FACTORS THAT AFFECT DISTRIBUTION OF WATER FROM A MEDIUM PRESSURE ROTARY IRRIGATION SPRINKLER

Thesis for the Degree of Ph. D.

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Walter K. Bilanski

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Factors that Influence the Distribution of Water from a Medium Pressure Rotary Irrigation Sprinkler.

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Ernest H. Kidder

E. H. Kidder

Major professor

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FACTORS THAT AFFECT DISTRIBUTION OF WATER FROM A MEDIUM PRESSURE ROTARY IRRIGATION SPRINKLER

By

Walter K. Bilanski

AN ABSTRACT

Submitted to the School for Advanced Graduate Studies of
Michigan State University of Agriculture and Applied Science
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DOCTOR OF PHILOSOPHY

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Approved by Ernest H. Kidder

In 1946 less than 250,000 acres were irrigated by means of sprinkler irrigation; by the latter part of 1954 an estimated 3,000,000 acres were being irrigated by this method and the acreage is increasing at an estimated 500,000 acres per year. Nearly all of the sprinklers installed in the past ten years have utilized the revolving head sprinkler.

Desirable distribution patterns from sprinklers range from a triangular-shaped pattern in which the fall-out is a maximum near the sprinkler and gradually tapers off to zero at the maximum trajectory distance, to a pattern in which the amount of fall-out is uniform along the greater portion of the radius and then decreases gradually for the remainder of the trajectory distance. Because many sprinklers presently in use do not give either of the above distribution patterns of water, and since to date to the author's knowledge no detailed analysis has been made to determine what factors affect the distribution pattern, the objective of this study was to make such an analysis.

This study was conducted indoors to eliminate weather variables. Only medium-pressure sprinklers were studied because this size was the most popular with irrigators and because it lent itself to study in a laboratory. Only one factor from one sprinkler with one nozzle was studied at a time; all other factors were in so far as possible, held constant.

The following factors were investigated and evaluated: oscillating arm, operating pressure, orifice diameter, length of the cylindrical part of the nozzle, angle of taper in the sprinkler nozzle, angle of inclination of the nozzle, rate of rotation of the sprinkler, roughness in the cylindrical part of the nozzle, length of the tube between the body of the sprinkler and the nozzle, non-circular orifices in the sprinkler nozzle, and use of cylindrical discharge tubes in place of nozzles.

It was found that the factors discussed below had the greatest influence in approaching the desired distribution of water. The oscillating arm accentuated the fall-out of water near the sprinkler. A decrease in rate of rotation, an increase in the angle of inclination of the sprinkler nozzle from the horizontal and an increase in the operating pressure all resulted in fall-out of the water approaching the desired distribution pattern. In general, the use of non-circular orifices or of short cylindrical tubes in place of conventional sprinkler nozzles resulted in a more desirable distribution pattern of water. The equilateral-triangular orifices in which the triangular shape extended for a considerable depth into the nozzle resulted in a distribution pattern approaching the ideal. The most desirable pattern was obtained from tube lengths ranging from 2 to 4 diameters.

Turbulence, distribution of velocities and amount of secondary motion affect the dispersion of the jet of water as it emerges from the sprinkler orifice.

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VITA

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INTRODUCTION

Presentation of the Problem

Since 1946, when less than 250,000 acres were irrigated by means of sprinkler irrigation, this method has spread from a few areas in the United States to the entire country. By the latter part of 1954 an estimated 3,000,000 acres were being irrigated with sprinklers, and the acreage is increasing at an estimated rate of 500,000 acres per year. (1)

Due to this increase in the use of irrigation sprinklers, and recognizing their ever-increasing importance, Secretary of Agriculture Ezra T. Benson in a letter to Mr. Joseph T. King, Secretary of the Sprinkler Irrigation Association, stated (1):

> The results achieved by the proper use and application of portable sprinkler irrigation equipment contribute to better management of our water supplies and are further testimony of industry's contribution in opening new agricultural frontiers. The tremendous growth in this method of irrigation has created a pressing demand for technical and general information on the engineering, design, layout, use and application of sprinkler irrigation equipment.

Nearly all of the sprinkler systems installed in the past ten years have utilized the revolving head sprinkler. These sprinklers range from the small, low volume, low pressure, single nozzle type to the giant, high pressure, large volume, multiple nozzle sprinklers. The most widely used are the medium pressure (30 to 60 pounds per square inch) sprinklers (1). These may be either the single or the double nozzle type.

Ideally water should be distributed uniformly over the entire area to be irrigated. However, as yet a sprinkler which will do this has not been developed.

Since rotating sprinklers cover circular areas, some over-lapping will be necessary for complete coverage of the area to be irrigated, and even then one can only hope to approach ideal distribution. How closely the ideal is approached will depend upon the geometric distribution pattern characteristic of the sprinkler employed and upon the spacing of the sprinklers. Under field conditions sprinklers placed on lateral lines are set out in some simple geometric design; hence, it is necessary for the distribution pattern from the sprinkler to be adaptable to a simple layout. There are two distribution patterns which lend themselves to both over-lapping and to a simple arrangement of the sprinklers:

1. A triangular-shaped pattern in which the fall-out is a maximum near the sprinkler and gradually tapers off to zero at the maximum trajectory distance.
2. A pattern in which the amount of fall-out is uniform along the greater portion of the radius

and then decreases gradually for the remainder of the trajectory distance.

The former pattern lends itself to either a rectangular or triangular spacing of sprinklers while the latter is more suited to triangular spacing.

Because many sprinklers presently in use do not give either of the above two patterns, especially at lower pressures, and since to date to the author's knowledge no detailed analysis has been made to determine what factors affect the distribution pattern, it was the objective of this study to determine how the various factors influence the distribution pattern and how they could be improved.

Approach to the Problem

This study was conducted indoors to eliminate weather variables. Only the medium-pressure sprinklers were studied because this size was the most popular with irrigators and because it lent itself to study in a laboratory. Trends found in the study may be applicable to both high-pressure and low-pressure sprinklers.

Only one factor from one sprinkler with one nozzle was studied at one time; in so far as was possible, all other factors were held constant. Only factors which affect the distribution pattern were studied; hydraulic losses were not determined.

The following factors were investigated and evaluated:

1. Oscillating arm.
2. Operating pressure.
3. Orifice diameter.
4. Length of the cylindrical part[1] of the nozzle.
5. Angle of taper in the sprinkler nozzle.
6. Angle of inclination of the nozzle.
7. Rate of rotation of the sprinkler.
8. Roughness in the cylindrical part of the nozzle.
9. Length of the tube between the body of the sprinkler and the nozzle.
10. Non-circular orifices in the sprinkler nozzle.
11. Cylindrical discharge tubes.

[1]Bore

REVIEW OF LITERATURE

Christiansen (2) states that sprinkling as a method of irrigation has been practiced in California and elsewhere for about forty years. Before 1920 it was limited primarily to truck crops, nurseries and small fruits, and was practiced mainly as supplemental irrigation in the more humid regions. The type generally known as a portable sprinkler system originated in about 1930. Slow-revolving sprinklers are most satisfactory for these portable systems.

A considerable amount of work has been done on determination of the size of water drops both from sprinklers and from natural precipitation. McCulloch and Schrunk (3) report that the average water drop size from three different sizes of nozzles was approximately the same at a given pressure and distance from the sprinkler, and that the higher pressures yielded smaller drops at any given distance.

Levine (4) found that the diameter of the drops was fairly small at a distance of 25 to 30 feet from the sprinkler; whereas, from 30 to 50 feet from the sprinkler the drops were larger in diameter and were a result of the main jet of water.

Hall and Boving (5) tested triangular-shaped sprinkler orifices (0.015 inch thick) with different height-to-base ratios. They found that considerable variation in distribution could be produced by changing the height-to-base ratio of the triangle. As this ratio was increased, the first effect seemed to be the placement of a greater quantity of water at larger radii. After a ratio of 3 to 1 was reached, the amount of water caught near the nozzle increased. This was attributed to the creation of finer droplets as the width of the orifice became the controlling dimension for dynamic similarity.

The slit orifice was observed to place nearly all of the water near the maximum trajectory radius. One distribution defect noted in all of the above tests was that almost no water fell out over approximately the first one-quarter of the radius.

Prandtl and Nikuradse (6) determined point velocities and carried out studies of flow patterns in non-circular shaped conduits. Some of the velocity data which they obtained for water flowing in non-circular conduits is shown in Figure 1. (The experimentally determined velocities are plotted on the cross section). They also found that there was flow toward the corners of and away from the side of the conduit. This motion was superimposed on the longitudinal motion of the fluid particles. The pattern of this secondary motion is shown in Figure 1. The effect of the secondary flow on the lines of constant velocity is to transpose these lines in the direction of the secondary flow. Hence, in the corners these lines are pushed toward the corner; and in the vicinity of the wall, they are pushed away from the wall.

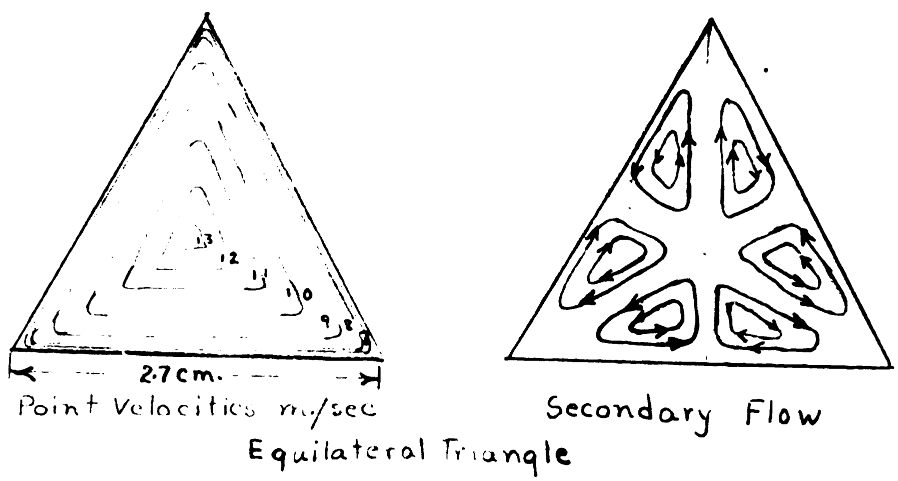

Fig. 1. Point velocities and secondary flow in non-circular conduits after Prandtl and Nikuradse.

Adams (7) points out that if a jet of water issues from an orifice which is not circular, the surface tension commences to rectify the departure from a circular section in the jet, and the momentum of the liquid causes the jet to become unsymmetrical again after passing through a circular form. Nodes and swellings appear periodically on the jet when it is observed from one side. If a spherical drop is deformed, the surface tension tends to restore the spherical form and oscillations are set up.

APPARATUS AND METHODOLOGY

Apparatus

Location. This study was conducted in the Land Development laboratory in the basement of the Agricultural Engineering building of Michigan State University. The room dimensions were 95 by 20 by 10 feet and it had adequate drainage outlets in the floor.

Source of water. Water was obtained from a concrete storage tank having a capacity of about 2500 gallons. The storage tank was refilled from the university water system.

Pump. A horizontal centrifugal pump capable of a rate of delivery of 150 gallons per minute at 160 feet of head and 3450 rotations per minute was used to deliver the water from the storage tank to the sprinkler. The pump was driven by a ten horsepower electric motor. The pump and motor unit were situated on top of the storage tank (Figure 2).

Delivery of water to sprinkler. A five foot length of 1-1/2 inch diameter pipe connected the pump to a 55-gallon pressure surge tank. A globe valve was placed in this line to control the pressure. A one-inch rubber hose three feet long made a flexible connector from the tank to

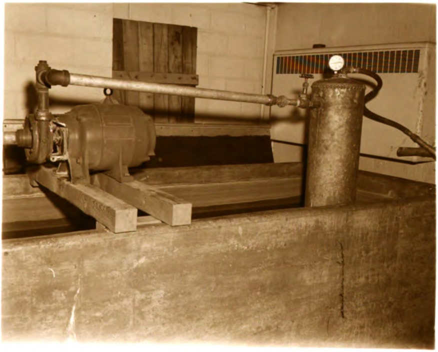

Fig. 2. Storage tank, pump unit and pressure tank.

a one-inch iron pipe eight feet long (Figure 2). The eight-foot pipe sloped from the pressure tank to the floor where a 90 degree elbow joined it to a one-inch pipe 3-1/2 feet in length. This pipe was connected to the sprinkler riser by a 90 degree elbow. A pressure gage was located in this pipe one foot from the sprinkler riser. A second globe valve was located near the elbow.

Sprinkler shield. To prevent water from the sprinkler from getting the walls of the laboratory wet and still obtain an uninterrupted jet of water, a 55 gallon oil barrel with one end cut out was placed over the sprinkler (Figure 3). A slot six inches wide and twenty inches high was cut out near the bottom of the barrel. A one-inch sheet metal, right-angle flange was bolted along the sides and top at the inside edge of the slot. When a sprinkler was rotating, this flange prevented the barrel-deflected water from coming out through the slot opening by re-deflecting it back into the barrel.

Anti-splash device. Wire window screening was used to minimize the ricocheting of the water droplets as they struck the concrete floor. The screen was mounted on a wooden frame two feet wide, fifty feet long and two inches high (Figure 3). Cross braces were placed at two-foot intervals to provide ample rigidity. They also served as reference points for the placement of measuring cans.

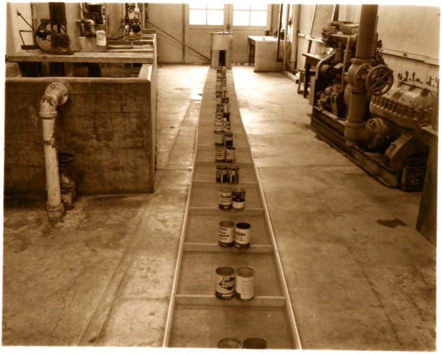

Fig. 3. Laboratory where tests were conducted with sprinkler slotted barrel shield in the background.

<u>Water measurement</u>. Unless otherwise stipulated, all runs were made for one hour. One quart oil cans with the tops cut out were used to catch the water fall-out from the discharging sprinkler. The tops of the oil cans were approximately level with the sprinkler riser connection. The water in each can was measured in a graduated volumetric cylinder. Oil cans were satisfactory catchment containers since one milliliter in the oil can was equal to a depth of 0.0050 inch of water, thus facilitating the conversion from milliliters to inches of water.

<u>Sprinkler rotating mechanism</u>. The sprinklers that were tested had a self-rotating mechanism which was actuated by the jet of water issuing from the sprinkler. It was necessary for certain tests to inactivate this mechanism and rotate the sprinkler mechanically. A variable-speed hydraulic reducer driven by a one-fourth horse power electric motor of 1725 rotations per minute was used for this purpose (Figure 4). By moving a lever arm on the hydraulic reducer, the rate of rotation could be varied from "zero" to six hundred rotations per minute. Since this reducer was not able to hold the lower rates of rotation constant, a second reducer was added. The rate of rotation could be varied from zero to fifteen rotations per minute with negligible drift.

A chain drive was used to transmit power from this driving mechanism to the sprinkler. This was accomplished

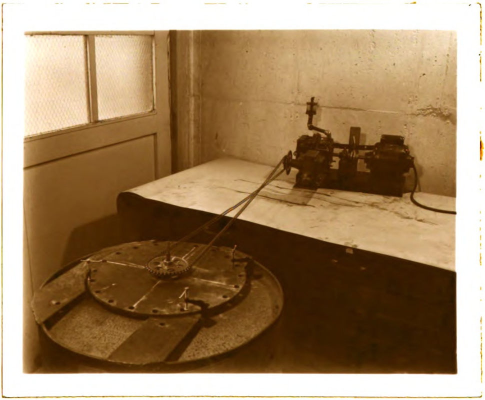

Fig. 4. Sprinkler-rotating mechanism.

by having a one-fourth inch vertical steel shaft attached to the top of the sprinkler and extending up through an opening in the top of the barrel. A sprocket placed at the end of the steel shaft was driven by the chain from the reducer.

Pressure measurement. Bourdon pressure gages were used to measure the pressure. A United States gage with a 3-1/2 inch diameter dial and a scale ranging from zero to one hundred pounds per square inch was placed on the pressure tank. An 8-1/2 inch diameter Certified gage with a scale ranging from zero to one hundred pounds per square inch was placed in the delivery line one foot from the sprinkler. The gages were checked for accuracy with a dead-weight gage tester.

Sprinklers. The two models of sprinkler heads used in this study were made by the same manufacturer. One of the sprinklers had a three-fourths inch riser outlet; the other had a one-half inch riser outlet. Both types were self-turning. The larger sprinkler had outlets for either one or two nozzles, but the smaller was only a one nozzle sprinkler. The nozzles used in this study were manufactured by the same company.

Methodology

Oscillating arm. At the present time the most popular method of rotating an irrigation sprinkler is by means of a jet driven, spring return oscillating reaction arm. In order to determine the effect of the oscillating arm upon the distribution of the fall-out of water from the sprinkler, tests were conducted both using the oscillating arm to rotate the sprinkler, and rotating it mechanically with the oscillating arm fastened to the body of the sprinkler so that it would neither operate nor interfere with the jet of water issuing from the sprinkler.

These tests were conducted using medium-pressure sprinklers with various size nozzles (from one-eighth to one-fourth inch in diameter) and operating at pressures ranging from 20 to 60 pounds per square inch. When rotated mechanically, the rate of rotation was set to approximate that of the oscillating arm under the same conditions.

Operating pressure and size of orifice. In this study it was decided that in order to make an adequate analysis of the effect of the size of the orifice in a nozzle, various sizes should be tested at various pressures. Conversely, it was decided that an adequate analysis of the effect of various pressures would entail the use of various orifice sizes for each pressure tested. Since this caused a considerable amount of repetition and many of the runs were applicable to both analyses, they will be considered together in this section, although the results will be discussed separately.

Tests were made using a sprinkler with a three-fourths inch riser and one with a one-half inch riser connection. The range of pressures tested when using the larger sprinkler was limited by the laboratory ceiling. In some of the tests the sprinklers were operated using the oscillating arm to rotate them; in others they were rotated mechanically without using the oscillating arm.

When the sprinklers were rotated by means of the oscillating arm, a change in pressure did not appreciably alter the rate of rotation. However, when the size of the orifice was changed, the rate of rotation of the sprinkler was altered quite radically in many instances. For this reason, only those tests in which the rate of rotation was relatively unchanged were compared. To verify the trend established with the oscillating arm, the tests were repeated rotating the sprinklers mechanically at the rate of one rotation every 60 seconds. This eliminated any effect a change in the rate of rotation might have had. All of the tests were run in triplicate.

The sprinkler with the one-half inch riser connection was tested: 1) using a three-sixteenths inch diameter nozzle and operating at pressures of 20, 30, 40, 50 and 60 pounds per square inch, 2) using a one-eighth inch and a nine-sixteenths inch diameter nozzle, and operating at pressures of 30 and 40 pounds per square inch, 3) using a thirteen-sixty fourths inch diameter nozzle, and operating at 30 pounds per square inch, and 4) with a one-fourth inch diameter nozzle at 40 pounds per square inch. The sprinkler with the three-fourths inch riser connection was tested using a one-eighth inch and a three-sixteenths inch diameter nozzle at pressures of 30 and 40 pounds per square inch.

Angle of inclination of the sprinkler nozzle. A majority of the medium-pressure sprinklers have the nozzle inclined so that the jet of water is discharged at 25 $\pm$ 3 degrees from the horizontal. To test the effect of a change in this angle it was necessary to find some means of varying the angle and yet keep the other variables constant. The ideal way to vary the angle of inclination of the jet of water would be to cast the body of the sprinkler with the desired angle. However, because of the expense and time that would be involved in doing this, it was found impractical for this study.

At first it appeared that the angle of inclination of the jet of water could be varied by tilting the sprinkler. This, however, proved unsatisfactory since the height of the end of the nozzle was altered with each change of angle. Another difficulty presented by this method was that the angle of inclination of the jet varied as the sprinkler rotated;

hence, any given angle would be constant only at one point around the axis of the sprinkler.

To avoid the above shortcomings, a sprinkler with a one-half inch riser connection was used, and a copper tube four inches long with a 7/16 inch inside diameter was placed between the body of the sprinkler and the nozzle. This tube was threaded at both ends. One of the threaded ends was screwed into the body of the sprinkler and the other end into a pipe coupling. The nozzle was screwed into the other end of the coupling. Care was taken to have the nozzle touching the copper tube in the coupling in order to minimize as much of the turbulence as possible which might result from a sudden expansion of the water in the coupling. The copper tube, being pliable, could be bent to vary the angle of inclination.

For the tests conducted at a pressure of 20 pounds per square inch, the angle of inclination was varied from 10 degrees to 35 degrees from the horizontal in 5 degree increments. At 30 pounds per square inch the angle was varied from 10 degrees to 30 degrees, and at 35 pounds per square inch it was varied from 15 degrees to 30 degrees from the horizontal. The maximum angle of inclination that could be studied here, even at the low pressure of 20 pounds per square inch, was 35 degrees from the horizontal; any angle greater than this caused the jet of water to hit the ceiling.

Tests were conducted at the higher pressures to verify the trend established at 20 pounds per square inch.

All of the tests were made using a one-eighth inch diameter nozzle, as a larger orifice would have further limited the testing of the higher angles of inclination. The oscillating arm was not used to rotate the sprinkler because the length of the extension tube prevented the operation of the oscillating arm. The sprinkler was mechanically rotated at the rate of one revolution per minute.

The angle of inclination was measured along the jet of water as it issued from the nozzle, the vertex being at the point where the water left the orifice. The height of the nozzle above the floor was kept constant by changing the elevation of the sprinkler.

Roughness in the cylinder of the sprinkler nozzle. In roughening the cylinder of the sprinkler nozzle care had to be taken not to change the cross-sectional area of the orifice, as any change in this area would affect the total discharge. Two different methods of accomplishing this were used. One method involved the use of a round, tapered file. The end of the file was inserted into the cylinder of the nozzle as far as it would go without exerting pressure. The file was then forced in a little farther by twisting it. This twisting of the file while in the cylinder of the nozzle

resulted in a roughening of the inside of the cylinder without changing the cross-sectional area. The second method of roughening the nozzle was through the use of a tap of the proper size so as not to enlarge the diameter.

The sprinkler with the one-half inch riser connection was used for these tests. It was rotated both with and without the oscillating arm, the rates of rotation being one rotation per minute without the oscillating arm and about one rotation every two minutes with the oscillating arm.

Nozzle diameters of 0.125 and 0.1590 inch were used. One set of the above nozzle diameters was roughened with the file; another set was threaded using a 6-32 tap on the smaller nozzle and a 10-32 tap on the larger one. A third set was left unroughened. All runs were made in duplicate. A comparison was then made between the distribution patterns of the roughened and the unroughened nozzles to determine what change had resulted.

Angle of taper in the sprinkler nozzle. In order to determine the effect of the angle of taper in a sprinkler nozzle on the distribution of water, various angles of taper were tested. A sprinkler with a three-fourths inch riser connection and nozzles with one-eighth and three-sixteenths inch diameter orifices were used. The larger sprinkler was used in this study in preference to the smaller because the nozzles used in the former had larger outside dimensions and therefore lent themselves more readily to modification.

After attempting several different methods of varying the angle of taper in the nozzle, it was found that this could most readily be accomplished by sharpening a drill to the desired taper and drilling it into the nozzle. Thus the desired angles of taper (θ) were obtained in the sprinkler nozzles (Figure 5).

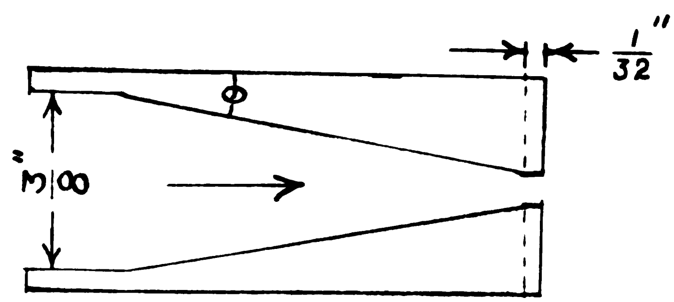

Fig. 5. Angle of taper in a sprinkler nozzle.

The values for the angle θ that were tested were 12, 20, 30, 40, 50, 60 and 80 degrees. These angles provided an assortment of nozzles ranging from one with a considerable length of taper (the 12 degree angle) to one with very little taper, hence approaching a sharp-edged orifice (the 80-degree angle). As indicated in Figure 5, the cylindrical part at the discharge end of each nozzle was only one-thirty second of an inch long, since a longer cylinder would tend to minimize the flow characteristics due to the angle of taper in the nozzle.

Since the total length of the nozzle was kept constant although the angle of taper in the nozzle was varied, the result was that when θ was 12 degrees the taper extended to almost the entire length of the nozzle, whereas in the others a cylindrical portion preceeding the taper resulted (Figure 5). The length of this cylindrical portion increased as θ increased. A three-eighth inch drill was used to make the taper. Extreme care had to be taken in sharpening the drill and in centering it within the nozzle, so that the jet of water would emerge parallel to the longitudinal axis of the nozzle.

Two series of runs were conducted with each of the different nozzles. In the first set the nozzle was screwed directly into the sprinkler; in the second set a three-inch extension tube with a three-eighths inch inside diameter was placed between the body of the sprinkler and the nozzle. The second series of runs was made to see whether any variation occurred when the nozzle was farther away from the influence of any turbulence that might occur due to the bend between the body and the tube of the sprinkler. The sprinkler was rotated mechanically at the rate of one rotation every 60 seconds, and all runs were made in duplicate.

Length of the cylindrical part of the nozzle. In determining the effect of the length of the cylindrical part of the nozzle, both a sprinkler with a three-fourths inch riser connection and one with a one-half inch riser connection were used. Since the cylindrical part of the nozzle usually varied from two to five diameters[1] depending upon the diameter of the orifice, it was necessary to add an additional cylindrical portion to the nozzle in order to test lengths greater than five diameters. This was accomplished by braze welding the desired length of brass of the same diameter as the sprinkler nozzle to the discharge end of the nozzle. A drill of the desired dimensions[2] was then used to bore out the cylinder, beginning at the tapered end. A reamer was used to smooth the inside of the cylinder.

Using a sprinkler with a one-half inch riser connection and a one-eighth inch diameter nozzle, and operating at a pressure of 40 pounds per square inch without the oscillating arm, the cylinder length was decreased from 14 to 4 diameters in increments of two diameters and from 4 to zero diameters in increments of one diameter. Using the same size sprinkler and nozzle and operating at pressures of 30 to 40 pounds per square inch, two replications were made decreasing the

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[1]Length of the cylinder is given here in terms of the inside diameter of said cylinder.

[2]In order to keep the diameter of the cylinder constant throughout its length, a drill one size smaller than the required diameter was used to make the initial bore.

cylinder length from 5 to zero diameters in increments of one diameter.

Using the same size sprinkler with a 9/64 inch diameter nozzle, and operating without the oscillating arm at pressures of 30, 40 and 50 pounds per square inch, the cylinder length was decreased from 17 to 4 diameters in increments of two diameters and from 4 to zero diameters in increments of one diameter. Three replications were made using the above size sprinkler and nozzle and operating at pressures of 30 and 40 pounds per square inch with the oscillating arm to compare the effect of the conventional nozzle (which has a cylinder length of slightly more than two diameters) with that of a nozzle with no cylinder length. This test was repeated at pressures of 30 and 40 pounds per square inch using the same diameter nozzle and a sprinkler with a three-fourths inch riser connection.

For further verification of the trend established by the previous tests, the sprinkler with the three-fourths inch riser connection was operated using a one-fourth inch diameter nozzle at pressures of 30, 40 and 60 pounds per square inch, and decreasing the cylinder length from 12 to 4 diameters in increments of two diameters and from 4 to zero diameters in increments of one diameter. In this last series of tests the angle of elevation of the sprinkler nozzle was lowered to prevent the jet of water from striking the ceiling.

Length of the tube between the body of the sprinkler and the nozzle. Since an extension tube was inserted between the body of the sprinkler and the nozzle, it was not possible to use the oscillating arm to rotate the sprinkler; therefore, it was rotated mechanically at the rate of one rotation every 60 seconds. A sprinkler with a three-fourths inch riser connection and a one-eighth inch nozzle were used. As the tube was shortened, the entire sprinkler had to be raised in order to keep the end of the nozzle at a constant height.

A brass tube which had a three-eighth inch inside diameter and was threaded at both ends was placed between the body of the sprinkler and the nozzle (Figure 22). One of the threaded ends was screwed into the body of the sprinkler and the other end into a pipe coupling. The nozzle was screwed into the other end of the coupling. Care was taken to have the nozzle touching the brass tube in the coupling in order to minimize as much of the turbulence as possible which would result from a sudden expansion of the water in the coupling.

The lengths of tube which were tested were 17 diameters, 12-1/2 diameters, 6 diameters, 2 diameters, and "zero" diameters, which was merely the conventional method of screwing the nozzle directly into the body of the sprinkler. All of the tests were made in duplicate.

Rate of rotation of the sprinkler. In this series of tests a sprinkler with a one-half inch riser connection was used. All of the tests were made at a pressure of 30 pounds per square inch and using a three-sixteenths inch diameter nozzle. The oscillating arm was not used for rotating the sprinkler since the rate of rotation cannot be precisely controlled when using the oscillating arm. The sprinkler was mechanically rotated at the rate of 3, 16, 23, 30, 45, 60, 150 and 540 seconds per rotation. Three separate tests were made using each rate of rotation and the results averaged. This range of rates of rotation seemed sufficient to establish any effects which may be due to the rotating motion.

The maximum trajectory distance was measured when the sprinkler was stationary in order to determine how slowly the sprinkler should be rotated to obtain a trajectory distance that approaches the stationary condition.

Non-circular orifices. In order to find the effect that sprinkler nozzles with non-circular orifices have upon the distribution of water from a sprinkler, and also which geometric shape of orifice gives the best results, various shapes of orifices were tested. In some orifices different depths through the non-circular orifice and two types of approaches to the nozzle were also tested. One of the types of approach was a gradual convergence in the nozzle up to the non-circular orifice (Figure 6a); the other was an abrupt entrance leading directly from a cylinder to the orifice (Figure 6b).

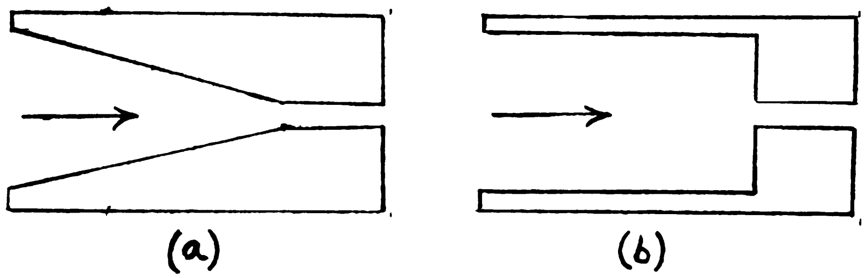


Fig. 6. Two types of entrances to the orifice in a nozzle.

Some of the non-circular orifices which were tested are shown in Figure 7; other shapes tested were the pentagon, semi-circle, and various shapes, angles and sizes of slits cut into the main orifices. All of these orifices were shaped by using drills and tool-and-die-maker files.

Tests were conducted using the oscillating arm for rotating the sprinkler and without the oscillating arm, where the sprinkler was rotated mechanically. In this series of tests no attempt was made to keep the various rates of rotation constant when using the oscillating arm, or to keep the cross-sectional areas of different shapes of orifices the same since only a qualitative analysis of the distribution obtained from a particular shape was desired, and no direct comparison between the different shapes was to be made.

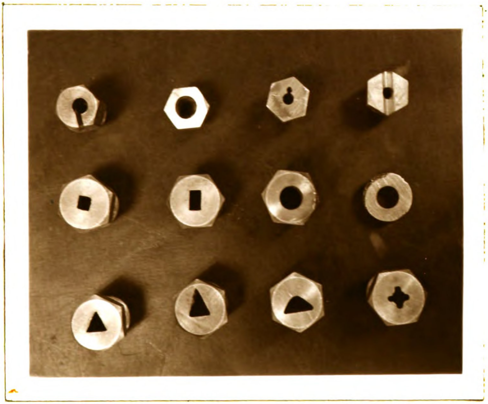


Fig. 7. Top view of nozzles with various shaped orifices.

<u>Cylindrical discharge tubes</u>. In order to determine the type of distribution obtained from a tube, and the effect of various tube lengths upon the distribution pattern, copper tubes of various diameters and lengths were tested. The tubes which were 5/16 and 7/16 inch in diameter were varied in length from six inches to one-fourth inch; the tubes which were 5/32 inch in diameter were varied in length from four inches to one-fourth inch. The lengths were varied from six to three inches in increments of one inch, from three (four in the one case) to one inch in increments of one-half inch, and from one to one-fourth inch in increments of one-fourth inch (except the 7/16 inch diameter tube which was reduced to a length of "zero" inches; that is, cut off directly at the sprinkler).

The 5/32 inch and the 5/16 inch diameter tubes were soldered into the sprinklers as shown in Figure 44. The 7/16 inch diameter tube was screwed into the body of the sprinkler as shown in Figure 38.

Tests were also conducted in which lengths of copper tubing 5/16 and 5/32 inch in diameter were bent and attached to the bearing nipple of the sprinkler to determine the effect on the distribution pattern when the vertical and the diagonal portions of the sprinkler were the same diameter (Figure 40). In these tests the length of the diagonal portion of the tube was varied as in the previously discussed tests.

All of the lengths of tube were tested without the oscillating arm at the rate of one rotation per minute and at a pressure of 40 pounds per square inch. Wherever tube length permitted, tests were also conducted using the oscillating arm to rotate the sprinkler. The 5/32 inch diameter tube at a length of one-half inch was also tested at pressures of 20, 30 and 50 pounds per square inch.

DISCUSSION OF RESULTS

Effect of the Oscillating Arm

The action of the oscillating arm caused the sprinkler to rotate and also increased the amount of water which fell out near the sprinkler. When a jet of water issuing from a circular orifice was not interrupted by an oscillating arm, the minimum fall-out of water occurred near the sprinkler. From this point the fall-out of water increased until it reached a maximum toward the outer portion of the trajectory distance. The rate of fall-out then decreased very rapidly to the outer limit of the trajectory radius of the jet of water.

The action of the oscillating arm was to frequently interrupt the jet of water issuing from the sprinkler. This regular interruption of the jet of water resulted in a considerable increase in the fall-out of water near the sprinkler. The amount of fall-out decreased as the distance from the sprinkler increased until a minimum point was reached somewhere around the first one-fourth point of the total trajectory distance of the jet of water. From this minimum point the rate of fall-out again began to increase, reached a maximum approximately three-fourths of the distance along the trajectory radius and then sharply decreased to the maximum trajectory distance as did the jet of water not interrupted by an oscillating arm.

Figure 8 shows diagrammatically the distribution of water along the trajectory radius of a jet of water issuing from a sprinkler nozzle with a circular orifice and operated both with and without the oscillating arm. Since the influence of an oscillating arm on the distribution of water from a sprinkler is dependent upon the operating pressure, size of nozzle, rate of rotation of the sprinkler, frequency of interruption of the jet by the oscillating arm, angle at which the oscillating arm strikes the jet of water, and several other factors, it was felt that the use of any one particular distribution as an example might be misleading. Hence, Figure 8 depicts a general distribution pattern which might be expected (to a greater or lesser degree) from most medium-pressure sprinklers.

As indicated in Figure 8 the distribution curve for a sprinkler operated with the oscillating arm did not rise as high as that for a sprinkler operated without the oscillating arm. This was mainly due to the fact that the oscillating arm deflected part of the jet of water so that it fell near the sprinkler; consequently less water was trajected to that part of the radius where the maximum fall-out of water occurred.

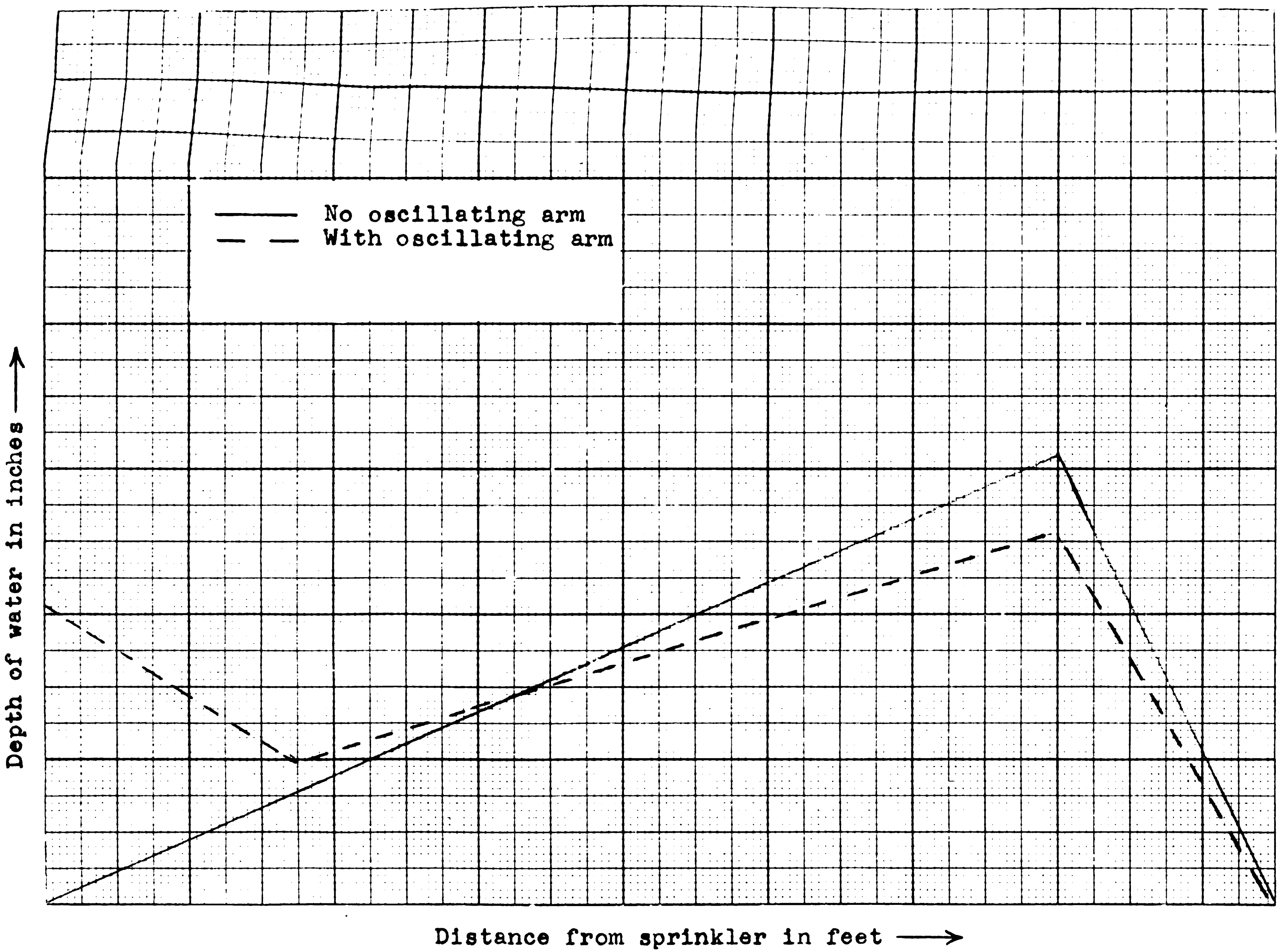
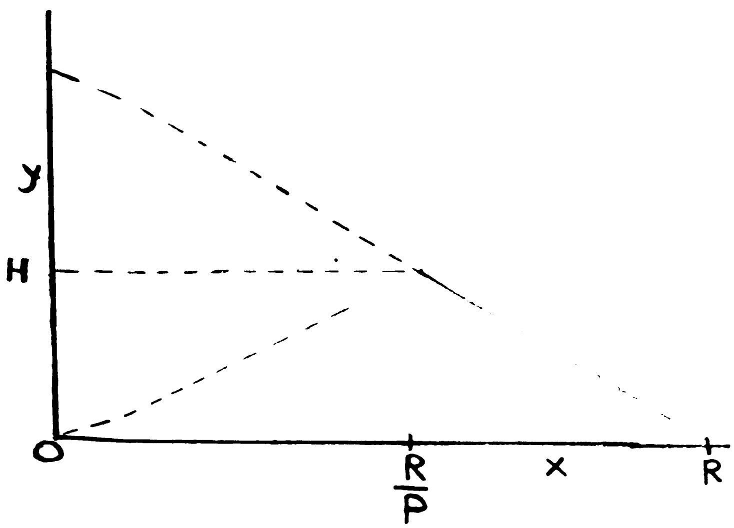


Fig. 8. Effect of oscillating arm on fallout of water from a medium-pressure sprinkler.

As mentioned previously the two desirable types of distribution curves are (1) a right triangular shaped one in which a maximum amount of fall-out of water occurs at the sprinkler and then gradually diminishes to zero at the maximum trajectory radius of the jet of water, and (2) a trapezoidal-shaped curve in which the amount of fall-out of water is constant from the sprinkler to a point some distance along the trajectory radius and then gradually diminishes to zero at the maximum trajectory radius. It may be seen from Figure 8 that neither of the two desired distribution curves was obtained regardless of whether the oscillating arm was used to rotate the sprinkler or it was rotated mechanically.

In general the above distribution curves may be expressed mathematically. For this purpose the distribution curve will be broken up into two parts (Figure 9). The first part of the curve will extend in a straight line with a constant slope "m" from the "y" axis to a point where there is a change in slope. From this point the second part of the curve will extend in a straight line with a constant negative slope until it reaches the "x" axis at point "R", which is the maximum trajectory radius of the jet of water from the sprinkler.

Let $\frac{R}{P}$ be the point along the trajectory radius where the slope of the distribution curve changes and "H" amount of fall-out of water occurs. If slope "m" is equal to or less than zero, a desirable distribution will result; if "m" is greater than zero, a poor distribution will result.



$$f(x) = mx + H - m\frac{R}{P} \qquad 0 \leq x \leq \frac{R}{P}$$

$$f(x) = \frac{-PHx}{R(P-1)} + \frac{PH}{P-1} \qquad \frac{R}{P} \leq x \leq R$$

Let $\frac{PH}{P-1} = C$

$$f(x) = \frac{-xC}{R} + C$$

x = any distance along trajectory radius R

y = depth of water at any point along R, trajectory radius

Fig. 9. General distribution curve from an irrigation sprinkler.

Effect of Operating Pressure

For the pressures tested in this study, it was found that the higher the pressure, the more desirable the distribution. A higher pressure caused a greater break-up of the stream of water as it left the nozzle. This breaking-up effect of the jet was apparent for the range of nozzle sizes studied. Also, as the pressure was increased, a greater trajectory distance was obtained. The drops of water appeared smaller at the higher pressures.

Figure 10 shows that the difference between the maximum and minimum points of accumulation of water were very

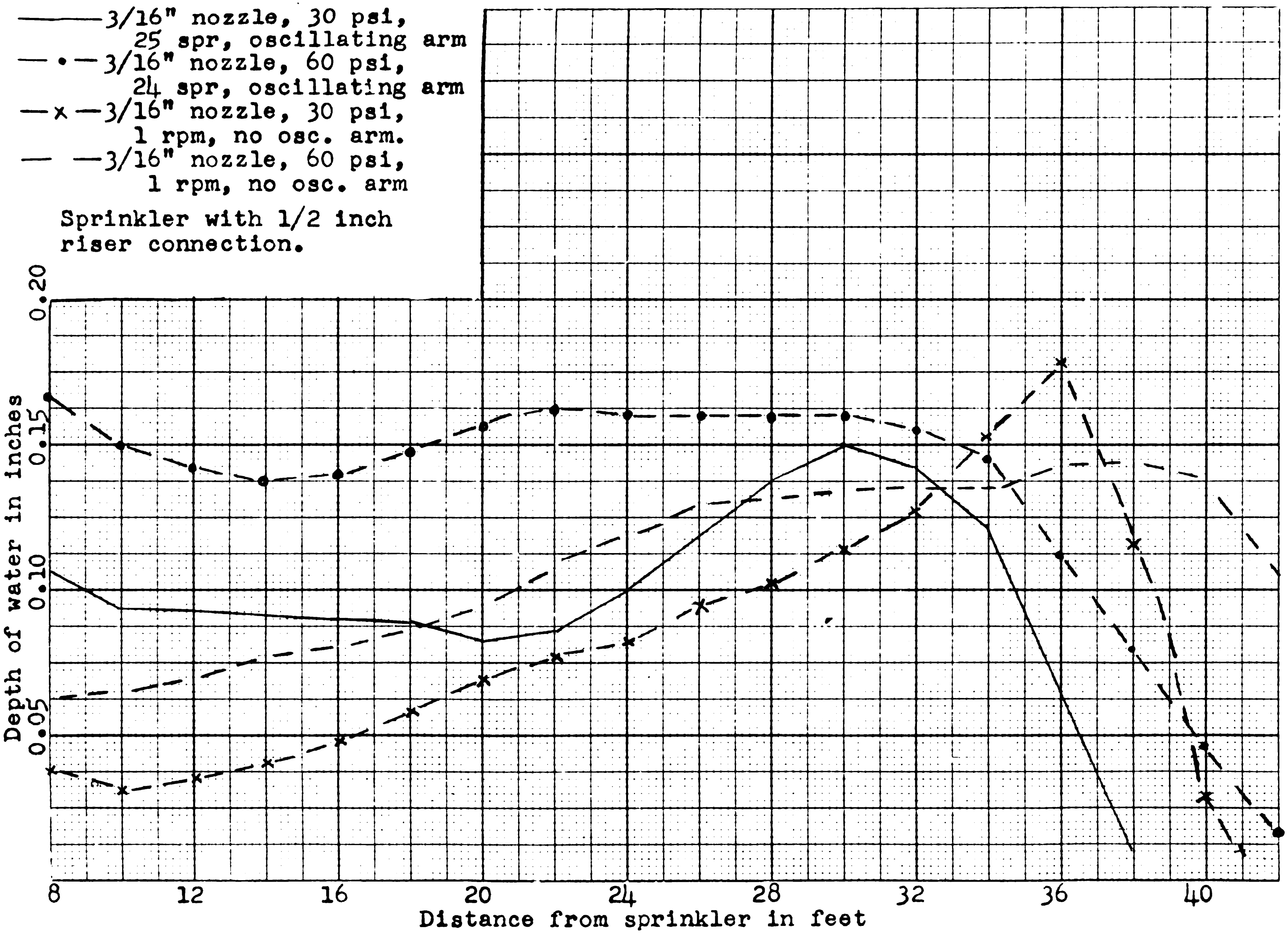


Fig. 10. Effect of pressure on distribution of water from irrigation sprinkler.

pronounced when using a sprinkler with a one-half inch riser and a three-sixteenths inch diameter nozzle, and operating at a pressure of 30 pounds per square inch both with and without the oscillating arm. When operating the sprinkler with the oscillating arm, the decrease was 45 percent; without the oscillating arm, the decrease was 82 percent. When the sprinkler was operated with the same nozzle but at a pressure of 60 pounds per square inch, the percent of decrease with the oscillating arm was 15 percent, and without the oscillating arm it was 60 percent.[1]

When operating the sprinkler at a pressure of 60 pounds per square inch with the oscillating arm, the maximum fall-out instead of occurring in a very short distance in the radius (in other words, coming to a peak as in the previous test) extended from 20 feet to 32 feet from the sprinkler. It then dropped to almost zero inches of water in the next 10 feet. The rate of decrease was about 0.014 inch of water per foot. The minimum occurred at about 14 feet with the total low extending from 10 feet to 20 feet from the sprinkler.

In the distribution curve for the sprinkler with an oscillating arm operating at a pressure of 30 pounds per square inch, no flat portion existed at the maximum. The minimum extended from a point 8 feet from the sprinkler to about 24 feet from the sprinkler. The fall-out of water then increased

[1]The rates of rotation for 60 and 30 psi with the oscillating arm were 24 and 25 seconds per rotation respectively; without the oscillating arm, the rate of rotation was 1 rpm.

quite rapidly, reaching a peak 30 feet from the sprinkler. After the peak was reached, there was a rapid decrease (about 0.0175 inch of water per foot) in the rate of fall-out.

When operating the sprinkler without the oscillating arm, the peak for the higher pressure was 0.145 inch of water; for the lower pressure it was 0.180 inch of water. This was a very significant increase since there was over 40 percent more water discharged at a pressure of 60 pounds per square inch than at 30 pounds per square inch.

As may be seen in Figure 10, the trajectory distance was increased only five feet by raising the pressure from 30 to 60 pounds per square inch when operating the sprinkler without the oscillating arm. The higher pressure caused a greater dispersion and break-up of the discharged stream of water resulting in smaller drops. Because the distance of travel of a drop of water is proportional to the size of the drop,[1] very small drops travel negligible distances. At high pressures which cause an excessive break-up of the jet of water, a further increase in the pressure may result in a decrease of total trajectory distance. However, the smaller drops resulting from the higher pressures tend to have a less deleterious effect upon the soil due to their smaller impact.

[1]See equation (1) under Effect of Rate of Rotation.

Effect of Orifice Diameter

There is a correspondingly greater quantity of fall-out of water along the trajectory distance from a larger diameter nozzle than from one with a smaller diameter operated at the same pressure. Hence, it would not be correct to make a direct comparison between the points of maximum and minimum accumulation of water from the different diameter nozzles. It seems much more reasonable to compare instead the maximum and minimum points for each particular diameter.

When a sprinkler with a one-half inch riser connection was operated with a one-eighth inch nozzle at a pressure of 40 pounds per square inch and was rotated by means of the oscillating arm at the rate of 103 seconds per rotation for one hour, the maximum fall-out was 0.075 inch of water at 36 feet from the sprinkler and the minimum accumulation was was 0.04 inch of water at 16 feet from the sprinkler (Figure 11). This was a decrease of about forty-seven percent.

Using the three-sixteenths inch nozzle and operating the sprinkler for one hour at a pressure of 40 pounds per square inch with the oscillating arm and at a rate of 92 seconds per rotation, the maximum accumulation of water was 0.145 inch at 30 feet from the sprinkler and the minimum accumulation was 0.11 inch at 20 feet; a decrease of about twenty-four percent. From this it may be seen that use of the nozzle

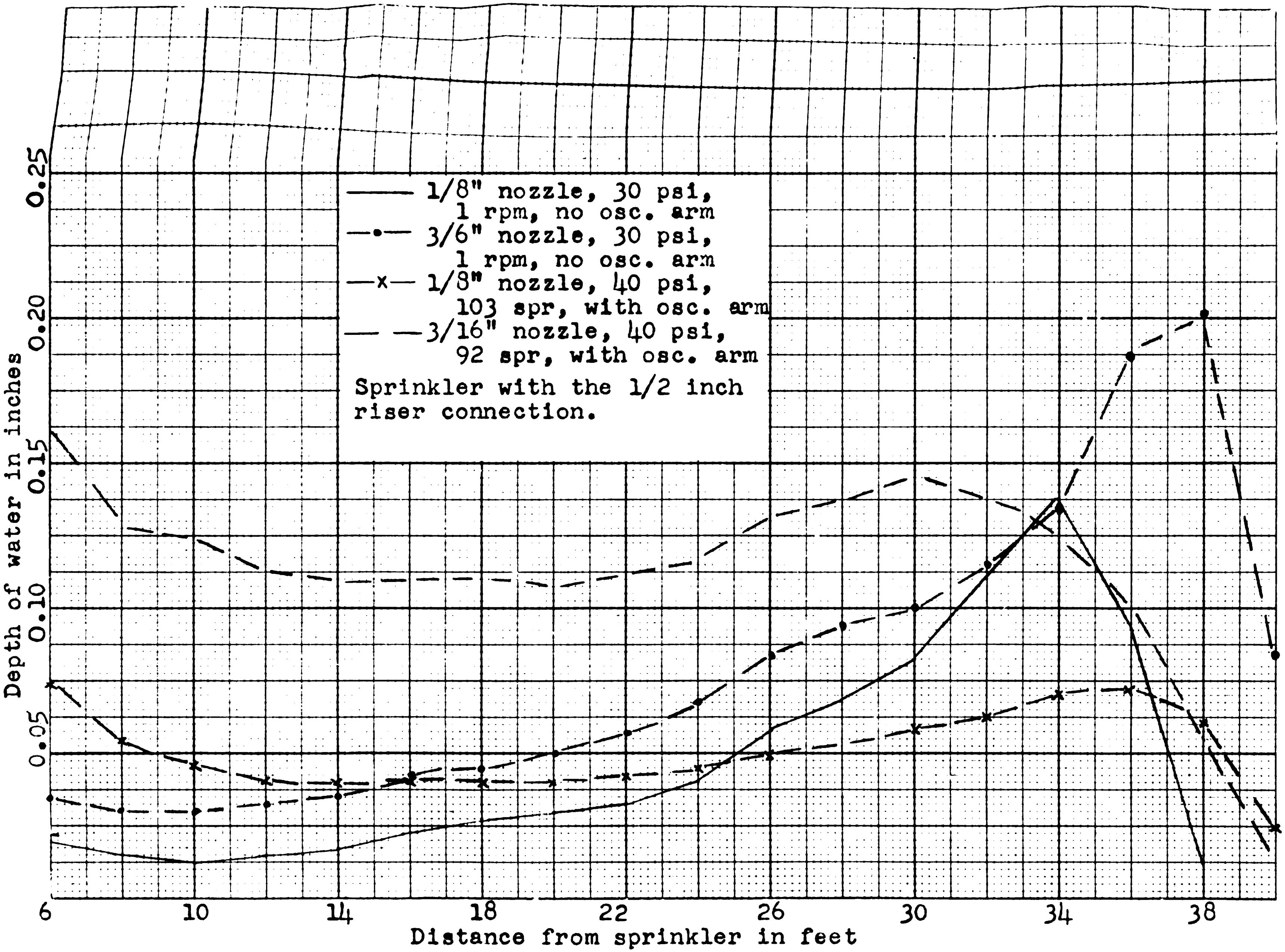


Fig. 11. Effect of orifice diameter on distribution of water.

with the larger diameter orifice resulted in a more desirable distribution.

When the same two nozzles (one-eighth and three-sixteenths inch diameter) were compared at a pressure of 30 pounds per square inch and without the oscillating arm, the nozzle with the three-sixteenths inch diameter again gave the better distribution when the percentage of decrease of the minimum from the maximum accumulation is considered. The decrease here was eighty-five percent for the larger and ninety percent for the smaller size nozzle. It should be pointed out that the larger diameter nozzle was operated in what is considered by sprinkler manufacturers to be an unfavorable pressure range.

When a one-fourth inch diameter orifice was drilled into a nozzle for a one-half inch riser connection sprinkler, the distribution was improved still further (Figure 12). At a pressure of 40 pounds per square inch and operating with an oscillating arm at the rate of 124 seconds per rotation, the decrease of the minimum from the maximum accumulation of water was only fifteen percent. The trajectory distance in this instance was 42 feet.

Tests run on the sprinkler with the three-fourths inch riser connection showed the same trend; however, it was not as pronounced (Figure 23). This size of sprinkler used a nozzle with larger outside dimensions than those of the

Fig. 12. Jet of water issuing at 40 psi from a 1/4 inch diameter circular orifice (using sprinkler with 1/2 inch riser connection).

nozzle used by the smaller sprinkler. This resulted in a much greater length of taper in the nozzle of the larger sprinkler. The angle[1] of taper for both nozzles, however, was the same; but, since there was much more taper length in the nozzle with the greater outside diameter, there was more guidance for the water through this nozzle when the same diameter orifice was used in both nozzles. Another point worth considering is that in the larger sprinkler the bend was more gradual and the distance between the bend and the nozzle greater than in the smaller sprinkler. These three factors, amount of taper, bend of sprinkler and distance between the bend and the nozzle,[2] overshadowed the desirable characteristics of the higher angle of inclination of the nozzle of the larger sprinkler and resulted in a poorer distribution of the water.

The reason that a larger diameter opening in a given nozzle gave a more desirable distribution can best be described in this way: as the size of the orifice is increased, the length of the taper in the nozzle decreases until the nozzle approaches a tube. Since the sprinkler with the larger nozzle had a longer taper or cone leading toward the cylindrical opening, a much larger opening was required in it than would be in a smaller sprinkler nozzle in order to

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[1] 24-degree angle.

[2] These factors are discussed in more detail in another part of this study.

approach a tube. It was found in another part of this study that a tube gives a more desirable distribution than a nozzle, especially when the discharge end of the tube is near the bend of the main body of the sprinkler.

Effect of the Angle of Inclination of a Nozzle

The angle of inclination of a sprinkler nozzle from the horizontal had a significant effect on the distribution of water. In Figure 13 a sprinkler with a one-half inch riser connection and a one-eighth inch nozzle was operated without the oscillating arm at a pressure of thirty pounds per square inch and at the rate of one rotation per minute for one hour. The angle of elevation was altered from 15 degrees to 30 degrees from the horizontal in increments of five degrees.

At 15 degrees the maximum trajectory distance was about 30 feet with a maximum of 0.25 inch of water at 28 feet. With the sprinkler nozzle at a 20 degree angle of inclination, the maximum trajectory distance was 34 feet with a maximum of 0.175 inch of water at 32 feet. When the angle of inclination was 25 degrees from the horizontal, the maximum trajectory distance became 38 feet with a maximum of 0.126 inch of water occurring at 35 feet. A 30 degree angle of inclination of the sprinkler nozzle resulted in a maximum trajectory distance of 40 feet with a maximum accumulation of 0.12 inch of water occurring at about 36.5 feet.

The rate of decrease from the point of maximum accumulation of water to the maximum trajectory distance was 0.12, 0.08, 0.04 and 0.03 inch of water per foot at an angle of inclination of 15, 20, 25 and 30 degrees respectively.

It is significant to notice that the maximum accumulation of water decreased as the angle of inclination of the sprinkler nozzle increased. The same trend is shown in Figure 14. The tests depicted here were run at a pressure of 20 pounds per square inch. At this low pressure it was possible to raise the angle of inclination of the sprinkler nozzle to 35 degrees from the horizontal without the jet of water hitting the ceiling.

As indicated in Figure 14 a 35 degree angle of inclination gave a more desirable distribution than a 30 degree angle. As stated previously it was not possible at the location in which the tests were conducted to test a larger angle of inclination because of the ceiling limitation.

It should also be noted that as the angle of inclination increased, the rate of decrease was diminished. That is, the difference between the points of maximum accumulation of water is not as pronounced between 25 degrees and 30 degrees as it is between 20 degrees and 25 degrees.

From the tests that were conducted it could be deduced that a 40 degree angle of inclination would given an even

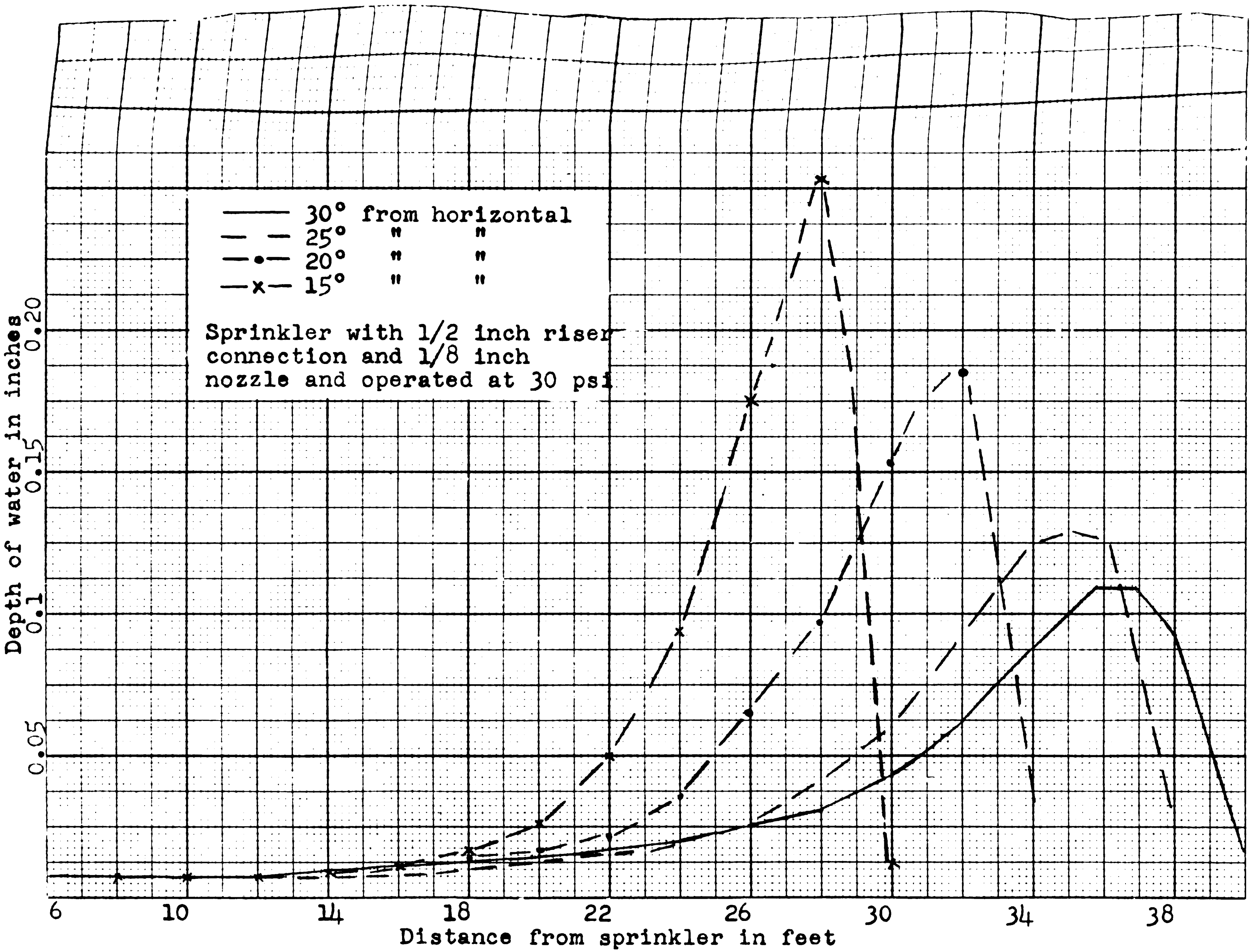

Fig. 13. Effect of angle of inclination on distribution of water.

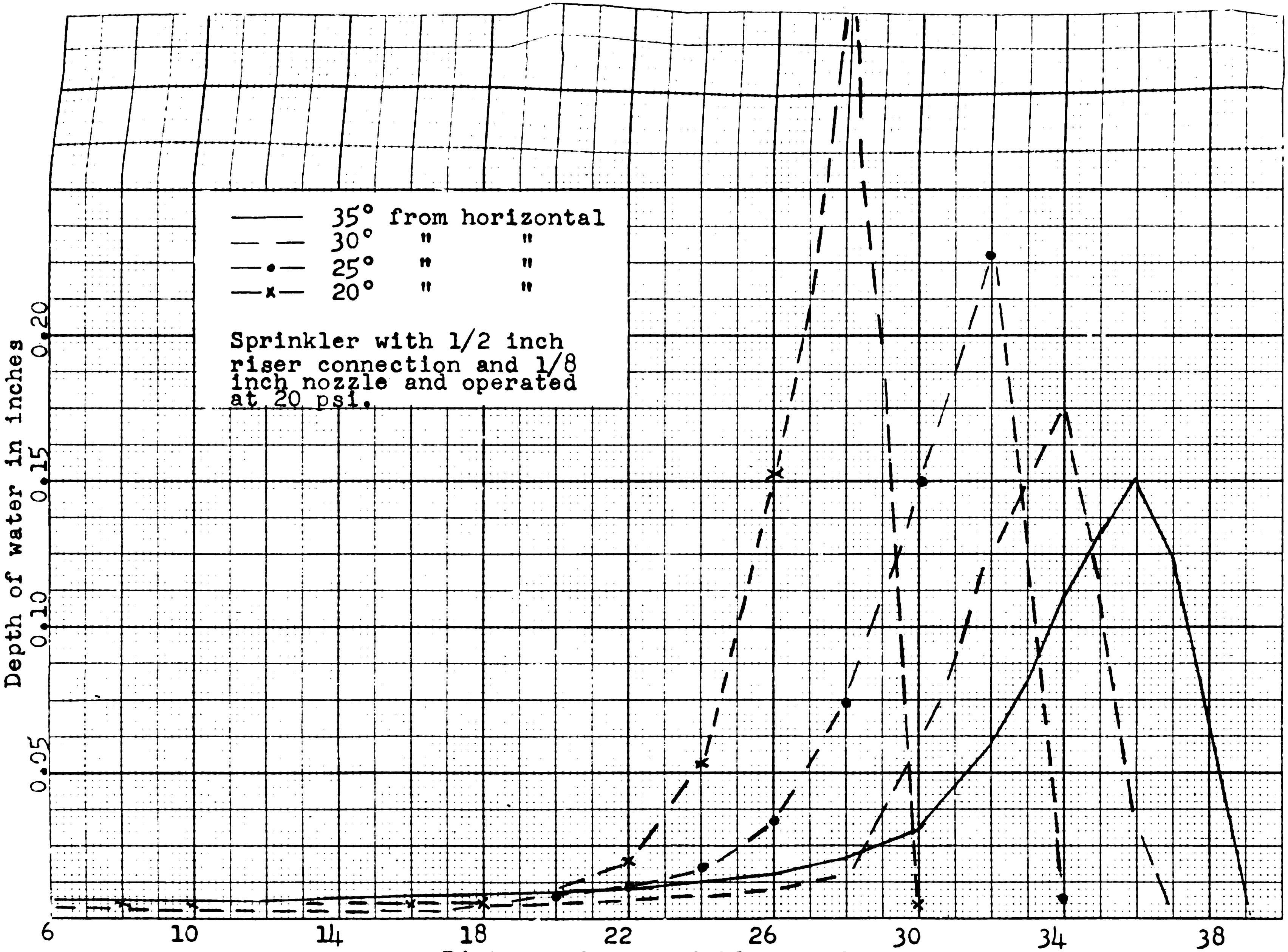

Fig. 14. Effect of angle of inclination on distribution of water.

more desirable distribution than the 35 degree angle. However, it should be remembered that according to the pattern established above, this rise of five degrees in the angle of inclination will have a less pronounced effect on the distribution than the five degree difference between a 30 degree and a 35 degree angle of inclination.

It was also found that pressure modified the effect of the angle of inclination. That is, at 35 pounds per square inch the difference between a 30 degree and a 25 degree angle of inclination from the horizontal was not as pronounced as it was at 30 pounds per square inch. When Figures 13 and 14 are compared, the same differences may be seen between the tests run at 20 and at 30 pounds per square inch, but the angle of inclination was much more critical at the lower pressure than it was at the higher pressure. The tests also indicated that the first 16 to 20 feet from the sprinkler were not appreciably affected by the change in angle of inclination of the sprinkler.

Under field conditions the higher the trajectory angle, the more opportunity the wind would have to affect the distribution of the water. There are two reasons for this:

1. The higher the angle of inclination, the longer the droplet of water is in the air, thus affording the wind more time to influence it.

2. The higher the angle of inclination, the greater the trajectory height; and since the wind velocity increases

with height, this higher velocity would have a greater effect on the distribution pattern.

Hence, it would appear that if wind conditions are taken into account, the optimum angle of inclination of the sprinkler nozzle might be about 35 degrees from the horizontal. However, before any definite conclusions are reached, these tests should be conducted under field conditions.

In order to explain the difference in distribution and trajectory distance at various angles of inclination, it would be desirable to consider the kinematics of a projectile in flight. Consider the water leaving the sprinkler nozzle as a series of projectiles. These projectiles will have various masses and velocities. The angle of inclination of the sprinkler nozzle from the horizontal will be designated as θ. Hence, the water leaving the nozzle will have an angle θ from the horizontal. Neglecting the effect of air resistance, the equation of trajectory, the range "R" on a horizontal plane and the maximum altitudes "h" (in feet) reached in flight by any drop of water will be determined.

Solution: With the air resistance being neglected, the only force acting upon the water droplet is its weight; hence, the acceleration at all times is due to gravity "g" directed vertically downward (Figure 15). Thus, $a_x = 0$ and $a_y = -g$.

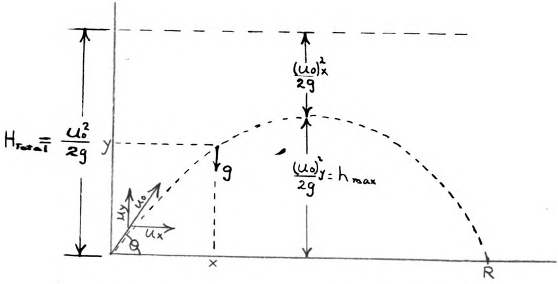

Fig. 15. Interrelationship of velocity head and jet elevation.

The resulting motion, then, is a superposition of two rectilinear motions with constant acceleration. With zero acceleration in the "x"-direction, the horizontal distance traveled equals the constant horizontal component of velocity multiplied by the time. Thus,

$$x = ut \cos \theta$$

The "y"-coordinate of the projectile may be stated as

$$y = ut \sin \theta - 1/2\, gt^2$$

The equation of the trajectory is obtained by eliminating the "t" between the two expressions and is

$$y = x \tan \theta - \frac{gx^2}{2u^2 \cos^2 \theta}$$

The range "R" is obtained by equating the above expression for "y" to zero; hence,

$$0 = x \left(\tan \theta - \frac{gx}{2u^2 \cos^2 \theta}\right)$$

The above has two solutions:

$x = 0$, which is of no concern; and

$$x = R = \frac{2u^2 \sin\theta \cos\theta}{g} = \frac{u^2 \sin 2\theta}{g} \qquad (1)$$

The maximum range occurs for $\sin 2\theta = 1$, or $\theta = 45$ degrees, and is

$$R_{max} = \frac{u^2}{g}$$

The time of flight for the range "R" is obtained by letting

$$y = 0 = t(u \sin\theta - 1/2\ gt)$$

$$t = \frac{2u \sin\theta}{g} \qquad (2)$$

The maximum altitude is

$$h = y = \frac{u^2 \sin^2\theta}{g} - \frac{g}{2} \frac{u^2 \sin^2\theta}{g^2} = \frac{u^2 \sin^2\theta}{2g} \qquad (3)$$

From equation (1) it is apparent that for any water droplet leaving with velocity "u", the maximum distance "R" will be obtained when θ is 45 degrees. Any angle smaller or greater than 45 degrees will decrease the distance.

Equation (2) indicates that as the trajectory angle θ is increased, the time "t" that the drop will be in the air will be increasing until θ is equal to 90 degrees, at which point the time will be a maximum.

The altitude "h" for any angle θ is indicated by equation (3). The maximum altitude will be attained when θ is equal to 90 degrees.

The decrease in the accumulation of water toward the periphery of the trajectory distance with an increase of the angle of inclination can be attributed mainly to the following factor: regardless of what the angle of inclination of the sprinkler is, the quantity of water will be the same if all other factors are kept constant. Hence, as seen by equation (1), if the trajectory distance "R" is increased with an increase of the angle of inclination, the water that does come out of the sprinkler will have to be spread out along a greater radius.

Accurate calculations for trajectories must take into consideration the effect of air resistance, which is appreciable for the high-velocity water droplets. However, the mathematical analyses presented here do give an insight into the basic reasons for the differences which occurred. A mathematical analysis which does take the effect of air resistance into consideration will be presented elsewhere in this study.

Effect of Roughness in the Cylinder of the Nozzle

In this study it was found that roughening the inside of the cylinder of the nozzle impaired the distribution characteristics of the sprinkler. The same trend resulted whether the cylinder was roughened with a round file or threaded with a National Coarse or a National Fine thread.

Figure 16 shows the distribution pattern of a sprinkler with a one-half inch riser and a 0.1590 inch diameter nozzle operated at a pressure of 40 pounds per square inch and at the rate of one rotation every 60 and 105 seconds with and without the oscillating arm respectively for both the roughened and unroughened nozzles. There was a larger fall-out near the sprinkler from the nozzle that was roughened[1] than from the one that was not roughened. This occurred regardless of whether the sprinkler was operated with or without the oscillating arm. Toward the center of the trajectory radius (at 24 feet from the sprinkler), the fall-out for the roughened nozzle was less than for the unroughened one, the difference being about 0.01 inch.

It is also significant to note that the nozzles that were roughened had a greater total fall-out at the point of maximum accumulation than did the unroughened ones. The difference here was 0.010 and 0.015 inch of water with and without the oscillating arm respectively. Roughening the nozzles caused a slight shortening (about two feet) of the total trajectory distance.

The important effect to note is that roughening the nozzle of the sprinkler tended to accentuate the fall-out where it was least desirable and to minimize it where it was desired. This was especially true when the sprinkler was

[1]10-32 tap.

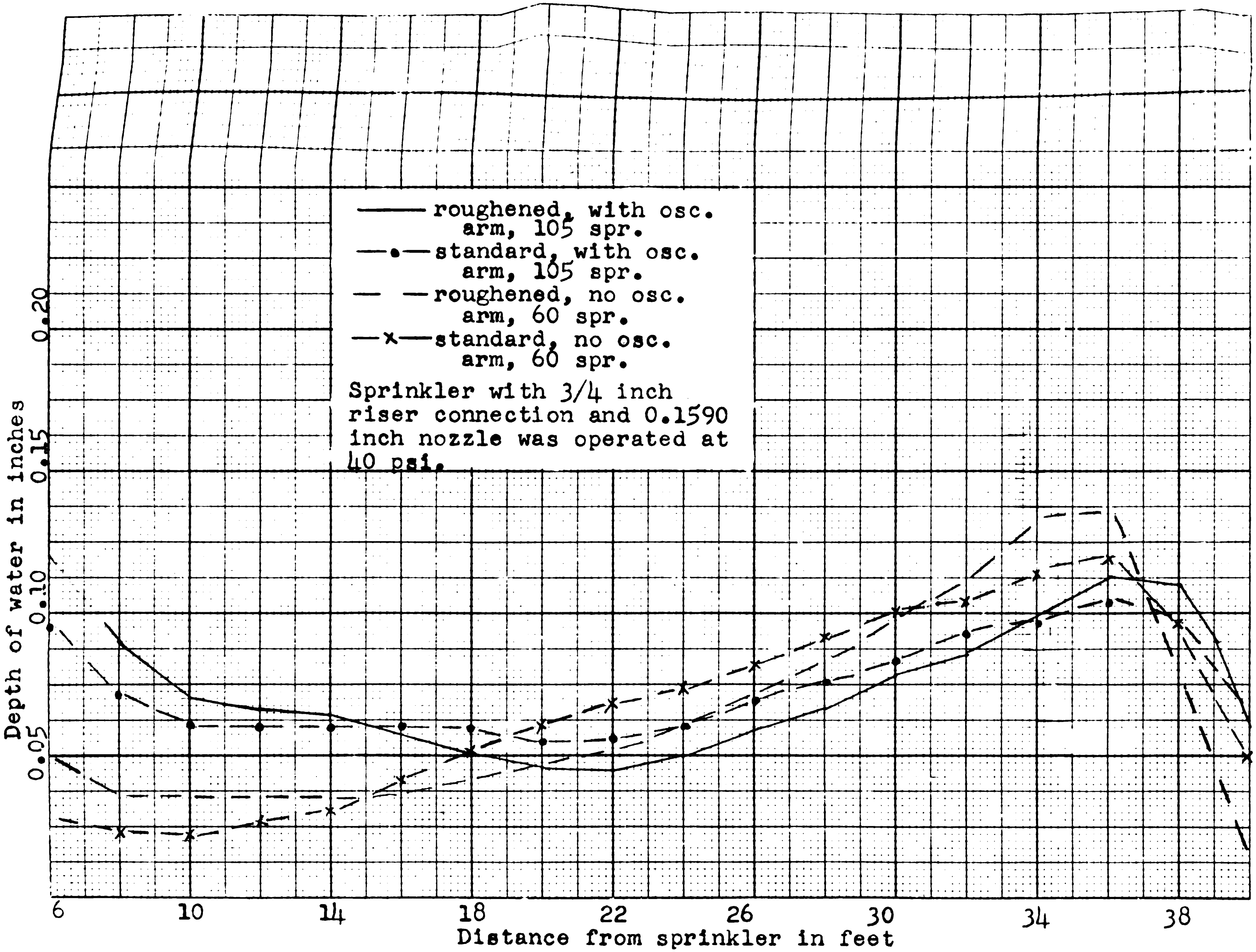

Fig. 16. Effect of roughness in the cylinder of nozzle on distribution of water.

rotated by means of the oscillating arm, where an excess of water due to the action of this arm usually occurs near the sprinkler.

Roughening the inside of the nozzle changed the drop size distribution. The drops of a size that normally would fall out in the center portion of the trajectory radius were fewer and hence the fall-out in this portion of the trajectory radius was less than in the unroughened nozzle. However, a greater amount of fall-out both near the sprinkler and toward the outer trajectory radius resulted. Roughening the nozzle changed the velocity distribution of the water through the nozzle. This change was reflected in the distribution pattern.

Effect of the Angle of Taper in the Sprinkler Nozzle

All of the tests in this part of the study were conducted using a sprinkler with a three-fourths inch riser connection and nozzles one-eighth and three-sixteenths inch in diameter both with and without an extension tube and operating at a pressure of 40 pounds per square inch without the oscillating arm at the rate of one rotation per minute.

It was found that as the angle of taper was increased (that is, approached a sharp-edged orifice) the total trajectory distance decreased. The amount of this decrease between 12 degrees and 80 degrees was about two feet.

When the one-eighth inch diameter nozzle was used without the extension tube, there was little difference in the amount of fall-out of water in the first 16 feet from the sprinkler between the various angles of taper in the nozzles tested (Figure 17). Beyond this point, the fall-out of water increased as the angle of taper in the nozzle was decreased; that is, at the point of maximum accumulation of water, which was between 34 and 36 feet, the amount of fall-out from the nozzle with the 80 degree taper was about 0.07 inch, while from the nozzle with the 12 degree taper the amount of fall-out was almost 0.09 inch. The same general pattern of distribution of water resulted when the three-sixteenths inch nozzle was used.

When the extension tube was used, the same trend resulted; however, the total trajectory distance of each of the angles of taper tested was increased by about two feet.

As the angle of taper in the nozzle was decreased, since the distribution curve rose to a higher position and the trajectory distance increased, more water was being discharged. This agrees with the known fact that the coefficient of discharge must increase as the angle of taper is decreased. Hence, although the nozzles with the larger angle of taper improved the distribution of water, this improvement was

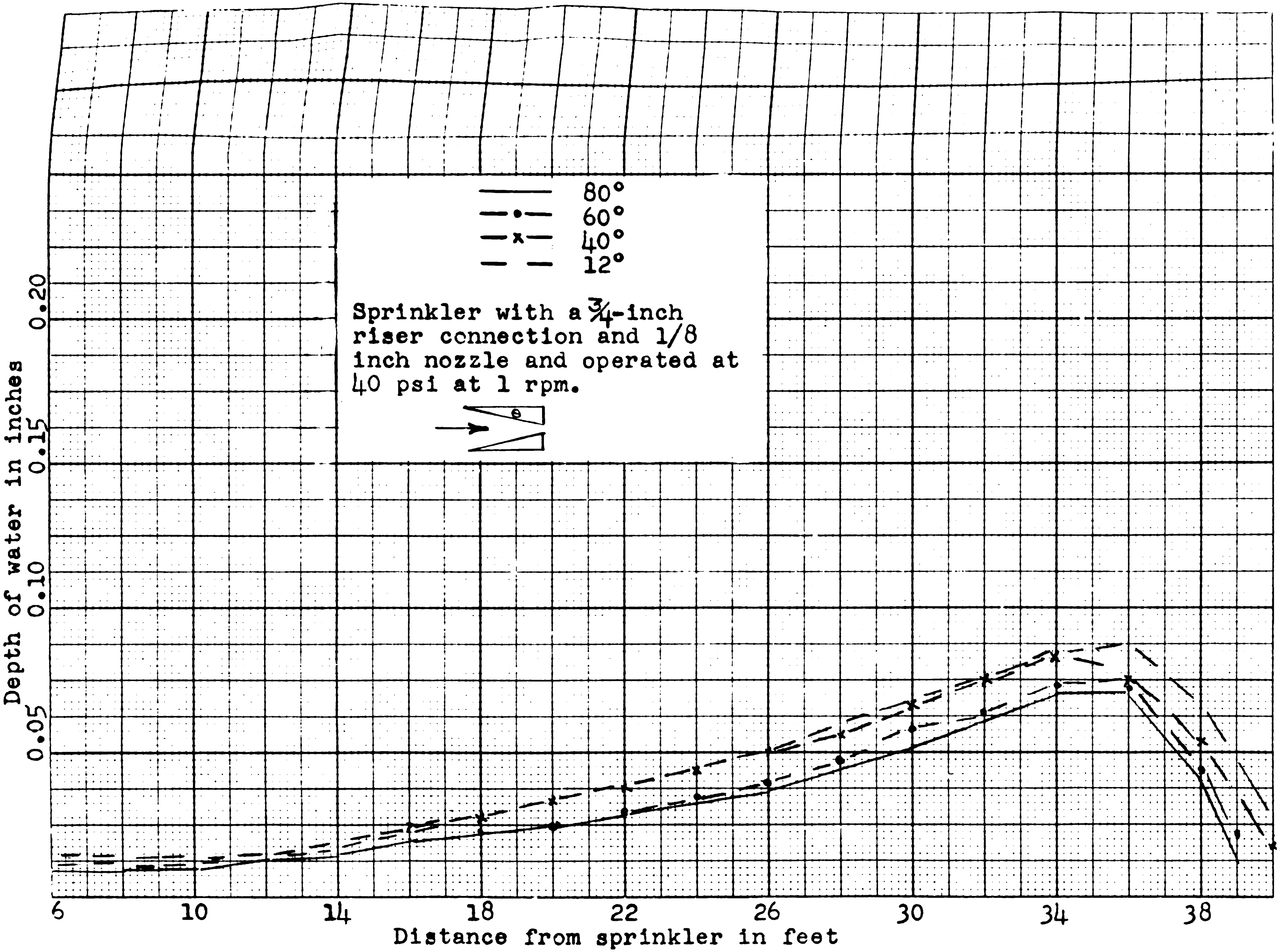

Fig. 17. Effect of the angle of taper in the sprinkler nozzle on distribution of water.

not justified in view of the resulting lower coefficient of discharge.

Effect of the Length of the Cylindrical Part of the Nozzle

It was found by varying the length of the cylindrical part of the nozzle that the shorter cylinder yields a more desirable distribution of water. Figures 18 and 19 give a representative illustration of the effect of shortening the cylindrical part of the nozzle. These figures contain data from only four different cylinder lengths for a 9/64 inch nozzle. However, as discussed in the Method of Procedure, tests were also conducted using a one-quarter inch diameter nozzle and a one-eighth inch diameter nozzle. All of the tests indicated the same trend shown in Figures 18 and 19 in which a 9/64 inch diameter nozzle was used. In these tests the sprinkler was operated for one hour without an oscillating arm at the rate of one rotation per minute and at a pressure of 30 and 50 pounds per square inch respectively. In all the tests conducted, the nozzle with the longest cylinder gave the poorest distribution.

The greatest improvement in the distribution resulting from the decrease in the length of the cylinder occurred in about the first two-thirds of the total trajectory distance (Figures 18 and 19). When using the nozzle with the cylinder three diameters long, a fall-out of about 0.03 inch

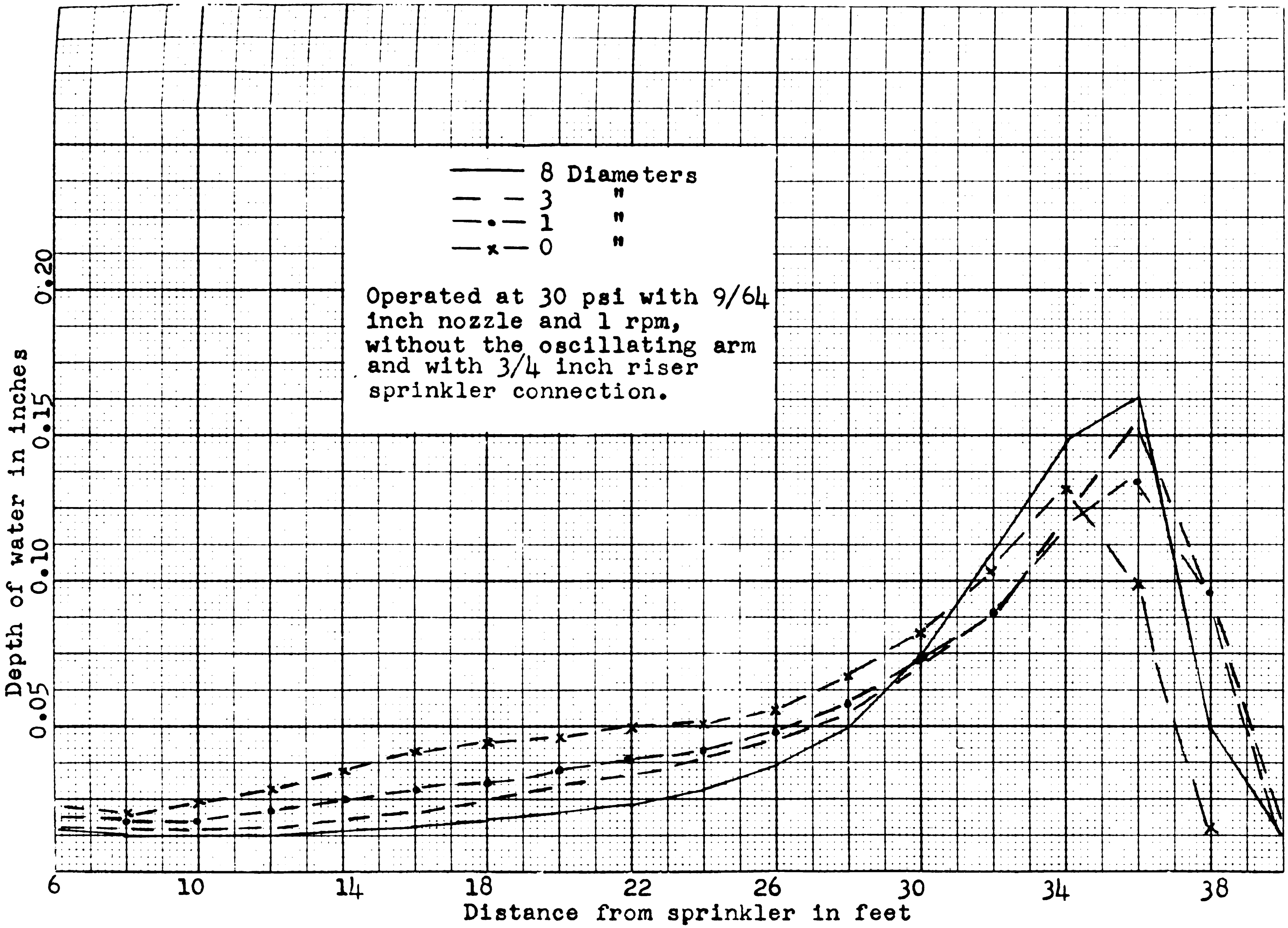

Fig. 18. Effect of length of cylinder in nozzle on water distribution.

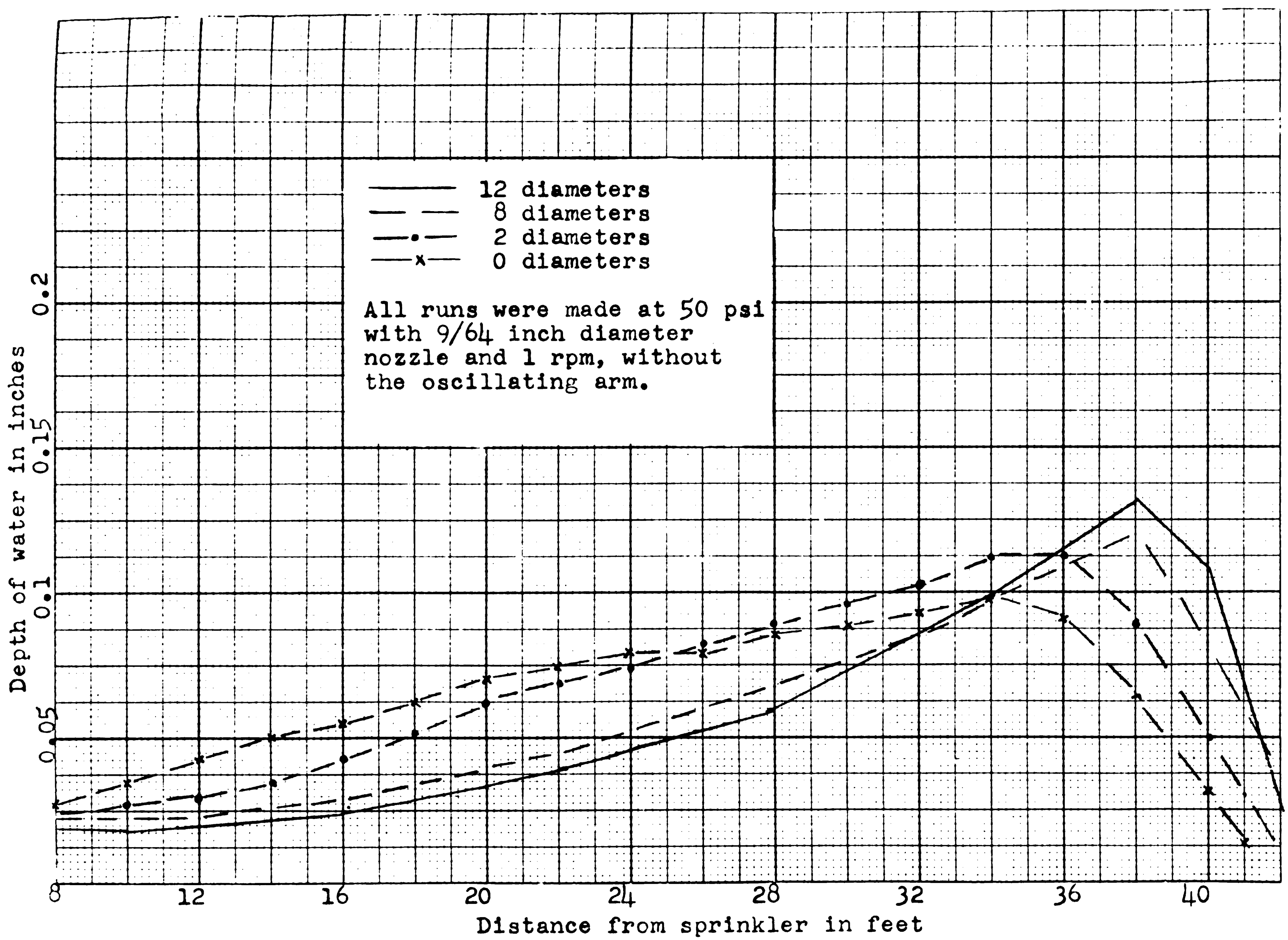

Fig. 19. **Effect of length of cylinder in nozzle on water distribution.**

of water occurred 18 feet from the sprinkler; while from the nozzle with the cylinder zero diameters long, the fall-out at the same distance was 0.045 inch of water--an increase of about fifty percent. There was an increase of thirty percent in the amount of fall-out from the nozzle with the cylinder zero diameters long over that from the cylinder one diameter long (Figures 18 and 19). The curves for the cylinder lengths not shown in Figures 18 and 19 fit into the pattern established for the plotted cylinder lengths.

The accumulation of the water toward the maximum trajectory distance was minimized by shortening the length of the cylinder. As indicated by Figures 18 and 19, the total trajectory distance for the nozzles with no cylinder as compared with those with a cylinder was shortened by one to two feet. Nozzles with cylinders 17 diameters long shortened the total trajectory distance by two feet from that produced by nozzles without a cylinder. This shortening of the trajectory distance was due principally to the high friction losses resulting from the high velocity[1] of flow through the long cylinder.

The increased amount of fall-out of water along the trajectory radius as the cylindrical part of the nozzle was shortened can be explained by considering the flow of water

[1]Approximately 65 and 85 feet per second through the 9/64 inch diameter nozzle at pressures of 30 and 50 pounds per square inch respectively, with a pressure drop of about 1 foot head of water at 30 psi and 17 diameters length.

through the nozzle. The stream lines converge through the tapered part of the nozzle toward the center. If the cylindrical part of the nozzle is of considerable length, the kinetic energy of the resulting excess turbulence will be dissipated through viscous shear and the effects of the transition upon the velocity and pressure distribution no longer will be noted, and the stream lines will become parallel. Hence, the water coming out of the nozzle will be in a direct line with the cylinder walls. If, however, the nozzle consists of only the converging taper and no cylindrical portion to straighten out the converging stream lines, the jet of water emerges from the nozzle in a conical rather than a cylindrical shape; that is, the water fans out from the orifice. This cone is minimized by the surface tension of the water, yet much unsteadiness does exist with a breaking away of some of the drops. These drops fall nearer to the sprinkler than they would if the jet of water was not as turbulent.

Figures 20 and 23 show the contrast in the breakup of a jet of water leaving a nozzle with and without a cylindrical tube. Both nozzles had an orifice opening one-fourth inch in diameter and both were operated at a pressure of 40 pounds per square inch.

The hydraulic losses through a nozzle without a cylindrical tube will be less than through a nozzle with a cylindrical tube. Friction losses will be increased by the

Fig. 20. Jet of water issuing at 40 psi from a 1/4 inch diameter circular orifice with cylindrical portion of nozzle removed at the end of the taper section.

additional length of tube and by the dissipation of the kinetic energy of the excessive turbulence in a confined space.

Effect of the Length of the Tube Between the Body of the Sprinkler and the Nozzle

The effect of the length of the tube between the body of the sprinkler and the nozzle upon the distribution of water is shown in Figure 21. A sprinkler with a three-fourths inch diameter riser connection was operated without the oscillating arm at one rotation per minute and at a pressure of 35 pounds per square inch using a nozzle one-eighth inch in diameter. The diameter of the inside of the tube was seven-sixteenths of an inch. This resulted in a mean velocity of the water through the tube of about seven feet per second and a Reynolds number of about 18,000,[1] indicating that the flow was in the turbulent range.

For a tube length of 17 diameters, no measurable fallout of water occurred in the first ten feet from the sprinkler. After operating for one hour, 0.010 inch of water was measured 20 feet from the sprinkler and 0.02 inch of water 26 feet from the sprinkler.

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[1]Sixty degrees F., temperature of water.

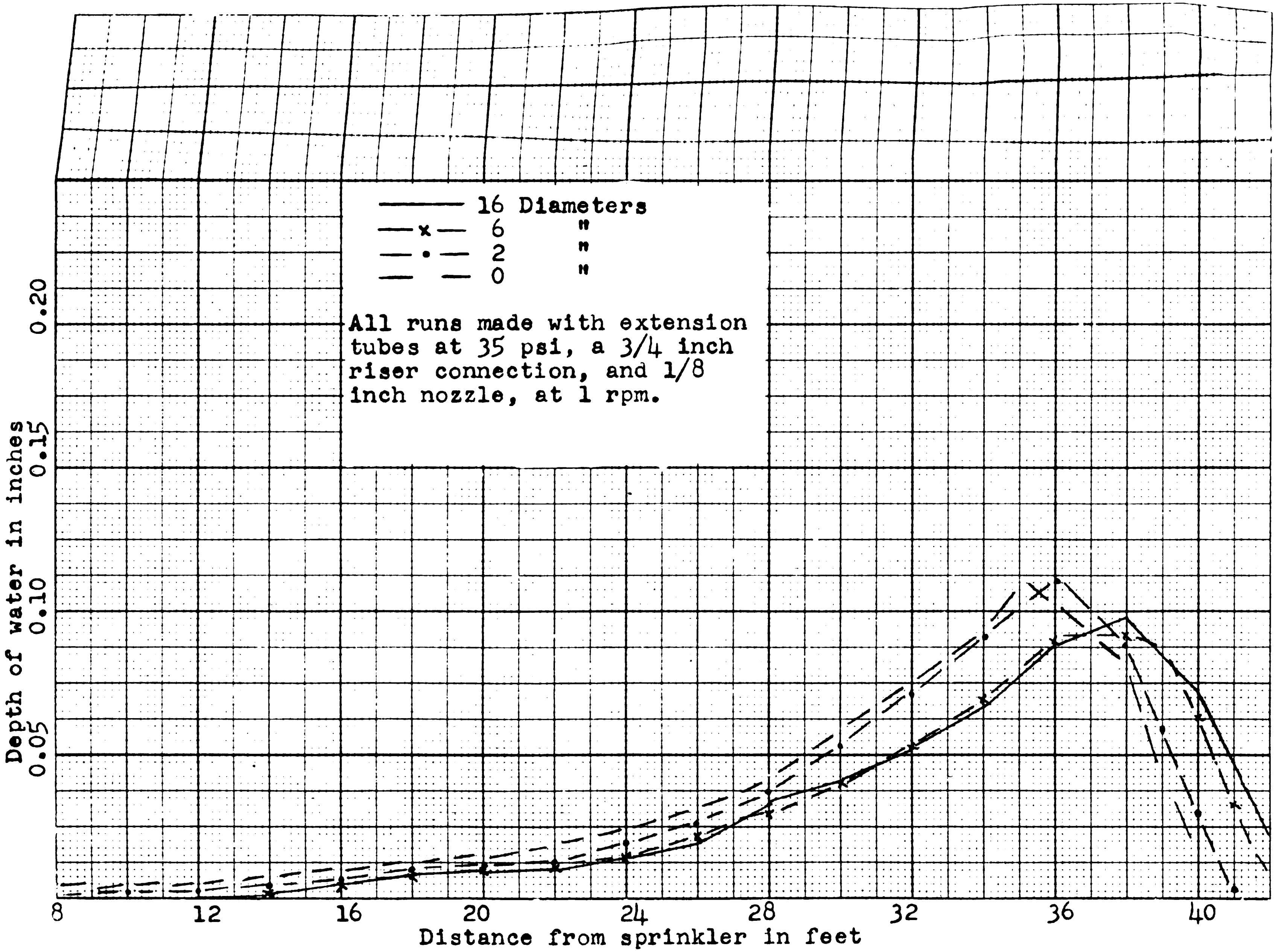

Fig. 21. Effect of length of tube between main body of sprinkler and the nozzle on water distribution.

In testing the sprinkler with no tube length[1] the readings were 0.015 and 0.03 inch of water at 20 and 26 feet respectively after a one-hour run. This represented an increase of fifty percent in the amount of water measured at both of these distances over the amount measured at the same distance from the 17 diameter tube.

The major difference between the longer tube and the shorter one was the lengthening of the total trajectory distance by two feet when using the 17 diameter tube as compared to no tube. This lengthening of the trajectory radius also resulted in moving the point of maximum accumulation of the water about two feet farther from the sprinkler.

It is evident from Figure 21 that there was very little difference in the distribution curves for the tube lengths between the 17 diameter and the six diameter tubes; however, there was a significant difference between the curves for the sprinkler with the six diameter tube and the two diameter tube. The distribution curve for the sprinkler with the six diameter tube began to drop away from the curve for the sprinkler with the two diameter tube at a radius of 22 feet from the sprinkler. This points out that any extension tube longer than six diameters has little additional effect in changing the distribution pattern for the conditions under which this sprinkler was tested.

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[1]The nozzle was screwed into the body of the sprinkler itself as is conventionally done.

The increase in the trajectory distance and the decrease in the amount of fall-out of water near the sprinkler resulting from the addition of the extension tube were due to a decrease in the turbulence and secondary motion of the water. This turbulence and secondary motion of the water were caused by the bend in the main body of the sprinkler. The water leaving the bend moves in a double spiral[1] which gradually diminishes in intensity as the water passes out through the tube.

The turbulent effect caused by the spiralling will be diminished by increasing the distance the water has to flow in the confined area after it makes the bend from the sprinkler riser toward the free air. Hence, for a larger diameter nozzle and/or a higher pressure, a longer length of tube of the same diameter would be required than that used for the pressure and size of nozzle discussed in this study in order to decrease the turbulence to the same degree. In addition, the more gradual the bend in the sprinkler is, the less turbulence will be caused. The difference in the break-up of the jet of water from a sprinkler with an extension tube and one without may be seen from Figures 22 and 23.

On a two-nozzle sprinkler the nozzle that actuates the oscillating arm usually deposits an excess of water near the sprinkler. Therefore, it would be desirable to have the

[1]The cause of the double spiralling of the water was discussed in another section of this study.

Fig. 22. Jet of water issuing at 40 psi from a 1/4 inch diameter circular orifice with a 6 diameter extension tube.

Fig. 23. Jet of water issuing from a 1/4 inch diameter circular orifice, pressure 40 psi (using sprinkler with 3/4 inch riser connection).

other nozzle apply a minimum amount of water near the sprinkler in order not to increase the overabundance of water already being deposited there. Hence, by keeping this nozzle an adequate distance from the bend in the sprinkler, the distribution of the water can be improved somewhat.

Effect of Rate of Rotation of Sprinkler

All of the tests conducted in this part of the study were made using a one-half inch riser sprinkler and a three-sixteenths inch diameter nozzle and operating at a pressure of 30 pounds per square inch for one hour without an oscillating arm. The rate of rotation was varied from three seconds per rotation to 540 seconds per rotation. The effect of the various rates of rotation upon the points and amounts of maximum and minimum accumulation of water and upon the maximum trajectory distance are shown in Table I.

As seen in Table I, at the rate of one rotation every three seconds, the minimum accumulation of water occurred at six feet and was 0.085 inch; the maximum accumulation occurred at 24 feet and was 0.26 inch of water. The maximum trajectory distance was 30 feet. When the rate was decreased to one rotation every sixty seconds, the minimum accumulation of water occurred at 10 feet and was 0.030 inch; the maximum occurred at 36 feet and was 0.175 inch of water; and the maximum trajectory distance was 41 feet. At the rate of one

TABLE I

EFFECT OF RATE OF ROTATION OF SPRINKLER ON THE DISTRIBUTION PATTERN

Rate of rotation in seconds	3	15	30	60	150	540
Point of minimum fall-out of water*	6 ft.	7 ft.	9 ft.	10 ft.	10 ft.	10 ft.
Minimum fall-out of water	0.085 inch	0.050 inch	0.030 inch	0.030 inch	0.030 inch	0.030 inch
Point of maximum fall-out of water*	24 ft.	30 ft.	33 ft.	36 ft.	39 ft.	42 ft.
Maximum fall-out of water	0.260 inch	0.215 inch	0.185 inch	0.175 inch	0.150 inch	0.135 inch
Maximum trajectory radius*	30 ft.	36 ft.	39 ft.	41 ft.	44 ft.	46 ft.

*Distance in feet from sprinkler.

rotation every 540 seconds, the minimum accumulation of water again occurred at 10 feet and was 0.030 inch; the maximum accumulation, however, occurred at 42 feet and was 0.135 inch; and the maximum trajectory distance was 46 feet.

If the percent of decrease from the maximum to the minimum is taken into consideration, disregarding the trajectory distance, then the rate of one rotation every three seconds gave a better distribution than either of the other rates of rotation. The percent of decrease was 63, 83 and 79 percent for the rates of one rotation every 3, 60 and 540 seconds respectively. It is interesting to note that the very slow rate of rotation (once every 540 seconds) gave a better distribution than the commonly used rate of one rotation every 60 seconds.

As seen from Figures 24 and 25, a very high rate of rotation increased the depth of accumulation all along the trajectory radius. This was most noticeable between three seconds and 15 seconds, and not as pronounced between 15 and 30 seconds.

For the first 12 feet from the sprinkler, the fall-out of water when operating the sprinkler at the rate of one rotation every 30 seconds was almost the same as for the slower rates; thereafter, however, it increased. The three slower rates (one rotation every 60, 150 and 540 seconds) had approximately the same fall out to about 16 feet where the fall out increased for the rate of one rotation every 60 seconds, the 150 and 540 remaining identical to 26 feet at which point the fall out for 150 seconds increased.

When the sprinkler was operated at zero rotations (i.e., in a stationary position) the maximum trajectory distance fluctuated between 46 and 48 feet. Therefore, it is apparent that a further decrease in the rate of rotation from one rotation every 540 seconds would not greatly increase the trajectory distance nor improve the distribution of the water.

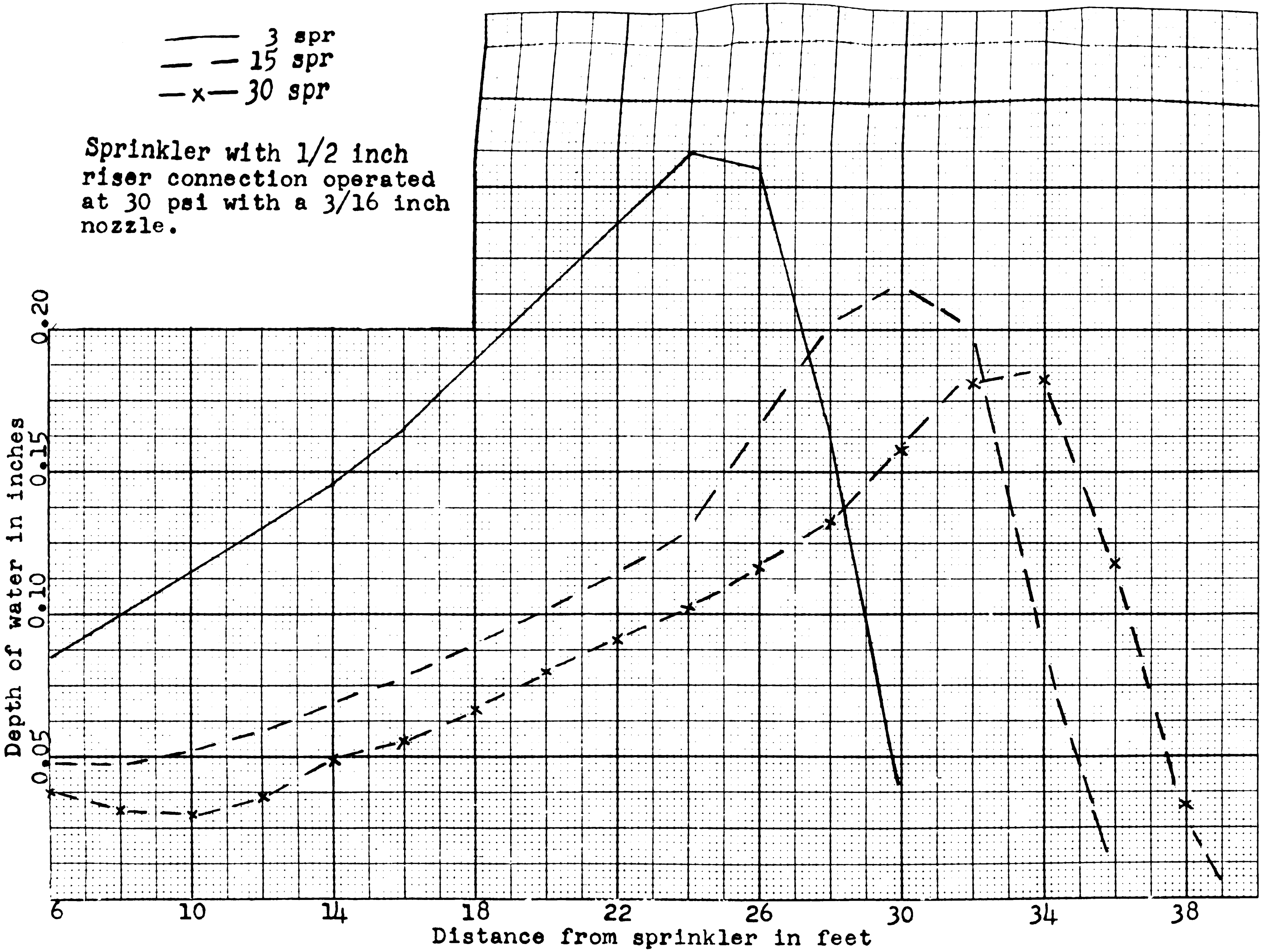

Fig. 24. Effect of rate of rotation of sprinkler on distribution of water.

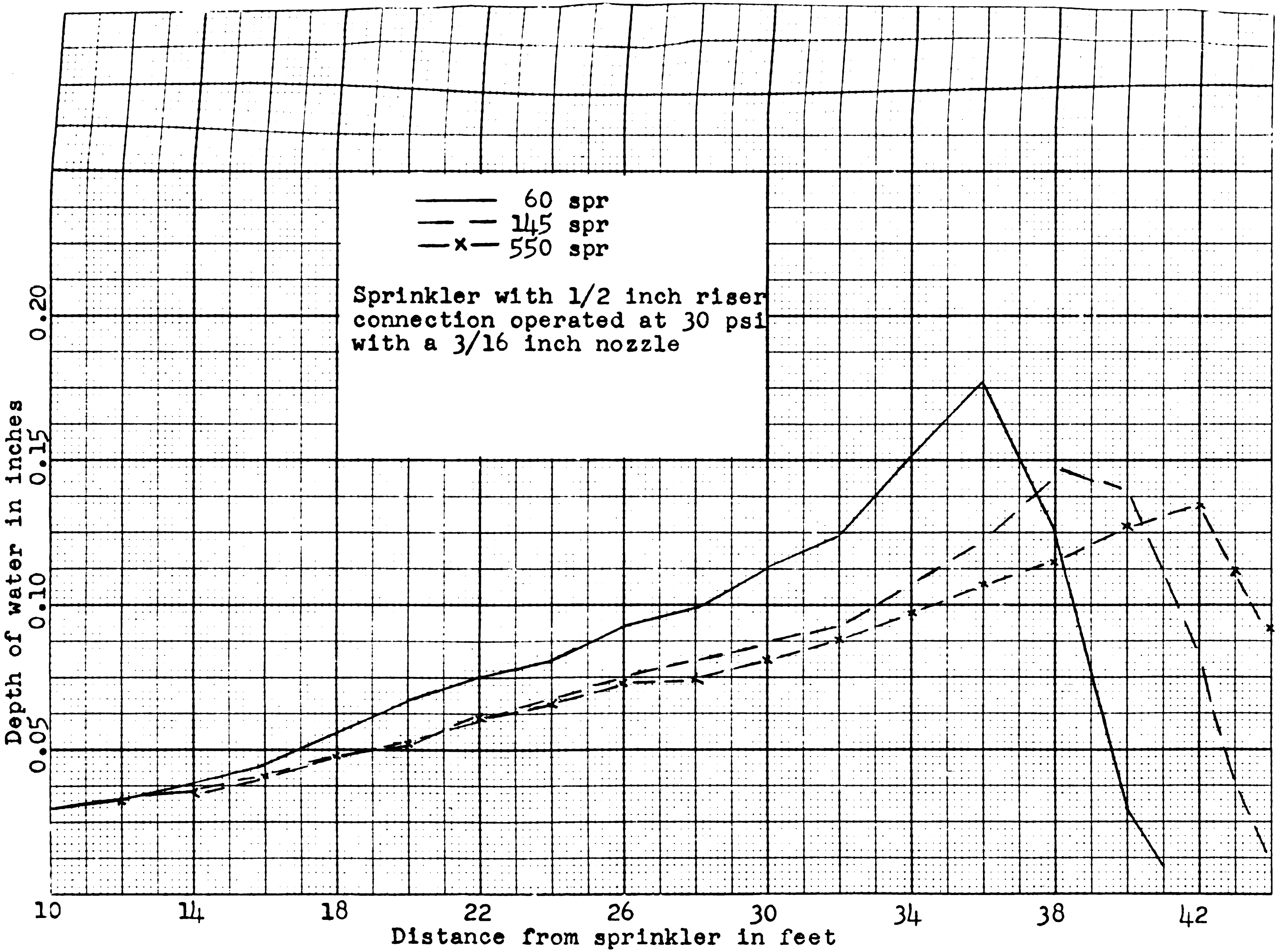

Fig. 25. Effect of rate of rotation of sprinkler on distribution of water.

For the medium-pressure sprinkler, it would seem that the rate of rotation should be less than one rotation per minute. It would appear that a rate between one rotation every 120 and every 240 seconds might be the desired range since between 240 and 550 seconds any change in trajectory and maximum accumulation will be negligible. For high-pressure sprinklers, which are capable of a greater trajectory distance, the rate of rotation should be slower than for medium-pressure sprinklers.

At this point some mention should be made of the reason that the trajectory distance decreased as the rate of rotation of the sprinkler increased. Analyzing the velocity relationship vectorially will show that the decrease in trajectory distance cannot be accounted for by the tangential component of velocity. The distance from the center of the sprinkler, or the center of the rotation, to the end of the nozzle for the sprinkler in Figure 26 was 1.25/12 feet; hence, at the rate of one rotation every three seconds the tangential velocity at the discharge end of the sprinkler nozzle was

$$V_T = 2\pi \times \frac{1.25}{12} \times \frac{1}{3} = 0.22 \text{ feet per second}$$

The mean radial velocity "V_r" of water was 60 feet per second. The resultant velocity "V_R" (Figure 26) will be only a negligible amount greater than the radial velocity "V_r" since

$$V_R^2 = V_T^2 + V_r^2$$

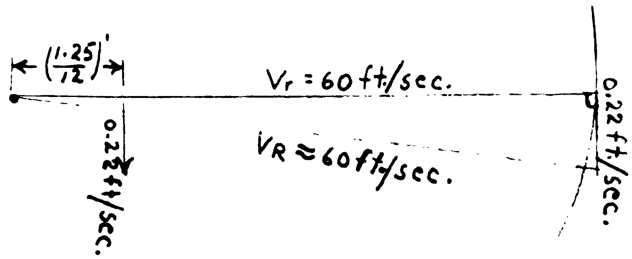

Fig. 26. Velocity components of water from a rotating sprinkler.

and V_T^2 was 0.048 feet per second. It is evident from the above that as the rate of rotation of the sprinkler is increased, the resultant velocity also increases, and that consequently, theoretically, the trajectory distance should also be increased. Actually, however, the trajectory distance decreased as the rate of rotation was increased.

Since an increase in tangential velocity should theoretically cause an increase in the trajectory distance, there must be another reason why the trajectory distance is shortened by rotating the sprinkler. In a solid jet of water, the maximum air resistance or drag encountered by the water occurs at the surface of the jet. The magnitude of the drag continues to decrease toward the center, at which point it is a minimum, since there it may be assumed, there is very little or no air to offer resistance. However, at the very periphery of the jet, the air completely surrounds the jet and is motionless until the water moving through it causes it to move.[1] This contact of the moving water with the stationary air causes a maximum amount of drag on the moving water particles, but at the same time it accelerates the air in the same direction in which the particles of water are moving.

It can be further concluded that as a stationary jet moves through a medium (in this instance, air) the velocity of the water and of the air at the outer surface of the jet come into equilibrium at the face of contact. Once this equilibrium is attained, a minimum amount of drag on the jet of water will ensue.

If, however, the jet is not solid, but is instead a broken-up mass of water drops, a great deal of air is dispersed between the drops, and the surface of each individual drop is acted upon as in the above described solid jet. Hence, when equilibrium conditions are attained between the air and the water droplets, the whole mass of air between the dispersed droplets is caused to move at some velocity approaching that of the water in the jet. At this time the resistance of the air to the moving water droplets will be a minimum and consequently the trajectory distance will be a maximum.

However, if the jet of water is continually made to change its position in space, it will not be in equilibrium,

[1]When smoke was introduced into a steady stream of water, velocities of about 15 feet per second could be measured with a stop watch.

and the drag will no longer be a minimum but will be increasing with the rotational velocity until each drop acts as if it were moving through relatively stagnant air. Under this condition, maximum drag will be encountered and the trajectory distance shortened.

It is possible to compute the theoretical distance that a drop of water of any given size will travel when trajected at any angle from the horizontal and taking air resistance into account. Although the velocity of the water issuing from a sprinkler nozzle often exceeds 100 feet per second, this is still within the range in which the air resistance can for a close approximation be considered to be proportional to the first power of the velocity (8). The distance that a drop of water will travel in any direction can be found from Newton's second law of motion as shown below. In these derivations the origin was considered to be at the orifice (Figure 27).

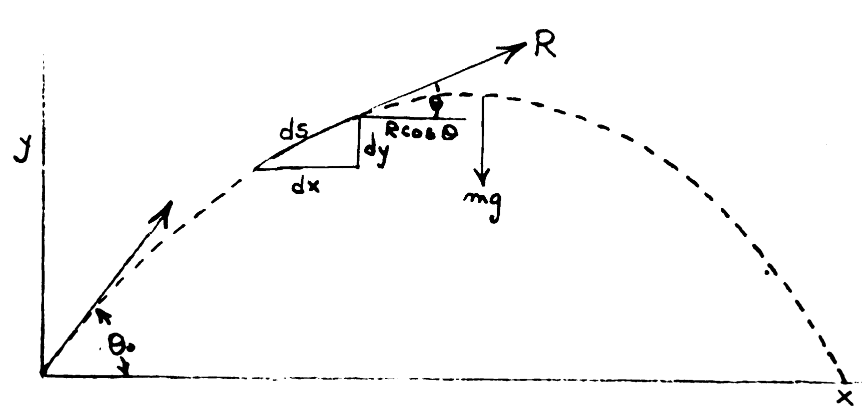

Fig. 27. Forces acting on a particle trajected through air.

$$t = 0 \qquad x = 0,\ y = 0,\ V = V_o \qquad V_x = V_o \cos \theta_o \qquad V_y = V_o \sin \theta_o$$

x = horizontal distance
y = vertical distance
V = velocity
m = mass
t = time
R = air resistance
C = constant

The mathematical development of the equation for the distance traveled by a particle in the "x" direction is

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

$$R = cV$$

$$\frac{md^2x}{dt^2} = - \frac{R}{V}\frac{dx}{dt}$$

$$\frac{md^2x}{dt^2} = -c \frac{dx}{dt}$$

$$(mD^2 + cD)\ x = 0$$

$$x = C_1 + C_2 e^{-\frac{c}{m}t}$$

The above constants may be evaluated from the initial boundary conditions. Hence,

$$x = \frac{m}{c} V_o \cos \theta \ (1-e^{-\frac{c}{m}t}) \qquad (1)$$

The distance traveled in the "y" direction is

$$\frac{md^2y}{dt^2} = -\frac{R}{V} \sin \theta - mg$$

$$R = cV$$

$$\frac{md^2y}{dt^2} + c \frac{dy}{dt} = -mg$$

$$(mD^2 + cD)y = -mg$$

$$y = C_1 + C_2 e^{-\frac{c}{m}t} - \frac{m}{c}gt$$

The above constants may be evaluated from the initial boundary conditions. Hence,

$$y = \frac{m}{c} V_o \sin \theta \, (1-e^{-\frac{c}{m}t}) + g(\frac{m}{c})^2 \, (1-e^{-\frac{c}{m}t}) - \frac{m}{c}gt \quad (2)$$

The time "t" can be found from equation (2) by letting $y = 0$ and solving for "t" as shown in equation (3).

$$\frac{m}{c} V_o \sin \theta \, (1-e^{-\frac{c}{m}t}) + g(\frac{m}{c})^2 \, (1-e^{-\frac{c}{m}t}) - \frac{m}{c}gt = 0 \quad (3)$$

Using the above equations, the distance traveled by a drop of water can be calculated if the ratio of $\frac{m}{c}$ is known, since the other factors can be determined readily.

When the sprinkler was operated at a pressure of 30 pounds per square inch with a three-sixteenths inch diameter nozzle and rotated at the rate of one rotation every three seconds, the diameter of the largest drop was found to be about three millimeters at the maximum trajectory distance of 30 feet from the sprinkler. The mean velocity of the water as it left the sprinkler was 60 feet per second under the above operating conditions. In this instance the angle of trajection was 24 degrees from the horizontal.

Green (9), using Laws' (10) data on the terminal velocities of water drops, calculated values for the ratio of $\frac{m}{c}$ for drops having various diameters. For a water drop three millimeters in diameter the ratio of $\frac{m}{c}$ was found by

Green to be 0.82. Substituting these values in equation (3) the time "t" was found to be 1.2 seconds. Substituting all of these valued in equation (1), the maximum trajectory distance "x" was found to be 34 feet. This concurs fairly well with the actual distance which was 30 feet.

Green found that as the diameter of a water drop approached zero, the ratio of $\frac{m}{c}$ also approached zero. Therefore, from an examination of equation (1), it is apparent that a decrease in the drop size results in a shortening of the trajectory distance.

Effect of Non-Circular Orifices in the Sprinkler Nozzles

Since all of the non-circular orifices in the nozzles tested here were shaped manually, it was not possible to obtain perfect replicas of the desired shapes. This was especially true in nozzles in which the non-circular shape extended a considerable depth into the nozzle. Such irregularities in the nozzle usually resulted in the emission of unsteady jets of water. Where the non-circular orifice was nothing more than a sharp-edged orifice (i.e., the irregular shape did not extend into the nozzle for any depth), precision of workmanship had a lesser effect. Imperfections which the author believes were due to workmanship will be pointed out.

In this study of the non-circular orifices the nozzles were not changed so as to deposit the water at any particular point along the distribution curve, but rather an attempt was made to make the orifices as symmetrical as possible and to report the data obtained without making any further changes in the nozzles.

Triangular orifices. Of all the non-circular orifices tested, the triangular gave the most desirable distribution of water. This was especially true when the triangular shape extended some distance into the nozzle; that is, when it was not a sharp-edged orifice. In all of the tests conducted in this part of the study, the nozzle was inclined so that the jet of water would be issued at about 25 degrees from the horizontal.

As may be seen from Figures 28, 29 and 30, the jet of water[1] came out parallel to the walls of the orifice. This resulted in a trihedron-shaped jet of water, the apex of which appeared to be back in the orifice of the nozzle. The size of the base of this jet increased rapidly with the distance from the orifice. As can be seen from the above figures, this jet of water spread out rather quickly as compared to jets of water issuing from circular orifices. The walls of the above triangular orifices were made as parallel as was manually possible.

The top view of the nozzles used in Figures 28, 29 and 30 is shown in Figure 7.[2] The nozzle used in Figure 28 had

[1]The operating pressure was 40 pounds per square inch.

[2]The first, second and third nozzles from the left side in the bottom row.

Fig. 28. Jet of water issuing from an equilateral triangular orifice at 40 psi.

Fig. 29. Jet of water issuing at 40 psi from an isosceles triangular orifice with one vertex rounded.

Fig. 30. Jet of water issuing at 40 psi from an isosceles triangular orifice with an abrupt entrance into the orifice.

an equilateral triangular-shaped orifice in which each side was one-fourth inch long. The parallel sides extended about three-eighths inch back into the nozzle where they gradually began to diverge.

Figure 29 shows a jet of water issuing from a nozzle with an isosceles triangular-shaped orifice in which one of the apexes was rounded out. The two equal sides of the triangle were 7/32 inch long, and the base was 6/15 inch long. These sides extended three-eighths inch into the nozzle and as in the previously described nozzle gradually diverged. In both of these triangular shaped orifices the jet of water formed a solid stream.

The shape of the orifice used in Figure 30 was an unmodified isosceles triangle. The two equal sides of this triangle were five-sixteenths inch long and the base was 7/32 inch long. The sides extended one-eighth inch into the nozzle where they met the cylindrical tube of the nozzle, which was three-eighths inch in diameter. In this nozzle the line from the vertex tapered back into the nozzle instead of running parallel to the base. The resulting spread can be seen at the top of the jet of water. It should be noted that the jet of water from this triangular orifice was not as solid as that from the other two triangular orifices (Figure 29). This was not due to any particular manner of orientation of the orifice or to the dimensions, but was mainly due to the entrance conditions into and through the triangular portion of the nozzle.

In each of the triangular-shaped orifices tested the break-up of the water jet appeared to be much greater than that from circular orifices. This break-up of the water resulted in smaller drops and consequently the total trajectory distance was shortened. A greater percentage of the total amount of water being discharged was deposited near the sprinkler when using a triangular orifice than when using a circular orifice when operating the sprinkler without the oscillating arm. As may be seen in Figure 30, if the nozzle was turned through 180 degrees, so that the part of the jet directed up in the figure would be directed down, a considerably greater amount of water would be deposited nearer the sprinkler. This difference in the distribution pattern obtained by varying the position of the apex of the triangle was small when using the equilateral triangular-shaped orifice.

The distribution curve of an equilateral triangular orifice with three-sixteenths inch sides which gradually diverged into the inner part of the nozzle which was operated with the apex of the triangle up is shown in Figure 31. When the sprinkler was operated without the oscillating arm at the rate of one rotation per minute and at a pressure of 40 pounds per square inch, there was a fall-out of water of 0.095 inch six feet from the sprinkler. The amount of fall-out increased with the distance from the sprinkler

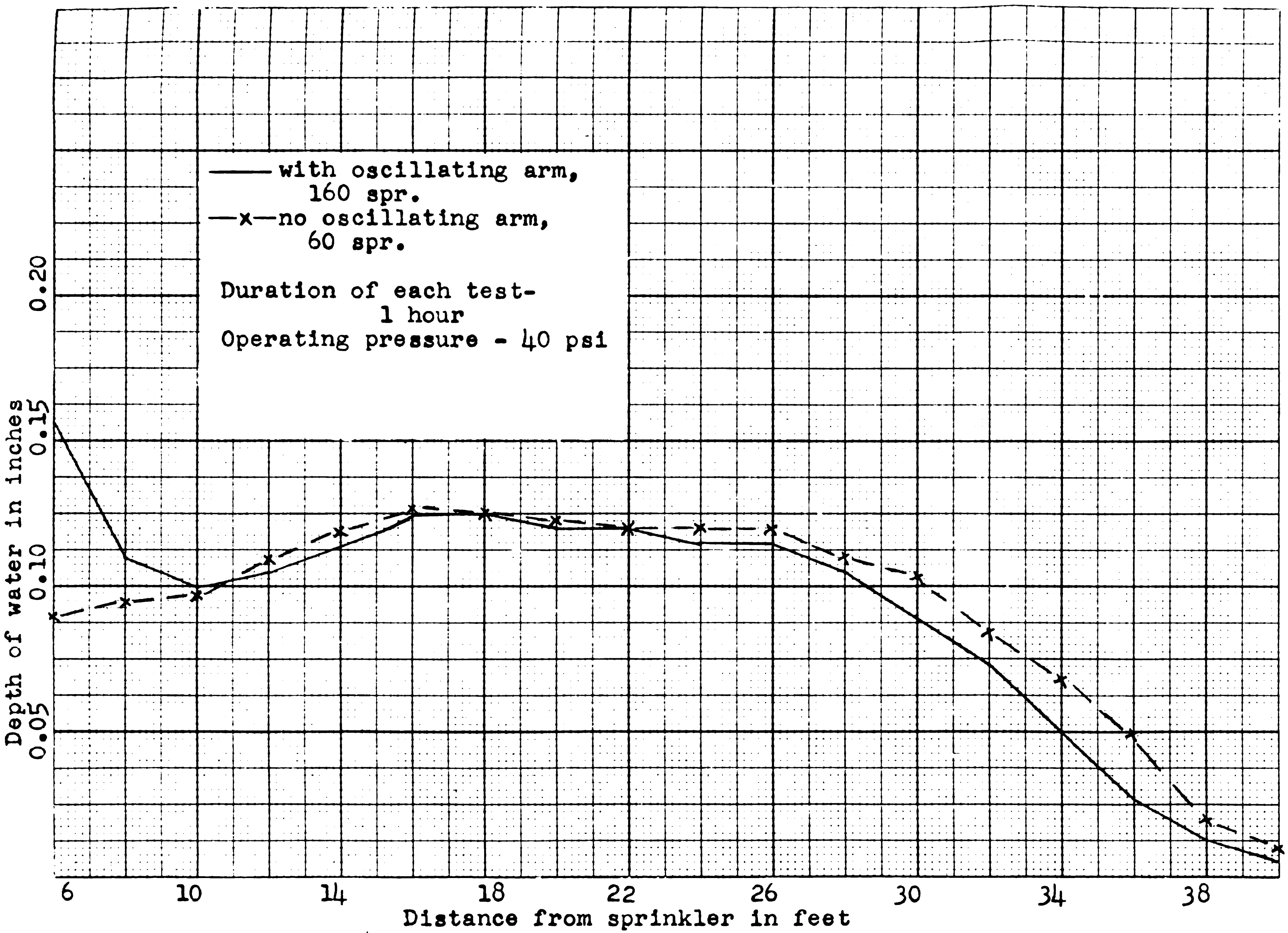

Fig. 31. Nozzle with gradual entrance into equilateral triangular orifice.

until a maximum of 0.125 inch occurred at 16 feet from the sprinkler. From this point to about 28 feet from the sprinkler there was a gradual decrease in the amount of fall-out of water; for the remainder of the trajectory distance, this decrease became more pronounced.

When the sprinkler was rotated with the oscillating arm, at the same pressure and at the rate of one rotation every 160 seconds and using the same nozzle, a greater fall-out of water occurred near the sprinkler and decreased with the distance from the sprinkler until about 10 feet from the sprinkler where the amount of fall-out was about the same as that from the sprinkler being rotated mechanically without the oscillating arm (Figure 31). Beyond 10 feet from the sprinkler the two distribution curves follow each other quite closely, the one with the oscillating arm having a somewhat shorter trajectory distance due to the action of the oscillating arm.

It is worthy of note that whether the sprinkler was operated with or without the oscillating arm, the maximum accumulation peak was not as pronounced when using the above orifice as when using a circular orifice and operating at the same pressure.

Figure 32 represents the distribution of water from the same orifice as Figure 28; however, in this figure the approach to the triangular orifice was altered. The sides were

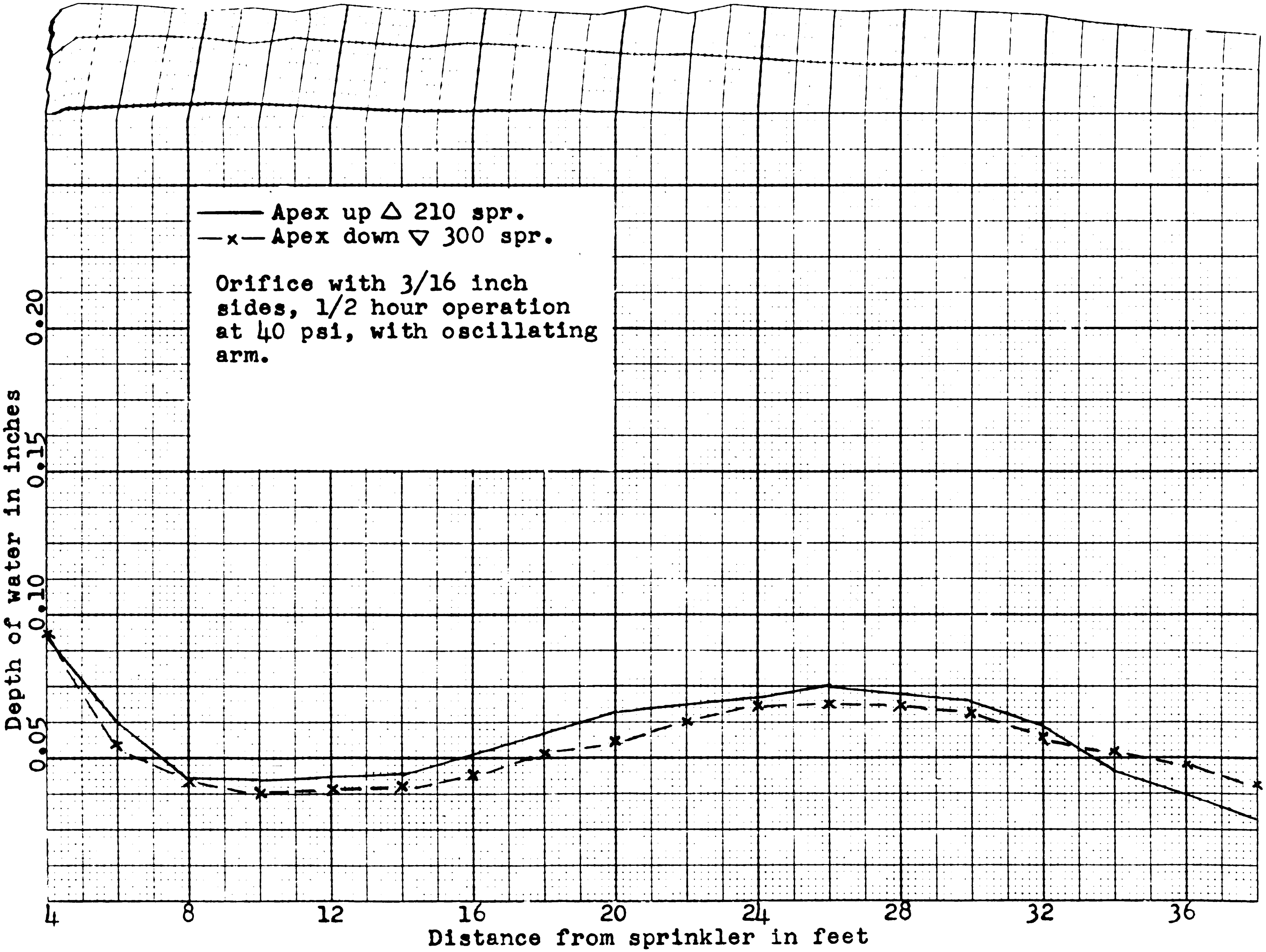

Fig. 32. Nozzle with abrupt entrance into equilateral triangular orifice.

still parallel and three-sixteenths inch in length, but there was not a gradual divergence from that point inward. A three-eighths inch drill had been used to take out the tapered portion. Essentially this drilling resulted in a three-eighths inch diameter cylinder leading up to the triangular part of the orifice (Figure 6b).

This figure is shown for two reasons. First, to indicate how a change in entrance conditions to the triangular portion of the orifice affects the distribution pattern of the water. When Figure 31 is compared with Figure 32 (note, Figure 31 was a one-hour test and Figure 32 was one-half hour), it is evident that the distribution in Figure 31 is more desirable than that shown in Figure 32. The second reason is to indicate that the distribution from an equilateral triangular orifice is not greatly affected by the position of the apex (apex up or down).

In one of the distribution curves in Figure 33 the same orifice as shown in Figure 30 was used. Here the sprinkler was rotated by an oscillating arm at the rate of one rotation every 80 seconds and at a pressure of 40 pounds per square inch. The parallel sides of this isosceles triangle were five-sixteenths inch long with a base 7/32 inch long. The nozzle was operated apex down. If it were not for the action of the oscillating arm, very little water would have been deposited near the sprinkler. There was also a considerable accumulation of fall-out of water at 18 feet from the sprinkler. From this point to the point of maximum trajectory (at 40 feet from the sprinkler), the distribution curve had a constant slope.

The other distribution curve shown in Figure 33 is for the same orifice shown in Figure 28. It was operated at a pressure of 40 pounds per square inch with the oscillating arm at the rate of about one rotation every 180 seconds. In this instance the apex of the triangular orifice was up. It is worthy of note that the distribution of the water from this orifice was good. The oscillating arm caused a considerable amount of fall-out in the first seven feet from the sprinkler. This represented less than 1/30 of the total area covered by the sprinkler. A low of 0.120 inch of water occurred at 12 feet from the sprinkler and a high of 0.132 inch of water at 20 feet from the sprinkler. From this point on the amount of fall-out decreased along the trajectory radius until 40 feet from the sprinkler where it was 0.015 inch. This type of distribution of water approached the desired pattern very closely.

Tests were also conducted using equilateral triangular-shaped orifices in which there was just a gradual taper into the triangular-shaped orifice and no depth through the triangular portion. The distribution from this nozzle was not as desirable as that from the equilateral triangular-shaped orifices with a gradual taper to the orifice and having

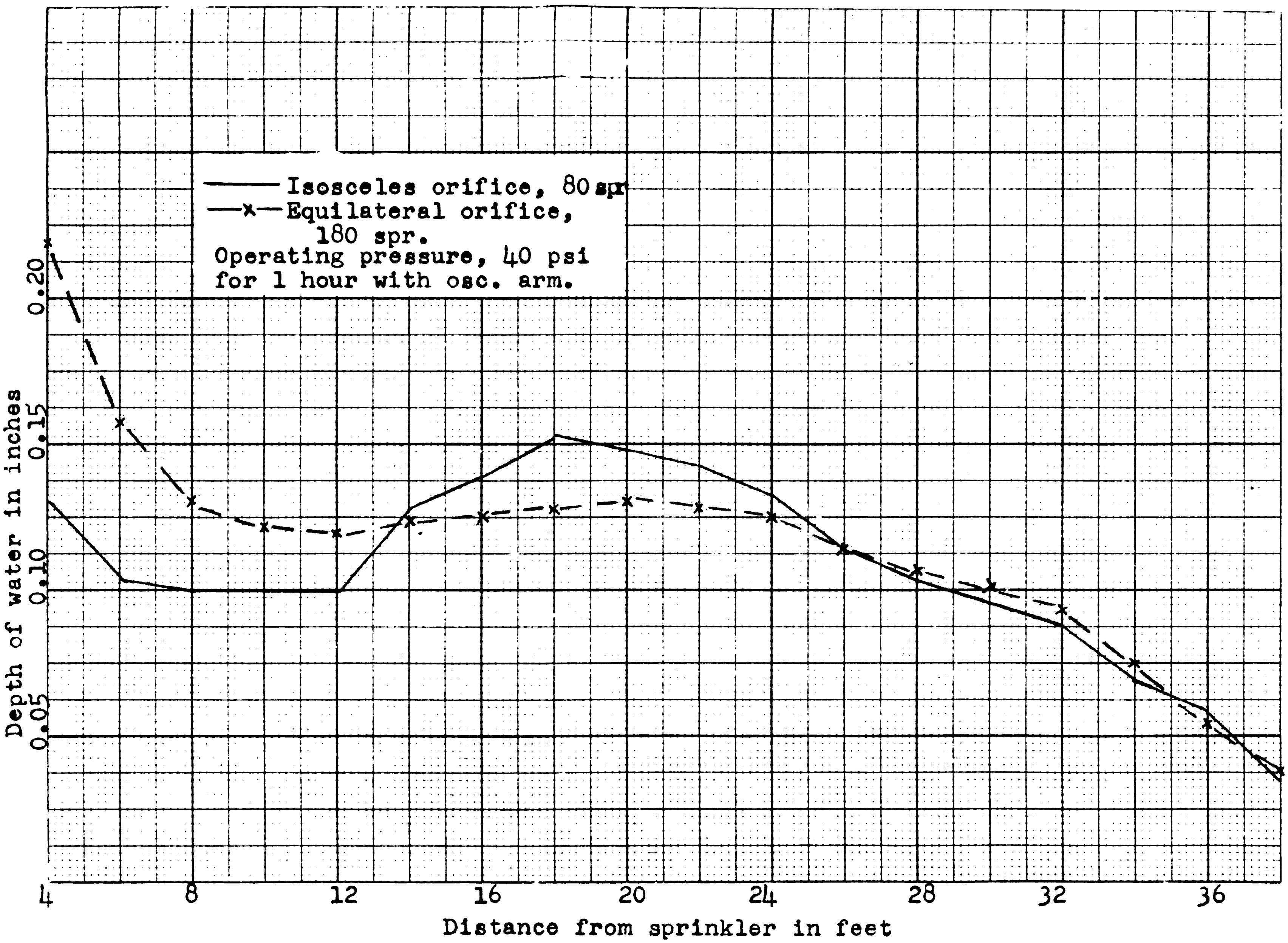

Fig. 33. Distribution of water from an isosceles and equilateral triangular orifice.

depth through the orifice. Over-all it would appear that the equilateral triangular-shaped orifice with considerable depth and then a gradual taper inward displayed favorable distribution characteristics.

Square orifices. The nozzles with the square orifices gave a more desirable distribution pattern of water than the nozzles with the circular orifices. Figure 34 shows the distribution of water from a nozzle with a square orifice. A sprinkler with a one-inch riser connection was operated at a pressure of forty pounds per square inch and rotated by means of the oscillating arm at the rate of about one rotation every 200 seconds. The square orifice had 5/32 inch sides which extended three-sixteenths inch back into the nozzle and then gradually diverged into the conical taper.

A fall-out of 0.06 inch of water occurred between 10 and 12 feet from the sprinkler. This increased to a maximum of 0.105 inch at 26 feet. The rate of fall-out of water then decreased rather gradually to 40 feet which was the point of maximum trajectory. It should be noted here that there was no sharp accumulation peak.

The discharge of a jet of water from a square orifice at a pressure of 40 pounds per square inch is shown in Figure 35. The jet of water issuing from the orifice appeared to be tetrahedral in shape, with the apex of the

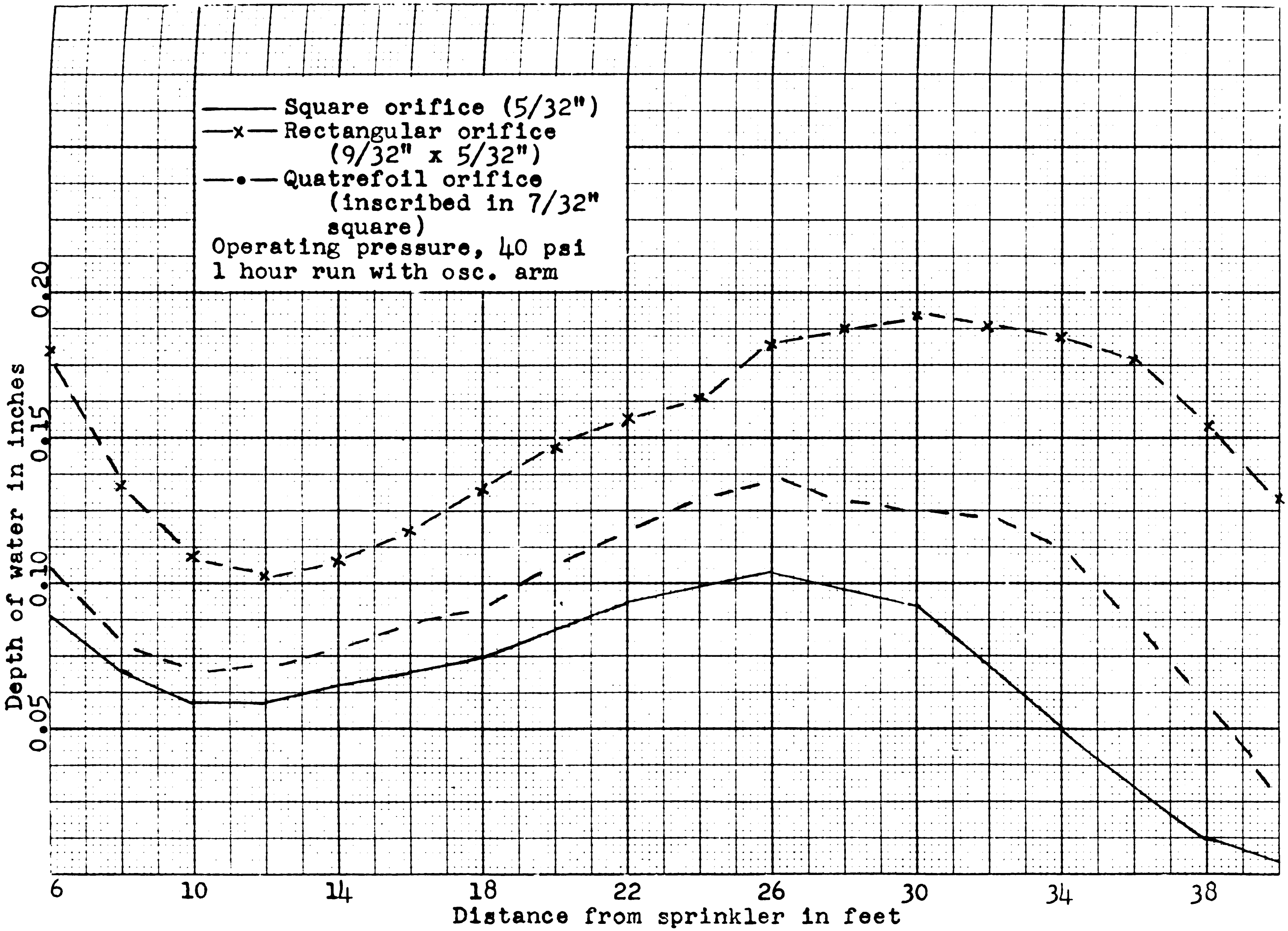

Fig. 34. Distribution of water from square, rectangular and quatrefoil orifice.

Fig. 35. Jet of water issuing from a square orifice at 40 psi.

tetrahedron appearing to be in the nozzle. The base increased very rapidly with the distance from the orifice until at about 12 inches from the orifice most of the resemblance to a tetrahedron was lost. The jet of water issuing from this orifice appeared to be much more broken up and the drops smaller than that from a circular orifice operated at the same pressure.

It may be seen upon close examination of the jet of water issuing from this orifice (Figure 35) that one side of the jet had an irregularity due to an imperfection of workmanship in shaping the orifice.

Rectangular orifices. The distribution of water from a rectangular orifice was similar to that from a square orifice. Likewise, the jet of water issuing from the rectangular orifice bore a close resemblance to that issuing from the square orifice except that a cross-section of this jet within the first few inches from the sprinkler would appear rectangular instead of square. The jet of water from the rectangular orifice also spread out very quickly as it left the orifice.

The orientation of the rectangular orifice in respect to the vertical and horizontal was found to be pertinent. When the rectangular orifice was placed lengthwise (that is, with the width of the rectangle perpendicular to the horizontal), the jet of water would disperse more in the horizontal plane than in the vertical plane. The converse was true when the nozzle was oriented so that the long axis of the rectangle was perpendicular to the horizontal. It is more desirable to have the jet of water dispersed in the vertical plane than in the horizontal since this type of dispersion results in a lesser concentration of fall-out of water in any particular segment along the trajectory radius.

Figure 34 shows a distribution curve from a rectangular orifice. (A top view of this orifice is shown in Figure 7.) The sprinkler was operated at a pressure of 40 pounds per square inch and rotated by means of the oscillating arm at a rate of approximately one rotation every 60 seconds. The rectangular orifice was 9/32 inch by 5/32 inch with the long axis perpendicular to the horizontal. The rectangular portion of the orifice extended three-eighths inch into the nozzle where it began to diverge gradually.

The distribution curve from the rectangular orifice closely resembled that from the square orifice. However, the maximum trajectory distance and the total amount of fall-out of water were greater for the rectangular orifice than for the square orifice because of the larger cross-sectional area of the former.

Quatrefoil orifices. Figure 36 shows water being discharged from a nozzle with a quatrefoil orifice at a pressure of 40 pounds per square inch. The dimensions of this quatrefoil orifice were such that it could be inscribed in a

Fig. 36. Jet of water issuing from a quatrefoil orifice at 40 psi.

one-fourth inch square. The walls of this orifice extended one-fourth inch into the nozzle and then gradually began to diverge. As may be seen from Figure 36, the jet of water as it issued from the nozzle closely resembled a quatrefoil, with a distinct jet of water issuing from each of the four foils. Within a few inches after leaving the orifice these separate jets blended into one another. A top view of the nozzle with the quatrefoil-shaped orifice is shown in Figure 7.

Figure 34 shows the distribution obtained from the above nozzle operated at the same pressure and rotated by means of an oscillating arm at the rate of one rotation every 150 seconds. It may be seen by comparing the three curves that the quatrefoil shaped orifice showed no improvement in distribution over the square or the rectangular orifices. Since the quatrefoil shape is more complicated and would therefore be more difficult and expensive to manufacture than either the square or rectangular shapes, there seems to be no advantage in using this particular shape.

Other non-circular orifices. In addition to the various shaped orifices discussed and shown in Figure 7, there were others that were tested. However, such shapes as a semicircle or a pentagon shows no desirable distribution characteristics over those previously discussed.

The distribution pattern from the circular nozzle with the "V"-shaped notch extending across it but not deep enough to change the cross-sectional area or alter the shape of the cross-section of the circular orifice (Figure 7)[1] was not materially altered from the distribution pattern of a nozzle with a circular orifice and without a "V"-shaped notch across it. When the "V"-shaped notch did change the cross-sectional area of the orifice, the distribution characteristics were altered.

The nozzle with the slit down one side in Figure 7[2] gave a very even distribution of water along the greater portion of the trajectory distance and then gradually decreased. The discharge from this nozzle operating at a pressure of 40 pounds per square inch is shown in Figure 37. The break-up of the water from this nozzle appeared to be much greater than from a standard circular nozzle of the same size. This resulted in smaller drops[3] and a shortening of the total trajectory distance. The above nozzle was comprised of a small cylinder discharging into a larger cylinder. The walls of the larger cylinder were not parallel with those of the smaller one but rather were at an angle to them; hence, part of the jet of water emerging from the smaller cylinder struck the walls of the larger cylinder resulting in a break-up of the jet of water. Although the slit extended

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[1]Top row, right-hand corner, Figure 7.

[2]Top row, left-hand corner, Figure 7; this was a commercially manufactured nozzle.

[3]Visual observation.

Fig. 37. Jet of water issuing at 40 psi from the nozzle with a side slot.

almost the entire depth of the larger cylinder, water did not emerge from the slit (Figure 37).

Tests were also conducted on nozzles with a slot or an auxillary orifice[1] at an angle to the main orifice. The main jet of water issued from the larger orifice and an auxillary jet issued from the slot. It was found that by the proper orientation of the slot, a concentration of water could be directed almost anywhere along the first three-fourths of the trajectory radius. Since any variation in angle, width, depth or orientation of such a slot would greatly change the distribution characteristics of the nozzle, various distribution patterns were obtained; however, this still did not remedy the sharp break-off that occurred toward the outer trajectory radius.

Jet inversion. Although the jets of water issuing from the non-circular orifices showed more instability than those from the circular orifices, inversion of the jet of water could not be seen as such when operating the sprinkler within the range of recommended operating pressures. However, when the pressure was decreased far below the recommended operating pressures, the inversion could be detected. In other words, the higher the velocity through the orifice the less pronounced this phenomenon became.

[1]First row, third nozzle from the left in Figure 7.

Effect of Cylindrical Discharge Tubes

A cylindrical tube when used in place of a nozzle showed a great deal of promise in giving a desirable distribution of water from a sprinkler. In obtaining a desirable distribution from such a tube, the length of the tube was very important. The most desirable pattern was obtained when the tube length was two to four diameters (of the inside diameter of the tube). This length was measured from the inside radius of the bend in the sprinkler body to the discharge end.

When the tube was shortened beyond the above length, the distribution became undesirable since it resulted in a shortened trajectory distance and caused a great deal of water to fall out next to the sprinkler. The rate of fall-out of water quickly diminished along the trajectory radius.

On the other hand as the tube was lengthened, the distribution became more like that from the conventional sprinkler nozzles; that is, an increase of trajectory distance resulted from a lengthening of the discharge tube. Also less water was deposited near the sprinkler and a build-up of water at the outer trajectory radius resulted.

Figures 38, 39 and 40 show the effect of the tube length on the break-up of the jet of water. The operating pressure was 40 pounds per square inch for all of these tests. Figure 38 shows a 7/16 inch inside diameter copper

Fig. 38. Sprinkler with 7/16 inch diameter tube 1 1/2 inches long operating at 40 psi.

Fig. 39. Sprinkler with 7/16 inch diameter tube cut off at body of sprihkler operating at 40 psi.

Fig. 40. Jet of water issuing at 40 psi from a 5/16 inch diameter tube with a 3-1/4 inch diagonal portion.

tube threaded into the body of a sprinkler so that 1-1/2 inches of the tube extended beyond the body of the sprinkler. Figure 39 shows the same tube cut off next to the body of the sprinkler. In both care was taken not to leave any rough edges on the inside. It is evident in Figure 39 that the jet of water is diverging much more quickly than in Figure 38.

Although the jet of water became less divergent and hence went a greater distance, eventually a length was reached at which the jet no longer converged. Beyond a given distance (depending on variables) from the bend, the increased turbulence, secondary motion and distribution of velocities caused by the bend did become dissipated.

Figure 41 shows the effects of the tube length on the distribution of water. A tube 7/16 inch in diameter was inserted into the body of the sprinkler as shown in Figure 38. The sprinkler was operated at a pressure of 40 pounds per square inch without an oscillating arm. When the length of the tube was three inches (measured from the body of the sprinkler), the amount of fall-out increased with the distance from the sprinkler. The maximum amount of fall-out was 0.21 inch and occurred at 40 feet; the minimum amount of fall-out occurred near the sprinkler and was about 0.03 inch. When the tube was cut off to zero right at the sprinkler (Figure 39), the distribution was almost linear

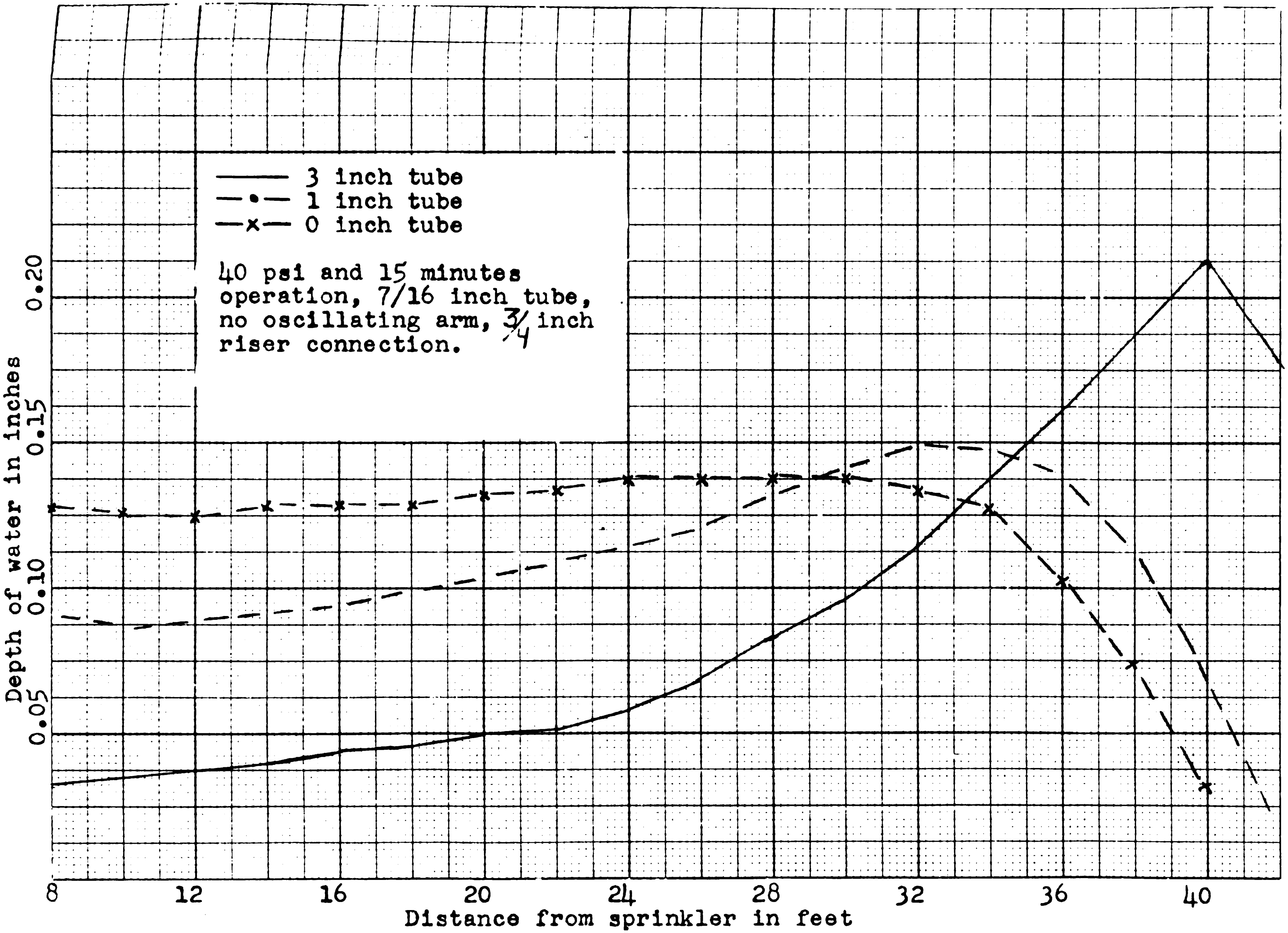

Fig. 41. Effect of tube length on distribution of water.

with a maximum fall-out of 0.14 inch of water at 28 feet and a minimum of 0.125 inch occurring near the sprinkler. Shortening the tube length from three inches to zero inches decreased the total trajectory distance by four feet.

Figure 42 shows the distribution from a 5/32 inch inside diameter tube of varied length and operated at a pressure of 40 pounds per square inch. The tube was bent as in Figure 42 so that the vertical height of the tube was one inch. It was found that the diameter of the vertical tube was not critical in the type of distribution obtained from the tube; the distribution still depended upon the tube length. It was found that as the vertical height of the tube was increased, the total discharge of water was decreased. From Figure 42 it may be seen that a tube length of four inches resulted in a poor distribution while a length of one-half inch resulted in a desirable distribution. Had the oscillating arm been operating, it would have filled in the depression that occurred in the first 16 feet along the trajectory radius when using the one-half inch tube length.

The effect of an oscillating arm on the distribution of water from a sprinkler with a tube is shown in Figure 43. A tube 5/32 inch in diameter and one-half inch long was inserted into the sprinkler as shown in Figure 44. In this figure the sprinkler was operated at a pressure of 40 pounds per square inch.

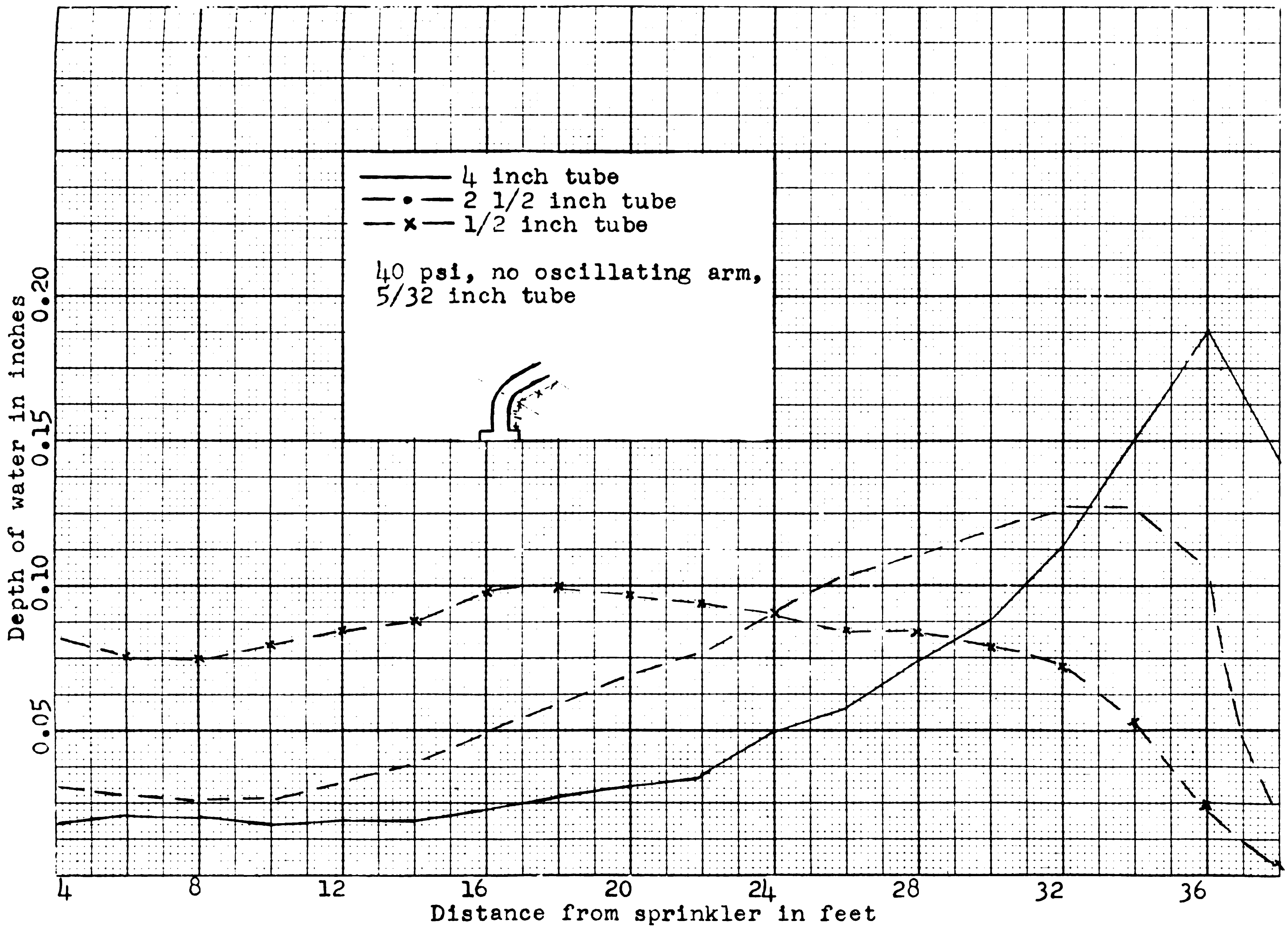

Fig. 42. Effect of tube length on distribution of water.

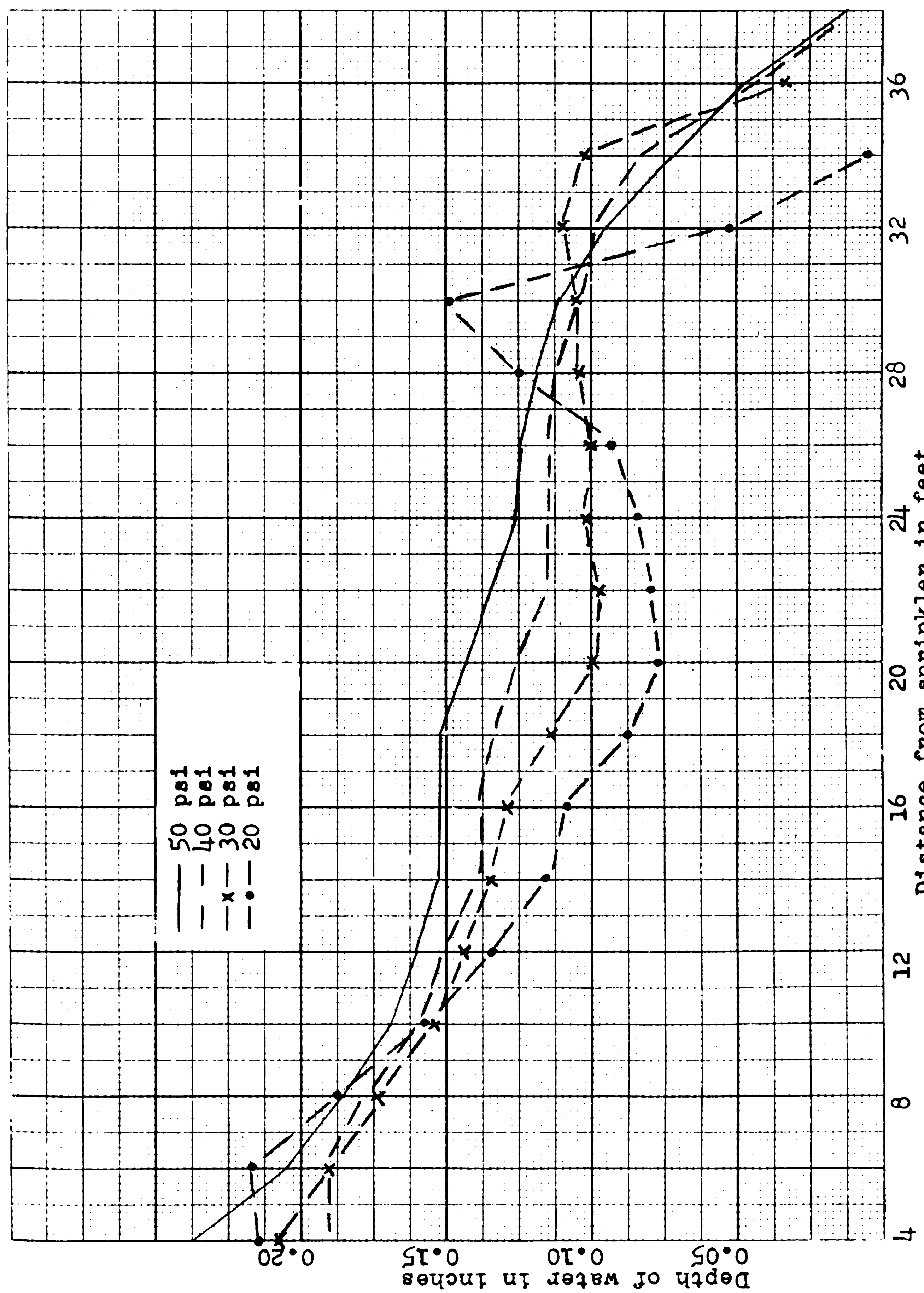

Fig. 43. Effect of tube 5/32 inch and 1/2 inch long in sprinkler with 1/2 inch riser.

Fig. 44. Jet of water issuing at 40 psi from a 5/32 inch diameter tube soldered into the sprinkler body.

When the sprinkler was operated at a pressure of 40 or 50 pounds per square inch, a fairly good distribution of water resulted. Neither one of the distribution curves at the above pressures had the characteristic low amount of fall-out of water near the sprinkler or the large fall-out toward the maximum trajectory radius. These two curves show a gradual decrease in the amount of fall-out of water from the sprinkler to the maximum trajectory radius, although in the last eight feet of the trajectory radius, the rate of drop-off was slightly sharper than would be desired. This characteristic would have been improved by increasing the trajectory angle of the jet of water from the horizontal.[1]

When the same sprinkler was operated at a pressure of 30 pounds per square inch, there was a slight rise (0.01 inch) in the amount of fall-out of water that occurred between 20 and 32 feet from the sprinkler. At a pressure of 20 pounds per square inch the distribution curve shows a low of 0.075 inch at 20 feet from the sprinkler and a high of 0.15 inch at 30 feet, which is a considerable increase; however, this was a notable improvement over the distribution obtained when using a conventional nozzle.

It appears from the results obtained that the distance of the outlet of the discharge tube from the bend in the

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[1]In these tests the trajectory angle of the jet of water was 24° from the horizontal.

sprinkler is very important in the type of distribution obtained. Increasing the distance between the outlet and the bend in the body of the sprinkler diminished the secondary motion caused by the bend. A qualitative explanation of this secondary motion as given by Goldstein (11) is presented below.

When fluid is flowing along a curved pipe, there must be a pressure gradient across the pipe to balance the centrifugal force. The pressure must be greatest at the outer wall, or the wall farther from the center of curvature, and least at the inner wall, or wall nearer the center of curvature. The fluid near the top and bottom walls is moving more slowly, however, than the fluid in the central portions, and requires a smaller pressure gradient to balance its centrifugal force. Consequently, a secondary flow is set up in which the fluid near the top and bottom moves inward and the fluid in the middle moves outward (Figure 45). The pressure at the outer wall is greater at the middle of the pipe than at the top or the bottom, while at the inner wall it is less. The secondary flow is superimposed on the main stream so that the resultant flow is helical in the top and the bottom of the pipe. As a result, the region of maximum velocity is displaced from the center of the pipe toward the outer wall.

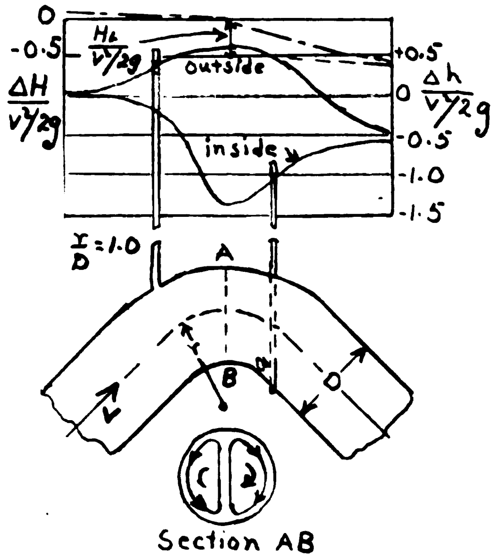

Fig. 45. Secondary flow and variation in head at a 90° short-radius bend (12).

The secondary flow also explains why there is a much thicker layer of slowly moving fluid at the inside wall of a curved pipe than at the outside. The faster-moving fluid at the middle is moving outward, pushing the fluid in the boundary layer at the outer wall to the top and bottom, and along the top and bottom walls toward the inner wall. Thus fresh fluid is continually being brought into the neighborhood of the outer wall and then forced around toward the inner wall, being continually retarded. There is thus an accumulation of retarded fluid at the inner wall.

Goldstein goes on to show that the dynamical similarity found under such flow conditions depends only on the following parameter

$$K' = \left(\frac{a}{L}\right)^{\frac{1}{2}} \left(\frac{2W_0 a}{v}\right)$$

where "a" is the radius of the pipe, "L" the radius of the curvature of the axis of the pipe, "v" the viscosity of the liquid and "W_o" the mean velocity in flow through a straight pipe under the same pressure gradient as that along the pipe axis in the curved pipe. This is true when the ratio of "$\frac{a}{L}$" is small and the terms of order "$\frac{1}{L}$" are neglected when compared with the terms of order "$\frac{1}{r}$".[1] Thus, it is apparent that the dynamic similarity depends on the diameter of the curved pipe, the radius of curvature of the pipe and the viscosity and velocity of the fluid flowing through the pipe.

[1]These limits were stated by Goldstein since the above formula is a simplification of one presented in a paper by Dean.

CONCLUSIONS

When a sprinkler was operated without the oscillating arm there was very little fall-out of water near the sprinkler. The amount of fall-out gradually increased until a maximum was reached near the outer limit of the trajectory distance. When the oscillating arm was used to rotate the sprinkler, the amount of fall-out of water near the sprinkler was considerably greater. This fall-out decreased to a point about one-fourth of the distance along the trajectory radius and then began to rise, reaching a maximum toward the outer limit of the trajectory radius. The depth of maximum accumulation of water obtained when using the oscillating arm was lower than that obtained when the oscillating arm was not used.

Operating the sprinkler at higher pressures resulted in a more desirable distribution of water. There was also a decrease in the mean drop size and an increase in the maximum trajectory distance.

Increasing the size of the orifice of a sprinkler nozzle, keeping all other factors constant, resulted in a better distribution of water. Increasing the angle of inclination of a sprinkler nozzle from the horizontal resulted in a marked improvement in the distribution of the water.

When the cylindrical portion of a sprinkler nozzle was artificially roughened, the distribution of water was poorer than that from an unroughened nozzle.

Changing the angle of taper in a sprinkler nozzle from a very gradual taper to one approaching a sharp-edged orifice resulted in little or no change in the amount of fall-out of water near the sprinkler; however, the one approaching a sharp edged orifice caused a lesser amount of fall-out along the remainder of the trajectory distance than did the other angles of taper.

Lengthening the cylindrical portion of the nozzle resulted in a poorer distribution of water. The best distribution was obtained using a convergent tube.

When the distance between the nozzle and the main body of the sprinkler was varied by using extension tubes of different lengths, it was found that the longer extension tube resulted in an increase in the trajectory distance and lessened the amount of fall-out of water near the sprinkler. However, beyond a certain length, a further increase in the length of the extension tube did not further affect the trajectory distance or the amount of fall-out of water near the sprinkler.

A slow rate of rotation resulted in a more desirable distribution of water than did a rapid rate of rotation. As the rate of rotation was increased, the trajectory distance decreased and there was a greater amount of fall-out of water both near the sprinkler and at the point of maximum accumulation near the outer trajectory radius.

The use of a short cylindrical tube in place of a sprinkler nozzle resulted in a more desirable distribution of water. The most desirable distribution pattern was obtained when the tube length was two to four diameters (of the inside of the tube) as measured from the beginning of the bend in the sprinkler body to the discharge end.

In general, the distribution patterns from nozzles with non-circular orifices were more desirable than from those with a circular orifice. The equilateral-triangular shaped orifices in which the triangular shape extended for a considerable depth into the nozzle gave the most desirable distribution.

In the majority of the above discussed factors, the improvement in the distribution pattern was due to some characteristic imparted to the jet by physical changes made in the sprinkler. In this study three factors which could have affected the flow characteristics of the jet of water as it emerged from the sprinkler so as to improve the distribution pattern for irrigation purposes stand out. These are turbulence, distribution of velocities and the amount of secondary motion in the jet.

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