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SPRINKLER PROFILE ANALYSIS TO PREDICT FIELD PERFORMANCE

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SUMMARY:
A method is 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. The method utilizes the concept of the shift in the center of gravity of the test pattern to characterize wind and the slope of the sprinkler profile under low winds to characterize the sprinkler.

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Sprinkler Profile Analysis to Predict Field Performance

by

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Sprinkler irrigation is a well accepted practice which is becoming more sophisticated with the development of new innovations and materials. Optimizing the economical potential of system design requires combining the concepts of system capacity, crop production versus water applied, operating costs with optimized fixed costs, spray losses, water quality, and water application distribution. The interaction between some of these factors has been considered by a number of other investigators, such as Culver and Sinker (1966), Howell (1964), Liang and Wu (1970), and Norum (1966). Water application distribution and crop production versus water application for given system capacities and climatic conditions are the major controlling factors necessary to begin the optimization process for system design.

There is a great deal of information available on the peak water requirements of crops, such as Pair et al. (1969). However, there is very little information concerning the yield of specific crops in terms of the water applied. The importance of such information has become generally recognized, and research or studies on the subject, such as presented by Musick and Dusek (1971) and Yaron (1971), are becoming more prevalent.

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Well known procedures, such as presented by Keller (1965), have been developed for optimizing fixed and operational costs in the hydraulic networks of sprinkler irrigation systems. Furthermore, with the use of computers, the optimization problem is being greatly simplified. The spray loss from sprinklers has been considered in detail by Sternberg (1967), who present a good review of the literature covering this area of activity. In many cases, the irrigation water quality is sufficiently high so that productivity is not adversely affected. However, a good understanding of the interactions between irrigation water quality and soils or plant folliage, such as presented by Hagan et al. (1967), is important where low quality irrigation waters are apt to be encountered.

This paper deals exclusively with the water distribution or uniformity of application aspects of sprinkler irrigation system design. As a first step in optimizing system design, the anticipated field performance of each sprinkler-pressure-nozzle-discharge selection must be predicted. A number of researchers, including Bilanski and Kidder (1958), Chu and Allred (1968), Seginer (1963), and Umback and Lembke (1966), have dealt with this problem 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, it has not been successfully applied to predicting sprinkler uniformity under field conditions.

Sprinkler Distribution

The uniformity of distribution from stationary sprinklers has been the subject of many studies. These studies can be broken into the following categories: studies dealing with the factors which affect the sprinkler uniformity, studies which deal with the measurement of sprinkler uniformity, and studies which deal with the prediction of field uniformity based on a knowledge of the general sprinkler performance characteristics and anticipated field environmental conditions.

Factors which affect sprinkler uniformity have been well documented, Christiansen (1942), Molenaar et al. (1954), Pair (1968), Pair et al. (1969), and Wiersma (1950). Redditt (1965) listed and reviewed the factors affecting sprinkler uniformity. These factors can be separated into the following groupings: spacing both along the line and between line; environmental factors including wind speed, wind direction, spray loss and the set time as it relates to the wind factors; and the mechanical operating conditions of the sprinkler which include physical sprinkler design, nozzle size, pressure and riser height.

Allison and Hesse (1969), Seginer (1969), and Wiersma (1950) analyzed the effect of wind direction on sprinkler performance. From these studies it appears that no single wind orientation would provide a superior uniformity for all sprinkler spacings and wind conditions. Branscheid (1971)* proposed using the shift in the center of gravity of sprinkler test data 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 gravity 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 gravity would remain at the sprinkler.

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*Verbal Communications

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

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

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 McDougald (1954), have compared various means of evaluating sprinkler uniformity and have generally concluded that for relatively high UC values, Christiansen's uniformity coefficient provides a good estimate of water distribution. Hart (1961) postulated that the water application distribution from closely spaced stationary sprinklers nearly approximates a normal or Gaussian distribution. Seniwongse et al. (1970) supported Hart for UC values greater than 75. Assuming a normal distribution, Hart (1965) 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.

Predicting Field Distribution

The purpose of most sprinkler testing is to predict the field distribution which can be anticipated under actual operating conditions. (Merriam (1968) suggested procedures for analyzing the performance of a given sprinkler system in the field. However, these procedures are not useful in anticipating expected performance for optimizing design.) 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 that 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 direction and velocity) 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 pattern profile concept. (The pattern profile is the plot of distance from the sprinkler versus depth of applications.) He explored the possibility of analyzing the pattern profiles in an effort to predict UC for various sprinkler spacing situations.

In his study, Christiansen worked with six basic sprinkler pattern profiles, some of which approximated actual sprinklers, as shown in Figure 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.

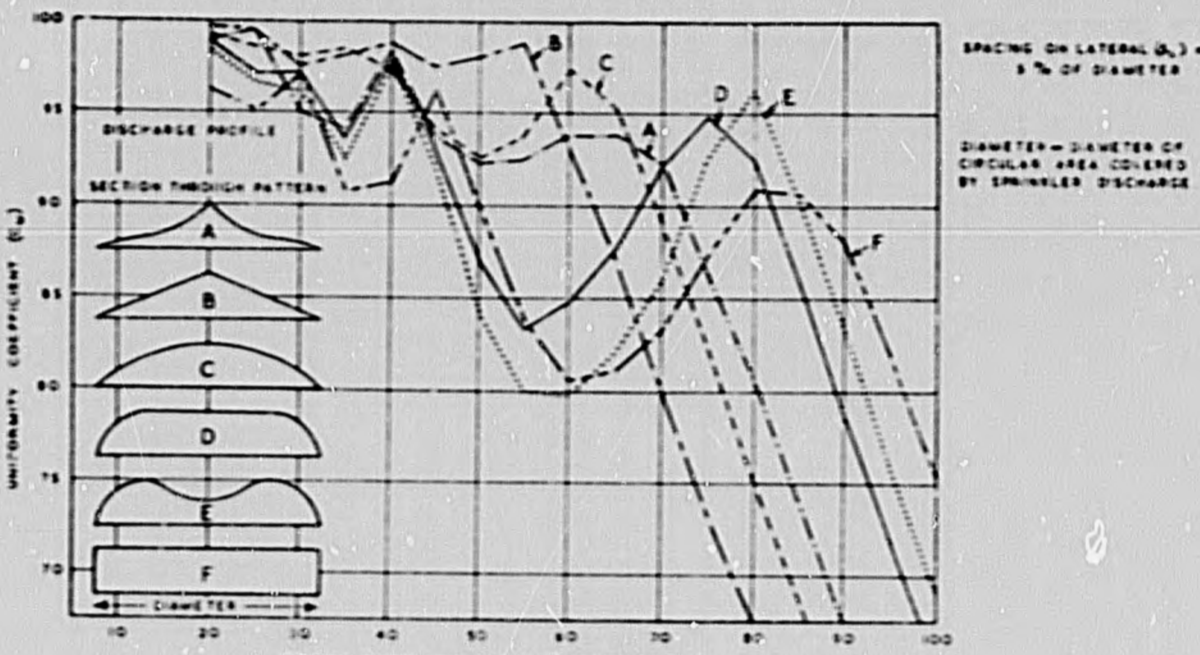

Figure 1. Christiansen's basic UC curves

Strong (1962) 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_l, 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_l. Further details of this method are presented by Keller et al. (1967).

Strong (1962) 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. 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

Single nozzle model 30 and double nozzle models 30W and 30EW sprinklers with 3/4 inch male inlets (manufactured by Rainbird Sprinkler Company) were tested. Range nozzle diameters between 9/64 inches and 7/36 inches were tested at pressures between 35 and 60 psi. Six sprinklers of each model were selected from "off the shelf" at a retail outlet and tested for uniformity of rotation and discharge at 50 psi. The rotation rates varied between 0.75 rpm and 1.8 rpm, and the discharges varied approximately ± 2 percent. An average sprinkler representing each model was selected for the test program.

A single sprinkler test sight was set up, which very nearly complied with recommendation ASAE R330, titled "Procedure for Sprinkler Testing for Research Purposes." The test sight deviated from the recommended as follows: (1) The collectors were only 6 inches above the ground instead of 12. (2) The rims of the collectors were only 3 inches above the crop of grass instead of 6. (3) At times only 50 or 60 collectors received water instead of a minimum of 80. (4) The sprinkler was located at a collector point on the grid instead of mid-way between the 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 at 45 degree angles were utilized with collectors at ten foot spacings.

White styrafoam cups were used as collectors. The cups had tapered sides so they could be nested and were 5.5 inches deep with a surface catch area diameter of 4.4 inches. The white styrafoam provided insulation capacity and repelled water which should have minimized container related losses.

Approximately 1/2 of the data utilized in the following analysis was produced at the above test sight. The rest of the data was provided through the courtesy of Rainbird Manufacturing Company, Glendora, California. (The fact that the two sets of data were similar in overlapping areas is encouraging.)

A computer program was developed to aid in analyzing the data. The program first calculates the direction and magnitude of the shift in center of gravity, C, of the wind affected single sprinkler pattern. The relative direction of C from the sprinkler location is taken as the effective wind direction, and the grid pattern is rotated to a 0° wind angle. The rotation is accomplished by the use of linear interpolation to determine the values of the rotated points. At this point in the program, the pattern can be rotated to any desired relative wind angle and superimposed to generate any desired rectangular spacing. The UC is then determined for the particular spacing combination. A more detailed review of the collection of field data and the analysis which follows is provided by Moynahan (1971) and Ptacek (1971).

Wind and Profile Analysis

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 velocity. The location of the center of gravity was computed for each of the 65 test patterns utilized in the study. The ratio of the distance between the center of gravity and the sprinkler, C, to the average effective radius (not trace radius) of the sprinkler under 0 to 3 mph winds, R_e was calculated. Figure 2 is a plot of $Cr = 100(C/R_e)$ versus the average wind velocity (or total wind passing divided by the test duration) during each test. All of the data in Figure 2 was fit by a second degree quadratic which was forced through the origin. The high degree of correlation demonstrates that C_r is a sensitive indicator of the magnitude of the integrated wind vector irrespective of the variations in the sprinkler-nozzle-pressure combination tested. The effective wind velocity, W_e, for any test was assumed equal to the wind speed represented by the regression line in Figure 2 for the C_r of the test.

<u>Wind direction</u>. The line connecting the sprinkler location and the wind affected center of gravity was assumed to be 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. The data for each test was then rotated in 22 1/2° increments so that UC analysis could be conducted for synthesized integrated wind directions parallel or 0°, 22 1/2°, 45°, 67 1/2°, and perpendicular or 90° to the lateral line.

Figure 3 shows representative plots of UC versus sprinkler spacing for low and high winds at 0°, 45°, and 90° to the lateral. A sprinkler spacing ratio, $S_\ell/S_m = 0.4$ (where S_ℓ is the sprinkler spacing on the lateral, and S_m is the spacing along the main) was used. From a study of the graph, it is apparent that the "preferred" wind direction depends on wind velocity and the sprinkler spacing in question. (This analysis confirms the results of the investigations referred to earlier.) For example, under low wind a spacing of 80 percent of the effective

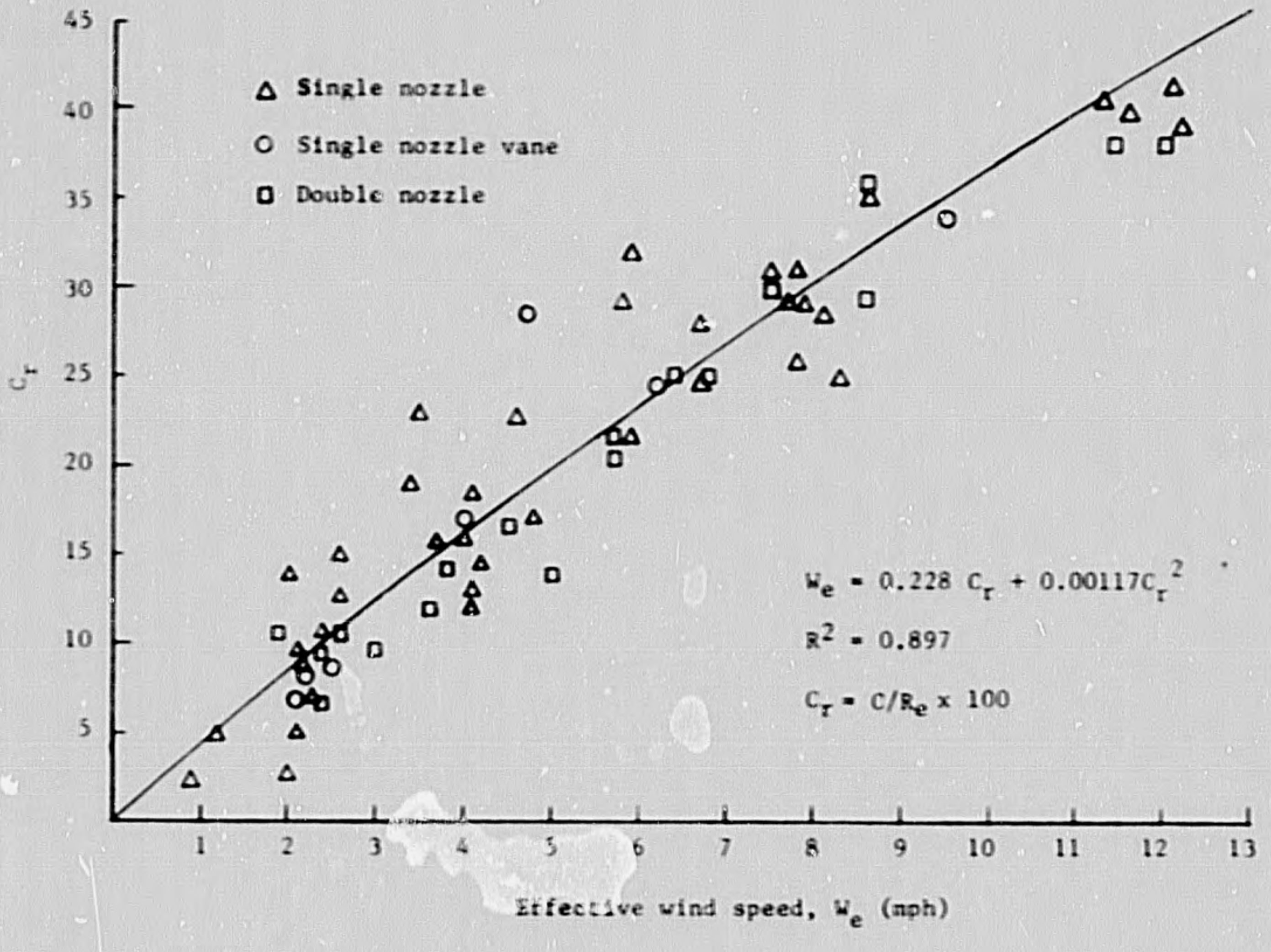

Figure 2. Shaft in center of gravity ratio, C_r, versus average steady state wind velocity or effective wind velocity, W_e

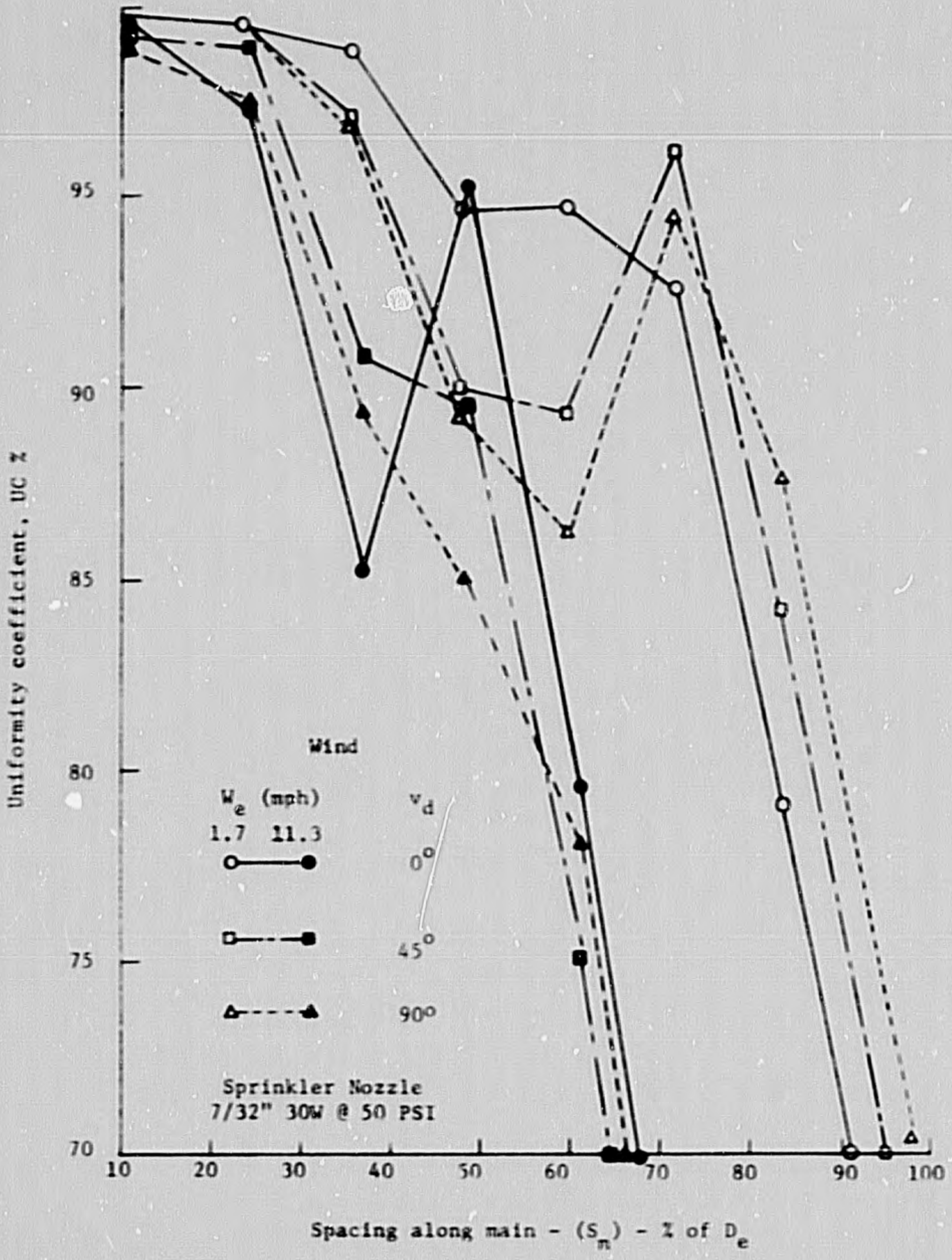

Figure 3. Uniformity coefficients, UC, for various spacings along the main under high and low winds with a $S_\ell/S_m = 0.4$

diameter, D_e, along the main would produce a UC of 93 when the wind is parallel ($W_d = 0^o$) and 95 when the wind is perpendicular ($W_d = 90^o$) to the lateral. At a spacing of 60 percent of D_e the corresponding UC values are 95 and 87. Since D_e is approximately 100 feet, the above spacings are 30 feet by 80 feet and 20 feet by 60 feet, respectively.

After an analysis of Figure 3 and similar plots for the other data, it was decided to conduct the remainder of the study with $W_d = 45^o$. The $W_d = 45^o$ plot generally falls midway between the $W_d = 0^o$ and $W_d = 90^o$ plots.

Profile Analysis - A number of efforts were made to develop sprinkler profile indices which would be helpful for design purposes. The most useful concept evolved was similar to Christiansen's (1941) suggestion (Figure 1) of plotting UC versus S_m for a small S_ℓ value.

The test data taken at various wind speeds with double nozzle and single nozzle (with and without vanes) sprinklers was utilized. Values of UC versus the spacing along the main as a percentage of the effective diameter, 100 S_m/D_e, were computed for $S_\ell = .03\ D_e$, and plots similar to Figure 4 were drawn up for each representative low wind sprinkler profile category. These plots or curves will be referred to as basic UC curves.

Figure 4 represents a series of tests using a typical 3/16 inch nozzle sprinkler operating at 50 psi with integrated wind speeds of 0, 0.6, 3.9, 7.7 and 11.0 mph at $W_d = 45^o$. 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. This sprinkler profile is between the Christiansen A and E profiles. 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

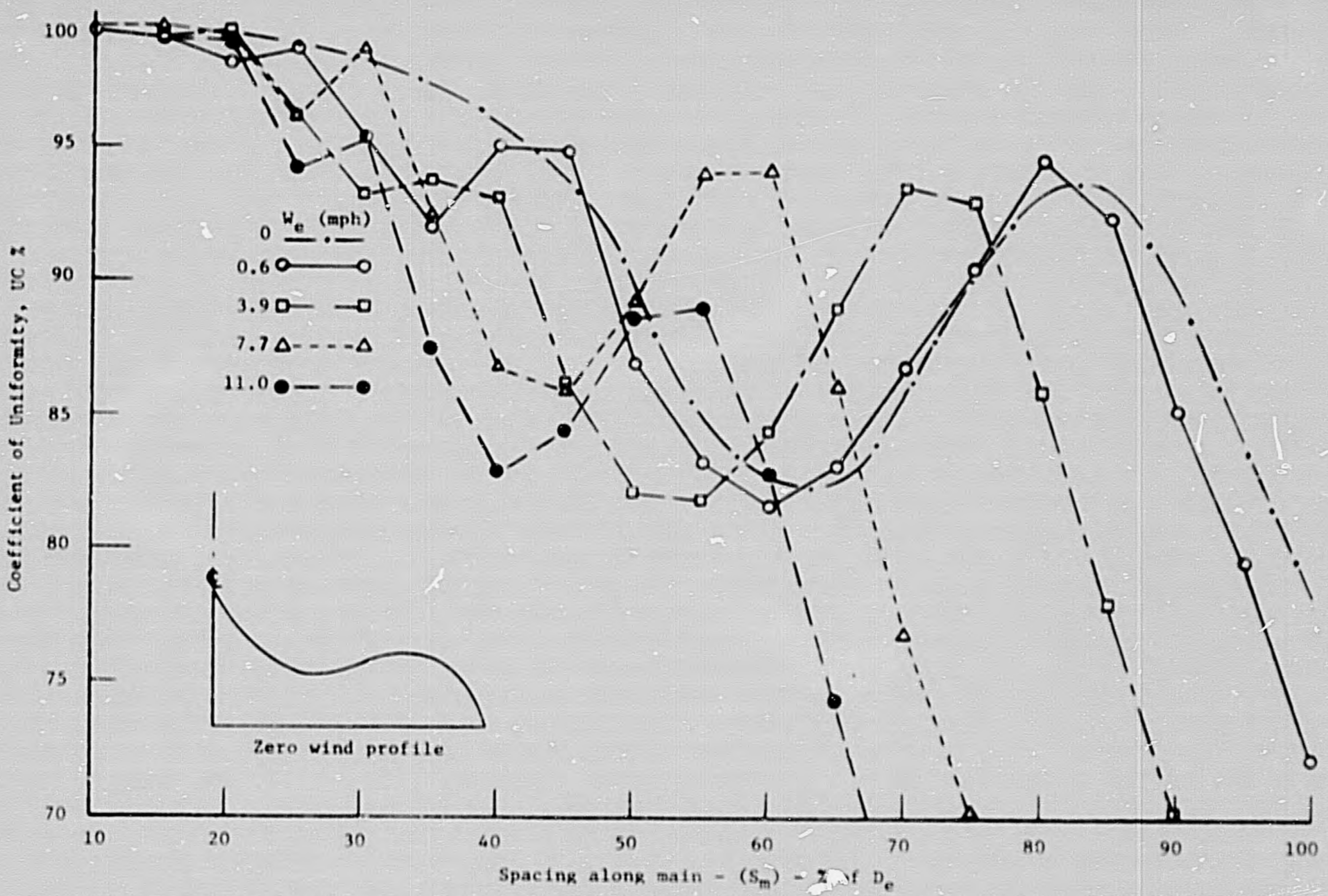

Figure 4. Basic UC curves showing UC versus the spacing along the main as a percentage of the wetted diameter for a 3/16 inch nozzle sprinkler operating at 50 psi and W_d = 45°

a D_e of approximately 100 feet, so any actual synthesized spacing selected would be equal to 3 feet by S_m feet, and the graph can be entered with 100 (S_m/D_e) = 100 $(S_m/100)$ = S_m.)

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 = 8.83, 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 that 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 rapdily as wind velocity increases. Therefore, extreme caution should be exercised when selecting such spacings based on no wind conditions.

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 $W_d = 45^\circ$, $S_\ell = 0.03\ D_e$, and various values of W_e is useful for the design of traveling sprinklers. There is little differences between plots with $S_\ell = 0.03\ D_e$ and the infintesimally small S_ℓ which represents a traveling sprinkler (i.e., for a traveling sprinkler S_ℓ is 0; however, this can be similated by a very small S_ℓ).

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_ℓ and S_m spacing values and the UC of the expanded spacing was assumed equal to the product of the individual UC values divided by 100. To evaluate the reliability of this procedure, the computer program was designed to produce synthesized UC values for a large number of S_ℓ by S_m spacing combinations. The calculated UC values predicted by the graphical method were then compared with the actual UC values computed numerically by the computer as shown in Figure 5.

A perfect correlation between computed and actual values of UC is represented by the 45° diagonal (solid line passing through 100 and 100) in Figure 5. 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 under-predict UC as indicated by the density of points between the perfect (solid) and 5 UC points under prediction (upper dotted) line in Figure 5.

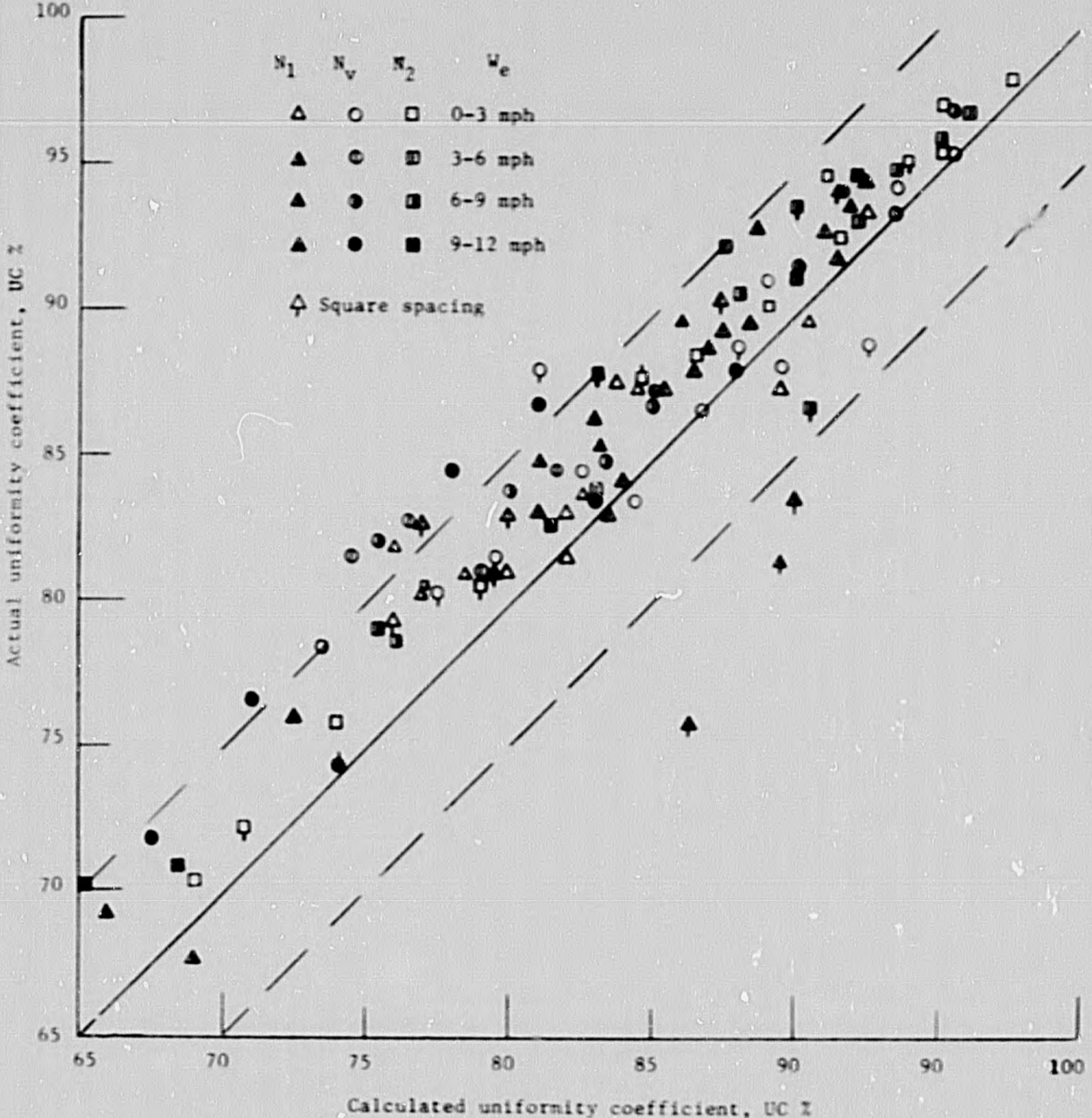

Figure 5. Calculated UC (from basic UC curves) versus actual UC computed numerically for various sprinkler profiles, wind speeds, and sprinkler spacings

All of the data for the double nozzle sprinkler tests falls between these two lines on Figure 5. Most of the points falling outside of this envelope represent single nozzle sprinklers at square spacings which produced UC values in dips (causing greater under-prediction) or on the outside peak (causing over-prediction) of the basic UC curves like Figure 4. A tendency to over-predict UC also occurred whenever the spacing was past the peaks and on the steep drop-off portion of the basic UC curves.

From the foregoing analysis it appears that this graphical method for estimating UC from the basic UC curves is valid. The method should be used with the greatest caution for square spacings of single nozzle sprinklers and spacings past the peak on the basic UC curves.

No analyses were conducted with triangular spacings; however, it is proposed that (a) when the spacing approaches an equilateral triangle where $0.8\ S_{\ell} < S_{\ell} \leq$, 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_{ℓ}, proceed as for rectangular spacings.

The reason the graphical method underestimates UC for a square spacing where S_{ℓ} 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 over-watering 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.

<u>Wind effects.</u> By studying Figure 4 it is evident that as the effective wind velocity, W_e, increases, the UC curves are shifted inward.

Closer study will show that the shift is relative, with the outside peak being shifted about twice as far as the inside slope of the dip. A plot relating the relative shift of the basic UC curves to W_e for most of the test data is shown in Figure 6. For convenience later, the relative shift is plotted in terms of a spacing shift ratio, S_s. The values for S_s 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.

The shift in the center of gravity versus wind speed data for all tests was closely correlated as shown in Figure 2. However, in Figure 6 a different first order regression curve was required for each of the three general sprinkler-spacing-nozzle combination studied, i.e., double nozzle, N_2, single nozzle, N_1, and single nozzle with vane N_v. The regression equations were forced through $W_e = 0$ and $S_s = 1.0$ and fit the data quite well as indicated by the correlation coefficients.

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. Furthermore, the rotation of the test data to simulate different wind directions was included earlier in this study. 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

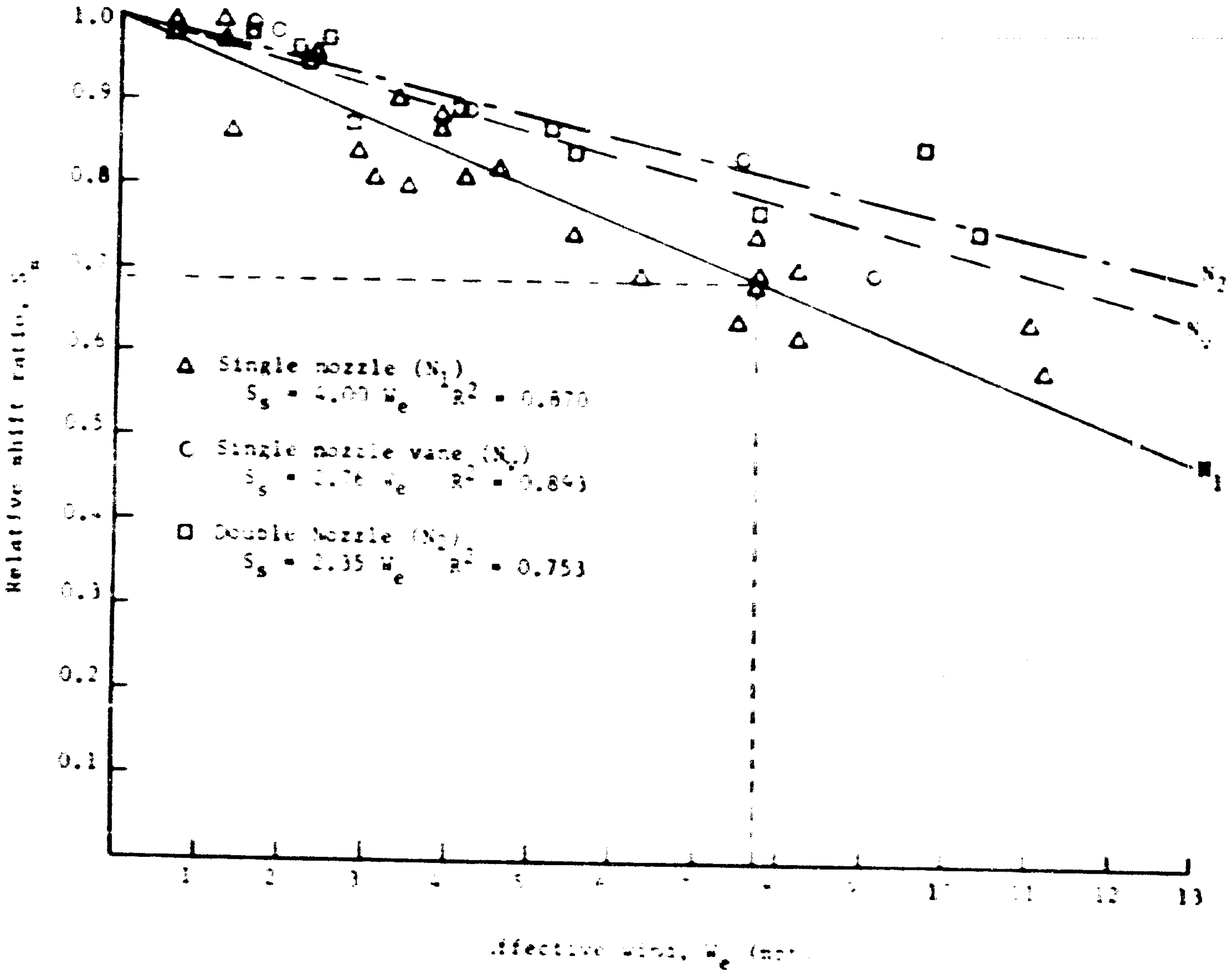

Figure 6. Relative shift ratios, S_s, of basic (zero wind) UC plots versus effective wind speed, W_e

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 lines in Figure 6 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.

Figure 7 shows basic (zero wind) UC curves for the three general sprinkler profiles which were analyzed. These zero wind curves were computed from the pattern profiles which are also presented in Figure 7. 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 spacing and W_e combinations for each of the basic (zero wind) UC curves presented in Figure 7. An example of the computation of these values is as follows. Given a 3/16" single nozzle sprinkler operating at 50 psi having a catalog diameter of 100' and De = 94' with W_e = 7.7 mph. The estimated UC_e for a 30' x 50' spacing is found by entering Figure 6 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_ℓ, for entering Figure 7 is

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

which gives a UC_ℓ = 93. The spacing along the main value, S_m, for entering

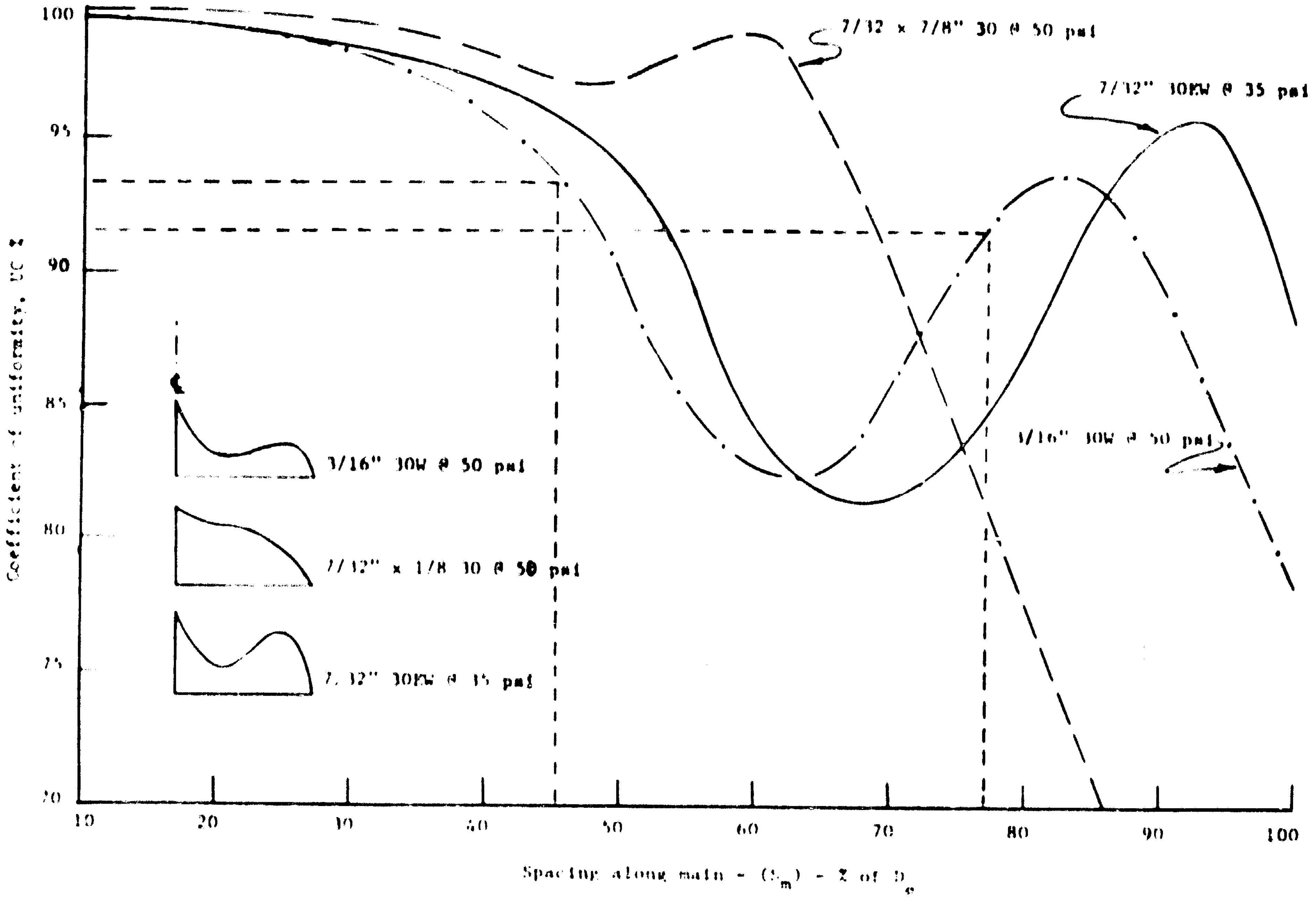

Figure 7. Basic (zero wind) UC curves calculated from the sprinkler profiles shown

Figure 7 is

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

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

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

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 are shown in Figure 8. A perfect correlation between estimated and actual 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 5 where the actual basic UC curves were used directly to compute UC values; however, the correlation is suprisingly good with most all of the estimated data within ±5 UC points of the actual numerically calculated values.

The data presented in Figure 8 does not include square spacings which were found difficult to predict by the graphical method as demonstrated in Figure 5. The few points which fall outside of the envelope in Figure 8 can generally be associated with W_e values represented by points which showed a poor correlation with the regression lines on Figure 6.

Discussions

The above methods for dealing with the effects of reasonably steady (velocity and direction) wind when predicting the field performance of sprinklers should prove useful for sprinkler system design. These methods

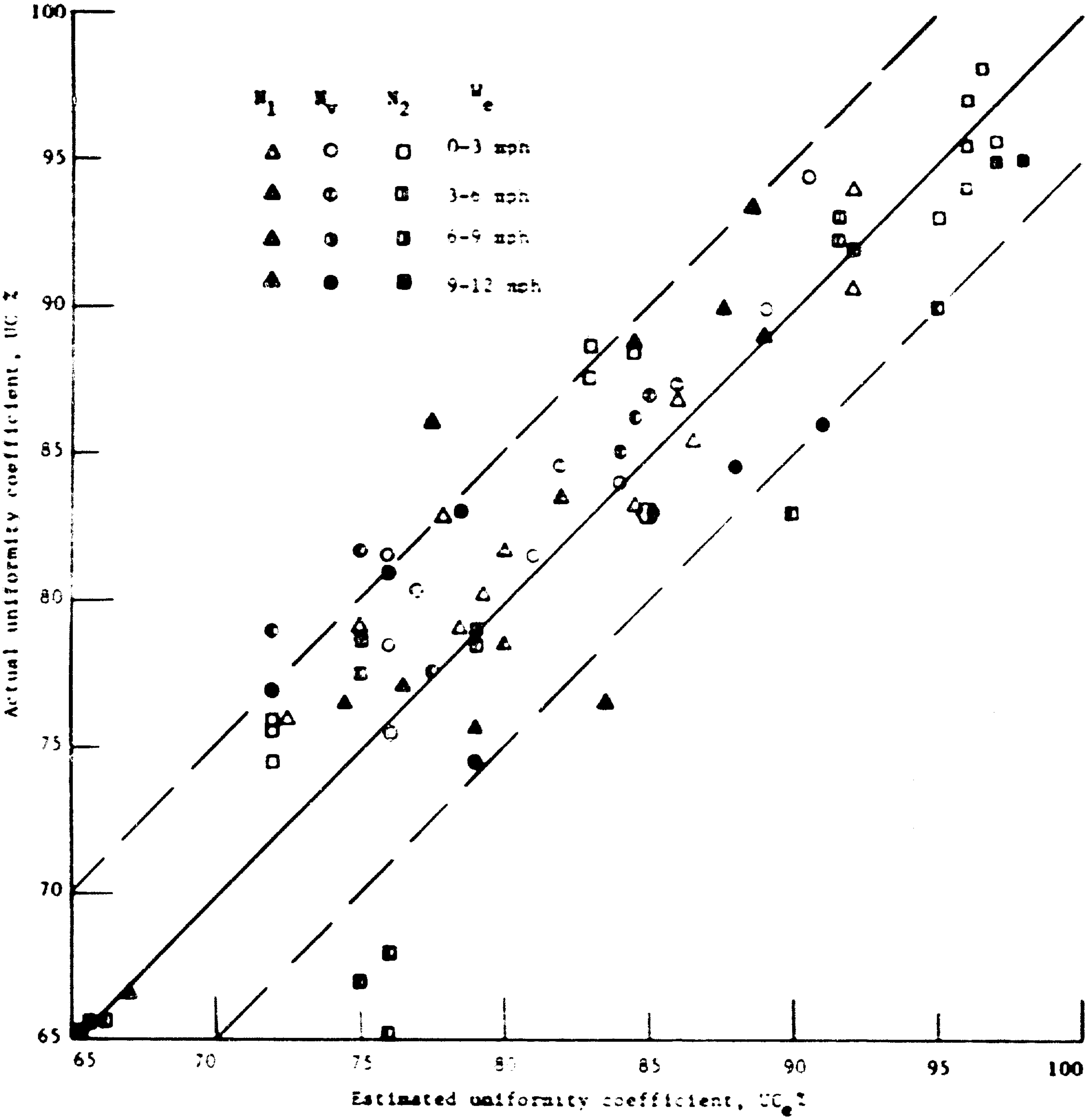

Figure 6. Estimated UC values (from basic [zero wind] UC curves) versus actual UC values numerically for various sprinkler profiles, wind speeds and sprinkler spacings

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. Furthermore, only a few sprinkler-nozzle-pressure combinations were considered. Additional work is recommended to extend the analysis to include: (a) wind speeds greater than 12 mph, (b) very small (less than 7/65 inch) and large (greater than 1/2 inch) nozzles, and (c) sprinklers having mechanical operating characteristics which greatly differ from the tesed sprinklers.

The above analysis deals specifically with steady state winds. The method presented herein for estimating UC_e is not recommended where the average wind velocity exceeds 3 mph and the wind speed or direction varies considerably during the sprinkler operating period. (Further study is recommended to cover unsteady wind conditions.) However, in general, UC improves as the variations in wind speed and direction increase. For example, Pair (1968) found that the sum of any two irrigations usually produced a higher UC than either of the individual irrigations.

The process of superimposition utilized in this report assumes the wind speed and direction remain steady throughout the period during which water from any sprinkler position is being received by the area under consideration. Such an assumption overlooks the possibility that the wind could shift between the operation of adjacent lateral lines. Branscheid and Hart (1968) demonstrated that such wind shifts generally reduce UC.

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