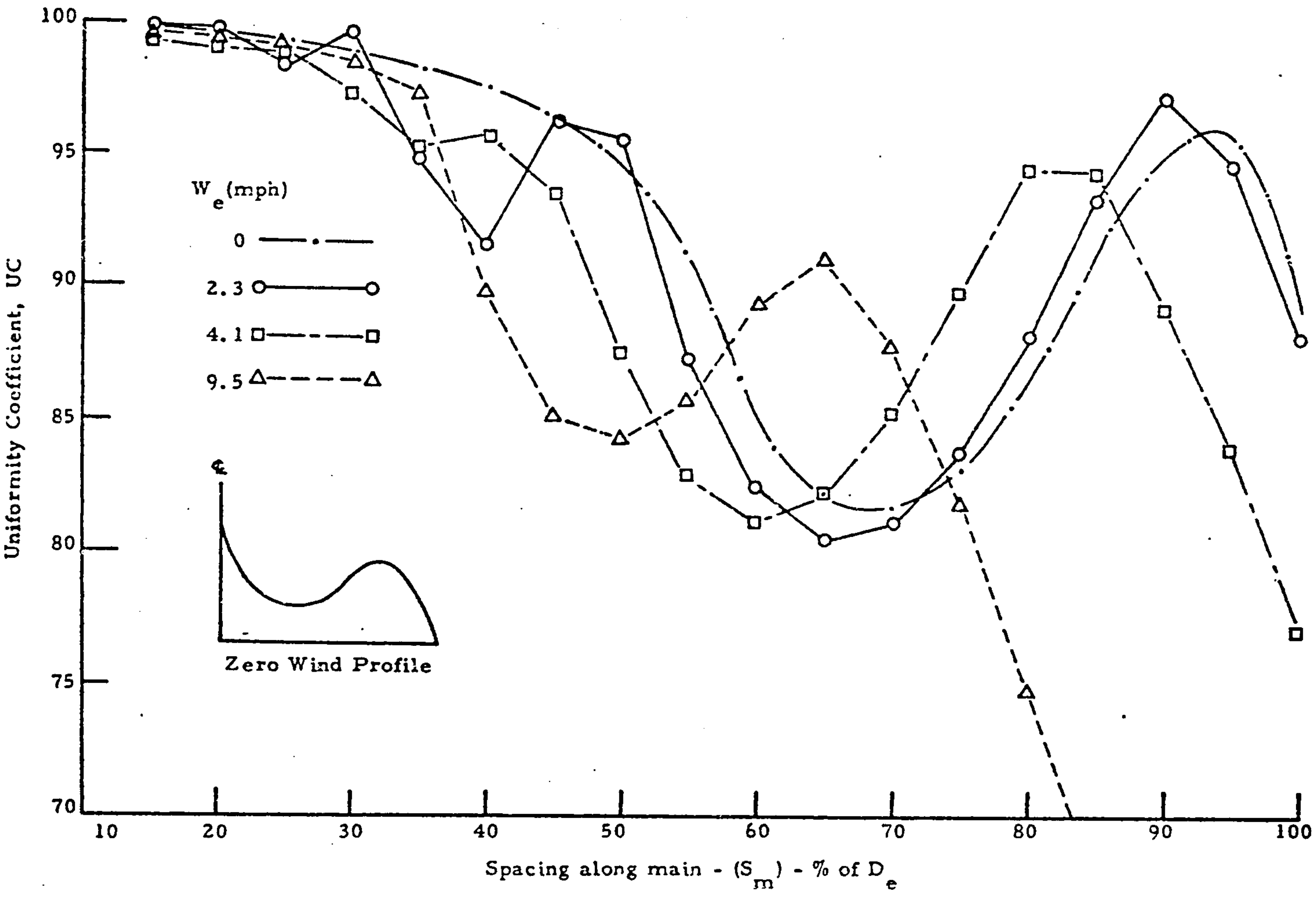

Figure 5. Basic UC curves showing UC versus the spacing along the main as a percentage of the wetted diameter for a 7/32" vaned single nozzle sprinkler operating at 37 psi and $W_d = 45°$.

velocity and were unable to resist the force of the wind adequately. Caution would have to be exercised when selecting spacings for this particular sprinkler combination.

Figure 6 represents a series of tests using a double nozzle sprinkler with a 7/32 inch range nozzle and 1/8 inch 20° spreader nozzle operated at 47 psi with effective wind speeds of 0, 2.4, 4.5, and 8.6 mph at $W_d = 45^{\circ}$. This double nozzle sprinkler produced a profile between Christiansen's B and C profiles.

When analyzing the effect wind has on the basic UC curves of a double nozzle sprinkler, shown in Figure 6, it is apparent that again the curves shift inward and the peaks tend to drop. The function of a spreader nozzle is to fill in the area near the sprinkler. The result is a more or less triangular profile shape. Due to the nature of the construction of a spreader nozzle and its relatively small nozzle size for the operating pressures used, the spray formed contains small drops. These small drops are easily affected by the wind and therefore the apparent profile breaks down fairly rapidly. However, the range nozzle, which has the same characteristics as the single nozzle sprinkler without vane, is able to resist the wind effectively and the net result is that the pattern holds up fairly well. Because of the triangular nature of the profile produced, the maximum spacing that can be used, while maintaining a high uniformity, is less than the maximum for the two single nozzle sprinklers tested.

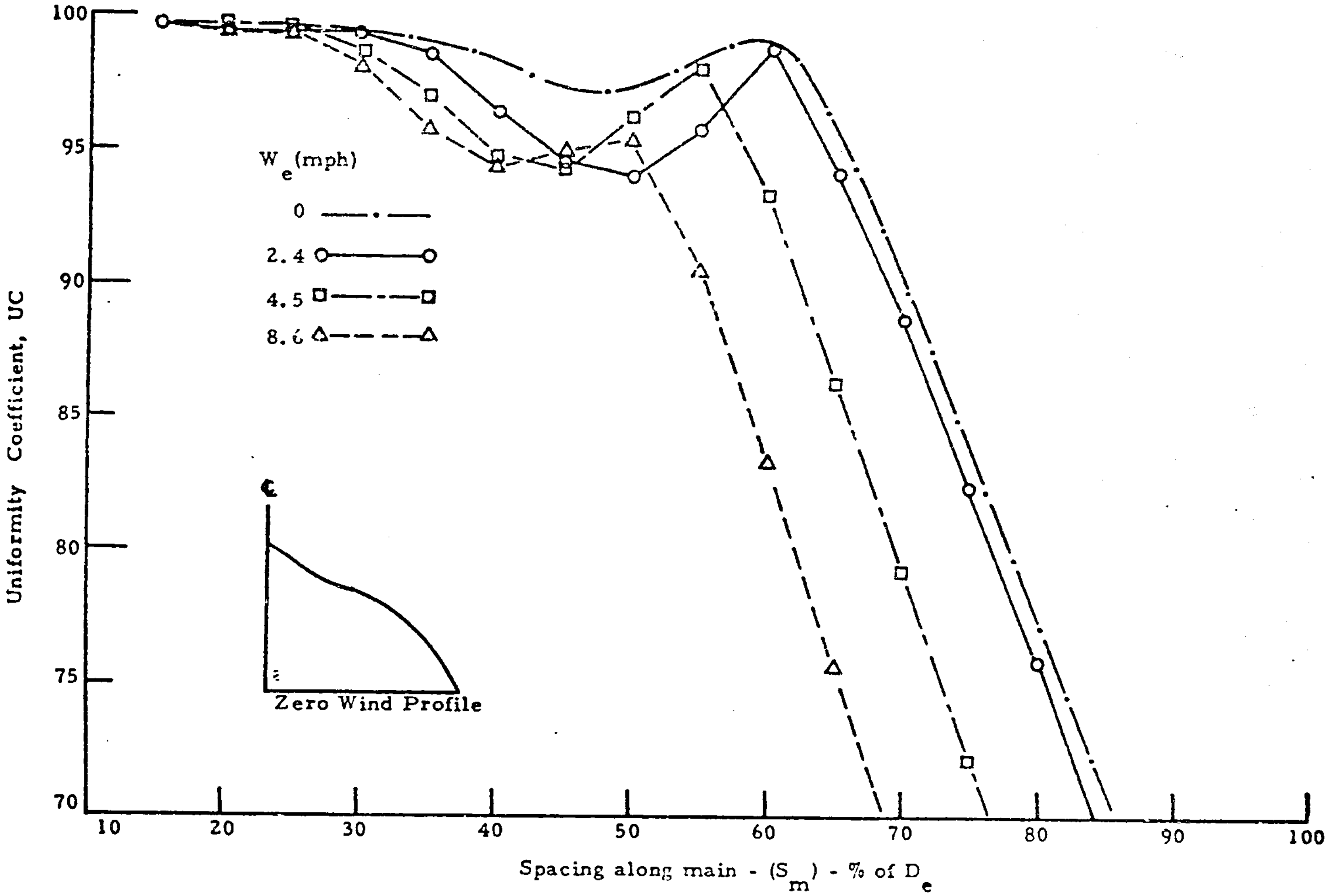

Figure 6. Basic UC curves showing UC versus the spacing along the main as a percentage of the wetted diameter for a 7/32" x 1/3" 20° double nozzle sprinkler operating at 47 psi and $W_d$ = 45°.

## Predicting Field Performance

A major objective of this investigation is to develop a means of organizing the limited test data in a manner useful for predicting field performance.

### Predictions from actual tests

The above analysis dealing with basic UC curves for $W_d$ = $45^o$, $S_\ell$ = 0.03 $D_e$, and various values of $W_e$ is also useful for the design of traveling sprinklers. There is little difference between plots with $S_\ell$ = 0.03 $D_e$ and the infinitesimally small $S_\ell$ which represents a traveling sprinkler (i.e., for a traveling sprinkler $S_\ell$ is 0; however, this can be simulated by a very small $S_\ell$).

In order to utilize the analysis for predicting the UC of relatively wide spacings in both directions, the approach suggested by Strong (1961) was utilized. The plots were entered with both the $S_\ell$ and $S_m$ spacing values and the UC of the expanded spacing was assumed equal to the product of the individual UC value divided by 100. To evaluate the reliability of this procedure, the computer program was designed to compute UC values using Christiansen's equation for a large number of $S_\ell$ by $S_m$ spacing combinations. The calculated UC values using the graphical method were then compared with the UC values computed numerically by the computer as shown in Figure 7.

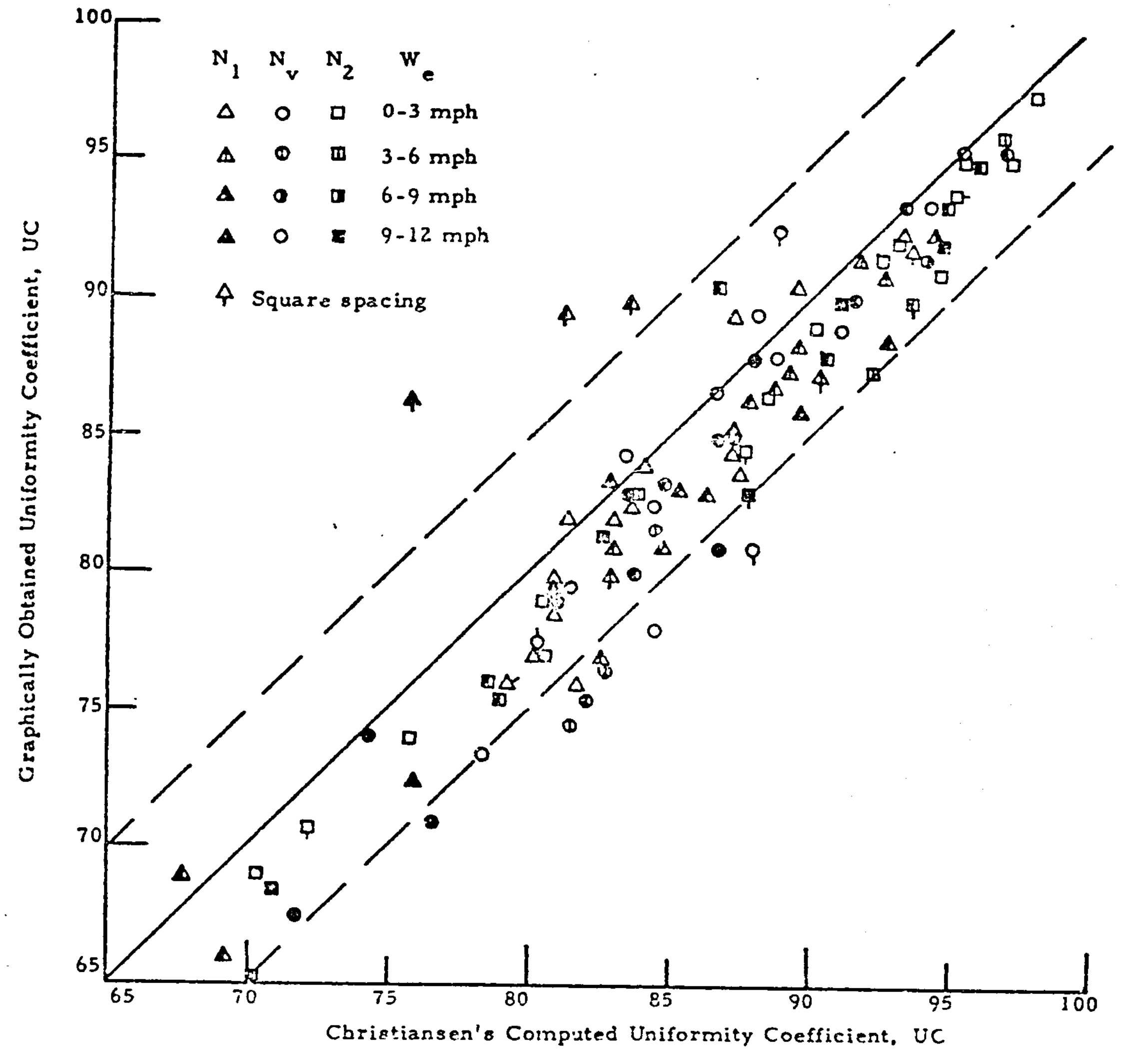

**Figure 7.** Graphically obtained UC (from basic UC curves) versus actual UC computed numerically for various sprinkler profiles, wind speeds, and sprinkler spacings.

A perfect correlation between the graphically obtained UC values and the computed UC values is represented by the $45^{\circ}$ diagonal (solid line passing through 100 and 100) in Figure 7. The reliability of the method is demonstrated by the closeness of the points to the solid line. With few exceptions the graphical method tends to slightly underestimate the computed UC values as indicated by the density of points between the solid line (perfect correlation) and 5 UC points under prediction (lower dotted) line in Figure 7.

All of the data for the double nozzle sprinkler tests falls between these two lines in Figure 7. Most of the points falling outside of this envelope represent single nozzle sprinklers at square spacings where the percent of $D_e$ of the spacing fell in the dip (causing greater underestimation) or on the outside peak (causing overestimation) of the basic UC curves like Figure 4. A tendency to overestimate UC also occurred whenever the spacing was past the peak and on the steep drop-off portion of the basic UC curve.

The reason the graphical method underestimates UC for a square spacing where $S_\ell$ and $S_m$ both fall in the dip and overestimates when they fall on the outer peak of the basic UC curves can be visualized as follows. The overwatering caused by an intermediate overlap is not necessarily accumulative on the diagonal as would be indicated by the product of UC values. However, when the overlap is insufficient, the effect is greatly exaggerated on the diagonal (dry areas may occur) and not sufficiently accounted for by the product of UC values.

No analyses were conducted with triangular spacings; however, it is proposed that (a) when the spacing approaches an equilateral triangle where $0.8\, S_\ell < S_m < S_\ell$ the calculated UC will normally fall 5 to 10 points below the value obtained by entering the basic UC curves with $S_m$ (deducted from Christiansen (1942)); and (b) when $S_m$ is much greater than $S_\ell$, proceed as for rectangular spacings.

From the foregoing analysis it appears that this graphical method for estimating UC from the basic UC curves is valid. However, it is felt that a better functional relationship could probably be developed utilizing the diagonal length along with the lengths of the two perpendicular legs. The new function, containing three variables, would then hopefully be able to handle square spacings, as well as spacings past the peaks.

Wind effects. By studying Figures 4, 5, and 6 it is evident that as the effective wind velocity, $W_e$, increases, the UC curves are shifted inward. A closer study of Figure 4 shows that the shift is relative, with the outside peak being shifted about twice as far as the inside slope of the dip. In order to analyze the shift of the curves relative to the effective wind velocity a parameter called the relative shift ratio, $S_s$, was developed. The values of $S_s$ for the single nozzle sprinklers were obtained by dividing the $S_m/D_e$ values at the peaks for the curves representing each effective wind value by the $S_m/D_e$ value at the peak for the zero wind curve developed for each sprinkler test profile. Because the basic UC curves for the double nozzle sprinklers, Figure 6, do not have definite peaks, it was decided to use the value of $S_m$ of the point obtained by the intersection of a line drawn tangent to the outside of the curve and a UC value of 100, then proceed as above.

Figure 8 shows a plot of $S_s$ vs $W_e$ for all the available test data. The shift in the center of mass versus wind speed data for all tests was closely correlated as shown in Figure 2. However, as can be seen in Figure 8, the apparent relative shift appears to be dependent on the sprinkler geometric profile. Therefore, a different first order regression curve was required for each of three general profiles studied, i.e., double nozzle sprinklers, $N_2$, single nozzle sprinklers, $N_1$, and single nozzle sprinklers with vanes, $N_v$. Under zero wind conditions no shift should occur, therefore the curves were forced through the point ($W_e = 0$; $S_s = 1.0$).

The results of this analysis shows a good correlation of $S_s$ vs $W_e$ for the single nozzle sprinklers without vanes, $N_1$, ($R^2 = 0.87$). Twenty-four points were utilized in the regression analysis for the $N_1$ sprinklers. The single nozzle sprinklers with vanes, $N_v$, also showed a fairly high correlation ($R^2 = 0.89$), however

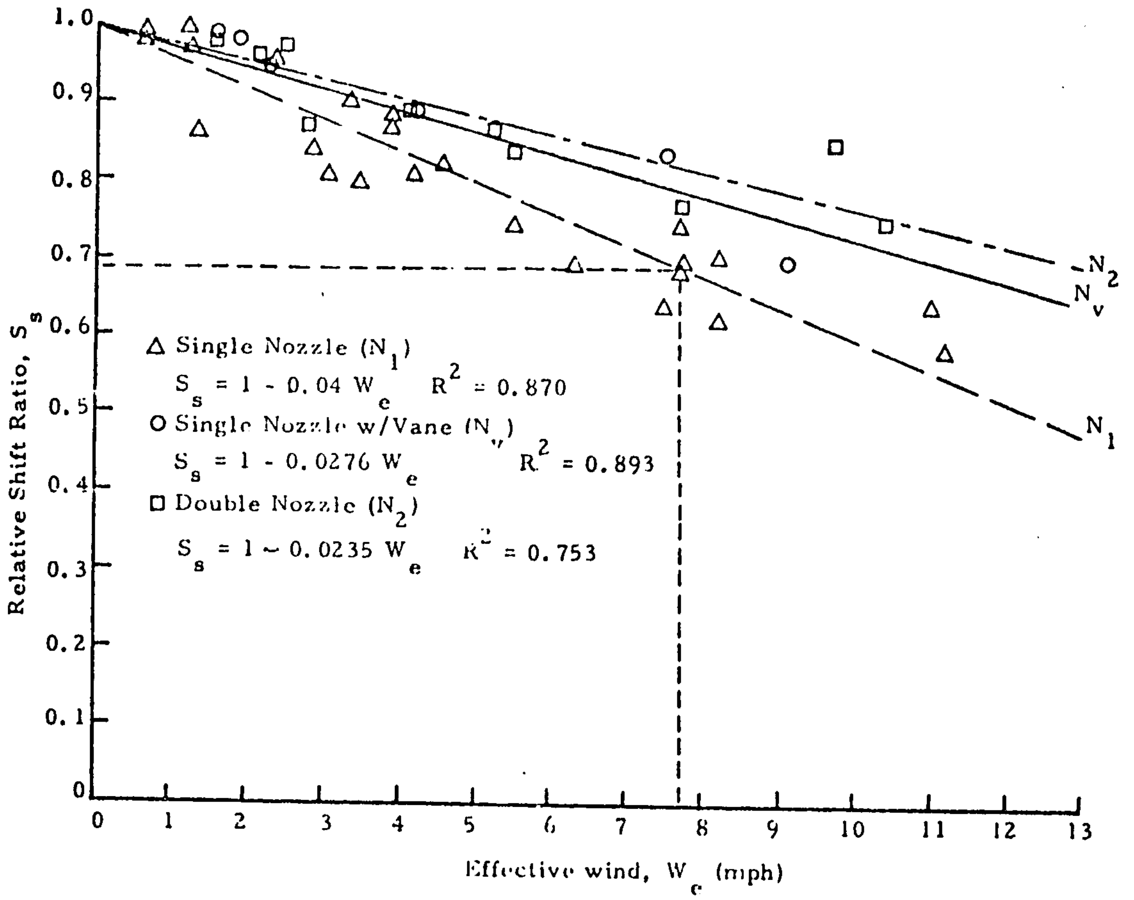

Figure 8. Relative shift ratios, $S_s$, of basic (zero wind) UC plots versus effective wind speed, $W_e$.

only 5 points were used in the analysis. The double nozzle sprinklers, $N_2$, using 11 points in the analysis, gave the poorest correlation ($R^2 = 0.75$). The scatter in the points for the $N_2$ sprinklers could be attributed partly to the method utilized in choosing the particular $S_m$ values used to compute $S_s$ versus $W_e$.

The functional relationships developed for $S_s$ shown in Figure 8 are one-dimensional and do not account for vertical deterioration of the basic UC curves with increasing wind. The peaks for the single nozzle sprinklers without vanes, $N_1$, do not appear to drop significantly with increased $W_e$, and therefore the method can be considered valid for these sprinkler combinations. However, the peaks for the $N_v$ sprinklers do drop significantly. The basic UC curves for the double nozzle sprinklers, $N_2$, have a lesser tendency to drop with increased $W_e$. Because of the lack of sufficient test data, no attempt was made to develop the functional relationship to account for the vertical shift of the basic UC curves.

### Synthesized predictions

To extend the usefulness of a limited amount of test data, it is necessary to predict sprinkler performance for environmental conditions for which the sprinkler has not been tested. Procedures referred to in the literature have been developed for estimating spray losses under different sprinkler mechanical and environmental operating conditions. A means for estimating sprinkler performance at any wind speed from a knowledge of performance from a limited number of tests at different wind speeds is also needed.

Strong (1961) used the concept of a reduced diameter to take wind speed into account before entering the basic UC curves which were developed for symmetrical patterns at no wind. Keller, et al. (1967) also suggested using the concept. However, there is confusion over the amount the diameter should be reduced for any given wind speed. The regression curves in Figure 8 give the ratio $S_s$ for any $W_e$ for the three general sprinkler profiles studied. By multiplying the $S_m/D_e$ values from a basic (zero wind) UC curve, by the $S_s$ for a given $W_e$, the basic (zero wind) UC curve can be shifted to represent the wind speed in question. The relative shift ratio is similar to a reduced diameter concept.

Figure 9 shows basic (zero wind) UC curves representing the three general sprinkler profiles which were analyzed. These zero wind curves were computed from the pattern profiles which are also presented in Figure 9. As previously mentioned, the profiles were obtained by averaging the profiles of the 8 radial legs obtained during a typical sprinkler test at the lowest wind speed encountered.

Values of $UC_e$ were estimated utilizing a number of spacings and $W_e$ combinations for each of the basic (zero wind) UC curves presented in Figure 9. An example of the computation of these

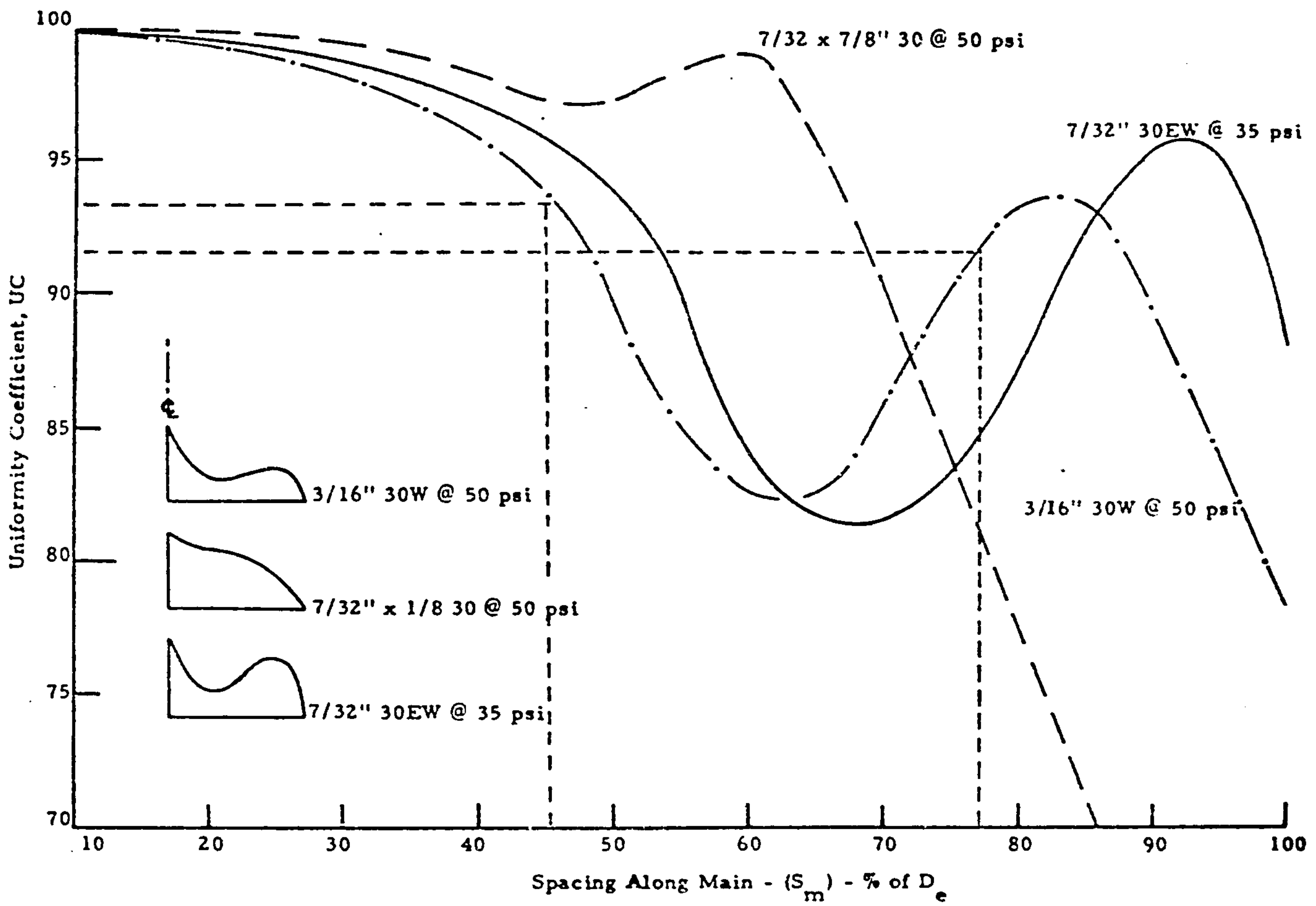

Figure 9. Basic (zero wind) UC curves calculated from the sprinkler profiles shown.

values is as follows. Given a 3/16" single nozzle sprinkler operating at 50 psi having a catalog diameter of 100' and $D_e = 94'$ with $W_e = 7.7$ mph. The estimated $UC_e$ for a 30' x 50' spacing is found by entering Figure 8 with $W_e = 7.7$ mph which gives $S_s = 0.69$. The reduced diameter, $D_r$, can be calculated by

$$D_r = S_s \cdot D_e = 0.69\,(94') = 65'$$

The lateral spacing value, $S_\ell$, for entering Figure 9 is

$$S_\ell = 100\,(S_\ell/D_r) = 100\,(30'/65') = 46\%$$

which gives a $UC_\ell = 93$. The spacing along the main value, $S_m$, for entering Figure 9 is

$$S_m = 100\,(S_m/D_r) = 100\,(50'/65') = 77\%$$

which gives a $UC_m = 92$. The estimated $UC_e$ for the 30' x 50' spacing is

$$UC_e = \frac{UC_\ell \cdot UC_m}{100} = \frac{93 \cdot 92}{100} = 85$$

The UC numerically computed from the test data for these exact given operating conditions is 83.

Values of $UC_e$ estimated by the above method, compared to UC values which were numerically computed from the test data using

Christiansen's equation are shown in Figure 10. A perfect correlation between estimated and computed UC values is represented by the diagonal (solid) line which passes through 100 and 100. The correlation is not quite as good as in Figure 7 where the actual basic UC curves were used directly to estimate UC values; however, the correlation is suprisingly good with most all of the estimated data within ± 5 UC points of the actual numerically computed values.

The data presented in Figure 10 does not include square spacings which were found difficult to predict by the graphical method as demonstrated in Figure 7. The few points which fall outside of the envelope in Figure 10 can generally be associated with $W_e$ values represented by points which showed a poor correlation with the regression lines on Figure 8.

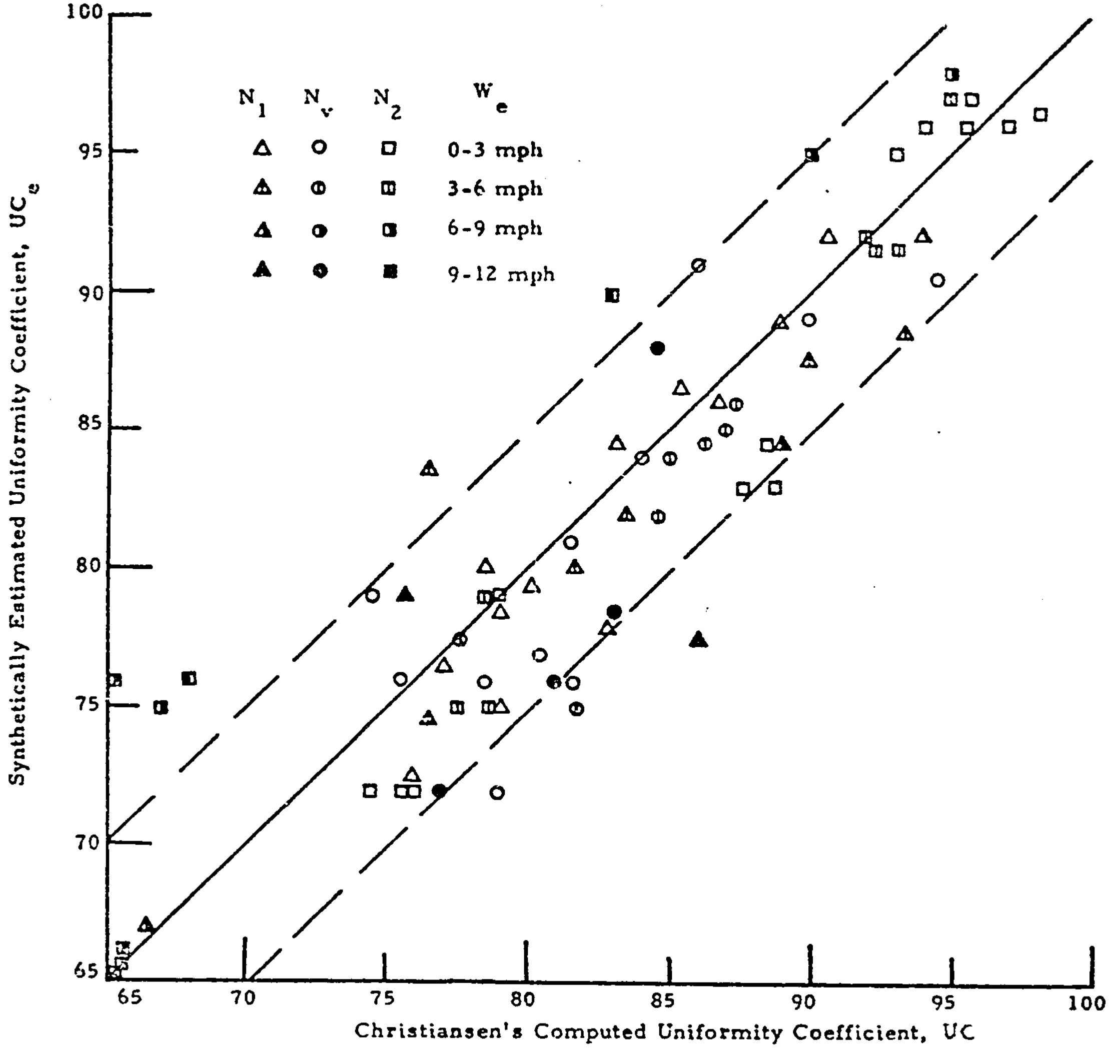

Figure 10. Synthetically estimated UC values (from basic [zero wind] UC curves) versus actual UC values computed numerically for various sprinkler profiles, wind speeds and sprinkler spacings.

## SUMMARY AND CONCLUSIONS

A method was presented and successfully tested for predicting the field performance of sprinklers for a variety of steady state wind conditions from a limited number of single sprinkler tests. Three basic geometric profile categories were investigated.

The method utilizes the concept of the shift in center of mass, C, of the test pattern to characterize the effective wind speed. A functional relationship was developed for the relative shift of the center of mass, $C_r$, versus the average wind speed of the test, where $C_r = 100\ C/Re$. The high degree of correlation demonstrated that $C_r$ is a reasonable indicator of the magnitude of the integrated wind vector irrespective of the variations in the sprinkler-nozzle-pressure combination. The effective wind speed, $W_e$, for all the tests was then assumed equal to the value corresponding to the computed $C_r$ of the test represented on the regression curve in Figure 3.

Values of UC versus the spacing along the main as a percentage of the effective diameter, $100\ S_m/D_e$ were plotted for $S_\ell = 0.03\ D_e$. These "basic UC curves" were plotted for a particular sprinkler-nozzle-pressure combination under a range of wind velocities (Figures 4, 5, and 6). UC values were estimated for various spacings from the basic UC curves by entering the plots with both the $S_\ell$ and $S_m$ spacing as a percentage of $D_e$. UC of the spacing was assumed equal to the product of the individual UC values divided by 100. By this method it was possible to estimate the uniformity coefficient within 5 UC points of the UC values obtained using Christiansen's equation. Almost without exception the estimated UC values were lower than the computed UC values as shown in Figure 7.

In order to extend the usefulness of a limited amount of test data, a means for estimating sprinkler performance at any wind speed was developed. A functional relationship was developed for the relative shift of the basic UC curves versus effective wind, $W_e$, for the three geometric profiles studied, see Figure 8. By multiplying the $S_m/D_e$ values from a basic (zero wind) UC curve, by the $S_s$ for a given $W_e$, the basic (zero wind) UC curve can be shifted to represent the wind speed in question. Synthesized UC values were then obtained from the basic (zero wind) UC curve by the method mentioned above. The synthesized UC values show a good correlation with the computed UC values with almost all of the synthesized data within ± 5 UC points of the numerically computed UC values, see Figure 10.

The above methods for dealing with the effects of steady state winds when predicting the field performance of sprinklers should prove useful for sprinkler system design. These methods should prove equally useful for organizing sprinkler test programs and developing sprinkler performance tables from limited test data.

The data utilized in the analysis was limited to steady wind speeds which never exceeded an average velocity of 12 mph over the duration of the test period. Additional work is recommended to extend the analysis to include: (a) wind speeds greater than 12 mph, (b) very small (less than 7/64 inch) and large (greater than 1/2 inch) nozzles, and (c) sprinklers having mechanical operating characteristics which greatly differ from the tested sprinklers.

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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 gage 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 | Noz | Base |
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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

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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 ____________________

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |

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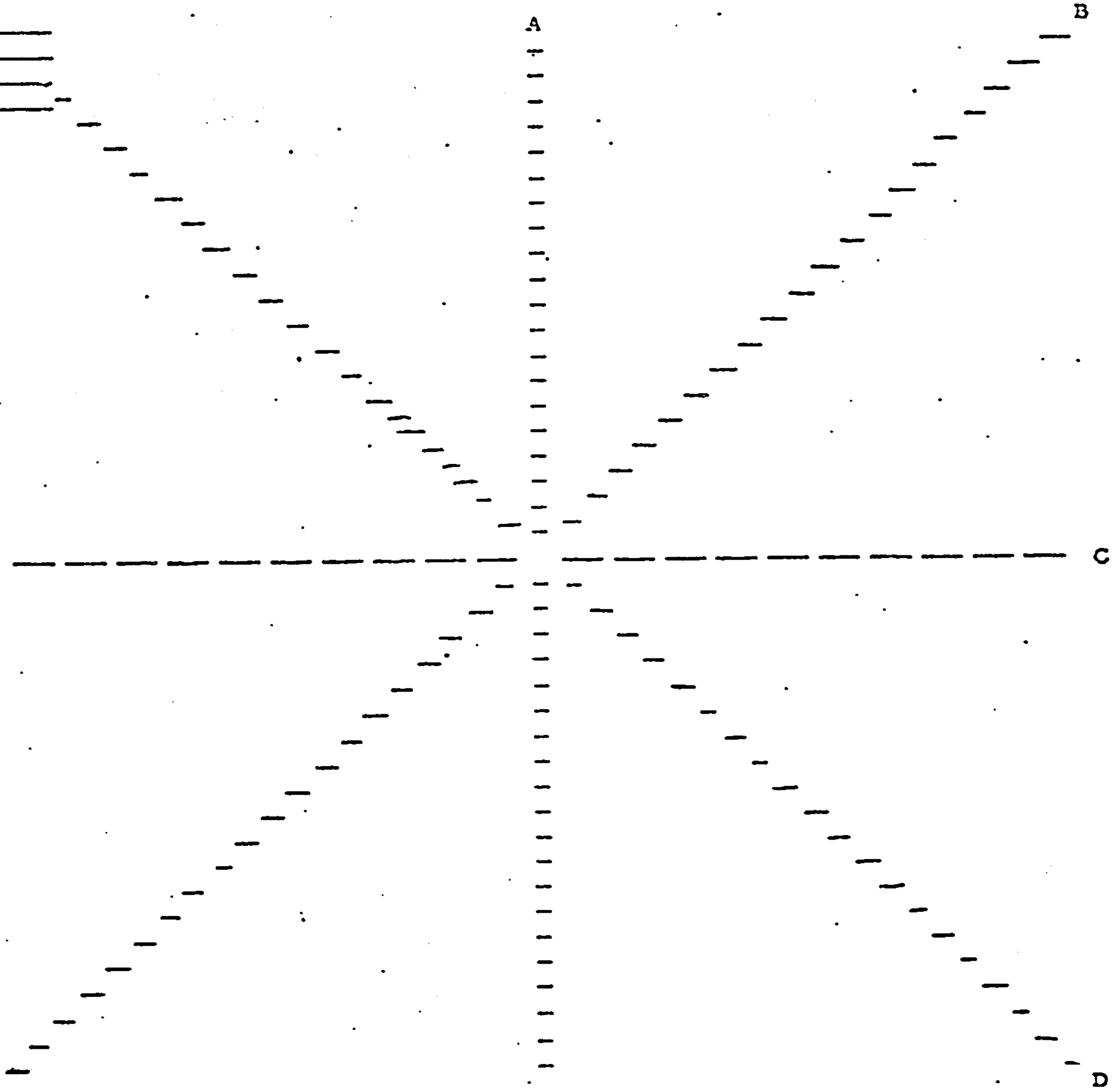
1. Test No. __________
2. Sprinkler No. ______
3. Range Nozzle ______
4. Spreader Nozzle____



# Appendix B

## Computer Programs

## Shift in Center of Mass Calculation

### Imput Procedure

Data Cards

First Card: A Format

| Column | |
|---|---|
| -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 remainder of the cards are the actual catch-can values. As mentioned the pattern must be symetrical about the sprinkler location. The values are read in on an F 4. 1, therefore, there are 20 can readings per card. Cans with zero depth must be accounted for by either putting zero or leaving the field blank.

## Output

This program computes the shift in the center of mass of the wind affected single sprinkler test pattern. The shift is in feet. The program also computes the angle of the shift measure from North. Plus (+) angles are clockwise, minus (-) angles are counter-clockwise.

```
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
```

## Grid Rotation and Uniformity Coefficient Program

### Imput Procedure

#### Data Cards

First Card:

| <u>Column</u> | |
|---|---|
| 1-5 | Number of spacing combinations to be investigated. |

Second Card:

| <u>Column</u> | |
|---|---|
| 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 in the first data card. The spacing combinations are read in consecutively starting at the beginning of the second card using a 20 F 4.2 format, 10 spacing combinations per card. It may take more than one card depending on the number of spacing combinations desired.

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 measures from North (plus angle 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 remainder of the cards are the actual catch-can values. As mentioned the pattern must be symetrical about the sprinkler location. The values are read in on an F 4.1, 20 values to a card. Cans with zero depth must be accounted for by either putting zero or leaving the field blank.

## Output

The rotated single sprinkler pattern is printed out first.

The uniformity coefficient is computed for each spacing combination and printed out showing the actual spacings in feet and the spacings as a percentage of the effective diameter.

```
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 (PL .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
```

```
 1 2 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)
      GOTO 4
    1 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)
2041  FORMAT(1H1)
      DO 2039 I=1,N
2039  WRITE(6,105) (CR(I,J),J=1,N)
105   FORMAT(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 800 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)
```

```
800    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
802    CE(I+K,J)=F1+FLOAT(K)/FLOAT(L)*(F2-F1)
803    CONTINUE
C
C      SUPERIMPOSITION OF SPRINKLER PATTERN AND
C      CALCATION OF UNIFORMITY COEFFICIENT
C
       ND=NN/2+1
804    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)
2030  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
2010  CONTINUE
      GO TO 2
 3    STOP
      END
```

# Appendix C

## Profile Factor

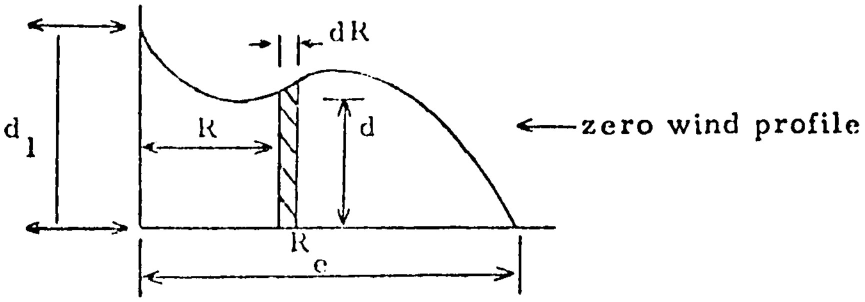
Because of the variety of nozzle-pressure combinations possible for any particular sprinkler model, it is possible to produce many variations of a single geometric profile, or even to produce several distinct profiles by using a wide range of pressures. Therefore, it was felt that in order to categorize a profile produced by a particular nozzle-pressure combination into one of the three general geometric profiles being studied, some criteria must be established. In the early stages of the research, an attempt was made to describe the shape and stability characteristics of the three general geometric profiles by a single dimensionless parameter. However, the parameter was never actually applied in the final analysis. It is presented in the Appendix section so that it could be used in future research.

Through a more or less trial and error dimensional analysis the "profile factor," P. F. was developed. The profile factor is defined by the following equation,

$$\text{P.F.} = \frac{G_v \times R_e}{d_{av}^{2}} \qquad (2)$$

Where $G_v$ is a weighted volume moment, $R_e$ is the effective radius, and $d_{av}$ is the average depth of the sprinkler pattern. These variables can be defined mathematically using a typical profile as follows.

Mathematical Definitions:



Vertical incremental area = A

$$A = dR \cdot d$$

Area A revolved around the axis = Vol.

$$Vol = 2\pi RA$$

(1) Weighted volume moment, $G_v$

$$G_v = \frac{\Sigma (R \cdot Vol.)}{\Sigma (Vol.)} \quad \begin{array}{l} \text{- Infinitesimal volume} \\ \text{- Total volume} \end{array} \tag{3}$$

$$G_v = \frac{\int_o^{R_e} 2\pi (d \cdot R^2)\, dR}{\int_o^{R_e} 2\pi (d \cdot R)\, dR} \tag{4}$$

$$G_v = \frac{\int_o^{R_e} (d \cdot R^2)\, dR}{\int_o^{R_e} (d \cdot R)\, dR} \tag{5}$$

(2) Average Depth, $d_{av}$

$$d_{av} = \frac{\text{Total Volume}}{\text{Bottom Surface Area}} \tag{6}$$

$$d_{av} = \frac{2\pi \int_{o}^{R_c} (d \cdot R)\, dR}{\pi R_e^{2}} \tag{7}$$

$$d_{av} = \frac{2 \int_{o}^{R_e} (d \cdot R)\, dR}{R_e^{2}} \tag{8}$$

By analyzing the variables which made up the profile factor, it can be seen that many of the parameters contributing to the general shape and stability of a geometric profile are contained in the P.F. The greater the distance the water falls from the sprinkler, the more the P.F. is effected by the $G_v$ term. $G_v$ is a function of several factors.

$$G_v = f(\text{Discharge per Unit Time, General Shape, } d_{av}, R_e)$$

where Discharge = f(Nozzle, Pressure)

$$G_v = f(\text{Nozzle, Pressure, Unit Time, General Shape, } d_{av}, R_e)$$

The terms $R_e$ and $d_{av}$ are the function of several factors also.

$$R_e = f(\text{Nozzle, Pressure, Mechanical Operating Characteristics})$$

$$d_{av} = f(\text{Nozzle, Pressure, Unit Time, } R_e)$$

It can be seen from the above crude analysis that P. F. is a function of (1) Discharge for a unit time; (2) Nozzle size and pressure; (3) General shape of the profile; and (4) Mechanical operating characteristics of the sprinkler such as speed of rotation, number of nozzles and angle of trajectory.

In order to apply the Profile Factor to the variety of geometric profiles encountered, graphical integration must be used to compute the variables. It is suggested that the profile be divided into five areas for the graphical integration. The standard unit time for a test to determine the zero wind profile should be one hour. If the test duration is not one hour, the depth can be converted by a simple ratio.

# VITA

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