SPRINKLER NOZZLE PERFORMANCE UNDER
SIMULATED WIND CONDITIONS

by

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Sprinkler irrigation is one of the principle methods by which water is applied to the soil. Sprinklers were originally used only for the production of high-value crops. With the advent of light weight portable pipes and quick couplers, the use of sprinklers has spread to pasture and field crops. Recently, mechanical-move systems for the transfer of pipe have been developed and they are finding increased use. One common mechanical system involves the use of the lateral line as the axle of powered wheels. Another recent development is the solid-set system in which sprinklers connected by buried plastic pipe are set out in the field and not moved. These new developments nearly eliminate the somewhat unpleasant task of handling sprinkler lines.

The use of sprinklers often entails a higher investment cost than surface methods. However, the sprinkler method of irrigation may be the only method suited for use in certain areas. Such areas include land which is too steep and irregular for proper leveling. Sandy and gravelly soils, which have a rapid intake of water, are especially suited to sprinkler irrigation. In areas of normally high rainfall, sprinklers can be readily used to apply water during drought periods. Conservation measures, such as terraces, are not disturbed through the use of sprinklers. Sprinkler irrigation can be conveniently used to supply relatively small quantities of water to insure the germination of crops. Water for this purpose may often be obtained by a small pump drawing water out of a farm pond.

One of the major criticisms of sprinkler irrigation is that poor performance results under windy conditions. The writer has heard statements by farmers that the distribution pattern of sprinklers is grossly destroyed

under the effect of wind. Observation of sprinklers operating in the field tends to support this position.

PURPOSE OF INVESTIGATION

In order to accurately assess the suitability of sprinklers for irrigation, information is required on the performance of sprinklers under windy conditions. As an introductory study, this project was undertaken to investigate the performance of the sprinkler nozzle under the limited conditions of operating directly with and directly against the wind.

The objectives of this study were:

1. To determine the effect of a change in wind on the distribution of water obtained from a sprinkler nozzle.

2. To determine the effect under windy conditions of a change in pressure, nozzle size, and trajectory angle on the distribution obtained from a sprinkler nozzle.

3. To determine the efficiency of application of a sprinkler nozzle under different wind velocities.

4. To relate factors, including wind velocity and particle size, to the distance of travel of water droplets from the sprinkler nozzle.

REVIEW OF LITERATURE

The objective of sprinkler irrigation is to distribute water uniformly and without loss over the area to be irrigated. Rotating sprinklers cover a circular area and it is difficult to obtain a completely uniform distribution. The overlapping of sprinkler patterns is required to obtain uniformity. Bagley and Criddle (1) point out that the uniformity obtained from sprinklers of a specific design will be affected by pressure at the nozzle, spacing of

the sprinklers, and wind movement.

Some of the earliest work in the investigation of sprinkler performance was conducted by Christiansen (3) at Davis, California. In order to compare sprinkler patterns, Christiansen defined the coefficient of uniformity by the equation

$$C_u = 100 \left(1.0 - \frac{\Sigma x}{mn}\right)$$

in which C_u is the coefficient of uniformity expressed as a percentage, x is the deviation of individual observations from the mean value m, and n is the number of observations. The individual observations are the amounts of water that fall in equally divided sections of the area covered by the sprinkler. A coefficient of 100 percent shows that complete uniformity has been attained.

In an analysis of the principles of sprinkler irrigation, Christiansen reasoned that a sprinkler rotated at a uniform speed in still air should produce a pattern that would be symmetrical about the center. He represented a sprinkler pattern by the amount of water that would fall, in a specific period of time, at various distances located from the center of rotation. One of the more common types of sprinkler patterns is conical in shape, a cross section through the center of which is a triangle with the apex located at the sprinkler. Christiansen used various combinations of spacings between laterals, and spacings of sprinkler heads on the laterals, and then superimposed the known sprinkler patterns to obtain values of C_u. He found that a conical pattern with a triangular cross section will give a nearly uniform application (C_u = 96% or higher) for spacings up to approximately 55 percent of the pattern diameter. This work by Christiansen shows that if the pattern produced by a sprinkler is known, an optimum uniformity can be obtained by the best spacing combinations.

Christiansen set up field tests to determine the patterns produced from

actual sprinklers. It should be mentioned that the sprinklers used by
Christiansen were mainly of the "old fashion" slow-rotation reaction type.
This type of sprinkler is seldom used at present in commercial irrigation.
In his tests, Christiansen placed small tin cans ten feet apart over the en-
tire area covered by the sprinkler. Water was pumped through a water meter
to the sprinkler and a pressure line from the base of the riser was returned
to a pressure gage located near the pump. A valve located at the pump was
used to obtain the desired pressure. A four cup anemometer was installed ten
feet above the ground adjacent to the pump and the wind velocities recorded
were those obtained at that location. Christiansen stated on his test data
the approximate average wind velocity and the general direction of the wind.
After each test, the water caught in the cans was measured and the amount was
then recorded on a map showing the can layout. Contours were drawn repre-
senting points of equal depth of catch, and the relative amounts gave an
indication of the sprinkler patterns obtained.

The patterns produced with the sprinklers used showed considerable dif-
ferences. Some of the patterns were triangular in cross section but many had
peak depths of application located at various distances outward from the
sprinkler. Several tests were made to determine the effect of using a pres-
sure that was lower than normal. It was found that the area covered by the
sprinkler was reduced and that a ring shaped area was produced near the outer
edge in which the depth of application was several times greater than closer
towards the sprinkler. This ring shaped or "doughnut" type of pattern was
considered by Christiansen to be unsuitable for the attainment of a uniform
distribution with any reasonable combination of sprinkler spacings.

Christiansen conducted a limited number of tests under conditions in
which the wind velocity was relatively large (as high as 14.0 mph). He found

in general that the water would be thrown further in the leeward direction, but that the depth of application in the leeward direction would be deficient. Christiansen concluded:

> ....The effect of wind on the uniformity of distribution over a large area, with sprinklers close enough together to provide an adequate overlap, is less serious than unevenness from other causes.

Wiersma (21) conducted field tests of a similar nature to those of Christiansen. The primary concern of Wiersma's tests was the effect of wind on the uniformity of distribution. The sprinkler heads used were made by one manufacturer and they were of the modern type of design, that is with spring and oscillating arm. Most of the tests were performed using one particular sprinkler head, but various nozzle sizes were interchanged. Wind movement was determined by a three cup totalizing anemometer which was mounted four feet above the ground. One-quart oil cans were spaced on a five foot grid around the sprinkler head and a pressure gage was mounted on the riser. An example was given by Wiersma of the results he obtained from a typical sprinkler under windy conditions. The pressure and nozzle size used were unstated. At 0 mph wind, the distribution pattern had essentially a triangular cross section with water being applied 50 feet out from the sprinkler in all directions. At 2 mph wind, the pattern remained triangular with water applied out to 60 feet in the leeward direction and only out to 40 feet in the windward direction. With a wind recorded at 14.3 mph, a triangular pattern was again obtained, but the pattern extended out to approximately 75 feet in the leeward direction and 25 feet in the windward direction.

Wiersma overlapped the sprinkler patterns that he obtained and computed coefficients of uniformity for various spacings of sprinklers. As an example, the above sprinkler when operated with a wind velocity of 14.3 mph gave a C_u

of 90 percent when the spacing between laterals was 40 feet and the spacing of heads within lines was 10 feet. The same sprinkler, operated under the same wind conditions, would give a C_u of 64 percent when the corresponding spacings were at 60 feet and 10 feet. It was shown, therefore, that a relatively large uniformity coefficient can be obtained under high wind conditions when the sprinklers are properly spaced.

Wiersma's tests also showed the effect that pressure and nozzle size have upon the uniformity coefficient. With the spacing between sprinklers and the pressure at each sprinkler maintained constant, the coefficient of uniformity is greater at low wind velocities than at high velocities. However for each particular value of wind velocity, the uniformity coefficient for larger nozzle sizes (which deliver greater quantities of water) was consistently greater than the coefficient for smaller nozzle sizes. In a similar manner, when the nozzle sizes and the spacing between sprinklers were held constant, the uniformity coefficient decreased as the wind velocity increased. However for each particular value of wind velocity, the uniformity coefficient was less when insufficient pressure was used than when the proper operating pressure was used.

The uniformity coefficient may be considered as actually a distribution efficiency, that is, it is the efficiency with which water is distributed over the area to be irrigated. The uniformity coefficient does not, however, take into account any losses that occur after water leaves the sprinkler nozzle and before it reaches the ground. Bagley and Criddle (1) define an application efficiency as:

> The ratio of the amount of water reaching the ground surface, as measured by the sampling cans, to the amount being discharged from the sprinkler nozzles.

Bagley and Criddle recommend that the product of the application efficiency

and the distribution efficiency should be used to determine an "overall efficiency".

Frost (7) conducted field experiments in order to determine the application efficiency of sprinklers under Arizona conditions. His primary interest was in the spray loss due to evaporation. Frost set up two sprinklers and in the overlapping area between the sprinklers he placed quart cans six feet apart. The amount of water discharged was measured by a calibrated meter and the pressure was determined from a pressure gage attached to the lateral at the base of each riser. Wind velocity was determined by a Biram anemometer equipped with a directional vane located six feet above the ground. Wet and dry bulb temperature readings were made several times during each test run. Frost determined the spray loss in the air from the difference between the metered discharge and the computed amount of water reaching the ground surface. An attempt was made to reduce the amount of loss attributed to spray loss in the air. Frost considered that most of this loss was actually due to evaporation loss after the water reached the gage cans. Oil was placed in the cans and the cans were painted white to reduce the heat absorbed by solar radiation.

The tests run by Frost employed sprinklers of the oscillating arm design. With nearly zero wind conditions, the amount of evaporation loss was found to vary from approximately three percent at very high relative humidities to approximately ten percent at very low relative humidities. The relative humidity in Arizona is commonly less than 20 percent. By changing nozzle sizes, the amount of evaporation loss was found to decrease slightly as the diameter of the nozzle was increased.

With respect to the effect of wind on spray losses, Frost made the following statement:

Losses were considerably higher at the high wind velocities as much of the fine spray was carried out of the collecting area and therefore failed to reach the ground surface in measurable quantities. As this drift did not moisten the soil outside of the can area, it was assumed that it was a complete loss for irrigation purposes.

Several tests were run with sprinkler pressures varied from 30 to 50 psi and with wind and relative humidity remaining essentially constant. Under the higher pressures a finer spray was produced and it was found that a certain percentage increase in pressure produced nearly the same percentage increase in spray loss. With the pressure and relative humidity maintained nearly constant, it was found that doubling the wind velocity approximately doubled the spray losses. Frost points out, however, that these results may not necessarily pertain to sprinklers and nozzle sizes that were not used in the tests.

Laboratory tests have been conducted by Bilanski and Kidder (2) to determine the factors that affect the distribution of water from sprinklers. The factors investigated included the operation of the oscillating arm and the effect of changes in pressure, nozzle size, and the angle of nozzle inclination. Since the tests were conducted indoors, all weather variables were considered to be eliminated. Wind velocity was not taken as a factor affecting distribution, i.e., air movement was considered to be zero at all times. Quart cans were placed at two foot intervals outward from the sprinkler location except that near the far edge of the trajectory limits the cans were placed at one foot intervals. The sprinklers used were from one manufacturer and were of the oscillating arm type. One nozzle was operated at a time and the oscillating arm either acted or was prevented from acting. The results of each test were recorded in the form of depth of water caught versus distance from the sprinkler. Application efficiency was not considered

as part of the tests, but due to the nature of the tests this probably would have been close to 100 percent.

The tests showed that when the oscillating arm was acting and regularly interrupting the jet of water, the amount of water which fell out near the sprinkler was increased. Without the action of the oscillating arm, more water tended to accumulate near the outer edge of the trajectory. When the nozzle size was increased but the pressure maintained constant, the distribution tended to be somewhat improved. That is, there tended to be less of a peak accumulation towards the outer edge of the trajectory. When the pressure was increased, other factors remaining constant, it was found that the maximum trajectory distance was increased. However because the higher pressure also resulted in the production of smaller droplet sizes, an increased amount of water fell out at distances closer to the sprinkler. At the higher pressures, therefore, the sprinkler pattern will be greater in extent but more uniform in coverage. The larger droplets will travel a greater distance outward from the sprinkler but the areas adjacent to the sprinkler will be more thoroughly filled in by smaller sized droplets.

Tests were performed by Bilanski and Kidder in which the angle of nozzle inclination was increased from 10 degrees to 35 degrees from the horizontal. In a manner quite similar to an increase in pressure, it was found that an increase in the angle of inclination resulted in an increase in the maximum trajectory distance. At the higher angles of inclination it was also found that relatively more water tended to accumulate out towards the maximum trajectory distance and less water accumulated near the sprinkler.

Laboratory tests have been performed by Levine (16) to determine the relationship between the distribution of water and the size of the water droplets. The nature of the tests were similar to those of Bilanski and Kidder

except that the size of the droplet deposited, and not the weight of accumu-
lated water, was determined at distances from the sprinkler. Drop size
measurements were made at five foot intervals outward from the sprinkler.
Paper toweling held horizontally was passed through the stream at specified
distances. The paper was photographed and the film was projected on a screen
to twice the original size. The drop diameters were then measured. Levine
recognized that the diameters were not the actual drop diameters and he de-
noted them as "apparent" drop diameters.

Levine found that for a given nozzle size and pressure, droplet diameter
increased with distance outward from the sprinkler. As sprinkler pressure
was increased, droplets of a given size traveled a greater distance. However
as the pressure was increased, more droplets were produced of a smaller size.
An increase in nozzle size also resulted in the production of smaller drop-
lets. These findings were true whether the oscillating arm did or did not
operate. It is pointed out by Levine, however, that the operation of the arm
interrupting the stream will be yet another factor causing additional produc-
tion of smaller sized droplets.

Frost (7) in connection with his tests mentioned above, conducted tests
which confirmed the results of Levine. The tests were performed in the field
but under essentially still air and constant weather conditions. The major
difference in Frost's tests was the method by which he determined droplet
size. The droplets were collected in small cans partially filled with
bentonite. The cans were weighed before and after several passes of the
sprinkler. The number of droplets falling into the cans were counted.
Assuming a spherical droplet shape and a specific gravity of one, Frost was
able to calculate the average size of the droplets falling into each can.

An examination of the nature of a water droplet is important in the

development of the theoretical relationship between droplet size and the distribution which may be attained from a sprinkler.

Laws (15) studied photographs made at right angles to the direction of flight of water droplets. He concluded that a droplet is not tear-shaped but is oblate, that is, it is a spheriod flattened at the poles. For a section cut parallel to the direction of fall, the droplet has a major axis normal to the fall direction. The objective of Laws' work was to determine the fall velocity of various sized particles. He used a "double-exposure" photographic technique. The measured distance between film images was related to the time between shutter exposures. For a statement of droplet size Laws used, "Diameter of a sphere equal in volume to the drop." The method used to determine droplet size was essentially the same as that used by Frost. The drops were caught in a bottle and the increase in weight was determined by an analytical balance.

Green (11) photographed water droplets which moved almost directly towards a camera. The trajectory from a sprinkler was placed so that the stream passed just beneath the camera bed. Green found that the drops were circular around their axis of flight. He calculated the drop volume by the volume generated by the circular area as it is rotated around an axis normal to the axis of flight.

Mention was made by Green of the various factors causing the dispersion of the stream issuing from a sprinkler nozzle. The velocity of water prior to leaving the nozzle varies from a minimum at the perimeter to a maximum at the center of the stream. Upon leaving the nozzle, an initial breakup in the stream is caused by the variation in velocity. Further breakup of the drops is related to the air resistance and the surface tension. Surface tension will tend to maintain the drops as spheres while air resistance will tend to

cause flattening or oblation. Green states:

> When the oblation is to such an extent that the air resistance exceeds the surface tension, the drops break up into two or more drops and several small droplets.

Green considered that a droplet smaller than 4.5 mm would remain stable.

Photography shows that even though a droplet remains stable in total mass, a continuous oscillation will occur which will change the degree of oblation of the droplet. This fact was referred to by both Green and Laws. With respect to the oscillation of droplets, Laws states:

> The effect of this change in shape is to add a new order of variation to a phenomenon already beyond the reach of current analytical tools.

Green notes that when droplet oblation is greatest, the increased flattening will increase the air resistance. The increased air resistance will result in a reduced fall velocity. Green concluded that for stable drops there is no true terminal velocity but a mean terminal velocity. Green used the results from Laws' photographic experiments (referred to above) to obtain values for droplet terminal velocities. However Green recognized that the values given for terminal velocities were actually just mean terminal velocities.

Examining the forces acting on a falling water droplet, Green (10) developed a relationship between particle mass and air resistance. This relationship was subsequently required by Bilanski and Kidder (2) in the determination of the trajectory of a water droplet. Air resistance was considered by Green to be directly proportional to droplet velocity. Green points out that even though water issuing from a sprinkler may exceed 100 fps, this is still relatively low and within the range that physicists consider the air resistance to be a function of the first power of the velocity.

The force equation set up by Green is

$$M \frac{dv}{dt} = Mg - KV$$

from which

$$\frac{dv}{dt} + \frac{KV}{M} = g$$

where M = mass

   g = gravity

   V = velocity

   t = time

   K = a constant related to air resistance

The solution of this equation with $V = V_t$, terminal velocity, and at time $t = \infty$ is

$$V_t = \frac{Mg}{K}$$

By substituting in values for V_t and M from Laws' data (15), Green was able to calculate K and the ratio $\frac{M}{K}$ for various diameter droplets. It was found that as the droplet sizes decreased, the ratio $\frac{M}{K}$ approached zero. Green plotted values of K versus droplet diameter and determined the relationship $K = 0.00122 \, D^{2.44}$. The constant K is in gm/sec and D, drop diameter, is in mm.

Bilanski and Kidder developed an expression to show the travel distance of definite sized droplets moving through still air. Using the same terminology as Green, and with reference to Figure 1, the following equations were developed

$$M \frac{d^2 x}{dt^2} = - R \cos \theta$$

$$M \frac{d^2 y}{dt^2} = - \frac{R}{V} \sin \theta - Mg$$
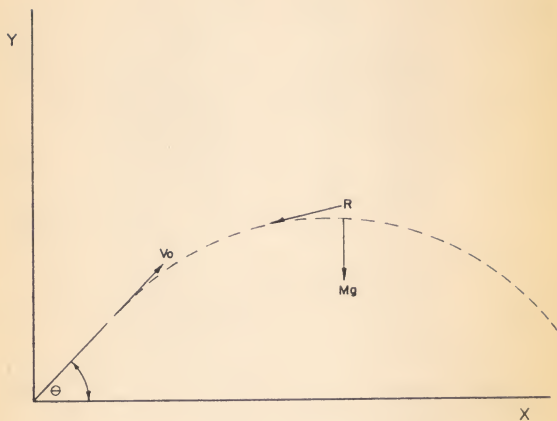
where $R = KV$

FIGURE 1. FORCES ACTING ON A PARTICLE TRAJECTED THROUGH STILL AIR.

The solution of these equations is

$$x = M/K \ V_0 \cos \theta \ (1-e^{-K/M \ t})$$

and $y = M/K \ V_0 \sin \theta \ (1-e^{-K/M \ t}) + g(M/K)^2 \ (1-e^{-K/M \ t}) - M/K \ g \ t$

By substitution in the above equations, the travel distance can be determined. Since the ratio $\frac{M}{K}$ approaches zero as droplet size decreases, an examination of the equation in the x direction will show that smaller droplets will have a reduced trajectory distance.

EQUIPMENT AND PROCEDURE

The attainment of controllable wind conditions was of primary concern to the nature of the investigation. For this purpose, a wind tunnel was constructed in the laboratory of the Agricultural Engineering Department of Kansas State University (Plate I). The tunnel was of two inch by four inch wood frame construction. Internal dimensions of the tunnel were eight feet ten inches high by four feet wide and the total length was 65 feet. Columns were placed every five feet and cross pieces were placed every five feet on the top and every ten feet on the bottom. The inside of the frame was covered on the top and sides by nylon reinforced clear plastic and the concrete laboratory floor served as the base of the tunnel. The plastic material was type No. 55 produced by the Griffolyn Company, Inc. The material stood up very well to the use for which it was employed.

Wind for the tunnel was obtained by use of an engine driven blower (Plate II). The blower had a nominal capacity of 34,000 cfm at 1/4" water static pressure. Control of the quantity of air moved by the blower was primarily by adjustment of vanes at the blower inlet (Plate III). Additional

control was possible by a change in engine speed. The blower outlet had a 43" I. D., and a ten foot galvanized steel transition section connected the outlet with the tunnel entrance. The tunnel cross-section, at the point of entrance, was filled with two inch diameter tubes which acted to straighten the path of the air upon entering the tunnel. The length of the tubes was 7 1/2" and they were cut from cardboard mailing containers. The tubes were stacked between screens made of hurricane wire; the position of the tubes was not affected by air movement through the tubes.

Wind velocity within the tunnel was determined by use of pitot tubes (Plate IV). Readings of velocity were made with inclined tube alcohol-filled manometers. The pitot tubes and manometers were obtained from, and previously calibrated by, the Wind Erosion Laboratory at Kansas State University. Readings were taken when four pitot tubes were arranged vertically at a point 20 feet downstream from the tunnel entrance (Plate V). The top three tubes were located at the 1/4, 1/2, and 3/4 points of tunnel elevation or, respectively, at 2' 2½", 4' 5", and 6' 7½". The bottom tube was placed at the sprinkler nozzle elevation, which was eight inches above the floor of the tunnel.

Operation of the blower showed that the wind velocity was nearly constant in horizontal planes across the tunnel but that the velocity was much higher at the center of the tunnel than at points nearer to the top and bottom. In order to obtain a velocity which could be considered as constant in the vertical direction, screening was required at the tunnel entrance. By a trial and error process, sections of window screening were applied to the downstream hurricane wire until the wind velocities at the 1/4, 1/2, and 3/4 points were essentially constant. The velocity at the bottom pitot tube was somewhat lower. At velocities in the upper three tubes of 2.5, 5.0, 7.5, and

10 mph, the velocities in the bottom tube were respectively 1.8, 3.7, 5.3, and 7.1 mph. In all cases, therefore, the velocity in the bottom tube was greater than 70 percent of the value for the other three tubes. By probing with the pitot tube, the velocity was observed to remain constant for several inches below the 1/4 point tube and then taper gradually to the value given for the bottom tube. The velocity above the 3/4 point tube was not considered since the trajectories of the water stream were contained within the 3/4 point. The values used for tunnel velocity readings were those obtained at the 1/4, 1/2, and 3/4 points when the tubes were set midway between the tunnel walls.

Water pressure at the sprinkler was determined by a Crosby pressure gage. The gage was calibrated by an Ashcroft Gage Tester belonging to the Mechanical Engineering Department, Kansas State University. The gage was found to read 0.5 psi too high in the range of 30 to 50 psi. The lead to the pressure gage was from a 1" pipe tee into which the sprinkler head was also fitted. Pressure adjustments were made by a globe valve placed between the sprinkler and the supply of water. The water was drawn from a 55 gallon drum, acting as a reservoir, by a $\frac{1}{2}$ HP motor driven centrifugal pump. Water flowed into the drum from a hose connected to a City of Manhattan water supply tap. A water meter for flow measurement was placed between the valve and the sprinkler (Plate VI). The water meter was manufactured by the Pittsburg Equitable Meter Company and it was checked for accuracy on a Neptune Meter Tester at the City of Manhattan Water Works. Water from the meter flowed to a riser supporting the 1" pipe tee and the attached sprinkler (Plate VII). The angle of the sprinkler nozzle from the horizontal was changed by changing the angle of the riser. A protractor with a level bubble aided in determining the exact angle setting. All references to nozzle angle setting in this

EXPLANATION OF PLATE I

Inside view of wind tunnel. Pans for determining sprinkler distribution
pattern shown placed in the tunnel.

PLATE I

PLATE II

SA1460-Q

PLATE III

2R 1460-1

EXPLANATION OF PLATE IV

Pitot tubes for determining air velocity shown located inside of wind tunnel.

PLATE IV

2 A 146
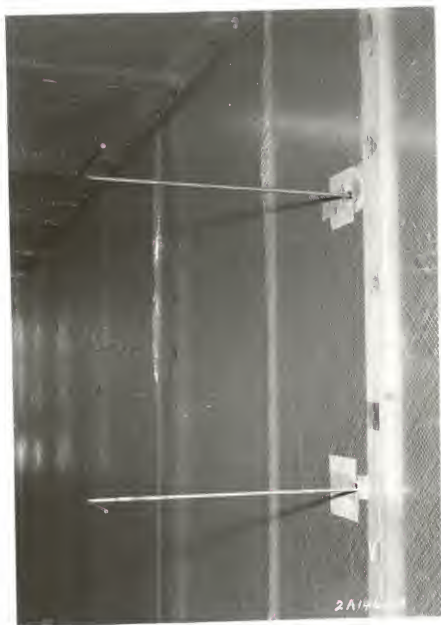
EXPLANATION OF PLATE V

View of pitot tubes mounted outside of wind tunnel. Ends of pitot tubes
shown connected to inclined manometers.

PLATE V

2 A 1460-4

EXPLANATION OF PLATE VI

Details of water control system. Valve for pressure adjustments shown
between pump and water meter.

PLATE VI

EXPLANATION OF PLATE VII

View of sprinkler mounted for testing. Water supply line shown entering at left-center of picture. Hose leading to pressure gage shown attached at base of sprinkler.

PLATE VII

investigation will be in terms of degrees above the horizontal.

The sprinkler nozzle was located five feet from the tunnel entrance for tests made with the water stream going with the wind, and the nozzle location was 20 feet from the end of the tunnel for tests when the water stream operated against the wind. Water from the sprinkler was caught in pans located five feet apart except near the outer reaches of the trajectory. At these points, the pans were placed two and one-half feet apart. The pans were sized 13.0" by 9.25" across the top and they were two inches deep. At each catch location, the pans were placed three across with the long dimension perpendicular to the tunnel axis (Plate I). The center pan was placed so that its rolled lip overlapped the outer two pans. The elevation of the top of the pans was six inches below that of the sprinkler nozzle.

The sprinkler model used for the tests was a Rain Bird Sprinkler Mfg. Corp. model No. 14. The oscillating arm was taped in a fixed position to prevent its operation. The duration of all tests was the time for ten gallons to be emitted for the sprinkler. Tests both with and against the wind were made at 0, 2.5, 5.0, 7.5, and 10 mph. The tests were made with a nozzle size opening of 7/64", a pressure of 40 psi, and an angle setting of 22 degrees. These values are considered by the manufacturer as the standard operating conditions. Additional tests were conducted with the wind velocity maintained at 5 mph but with one of the above-mentioned values varied at a time from standard. Tests were made with 3/32" and 1/8" nozzle size openings, 30 and 50 psi pressure settings, and 17 and 12 degree angle settings.

The amount of water falling at each pan location, in terms of inches over the pan area, was determined in the same manner used for a rain gage. The water caught in the three pans was poured into a graduated cylinder. The cross-sectional area of the cylinder was 4.16 square inches and the cylinder

had ten divisions to each 1.37 inches. The total area for the three pans was 119.50 square inches. The number of tens of divisions of water in the cylinder times 1.37 inches and multiplied by the ratio of the cylinder area to the pan area gave the inches of water over the pan area. The inches of water caught were therefore the number of tens of divisions of water in the cylinder multiplied by 0.0161. Marks in terms of 0.01 inches were made on the cylinder to enable readings to be made directly.

The distance that a drop of water of any given size will travel when subjected to wind was investigated from both a theoretical and experimental standpoint. The theoretical development was based on the assumption made by Green (10) that the drag force on the drop is proportional to the particle velocity with respect to the air. The following factors were used in the theoretical development:

M = particle mass

V_x = velocity of the particle in the x direction

V_y = velocity of the particle in the y direction

V_w = velocity of the wind

$V_{P/E}$ = velocity of the particle with respect to the earth

$V_{P/A}$ = velocity of the particle with respect to the air

$V_{A/E}$ = velocity of the air with respect to the earth

θ = angle of the sprinkler nozzle from the horizontal

V_o = initial particle velocity upon leaving the nozzle

y = distance of travel in the y direction

x = distance of travel in the x direction

a = acceleration

g = gravity

F = force

K = a constant related to air resistance

t = time

With reference to the assumption made above, the drag force equals a constant multiplied by $(V_x - V_w)$. That this is true is shown by

$$V_{P/E} = V_{P/A} + V_{A/E}$$

However, $V_{P/E} = V_x$ and $V_{A/E} = V_w$. Therefore the drag force equals $K (V_x - V_w)$.

The distance of drop travel in the x and y directions, shown in Figure 2, can be found from the following force equations:

In the x direction

$$m \frac{dv}{dt} = -K (V_x - V_w)$$

In the y direction

$$m \frac{dv}{dt} = -mg - KV_y$$

The solution of these equations is

$$x = (V_o \cos \theta - V_w) (M/K) (1 - e^{-K/M \ t}) + V_w t$$

$$y = M/K \ V_o \sin \theta (1 - e^{-K/M \ t}) + g(M/K)^2 (1 - e^{-K/M \ t}) - M/K \ g \ t$$

Travel in the y direction is shown to be unaffected by wind and the equation is the same as that determined by Bilanski and Kidder (2) for still air. The complete solution for the above equations is given in the following section on derivations.
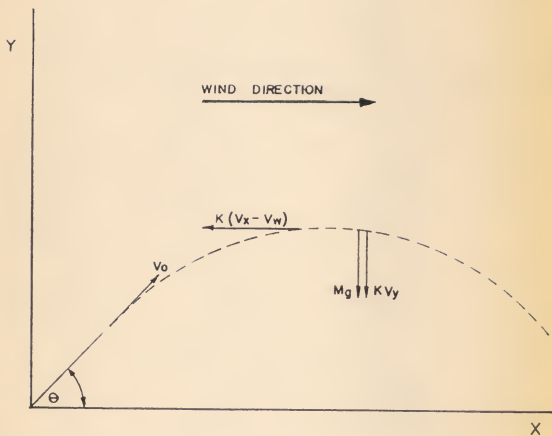
FIGURE 2. FORCES ACTING ON A PARTICLE TRAJECTED THROUGH WIND.

The time t for the drop to return to the elevation of the sprinkler nozzle can be determined by setting y equal to zero. The time t is then found to be

$$t = A(1-e^{-K/M \, t})$$

where $A = \dfrac{V_o \sin \theta}{g} + M/K$

The development of this equation is also given in the section on derivations.

Water drops emitted from the sprinkler were caught in order to test the above equations. The drops were caught by 5" by 7" sections of paper toweling with the long dimension perpendicular to the tunnel axis. A fixture was used to hold the paper at the elevation of the sprinkler nozzle (Plate VIII). The fixture contained four pins onto which the paper was affixed. The paper was exposed to the water stream for only a short period so that the number of drops caught at a time was limited but distinct. For this purpose, a shutter type of arrangement was used. Two thin metal shields, each 1' by 2', were placed so that there was just a slight clearance between the shields and the paper held underneath them. A two inch opening, running parallel to the tunnel axis, was maintained between the two shields. A rod was attached to the fixture so that the paper could be moved from outside the tunnel. With the sprinkler in operation, the fixture located under one shield was pulled across the gap until the paper was entirely under the second shield. Movement across the gap had to be sufficiently rapid to prevent an excessive number of drops from falling on the paper.

The paper was weighed on a Chainomatic Analytical Balance before and after exposure to water. The number of drops was counted and the weight per

drop was determined. Assuming the drops to be spheres and the specific gravity of water to be one, the average diameter of the drops were determined.

Tests were made at 5 mph wind velocity, both with and against the stream directions, and at 0 mph wind velocity. Initial stream velocity was determined from the gallons per minute flow rate and the area of the nozzle opening. The number of gallons was determined from the water meter and the time was determined by stopwatch. The fixture was set at 35 feet from the sprinkler for both the 5 mph test with the wind and the 0 mph test. The distance from the sprinkler was 25 feet for the 5 mph tests against the wind. For all three wind velocities, the sprinkler was set at the standard conditions of 22 degrees nozzle angle, 40 psi pressure, and 7/64" nozzle opening.

EXPLANATION OF PLATE VIII

View of paper toweling placed on fixture for catching water drops. Shields
to prevent an excess number of drops from falling on paper are shown in back
of the fixture. The rod for pulling fixture from under one shield to the
other shield is shown attached to right side of the fixture.

PLATE VIII

DERIVATIONS

The following derivations were made using the notation on pages 33 and 34, and with reference to Figure 2.

Distance of drop travel in the x direction:

$$F = Ma$$

$$Ma = -K \ (V_x - V_W)$$

$$M \frac{dv}{dt} = -K \ (V_x - V_W)$$

$$\frac{dv}{V_x - V_W} = -K/M \ dt$$

$$\int_{V_{O_x}}^{V_x} \frac{dv}{V_x - V_W} = \int_0^t -K/M \ dt \qquad \text{where } V_{O_x} = V_o \cos \theta$$

$$\ln \ (V_x - V_W) \ \Big|_{V_{O_x}}^{V_x} = -K/M \ t \ \Big|_0^t$$

$$\ln \frac{V_x - V_W}{V_{O_x} - V_W} = -K/M \ t$$

$$\frac{V_x - V_W}{V_{O_x} - V_W} = e^{-K/M \ t}$$

$$V_x = (V_{O_x} - V_W) \ e^{-K/M \ t} + V_W$$

$$\frac{dx}{dt} = (V_{O_x} - V_W) \ e^{-K/M \ t} + V_W$$

$$\int_0^x dx = \int_0^t (V_{O_x} - V_W) \ e^{-K/M \ t} \ dt + \int_0^t V_W \ dt$$

$$x = (V_{O_x} - V_W) \ (-M/K) \ e^{-K/M \ t} \ \Big|_0^t + V_W \ t \ \Big|_0^t$$

$$x = (V_{O_x} - V_W) \ (-M/K) \ (e^{-K/M \ t} - 1) + V_W \ t$$

$$x = (V_o \cos \theta - V_W) \ (M/K) \ (1 - e^{-K/M \ t}) + V_W \ t$$

Distance of drop travel in the y direction:

$$F = Ma$$

$$Ma = -Mg - KV_y$$

$$M\frac{dv}{dt} = -Mg - KV_y$$

$$M/K \frac{dv}{dt} = -M/K \, g - V_y$$

$$\frac{dv}{M/K \, g + V_y} = (-1) \, K/M \, dt$$

$$\int_{V_{o_y}}^{V_y} \frac{dv}{V_y + M/K \, g} = \int_{0}^{t} -K/M \, dt \qquad \text{where } V_{o_y} = V_o \sin \theta$$

$$\ln (V_y + M/K \, g) \, \Big|_{V_{o_y}}^{V_y} = -K/M \, t \, \Big|_{0}^{t}$$

$$\ln (V_y + M/K \, g) - \ln (V_{o_y} + M/K \, g) = -K/M \, t$$

$$\ln \frac{V_y + M/K \, g}{V_{o_y} + M/K \, g} = -K/M \, t$$

$$\frac{V_y + M/K \, g}{V_{o_y} + M/K \, g} = e^{-K/M \, t}$$

$$V_y = \frac{dy}{dt} = (V_{o_y} + M/K \, g) \, e^{-K/M \, t} - M/K \, g$$

$$\int_{0}^{y} dy = \int_{0}^{t} (V_{o_y} + M/K \, g) \, e^{-K/M \, t} - \int_{0}^{t} M/K \, g \, dt$$

$$y = (V_{o_y} + M/K \, g) \, (-M/K) \, e^{-K/M \, t} \, \Big|_{0}^{t} - M/K \, g \, t \, \Big|_{0}^{t}$$

$$y = (V_{o_y} + M/K \, g) \, (-M/K) \, (e^{-K/M \, t} - 1) - M/K \, g \, t$$

$$y = M/K \, V_o \sin \theta \, (1 - e^{-K/M \, t}) + g(M/K)^2 \, (1 - e^{-K/M \, t}) - M/K \, g \, t$$

Time t for drop to return to its initial elevation:

$$y = 0 = M/K \, V_0 \sin \theta \, (1 - e^{-K/M \, t}) + g \, (M/K)^2 \, (1 - e^{-K/M \, t}) - M/K \, g \, t$$

Let $K/M = Z$

$$\frac{V_0 \sin \theta}{Z} \, (1 - e^{-Zt}) + \frac{g}{Z^2} \, (1 - e^{-Zt}) - \frac{gt}{Z} = 0$$

$$\frac{V_0 \sin \theta}{Z} - \frac{V_0 \sin \theta}{Z} \, e^{-Zt} + \frac{g}{Z^2} - \frac{g}{Z^2} \, e^{-Zt} - \frac{gt}{Z} = 0$$

$$\left(e^{-Zt} \right) \left(-\frac{V_0 \sin \theta}{Z} - \frac{g}{Z^2} \right) + \frac{g}{Z^2} + \frac{V_0 \sin \theta}{Z} = \frac{gt}{Z}$$

$$t = \frac{Z}{g} \left[\left(e^{-Zt} \right) \left(-\frac{V_0 \sin \theta}{Z} - \frac{g}{Z^2} \right) + \frac{g}{Z^2} + \frac{V_0 \sin \theta}{Z} \right]$$

$$t = e^{-Zt} \left(-\frac{V_0 \sin \theta}{g} - \frac{1}{Z} \right) + \frac{1}{Z} + \frac{V_0 \sin \theta}{g}$$

Let $A = \frac{V_0 \sin \theta}{g} + \frac{1}{Z}$

$$t = e^{-Zt} \, (-A) + A$$

$$t = A(1 - e^{-K/M \, t})$$

RESULTS

Sprinkler Distribution Patterns

The results of the tests of the effects on the distribution from the sprinkler with a change in wind are shown in Table 1 and are presented graphically in Figures 3 and 4. The results of the tests made at constant wind velocity showing the effect on distribution with a change in pressure, nozzle size opening, and nozzle angle setting, are given in Table 2 and are presented graphically in Figures 5 through 10. Checks on the test results were

made by repeating tests and obtaining second readings from the pans at one or
possibly two locations. The variation was such that the readings would not
be increased or decreased by .01 of an inch.

An examination of Figure 3, with wind moving in the same direction as
the water stream, shows that wind did not greatly affect the distribution
pattern until a velocity greater than 7.5 mph was reached. In all cases,
however, the amount of water falling relatively close to the sprinkler de-
creased as the velocity increased. Operation of the sprinkler against the
wind, shown in Figure 4, had a profound effect on the distribution obtained.
As the velocity increased, the extent of stream travel was considerably de-
creased. Operation directly into the wind rapidly broke up the water stream.
Pans were placed back of the sprinkler but only a fine mist (essentially no
water) was accumulated. At the higher wind velocities, a noticeable quantity
of mist could be observed leaving the tunnel exit.

Figures 5 through 10 show general trends when the pressure, nozzle size
opening, and nozzle angle setting were varied about the standard conditions
of 40 psi, 7/64" diameter opening, and 22 degree nozzle angle. Figures 5 and
8 show that an increase in pressure tended to distribute the water somewhat
more uniformly throughout the trajectory distance. A decrease in pressure
resulted in more of a concentration of water at peaks. Figures 6 and 9 show
that the nature of the distribution pattern was not greatly changed over the
range of nozzle sizes used. The maximum trajectory distance was, however,
increased with an increase in nozzle size. Figures 7 and 10 show a consist-
ent change in the distribution pattern with an increase in the nozzle angle
setting. A larger angle setting served to extend the distribution pattern
through a greater distance. As the angle was decreased, relatively more
water was deposited closer to the sprinkler.

Table 1. Depth of water (inches) deposited from sprinkler operating under conditions of 40 psi pressure, 7/64" nozzle opening, and 22 degree nozzle angle setting.

Distance from nozzle (feet)	Wind Velocity				
	0 mph	2.5 mph with stream	5.0 mph with stream	7.5 mph with stream	10.0 mph with stream
2.5	-	-	-	-	-
5.0	.01	0	0	-	-
7.5	-	-	-	-	-
10.0	.03	.01	.01	0	-
12.5	-	-	-	-	-
15.0	.06	.03	.02	.01	0
17.5	-	-	-	-	-
20.0	.09	.07	.05	.03	.01
22.5	-	-	-	-	-
25.0	.11	.12	.11	.08	.04
27.5	.13	-	-	-	-
30.0	.15	.17	.19	.17	.11
32.5	.17	-	-	-	-
35.0	.21	.24	.28	.26	.19
37.5	.27	.31	.33	.32	.23
40.0	.32	.31	.28	.33	.27
42.5	.14	.12	.08	.18	.20
45.0	.01	.01	.01	.04	.21
47.5	-	-	-	-	.05
50.0	-	-	-	-	-

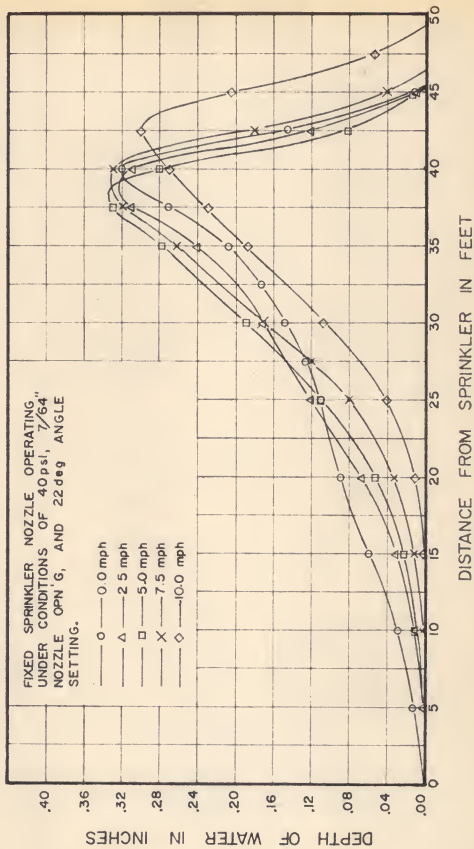| Distance from nozzle (feet)	Wind Velocity			
	2.5 mph against stream	5.0 mph against stream	7.5 mph against stream	10.0 mph against stream
2.5	-	.04	.10	.26
5.0	.04	.08	.16	.39
7.5	-	.12	.24	.35
10.0	.10	.16	.29	.16
12.5	-	.19	.30	.02
15.0	.15	.22	.27	-
17.5	.17	.23	.21	-
20.0	.19	.24	.08	-
22.5	.21	.26	-	-
25.0	.24	.20	-	-
27.5	.27	.04	-	-
30.0	.22	-	-	-
32.5	.04	-	-	-
35.0	-	-	-	-

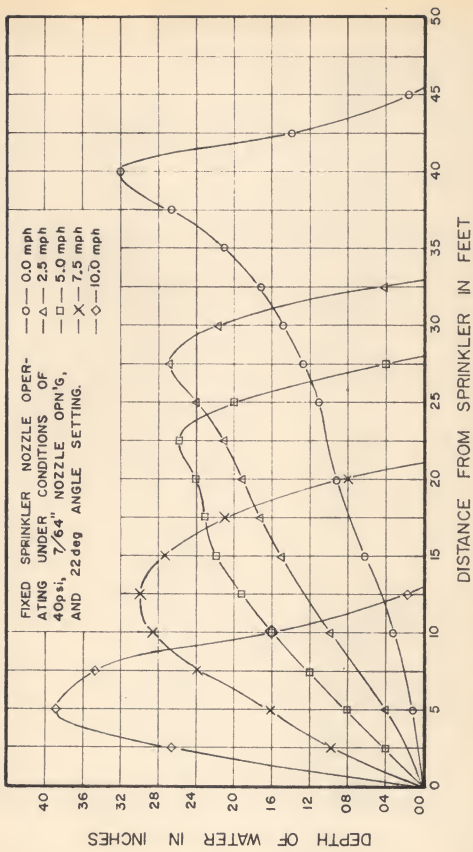FIGURE 3. EFFECT OF WIND ON DISTRIBUTION WHEN WATER STREAM TRAVELS WITH THE WIND.

FIGURE 4. EFFECT OF WIND ON DISTRIBUTION WHEN WATER STREAM TRAVELS AGAINST THE WIND.

Table 2. Depth of water (inches) deposited from sprinkler operating under varying conditions of pressure, nozzle opening, and nozzle angle setting.

Distance from nozzle (feet)	Wind Velocity—5 mph with water stream					
	30 psi	50 psi	3/32" opn'g	1/8" opn'g	17 deg	22 deg
2.5	-	-	-	-	-	-
5.0	-	0	-	0	0	0
7.5	-	-	-	-	-	-
10.0	0	.01	0	.01	.01	.01
12.5	-	-	-	-	-	-
15.0	.01	.02	.01	.02	.02	.03
17.5	-	-	-	-	-	-
20.0	.04	.05	.04	.05	.05	.08
22.5	-	-	-	-	-	-
25.0	.11	.12	.11	.10	.12	.16
27.5	-	-	-	-	.16	.20
30.0	.20	.18	.19	.16	.21	.25
32.5	-	-	-	-	.25	.31
35.0	.40	.24	.30	.21	.30	.35
37.5	.39	.28	.36	.26	.33	.20
40.0	.18	.27	.27	.32	.22	.03
42.5	.03	.14	.06	.22	.04	-
45.0	-	.03	-	.05	-	-
47.5	-	-	-	-	-	-

Distance from nozzle (feet)	Wind Velocity—5 mph against stream					
	30 psi *	50 psi **	3/32" opn'g ***	1/8" opn'g ***	* 17 deg	* 22 deg
2.5	.02	.06	.03	.03	.06	.07
5.0	.05	.10	.07	.06	.12	.13
7.5	.07	.14	.10	.09	.18	.23
10.0	.11	.17	.15	.12	.25	.33
12.5	.16	.19	.19	.14	.28	.38
15.0	.20	.20	.22	.16	.29	.40
17.5	.23	.21	.24	.18	.30	.49
20.0	.27	.23	.27	.20	.22	-
22.5	.31	.22	.28	.22	.05	-
25.0	.33	.17	.20	.26	-	-
27.5	.08	.03	.01	.25	-	-
30.0	-	-	-	.07	-	-
32.5	-	-	-	-	-	-

* 40 psi pressure
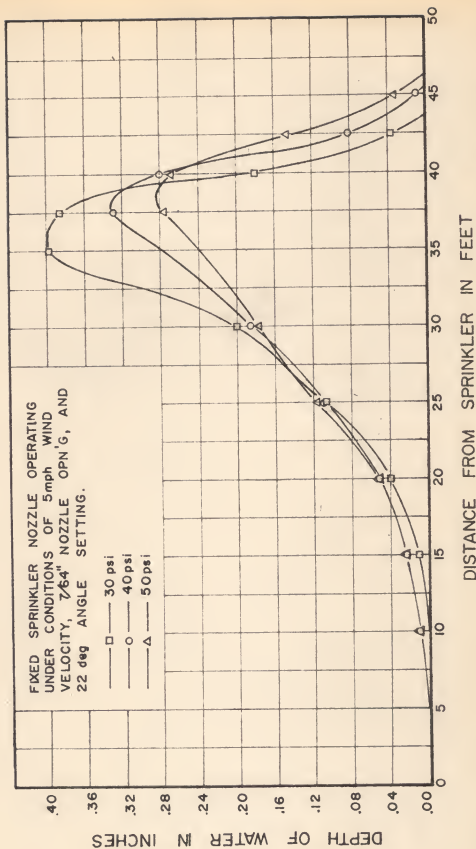** 7/64" nozzle opening
*** 22 degree angle setting

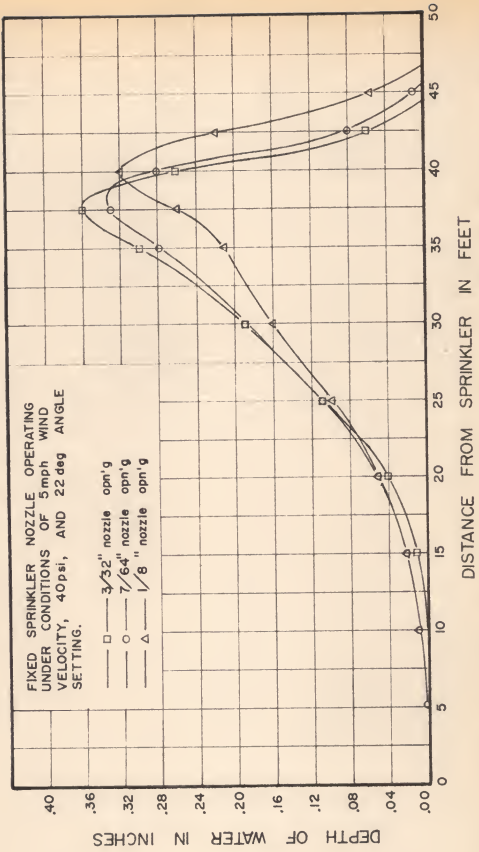FIGURE 5. EFFECT OF CHANGE IN PRESSURE ON DISTRIBUTION WHEN WATER STREAM TRAVELS WITH THE WIND.

FIGURE 6. EFFECT OF CHANGE IN NOZZLE SIZE ON DISTRIBUTION WHEN WATER STREAM TRAVELS WITH THE WIND.

FIXED SPRINKLER NOZZLE OPERATING
UNDER CONDITIONS OF 5mph, WIND
VELOCITY, 40psi, AND 7/64" NOZZLE
OPN'G.

□——12 deg from horizontal
△——17 deg from horizontal
○——22 deg from horizontal

DEPTH OF WATER IN INCHES
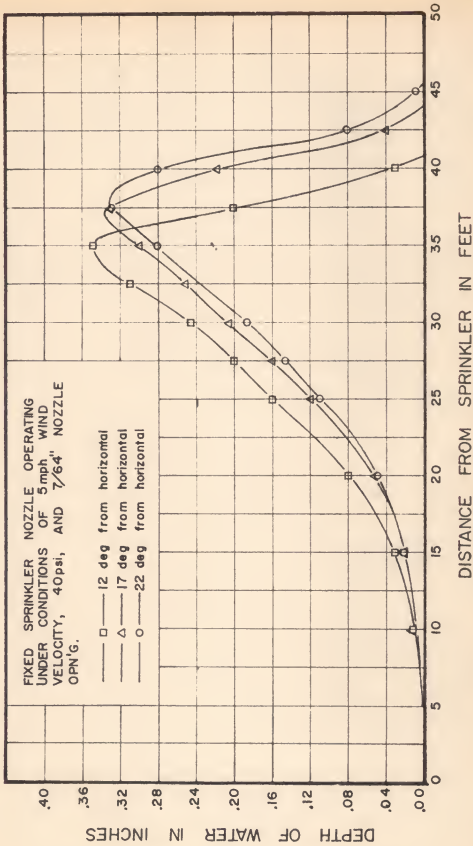
DISTANCE FROM SPRINKLER IN FEET

FIGURE 7. EFFECT OF CHANGE IN NOZZLE ANGLE ON DISTRIBUTION WHEN WATER STREAM TRAVELS WITH THE WIND.

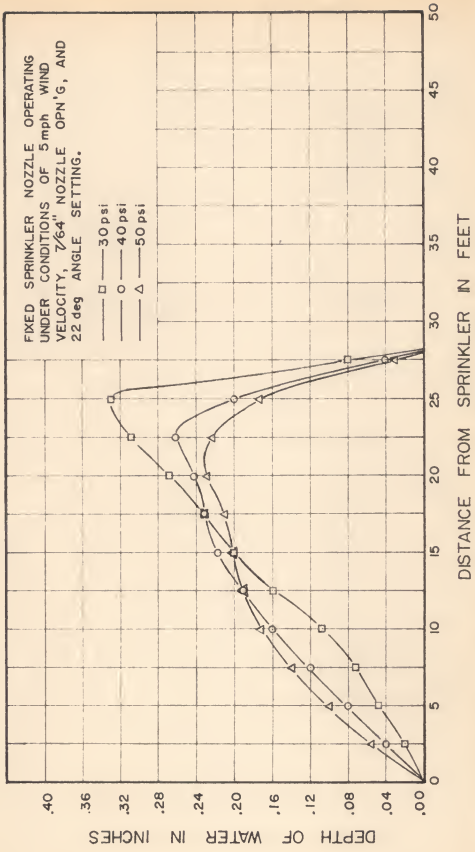FIGURE 8. EFFECT OF CHANGE IN PRESSURE ON DISTRIBUTION WHEN WATER STREAM TRAVELS AGAINST THE WIND.
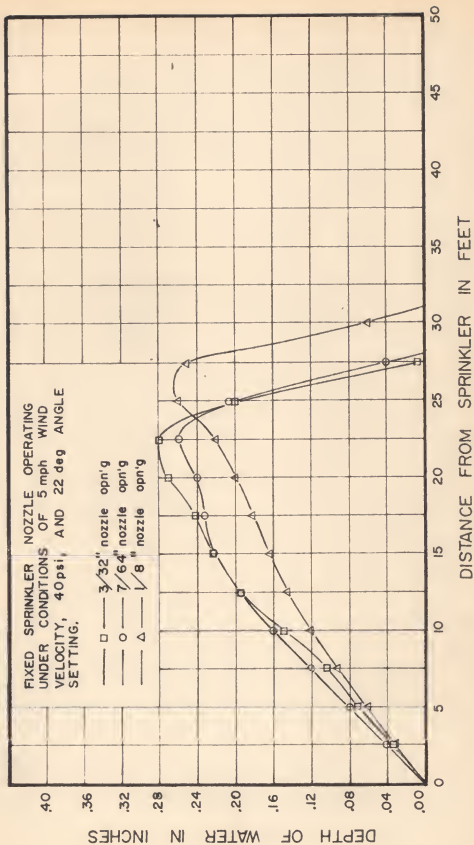
FIXED SPRINKLER NOZZLE OPERATING
UNDER CONDITIONS OF 5 mph WIND
VELOCITY, 40 psi, AND 22 deg ANGLE
SETTING.

□ ── 3/32" nozzle opn'g
○ ── 7/64" nozzle opn'g
△ ── 1/8 " nozzle opn'g

FIGURE 9. EFFECT OF CHANGE IN NOZZLE SIZE ON DISTRIBUTION WHEN WATER STREAM TRAVELS AGAINST THE WIND.

FIXED SPRINKLER NOZZLE OPERATING
UNDER CONDITIONS OF 5 mph WIND
VELOCITY, 40 psi, AND 7/64" NOZZLE
OPN'G.

- □ — 12 deg from horizontal
- △ — 17 deg from horizontal
- ○ — 22 deg from horizontal

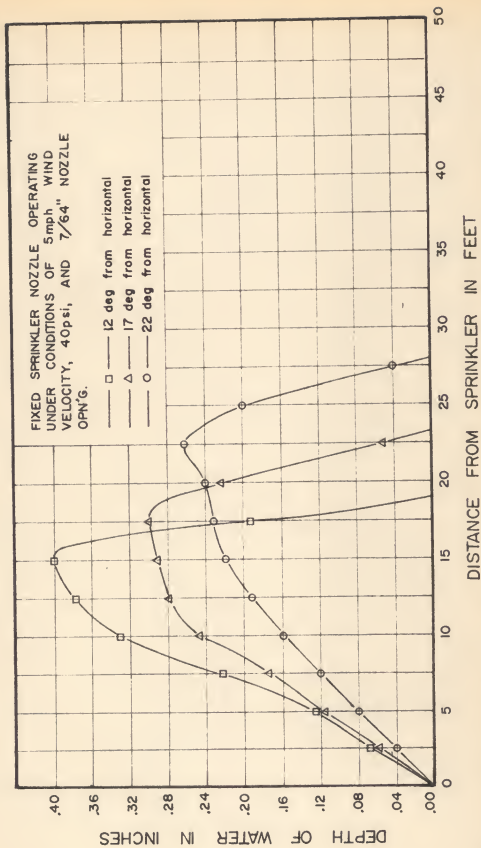DISTANCE FROM SPRINKLER IN FEET

DEPTH OF WATER IN INCHES

FIGURE 10. EFFECT OF CHANGE IN NOZZLE ANGLE ON DISTRIBUTION WHEN WATER STREAM TRAVELS AGAINST THE WIND.

Sprinkler Application Efficiency

The effect of a change in wind on sprinkler application efficiency was determined through an approximate method based on Figures 3 and 4. The area under the curve for each wind velocity provides a measure of the amount of water deposited by the sprinkler. The input of water for all tests was ten gallons. The distribution curve at 0 mph wind velocity was considered to represent 100 percent application efficiency and this was justified as follows. The area under the 0 mph curve was found by the use of a planimeter to be 4.88 inch-feet, or .406 square feet. The length of the pans, facing perpendicular to the water stream, was 3.25 feet. This latter dimension multiplied by .406 square feet gave 132 cubic feet for the amount of water caught in the pans. Using the conversion of 7.48 gallons per cubic feet, the amount caught was 9.87 gallons and the efficiency was 98.7 percent. Since the area under the curve could vary by one percent, or perhaps more, depending on the exact manner in which the curve was drawn connecting the points, it was decided to consider the efficiency at 0 mph as 100 percent.

The change in efficiency when subjected to wind was determined by comparing the ratio of the area of the other curves with that of the curve at 0 mph. These ratios are given in Table 3 and are presented graphically in Figure 11. The ratios are expressed in terms of percent.

Figure 11 shows a greater decrease in efficiency, with an increase in wind velocity, when the sprinkler operated against the wind rather than with the wind. In both cases, there appeared to be a more rapid drop off in efficiency as the wind velocity exceeded 7.5 mph.

Table 3. Sprinkler application efficiency at different wind velocities under operating conditions of 40 psi pressure, 7/64" nozzle opening, and 22 degree nozzle angle setting.

Wind Velocity	Application Efficiency in percent
0 mph	100
2.5 mph with stream	97.5
5.0 mph with stream	95.1
7.5 mph with stream	93.2
10.0 mph with stream	86.5
2.5 mph against stream	95.6
5.0 mph against stream	90.9
7.5 mph against stream	85.0
10.0 mph against stream	64.1

FIXED SPRINKLER NOZZLE OPER-
ATING UNDER CONDITIONS OF
40psi, 7/64" NOZZLE OPN'G,
AND 22 deg ANGLE SETTING.

—O— water stream traveling
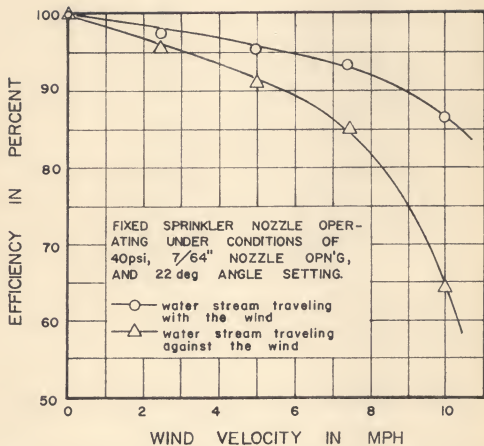with the wind
—△— water stream traveling
against the wind

FIGURE II. EFFECT OF WIND ON SPRINKLER APPLICATION EFFICIENCY.

Travel Distance of Droplets

The results of the tests in which water droplets were caught at a set distance from the sprinkler, under specific wind conditions, are given in Table 4. The average drop weights were determined from the average of ten good tests. Tests were rejected when the number of drops could not be discerned because of overlapping. Tests were also rejected when drops fell at the edge and not completely on the paper. Care was necessary to discern when more than one drop fell at almost exactly the same point. Doubtful cases were rejected.

The initial velocity of the drops was determined from the fact that 2.1 gallons per minute flowed from the 7/64" nozzle, the area of which is 0.654×10^{-4} square feet. Using the conversion of 1 cfs equals 449 gpm, the initial velocity was found to be 70.8 feet/second. At a tunnel velocity of 5 mph, the term V_w is 7.34 feet/second when the sprinkler operates with the wind, and -7.34 feet/second when the sprinkler operates against the wind. The constant for air resistance was determined from the relationship $K = .00122 \ D^{2.44}$ developed by Green (10).

An outline of the calculations for droplet travel distance is given in Table 5. With a wind velocity of 5 mph in the same direction as the water stream, a droplet that actually traveled 35 feet should theoretically have traveled 39.8 feet. When the wind velocities were 0 mph and 5 mph in the opposite direction to the water stream, actual travel distances were 35 feet and 25 feet as compared, respectively, to the theoretical distances of 39.9 feet and 29.5 feet.

Table 4. Weight of water droplets caught at fixed distances from the
sprinkler nozzle.

Distance from nozzle (feet) :	Wind Velocity :	Number of drops	Total weight of drops (gm)	Weight per drop (gm)
35	5 mph with stream	17	.057	.00335
"	"	20	.061	.00305
"	"	12	.049	.00408
"	"	15	.050	.00334
"	"	15	.041	.00273
"	"	9	.020	.00222
"	"	15	.066	.00440
"	"	16	.052	.00325
"	"	15	.040	.00267
"	"	10	.034	.00340
			Average	.00325
25	5 mph against stream	13	.051	.00340
"	"	21	.068	.00309
"	"	22	.117	.00532
"	"	16	.062	.00388
"	"	20	.069	.00345
"	"	13	.048	.00368
"	"	12	.033	.00275
"	"	22	.086	.00372
"	"	8	.034	.00425
"	"	12	.041	.00342
			Average	.00370
35	0 mph	21	.190	.00905
"	"	14	.114	.00815
"	"	10	.110	.01100
"	"	11	.096	.00872
"	"	14	.108	.00771
"	"	9	.087	.00946
"	"	15	.134	.00894
"	"	9	.082	.00911
"	"	6	.057	.00950
"	"	6	.067	.01120
			Average	.00928

Table 5. Determination of theoretical particle travel distance.

M	D	V_o	V_w	θ	K	K/M	A	t	x
0.00325	1.84	70.8	7.34	22	0.00541	1.664	1.425	1.25	39.8
0.00370	1.93	70.8	-7.34	22	0.00607	1.642	1.433	1.25	29.5
0.00928	2.61	70.8	0	22	0.01270	1.369	1.555	1.29	39.9

M = average weight of particle (gm)

D = particle diameter (mm)

$\quad$ from Volume = $\frac{\pi}{6} D^3$; and using 1 gm water equals 1 cm^3

V_o = initial particle velocity (fps)

V_w = wind velocity (fps)

θ = angle of sprinkler nozzle from horizontal (deg)

K = constant representing air resistance (gm/sec)

$\quad$ from K = 0.00122 D$^{2.44}$

$A = \dfrac{V_o \sin \theta}{g} + \dfrac{M}{K}$

$\quad$ where g = 32.2 ft/sec^2

t = time for droplet to return to initial elevation (sec)

$\quad$ from $t = A(1 - e^{-K/M\ t})$

x = particle travel distance (ft)

$\quad$ from $x = (V_o \cos \theta - V_w)(M/K)(1 - e^{-K/M\ t}) + V_w\ t$

SUMMARY AND CONCLUSIONS

The nozzle component of a sprinkler irrigation unit was investigated under simulated wind conditions. Distribution patterns were established when the water stream traveled directly with and directly against the wind. Operation of the sprinkler against the wind produced a greater change in distribution, with a change in wind velocity, than did operation with the wind. When the sprinkler operated against a 10 mph wind, most of the water was deposited adjacent to the nozzle.

Changes in pressure, nozzle angle setting, and nozzle size opening produced definite changes in the distribution patterns obtained. The general nature of the pattern changes was similar for operation both with and against the wind. By comparing the amount of water entering the sprinkler to the amount of water deposited by the sprinkler, as represented by the distribution pattern, the change in efficiency with an increase in wind was determined. Winds of over 7.5 mph resulted in a relatively large decrease in efficiency.

The wind conditions within the laboratory wind tunnel were essentially uniform, whereas out in the field, the wind varies with elevation in a manner dependent upon the specific ground roughness conditions. In order to apply the results obtained in the wind tunnel to the outdoors, some means of relating outdoor wind conditions to those in the laboratory are required. The United States Weather Bureau has studied the changes in wind with an increase in elevation above the ground (20). According to information determined empirically, the ratios at any particular location—under most usual wind conditions—of the wind velocity at 20 feet to those at 2' 2½", 4' 5", and 6' 7½" are, respectively, 1.38/1, 1.26/1, and 1.20/1. The 2' 2½", 4' 5", and

6' 7½" points represent the 1/4, 1/2, and 3/4 wind tunnel elevations. The
Weather Bureau has denoted the most usual wind conditions as dry-adiabatic
and they have established the 20 foot elevation as the most satisfactory for
the determination of wind velocity.

With reference to the velocity ratios, the results obtained with a tun-
nel wind velocity of 10 mph could be used to provide an indication of the
results expected when the wind velocity at a 20 foot elevation was approxi-
mately 12 to 14 mph. In the same manner, the results for a 5 mph tunnel
velocity give an indication of the results for a wind of approximately 6 to 7
mph determined at the 20 foot elevation. The ratios given above should be
applied only when the ground roughnesses at the location of the 20 foot ele-
vation reading and the lower elevation readings are similar. This will prob-
ably not be the case when the higher elevation readings are reported from
sites in non-agricultural areas.

The distance of travel of water droplets, as affected by wind, was stud-
ied from both an experimental and a theoretical standpoint. The theoretical
equations developed for predicting droplet travel distances involved factors
of initial droplet velocity, initial trajectory angle, droplet mass, and air
resistance. Experimental results showed that the predicted travel distance
of droplets was close to, but somewhat higher than, the actual travel dis-
tance. Assuming all other factors to be correct, the reason why predicted
travel distances were greater than actual travel distances can be attributed
to the value used for initial droplet velocity. The velocity of the water
upon leaving the nozzle was used for the initial droplet velocity. A coeffi-
cient of velocity was not applied to the water stream velocity at the point
of entrance into the air. For nozzles, however, the coefficient of velocity
is given in textbooks (18) to be in the order of 0.99. A definite reduction

in velocity, not accounted for by subsequent air resistance on the particles, may occur during the process of breakdown of the stream into particles. The velocity reduction can be explained on the basis of a dissipation of energy during the process or breakdown. This would agree with the concept, referred to by Green (11), in which changes in particle oblation occur during the breakdown process. Further consideration of the velocity of water upon leaving the sprinkler will be given in connection with suggestions for future research.

SUGGESTIONS FOR FUTURE RESEARCH

The distribution patterns obtained represent conditions of sprinkler operation only directly with and directly against the wind. Generalizations could be made that these conditions are indicative of maximum and minimum limits on both the displacement of the patterns and the resulting efficiencies. However, it would be difficult to predict the expected performance when the sprinkler operated at some other angle with the wind because of the somewhat indefinite manner in which the water stream breaks up into droplets. The performance of the sprinkler when operating at any angle with the wind, either while the sprinkler rotated or while it was in a fixed position, could be determined if a sufficiently large tunnel width were used. The maximum tunnel width required would be that necessary to contain the water stream trajectory when the sprinkler operated in a direction perpendicular to the stream.

For a complete study at all angles with respect to the wind, the sprinkler would be required to turn only 90 degrees. The sprinkler would be located adjacent to one wall and operated first near the tunnel entrance and then moved to a position near the tunnel exit. In the first position, the

sprinkler would operate with the wind and at angles up to 90 degrees with respect to the wind; in the second position, operation would be against the wind and at angles again up to 90 degrees with respect to the wind. Containers for catching the water emitted from the nozzle would be located radially outward from the sprinkler. In order to more accurately determine the application efficiency of the sprinkler, a catching device could be used which covered the entire tunnel area. The amount of water deposited by the sprinkler, excluding that portion of the water blown as a fine mist beyond the apparent trajectory distance, would be determined from the weight increase of the catching device and its contents. The weight increase could be found through the use of scales or perhaps by the use of a suitable strain gage device. If it were desired to completely exclude all mist falling beyond the maximum trajectory distance, the size of the catching device would have to be variable so as to conform to the water stream travel distance. The writer assumes that the mist deposited beyond the maximum trajectory distance will be readily evaporated and should not be considered available for irrigation.

Questions have arisen in this study in respect to the specific amount of velocity change which occurs after the water leaves the sprinkler nozzle. Information could be obtained from an experimental method which examines changes in velocity during the process of breakdown into particles. Small grains of a radioactive material would be slowly metered into the water upstream from the nozzle. Detectors of radioactivity would be placed at the nozzle exit and at points downstream until the process of breakdown was essentially complete. The change in velocity would then be determined from the time of passage between detectors. High speed motion picture photography would also be of considerable help in examining the breakdown process. Photography could be used in conjunction with the method involving

radioactive particles so that the region at which breakdown was complete, and stable drops were formed, would be delineated.

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SPRINKLER NOZZLE PERFORMANCE UNDER
SIMULATED WIND CONDITIONS

by

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AN ABSTRACT OF A MASTER'S THESIS

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requirements for the degree

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The purpose of this project was to investigate the performance of a fixed sprinkler nozzle operating under laboratory controlled wind conditions. Information was obtained for the extreme conditions of the water stream traveling directly with and directly against the wind.

A wind tunnel was constructed so that controlled wind conditions could be attained. Internal dimensions of the tunnel were eight feet ten inches high by four feet wide and the total length was 65 feet. The tunnel was lined on the top and sides by nylon reinforced plastic and the concrete laboratory floor served as a base. Wind for the tunnel was obtained from an engine driven blower. Readings of wind velocity were taken through the use of pitot tubes. Screens were placed at the tunnel entrance to give essentially a constant wind velocity throughout the area of the tunnel traversed by the water stream. Changes in wind velocity were affected by vane adjustments at the blower inlet.

A pressure tap from the base of the sprinkler was connected to a gage located outside of the tunnel. Pressure adjustments were made by a globe valve placed between the sprinkler and the water supply. The flow of water to the sprinkler was determined by a water meter. Water from the sprinkler was caught in pans located five feet apart except near the outer reaches of the trajectory, where they were placed two and one-half feet apart. The amount of water caught at each pan location was found by pouring the water into a cylinder. The depth of water in the cylinder times the ratio of the cylinder area to the pan area gave the depth of water in the pans.

Tests both with and against the wind were made at 0, 2.5, 5.0, 7.5 and 10 mph; the pressure, nozzle size opening, and nozzle angle setting were maintained constant during these tests. A second group of tests were conducted with the wind velocity maintained at 5 mph but with increases or

decreases made in the values used for pressure, nozzle size opening and nozzle angle setting. One factor--for example, pressure--would be changed at a time while the other factors were held constant. The duration of all tests was the time for ten gallons to be emitted from the sprinkler.

The data from the tests were plotted in terms of depth of water caught at each location versus distance outward from the sprinkler. The results from the first group of tests showed that when wind traveled with the water stream, the distribution pattern was not greatly affected until a wind velocity of more than 7.5 mph was reached. When the wind traveled against the water stream, a noticeable decrease in the extent of water travel occurred at 2.5 mph and the amount of decrease became larger as the wind velocity increased. The second group of tests showed general trends when the pressure, nozzle size opening, and nozzle angle setting were varied. An increase in pressure distributed the water more uniformly throughout the trajectory distance. An increase in nozzle size increased the maximum trajectory distance. A larger angle from the horizontal served to extend the entire distribution pattern through a greater distance.

The effect of an increase in wind on sprinkler application efficiency was determined by a method based on the graphs of the test results when wind velocity was increased from 0 to 10 mph. The area under each distribution pattern curve can be expressed in terms of inch-feet. This area, projected over the length of the pans perpendicular to the water stream, gives a measure of the volume of water emitted from the sprinkler. The area under the curve for 0 mph wind was considered to represent 100 percent efficiency. The ratio of the area of the distribution pattern at any wind velocity to that at 0 mph was then taken as the application efficiency. When the sprinkler operated with the wind, the application efficiency decreased as wind velocity

increased. When the sprinkler operated against the wind, a more rapid decrease in application efficiency occurred as the wind velocity increased. The rate of drop off in efficiency became greater as wind velocity increased above 7.5 mph.

The travel distance of water droplets emitted from the sprinkler and subjected to wind was investigated from both a theoretical and experimental standpoint. The theoretical development was based on the assumption of previous researchers that the drag force on water droplets is proportional to the particle velocity with respect to the air. The following factors were used in the theoretical development:

M = particle mass

V_x = velocity of the particle in the x direction

V_y = velocity of the particle in the y direction

V_w = velocity of the wind

θ = angle of the sprinkler nozzle from the horizontal

V_o = initial particle velocity upon leaving the nozzle

a = acceleration

g = gravity

K = a constant related to air resistance

t = time

The distance of drop travel can be found from the following equations:

In the x direction

$$m \frac{dv}{dt} = -K(V_x - V_w)$$

In the y direction

$$m \frac{dv}{dt} = -mg - KV_y$$

The solution of these equations is

$$x = (V_o \cos \theta - V_w)(M/K)(1 - e^{-K/M \, t}) + V_w t$$

$$y = M/K \, V_o \sin \theta \, (1 - e^{-K/M \, t}) + g(M/K)^2 (1 - e^{-K/M \, t}) - M/K \, g \, t$$

The time t for the drop to return to the elevation of the sprinkler nozzle can be found by setting y equal to zero. Values for K were obtained from published results.

Water drops emitted from the sprinkler were caught in order to test the above equations. The drops were caught on 5" by 7" sections of paper toweling held by a fixture at the elevation of the sprinkler nozzle. The paper was exposed to the water stream for only a short period so that the number of drops caught was limited but distinct. The number of drops was counted and the weight per drop was determined from the increase in weight of the paper. Tests were made at 5 mph wind velocity, both with and against the stream directions, and at 0 mph wind velocity. Initial stream velocity was determined from the gallons per minute flow rate and the area of the nozzle opening. The results of the tests showed that with a wind velocity of 5 mph in the same direction as the water stream, a droplet that actually traveled 35 feet should theoretically have traveled 39.8 feet. When the wind velocities were 0 mph and 5 mph in the opposite direction to the water stream, actual travel distances were 35 feet and 25 feet as compared, respectively, to theoretically determined distances of 39.9 feet and 29.5 feet.