NBS-GCR-77-105

Effect of Selected Variables on the Distribution of Water from Automatic Sprinklers

June 1977

Sponsored by

U.S. Department of Commerce
National Bureau of Standards
Washington, D.C. 20234

and

U.S. Department of Health, Education & Welfare
Public Health Service
Washington, D.C. 20201

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EFFECT OF SELECTED VARIABLES ON THE DISTRIBUTION OF WATER FROM AUTOMATIC SPRINKLERS

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June 1977

Grant No. 4-36092

Sponsored by
U.S. Department of Commerce
National Bureau of Standards
Washington, D.C. 20234
and
U.S. Department of Health, Education & Welfare
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Preface

This report is a product of a joint effort of the Department of Health, Education and Welfare (HEW) and the National Bureau of Standards (NBS), Center for Fire Research. The Program is a five year activity initiated in 1975. It consists of projects in the area of:

1. Decision Analysis
2. Fire and Smoke Detection Systems
3. Smoke Movement and Control
4. Automatic Extinguishment
5. Behavior of Institutionalized Populations in Fire Situations

The objective of this report is to present design implications for automatic sprinkler heads and systems. The report includes a description of test method, results and analysis. The study examined the effect of several variables on the distribution of water from sprinklers through a horizontal plane. Variables studied were flow rate, size of supply pipe, direction of supply, deflector to ceiling clearance, arm orientation, angle of the sprinkler head, and the use of sprinkler guards. Methodology utilized three collection container arrays to measure densities from one or two sprinklers. In order to evaulate the effects of the variables, data from tests were used in conjunction with a Synagraphic Mapping System (SYMAP) computer program to produce isodensity mappings of the sprinkler discharges. The mappings clearly demonstrate the effect of obstructions in the spray patterns such as, piping, deflector arms and sprinkler guards as well as the other variables mentioned above. Isodensity mappings can serve as useful tools in sprinkler head and system designs.

The Effect of Selected Variables on the Distribution of Water from Automatic Sprinklers

Abstract

The effects of flow rate, supply pipe size, direction of supply, deflector to ceiling clearance, orientation of sprinkler arms, angles of the sprinkler head, and sprinkler guards on the distribution of water from sprinkler heads have been studied. Implications for the design of sprinkler heads and systems have been identified.

The report is contained in three volumes. Volume 1 includes a description of the test method, results, and analysis. Volume 2 includes all the test and comparison mappings produced for analysis. Volume 3 contains the data in tabular form.

Contents

1. Introduction

The evolution of sprinklers and sprinkler system design has brought with it a series of new designs and design methodologies. Refinements in sprinkler head design have included improved actuation devices as well as major modifications in the spray formation hardware. Advances in sprinkler system design have resulted in hydraulically calculated systems and improved methods for protection of high racked storage.

Current initiatives toward further refinements of sprinkler heads and sprinkler system design are centered on the realization that further improvements will need to be based on an understanding of three physical processes. These processes are; the actuation of sprinklers by convected heat from developing fires, the distribution of water from sprinklers once actuated, and the effect on developing fires of various application densities and particle sizes within the water spray.

This study examined the effect of several variables on the distribution of water from sprinklers through a horizontal plane. Variables studied were flow rate, size of supply pipe, direction of supply, deflector to ceiling clearance, arm orientation, angle of the sprinkler head, and the use of sprinkler guards. Both an upright head (SSU) and a pendent head (SSP) were studied.

In order to determine the distribution pattern from multiple heads in any given configuration, a means of synthesizing the multiple head pattern from single head patterns is needed. To this end, the applicability of the superposition principle to generate multiple sprinkler distribution patterns from single head patterns was studied.

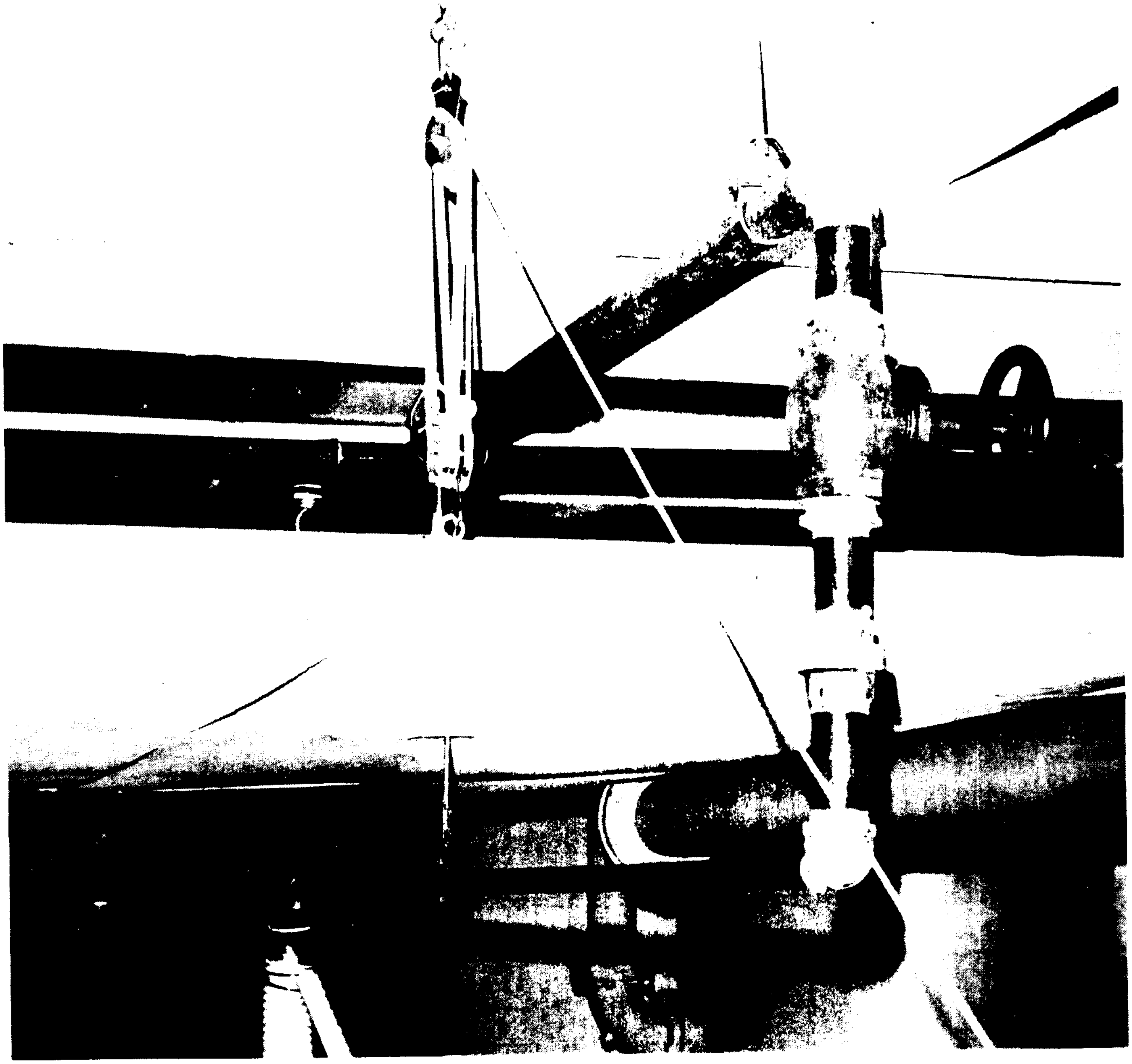


Figure 1

2. Experimental Arrangement

The sprinkler head was mounted on a supply pipe beneath a smooth ceiling as shown in figure 1. This configuration allowed easy variations in pipe size and direction of supply. The ceiling was supported by steel rods at the corners of the ceiling and the ceiling height could easily be adjusted using the hoisting system show. This method allowed variation in the deflector to ceiling clearance while maintaining a constant distance from the deflector to the collection containers; 2.1 meters (6.9 feet) for upright heads, 1.9 meters (6.2 feet) for pendent heads. The looped piping system and the valve shown in figure 1 allowed one or two directional supply to the sprinkler head.

Water was supplied to the head from a sump by a centrifical pump. The churn pressure of the pump was 276 KPa (40 psi). This limited the flow range that could be studied. An OS & Y valve was used to adjust the flow and the tests were terminated using a quarter turn valve.

An Annubar Flowmeter, which makes use of the principle that the velocity pressure in pipe flow is a function of the flow, was used to measure flow rates. The meter samples the pressure profile with a multiple port pitot tube facing upstream and with a second pitot tube facing downstream samples the pressure in that orientation. The pressure differential is displayed on a differential manometer. The device was calibrated for flows from 20 - 120 dm^3/min. (5-32 gpm) by timing flows into a drum and weighing the discharge.

Three collection container arrays were evaluated. Figures 2, 3, and 4 illustrate the arrays. The radial array was chosen for use as it provided a larger collection area and provided data directly in polar coordinates for any future theoretical work. The area of the array included an angle of 180 degrees about the sprinkler head and a radius of 3.84 m (12.6 feet) from the head. Figure 5 shows the array as utilized including measures used to keep the containers free of water before the start of the test. The collection array consisted of .305 m x .305 m (12.0 inches x 12.0 inches) containers. The distance between the

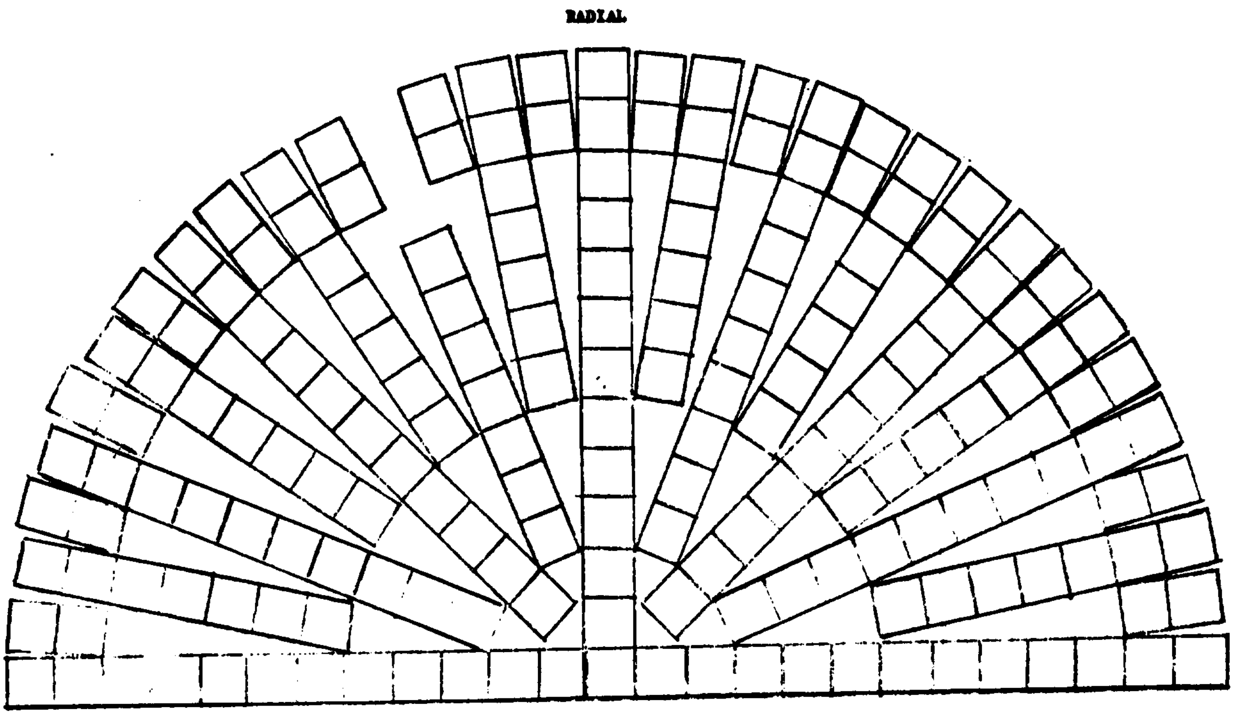


Figure 2

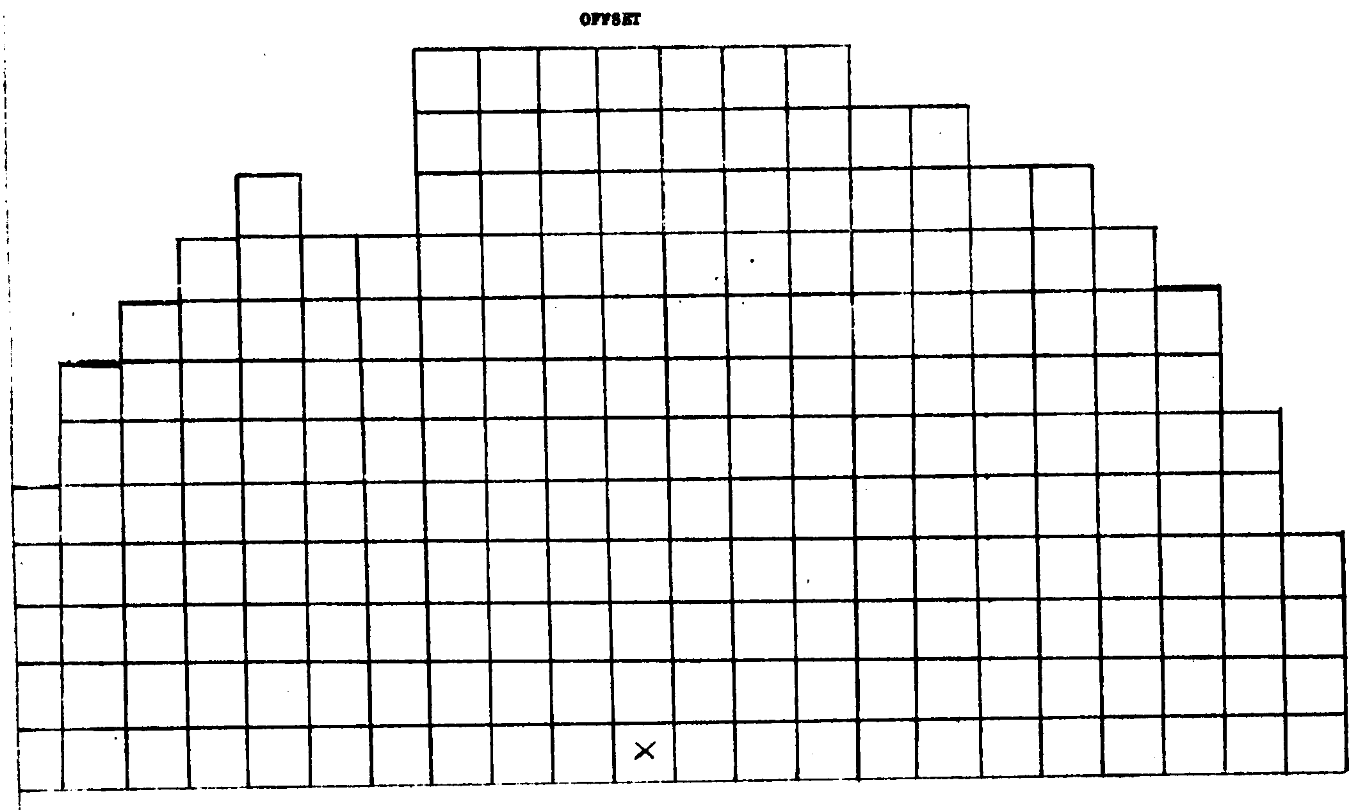


Figure 3

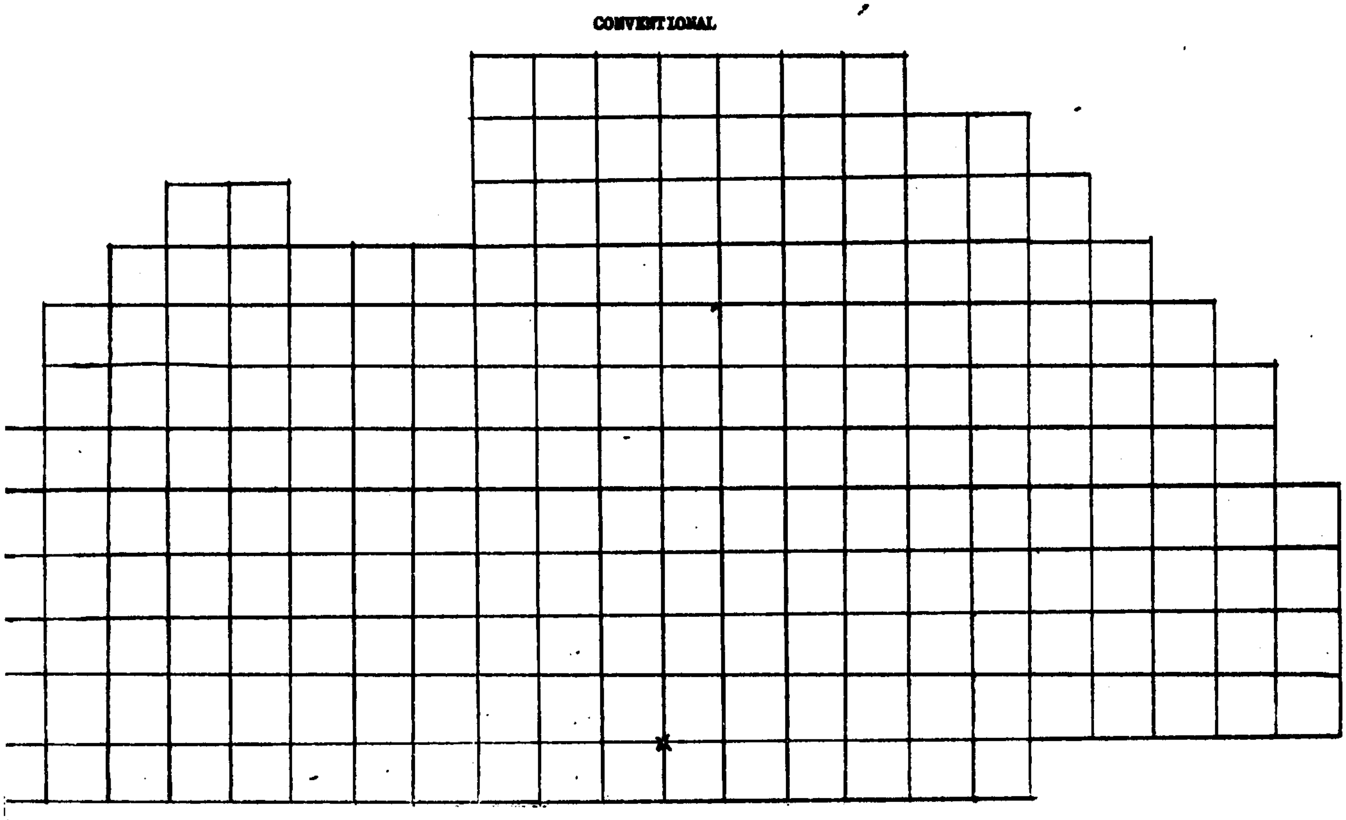


Figure 4

centers of tightly packed containers was .317 m (1.04 feet).

The collection array used for the tests where the applicability of the superposition principle was evaluated was the tightly packed rectangular array shown in figure 6. This array was chosen over the radial array because the data point locations from radial arrays with origins at two different locations did not coincide.

The sprinkler heads used were 12.7 mm (0.5 inches) diameter Grinnel Duraspeed C upright and pendent sprinkler heads (Figure 7). Special care was taken to install the heads level and arms parallel to the supply pipe. Leveling was accomplished using a pocket size level and the alignment of the arms was done visually. Care was also taken to be sure that the same side of the deflector faced the collection array. These measures insured that variations in the sprinkler head orientation and the possible

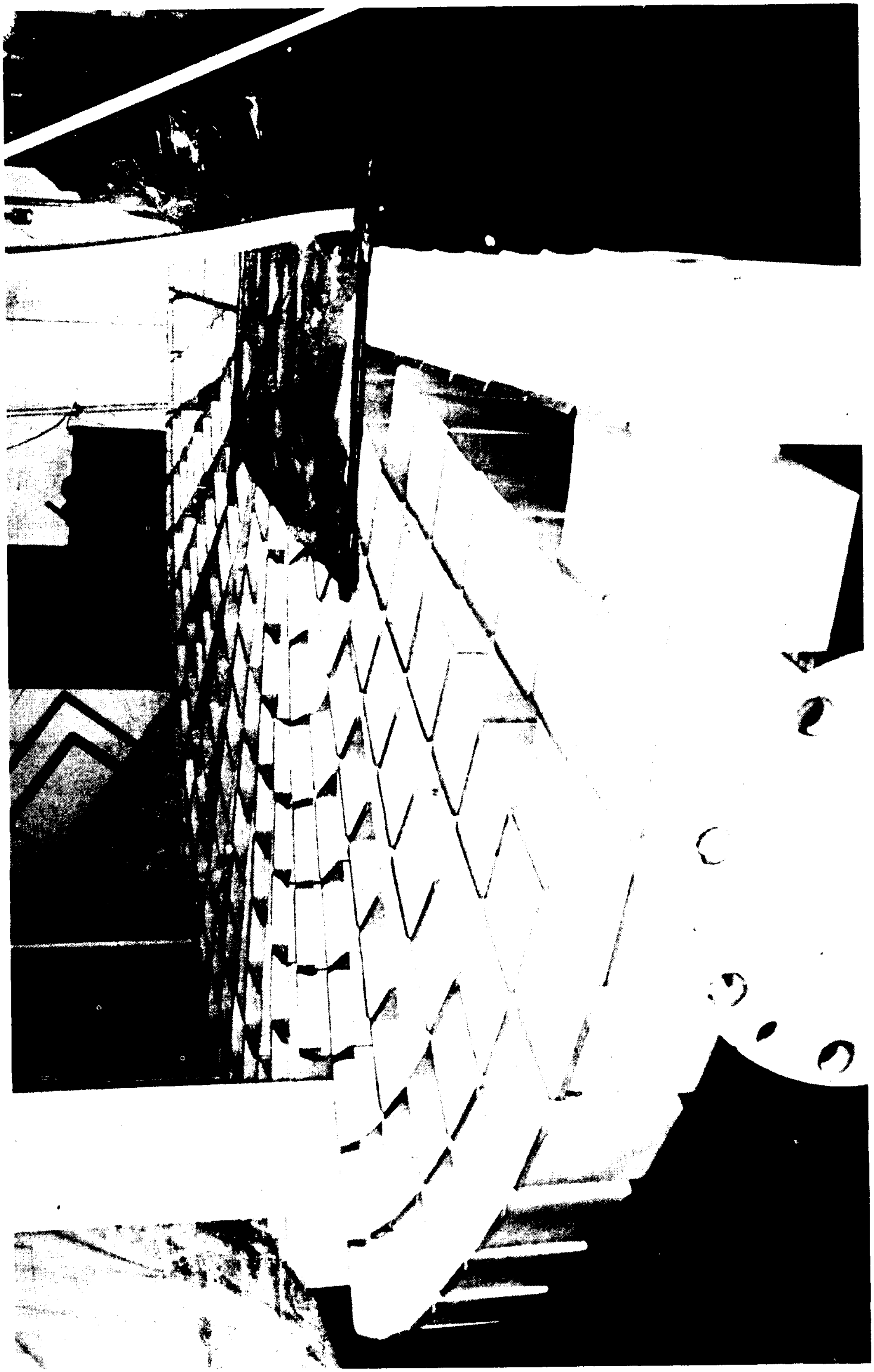


Figure 5

TWO HEAD TESTS

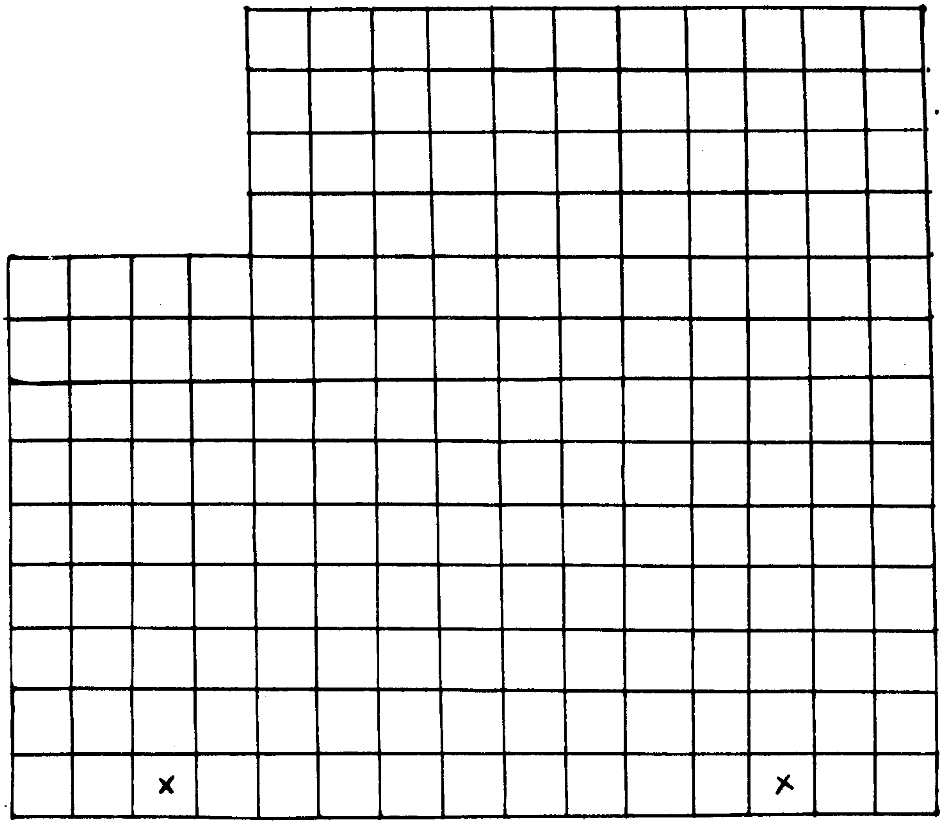


Figure 6

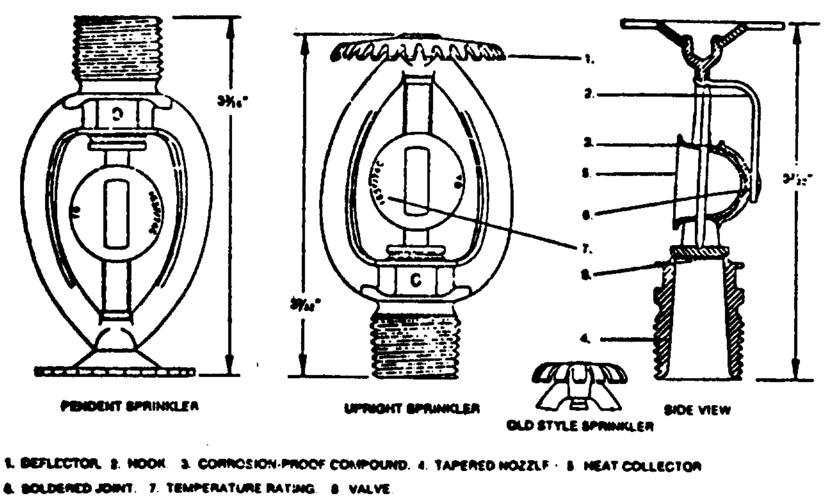


Figure 7

irregularities in the sprinkler head deflector did not effect the results of test comparisons.

3. Test Procedure

Tests were started by adjusting the flow to the desired rate while the discharge from the head was directed from the collection array. This process was accomplished in the upright head tests using a 19 mm (.75 in.) copper elbow placed inside the arms of the sprinkler as shown in figure 8 and 9. The elbow could be removed remotely using a string attached to the elbow. A 19 mm (.75 in.) O.D. plastic tube inside the elbow acted as a sealing gasket at the sprinkler orifice. The compressible rubber tape around the elbow insured a tight fit without undue pressure on the sprinkler arms. In the pendent head tests, a 76 mm (3.0 in.) diameter flexible plastic tube was held over the head to divert the flow as shown in figures 10 and 11. The apparatus was fitted at the top with a rubber cross-slitted membrane which allowed the tube to be pushed over the head while preventing upward splashing and leakage. The tube was held in place using a plastic pipe section which was sufficiently long to allow remote removal. The plastic sheeting shown in figure 10 prevented minor leakage from partically filling containers before the test was begun. Both methods used for flow diversion worked well, but required some practice for best results.

Once the desired flow rate was achieved, the diversion apparatus was quickly removed and the timed flow period began. The tests were run for 21, 24, and 30 minutes at 37.8, 75.7, and 113.6 dm^3/min. (10, 20, and 30 gpm) respectively. In tests using upright heads, the containers

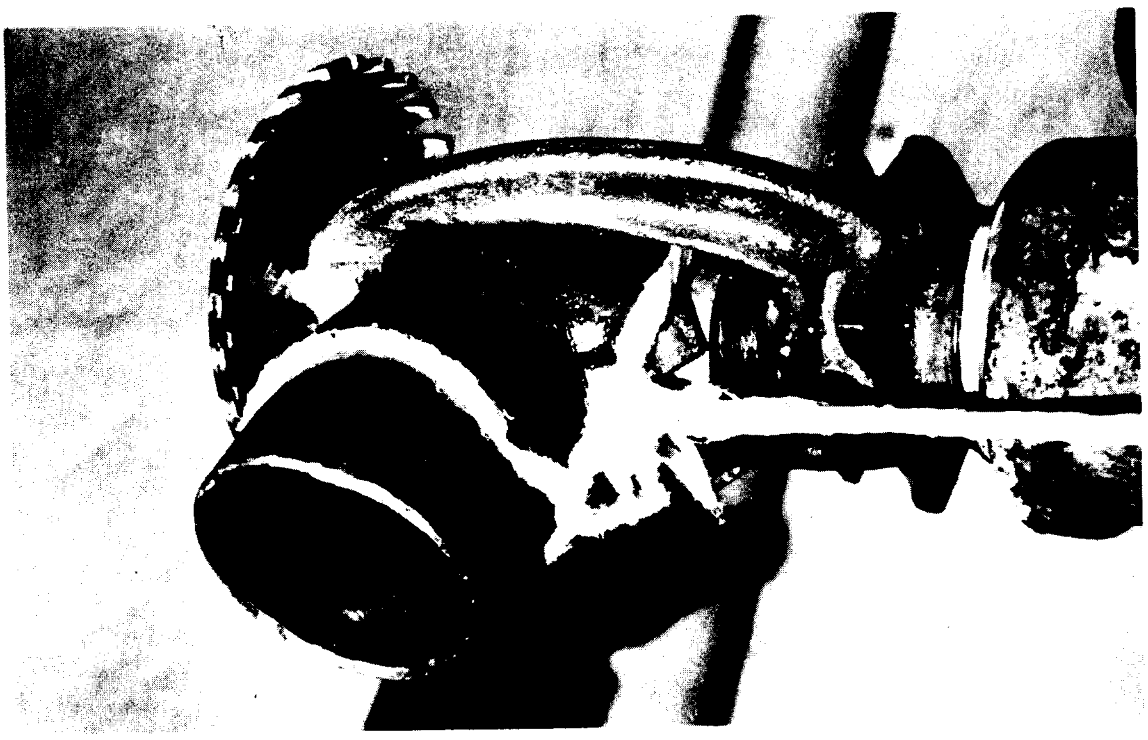


Figure 8

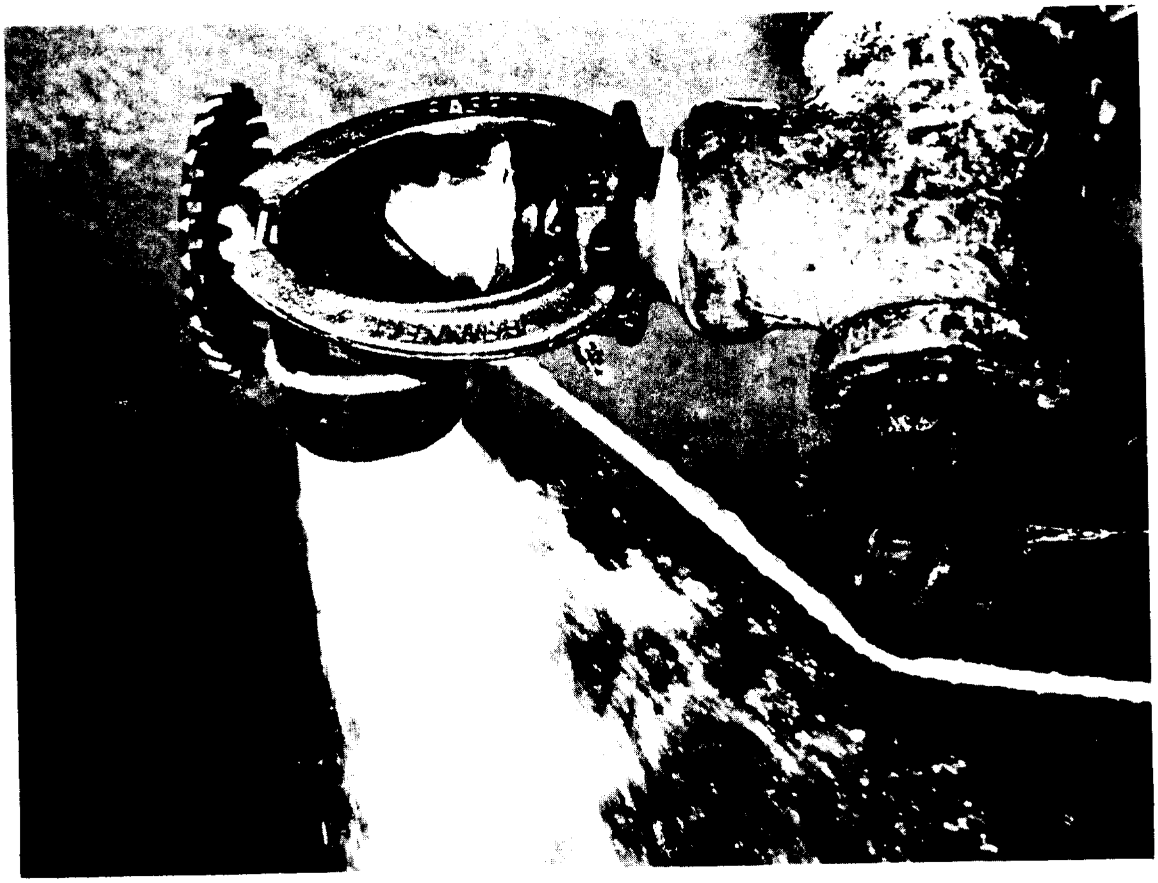


Figure 9

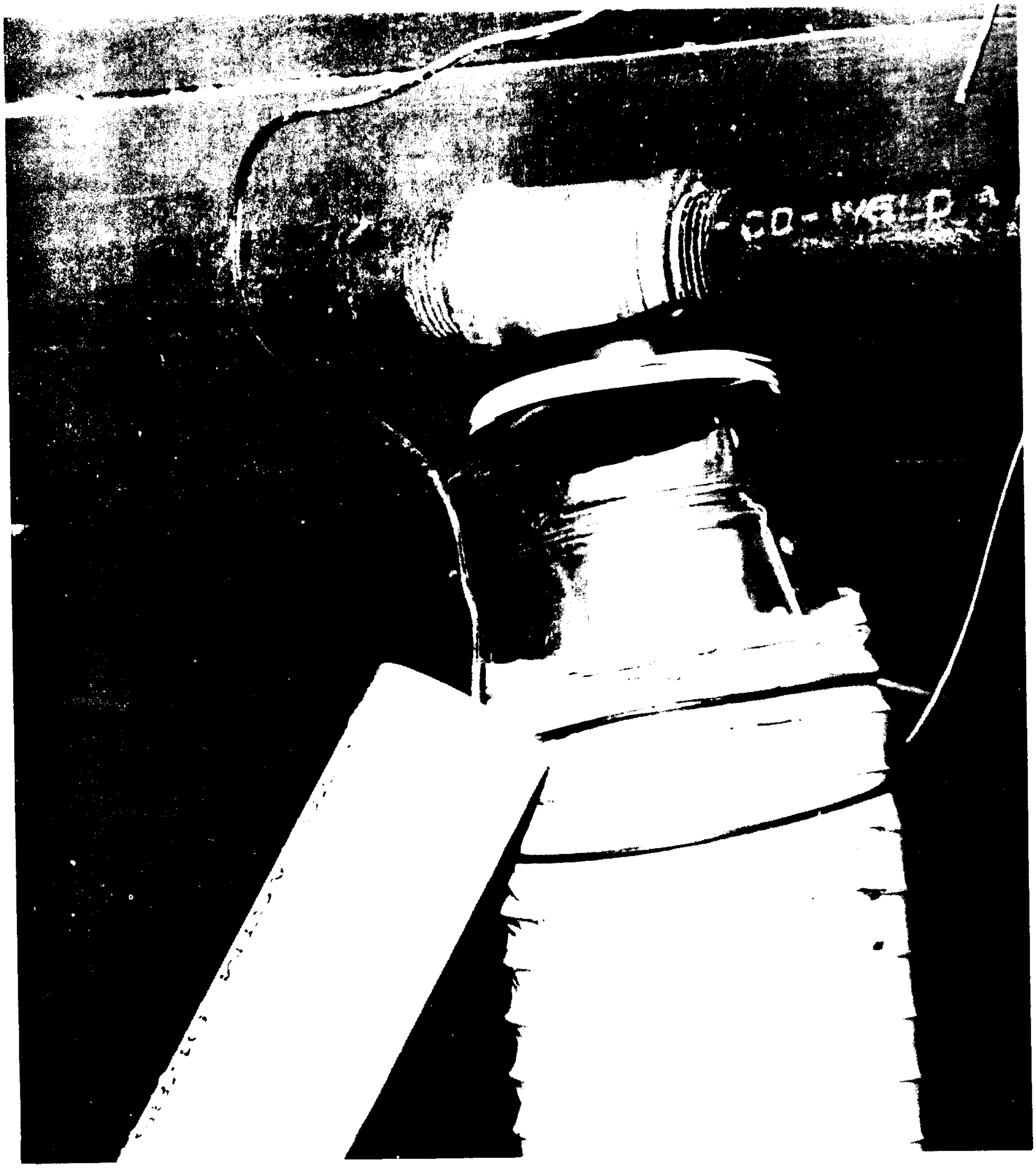


Figure 10

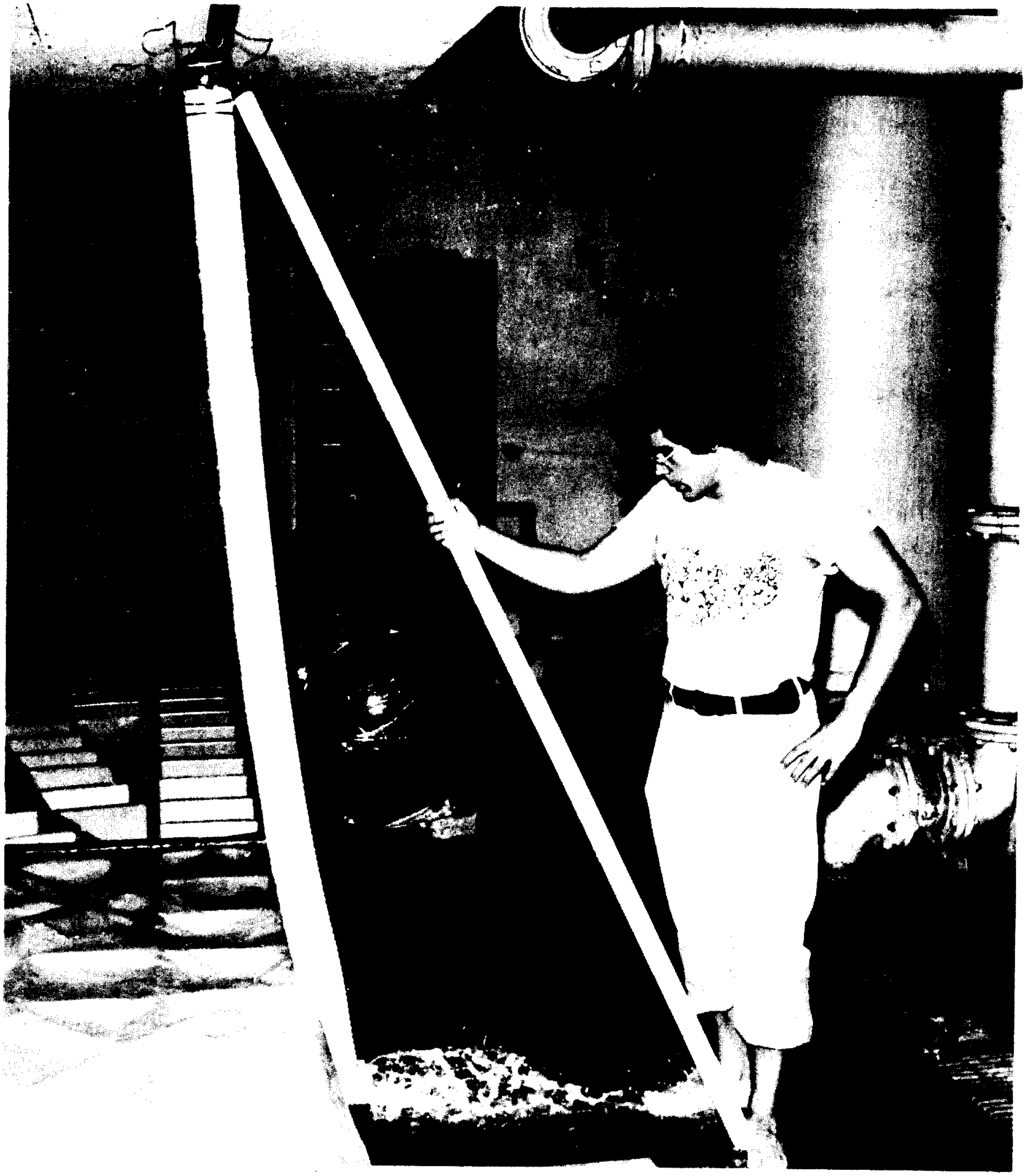


Figure 11

directly under the supply pipe filled quickly. As a result, the tests were necessarily interrupted; the contents of nearly full containers were measured and dumped; and the test was restarted. Tests with 52.5 mm (2.067 in.) and 40.9 mm (1.610 in.) diameter supply pipes required two interruptions. Upright head tests with 26.6 mm (1.049 in.) diameter pipes required one interruption while restarts were not necessary in the pendent head tests.

4. Measurement of Density

Two methods of measurement of the water collected were used. For containers with less than 4000 ml (1.06 gal.) the water was poured into a graduated cylinder for determination of the volume. At volumes greater than 4000 ml (1.06 gal.) the transfer of the water to another container became infeasible and the instrument shown in figures 12, 13, and 14 was developed to determine the depth of water in the collection container. The instrument was placed vertically into the container, and the slide was moved downward until both the probes touched the water's surface. When the probes touched the water's surface, a current flow was allowed between the base and collector of a 2N 3646 transistor. Acting as a switch, the transistor allowed a Light Emitting Diode (LED) to be powered. When the LED was activated, the instrument was removed and the depth was read at the crosshair of the slide. This depth measurement method proved reproducible to 1 mm.

The irregularities of the collection containers as shown in figure 15 did not allow a linear correlation between depth and volume. As a result, the containers were graded as to their regularity. The more irregular

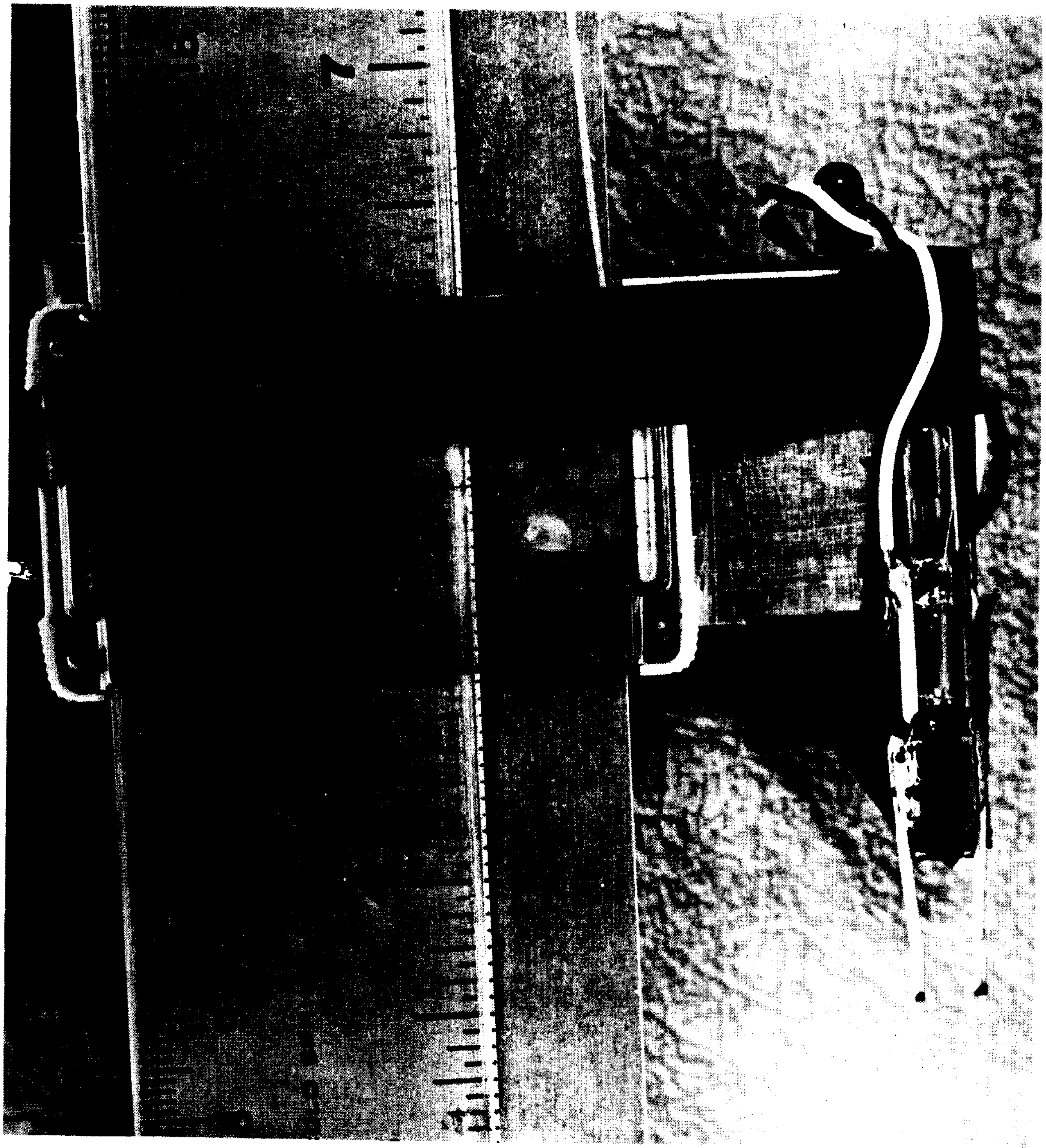


Figure 12

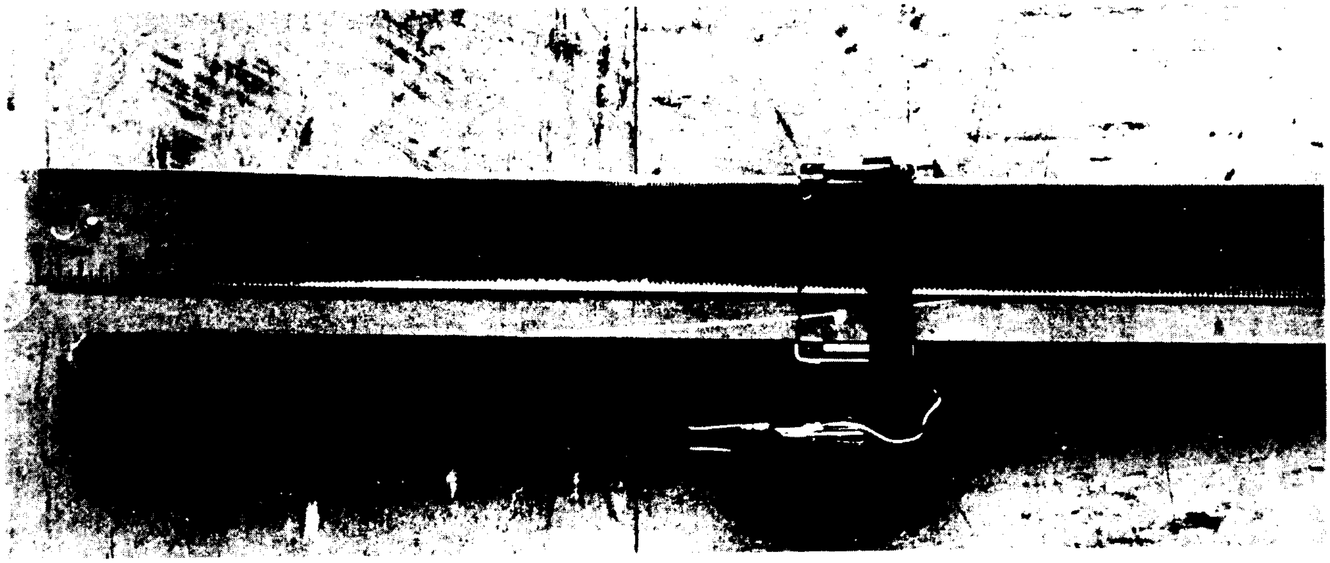


Figure 13

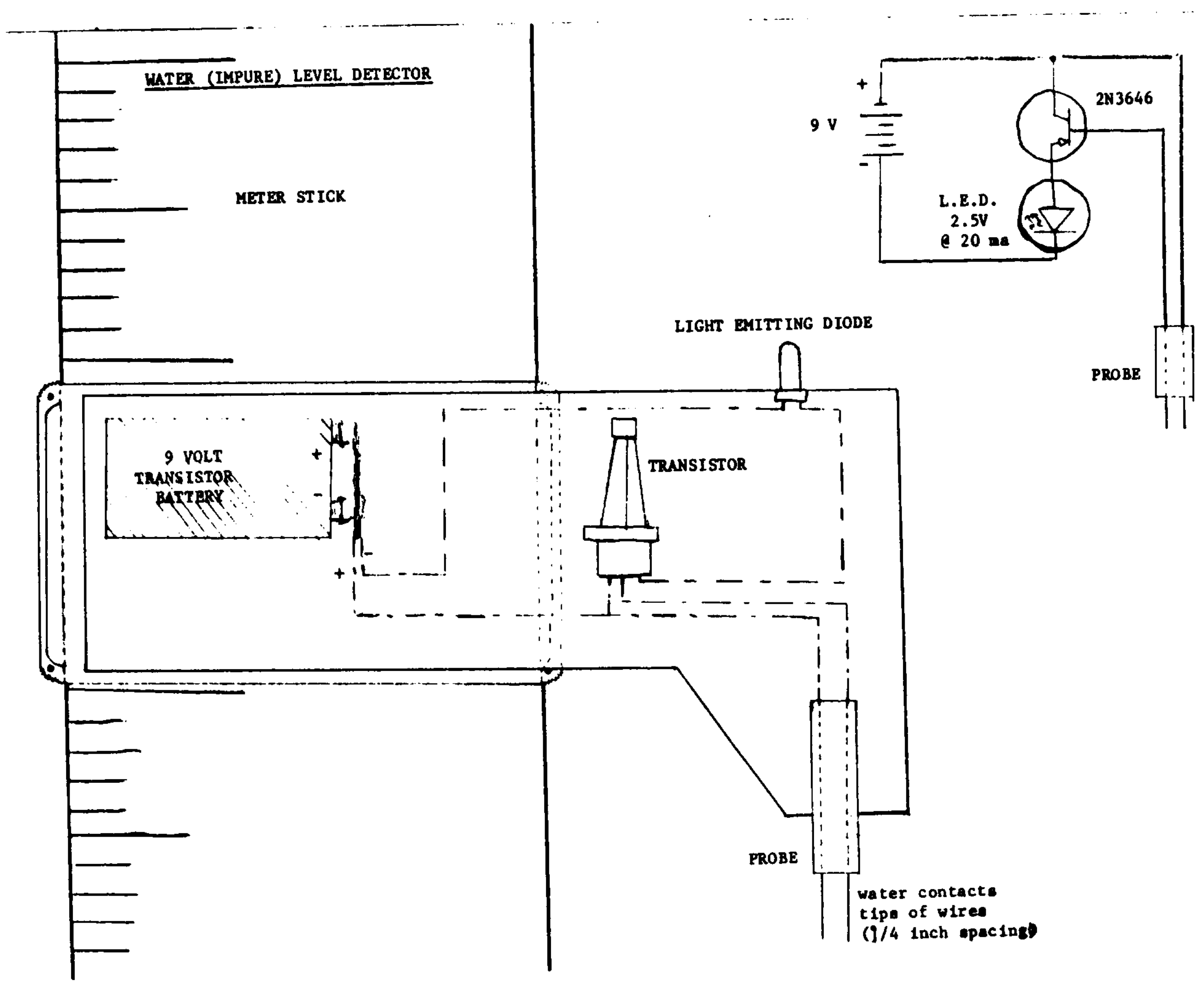


Figure 14

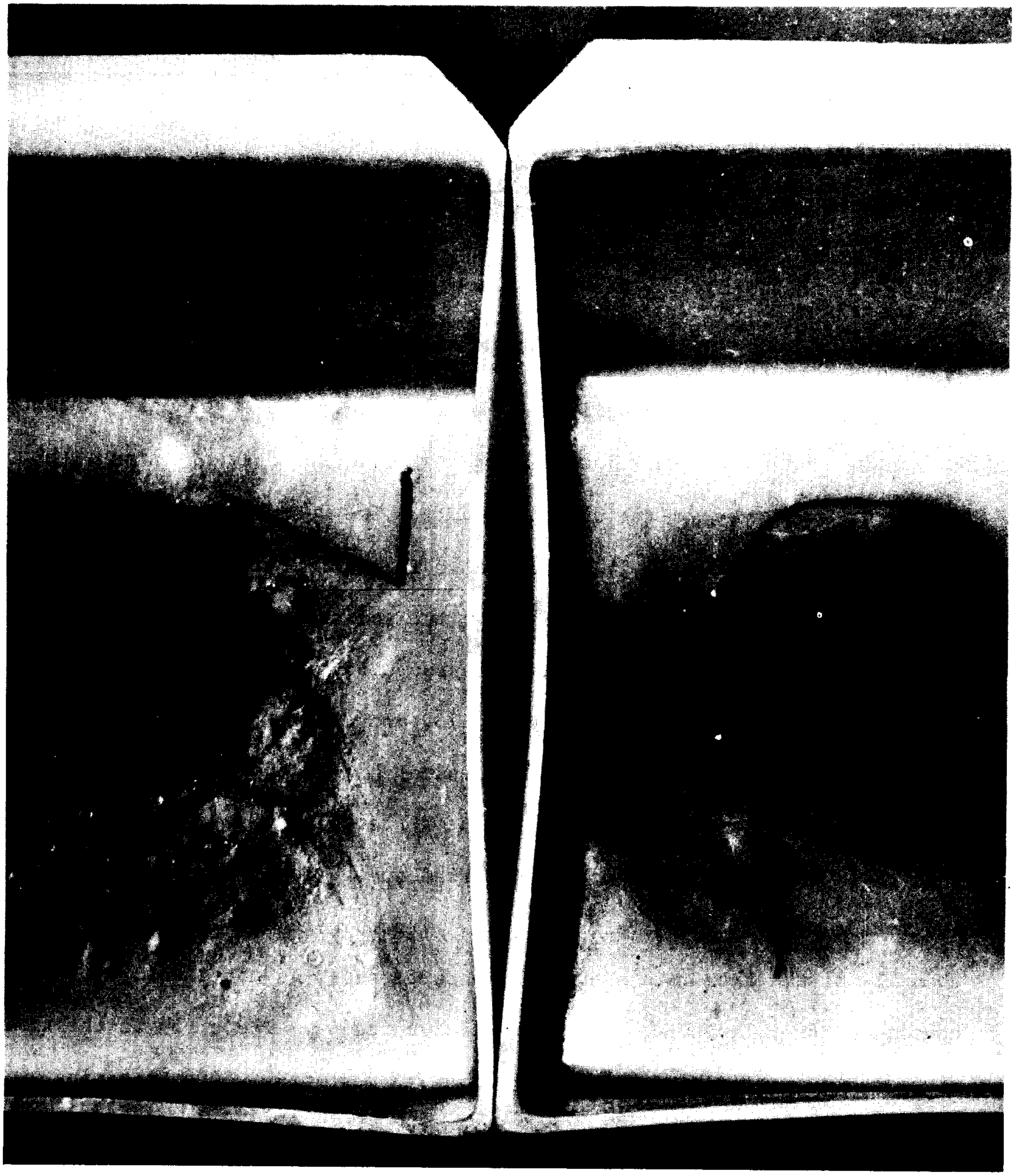


Figure 15

containers were utilized in the outermost parts of the pattern to insure that no more than 4000 ml (1.06 gal.) would be collected in them. From the remaining 100 containers, a sample of 20 was used to develop a calibration curve to relate depth to volume. The piecewise linear relation developed is given in Appendix D. Erros up to 4% were induced by the irregularities of the containers.

5. Reproducibility and Error

Six pairs of reproducibility tests were run. The tests were conducted with a 26.6 mm (1.049 in.) inside diameter black steel supply pipe with supply to the head from one direction only. The sprinkler was installed with the deflector perfectly horizontal. The deflector was 178 mm (7.0 in.) from the smooth ceiling and the arms of the sprinkler were aligned with the supply pipe. Three pairs of tests were run using an upright head flowing at 37.8, 75.7, and 113.6 dm^3/min. (10, 20, and 30 gpm) respectively and three pairs of tests were run with a pendent head at the same flow rates. The results of these tests indicated the differences found were greater than could be explained by errors incurred due to control of the test and measurement of the water collected. Errors were estimated at less than 1% for the flow rate and depth measurements. As noted before, the container irregularities introduced error up to 4%. The error in the timing of tests was negligible and the error due to restarts, while appearing small, was not directly measurable. In addition to the experimental error, random fluctuations and unsteadiness were observed in the discharge sprays. This was particularly true for the 26.6 mm (1.049 in.) diameter supply pipe tests. This diameter pipe was used for all of the reproducibility tests in order to evaluate the worst condition.

In order to assess the percent error which could be attributed to experimental error and unsteadiness, the pairs of reproducibility tests were averaged and the percent difference of the tests relative to the average was calculated for all points. The data points which were used to determine the maximum error were restricted to those with densities greater than 1.5 mm/min. (.037 gpm/ft.^{2}) For design purposes, densities below this level are of little importance. A maximum density to be considered in the error analysis was also established based on the potential coverage area of 37.8, 75.7, and 113.6 dm^3/min. (10, 20, and 30 gpm) tests. At 37.8 dm^3/min. (10 gpm) the data point density of 3.0 mm/min. (0.74 gpm/ft.^{2}) was defined as the maximum data point density of practical interest. Similarly, 6.0 and 9.0 mm/min. (.147 and .221 gpm/ft.^{2}) were established as maximum values of interest in 75.7 and 113.6 dm^3/min. (20 and 30 gpm) tests, respectively.

The results of this error analysis are shown in Table 1. It was found that differences of up to 25% could be the result of experimental error and distribution pattern unsteadiness. Table 1 indicates that the reproducibility of the tests was worse for upright heads than pendent heads. This could be due to the need for a restart midway through the test due to the filling of containers directly below the head. A second possible cause is the observable difference in the steadiness of the spray pattern. Upright heads were visually observed to have a greater randomness associated with the spray pattern than pendent heads. This will be discussed further when discussing the results of the tests.

Table 1

Distribution of Replication Test Data Point Values

About the Mean of Replication Test Data

Flow Rate - Head Type (gpm)	Percent Deviation About Average of Two Tests -30% to -20%	-20% to -10%	-10% to +10%	+10% to +20%	+20% to +30%
10 - Upright	1	6	70	6	1
20 - Upright	0	19	98	19	0
30 - Upright	0	1	138	1	0
10 - Pendent	0	0	92	0	0
20 - Pendent	1	0	110	0	1
30 - Pendent	0	1	138	1	0

Maximum Deviation from the Mean = 24.2%

Data points with densities in the following ranges are included in the analysis:

10 gpm tests - 1.5-3.0 mm/min.

20 gpm tests - 1.5 - 6.0 mm/min.

30 gpm tests - 1.5 - 9.0 mm/min.

As a result of this analysis, in the consideration of the effects of the variables being studied, only differences greater than 25% were considered as representing significant effects of the variable being studied. Additionally, only differences in data points where the density was between 1.5 and 9.0 mm/min. (.037 and .221 $gpm/ft.^2$) were given consideration is assessing the effects of the environmental variables.

6. Graphic Display Techniques

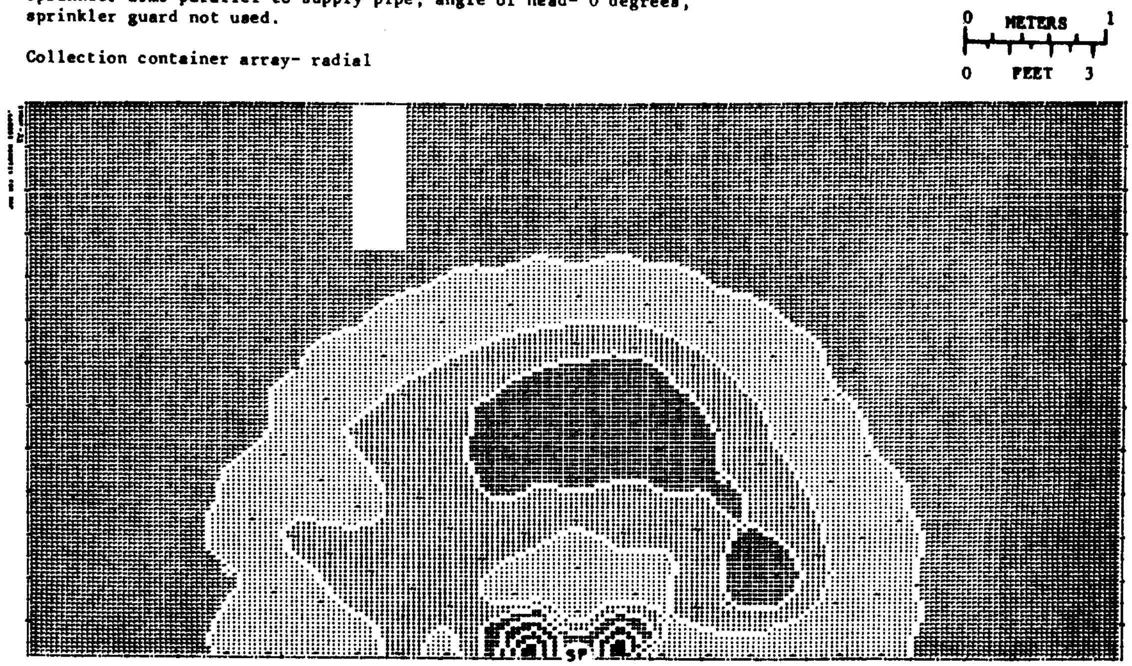
In order to evaluate the effects of the variables studied, it was necessary to develop methods for representing and comparing the spatial data collected. The data from the tests was used in conjunction with a Synagraphic Mapping System (SYMAP) computer program to produce isodensity mappings as shown in figures 16 - 21. A discussion of the SYMAP program developed at the Laboratory for Computer Graphics and Spatial Analysis, Harvard University, is included as Appendix B.

Two methods for representing the effects of the variables on the distribution pattern were developed. They are illustrated in figures 22 and 23. The first and most accurate comparison method made use of the mapping of one of the patterns and numerical overlays. The overlays indicated the percent difference of the test pattern relative to the mapped base pattern. In this way, the magnitude and spatial location of the effects of variables were shown. While constituting an accurate representation, the comparison maps which result are not easily analyzed. In order to facilitate easy interpretation, a second method was used. This method consisted of simply superimposing the isodensity lines of the two tests being compared. Where and to what extent the isodensity lines diverge indicates the magnitude and spatial location of effects. Percent differences less than 25% did not cause a shift in the location of the isodensity lines in the reproducibility comparisons. A danger inherent in this method results from the relative values of adjacent isodensity lines. In most cases, the difference is a factor of two; for example, 3.0 and 6.0 mm/min. (.074 and .147 gpm/ft.^{2}) It is possible for significant effects (> 25%) to go unnoticed if the configuration of data is such that adjacent data values all lie between two isodensity lines. Thus, both methods were necessary to realize full analytical potential and to be sure that the insensitivities of method two did not lead to erroneous conclusions. Comparisons of methods one and two indicated the insensitivities of method two were never manifested. This is the result of the relatively

Test #22

Upright head, flow rate- 10 gpm, size of supply pipe- 1.0 inches, directionality of supply- one, deflector to ceiling clearance- 7.0 inches, sprinkler arms parallel to supply pipe, angle of head- 0 degrees, sprinkler guard not used.

Collection container array- radial



See Appendix A for explanation of density coding.

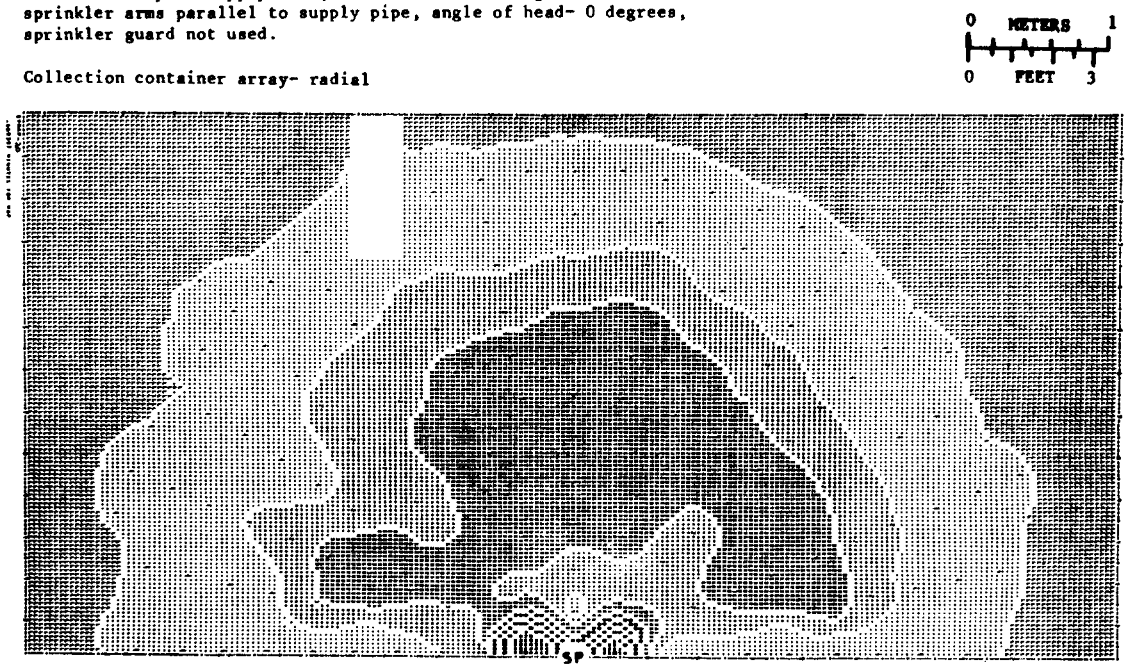
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 16

Test #20

Upright head, flow rate- 20 gpm, size of supply pipe- 1.0 inches, directionality of supply- one, deflector to ceiling clearance- 7.0 inches, sprinkler arms parallel to supply pipe, angle of head- 0 degrees, sprinkler guard not used.

Collection container array- radial



See Appendix A for explanation of density coding.

SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

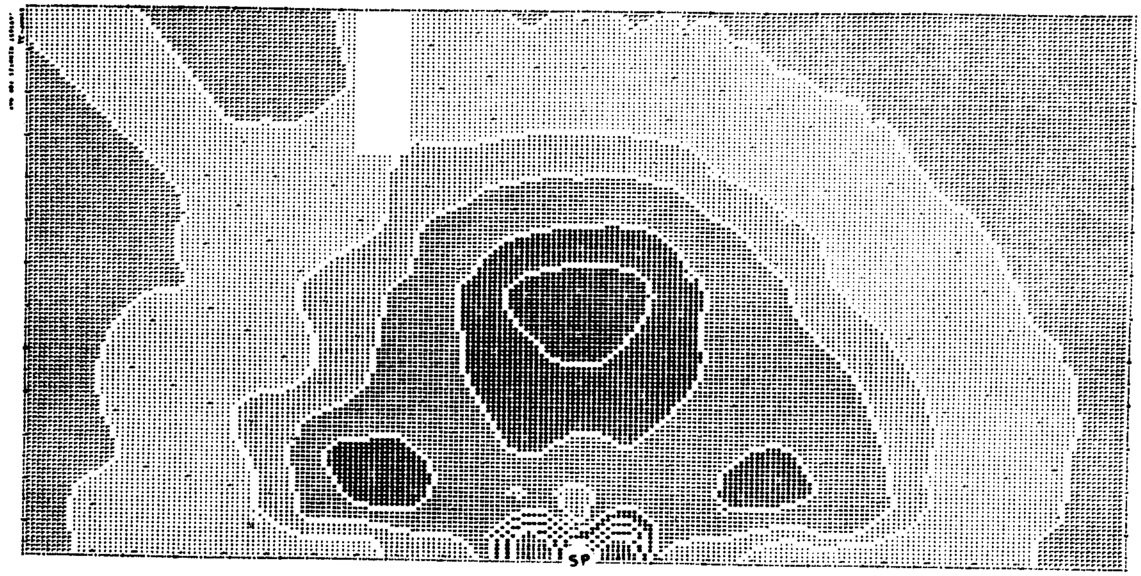
Figure 17

Test #21

Upright head, flow rate- 30 gpm, size of supply pipe- 1.0 inches, directionality of supply- one, deflector to ceiling clearance- 7.0 inches, sprinkler arms parallel to supply pipe, angle of head- 0 degrees, sprinkler guard not used.

Collection container array- radial

0 METERS 1
0 FEET 3



See Appendix A for explanation of density coding.

SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

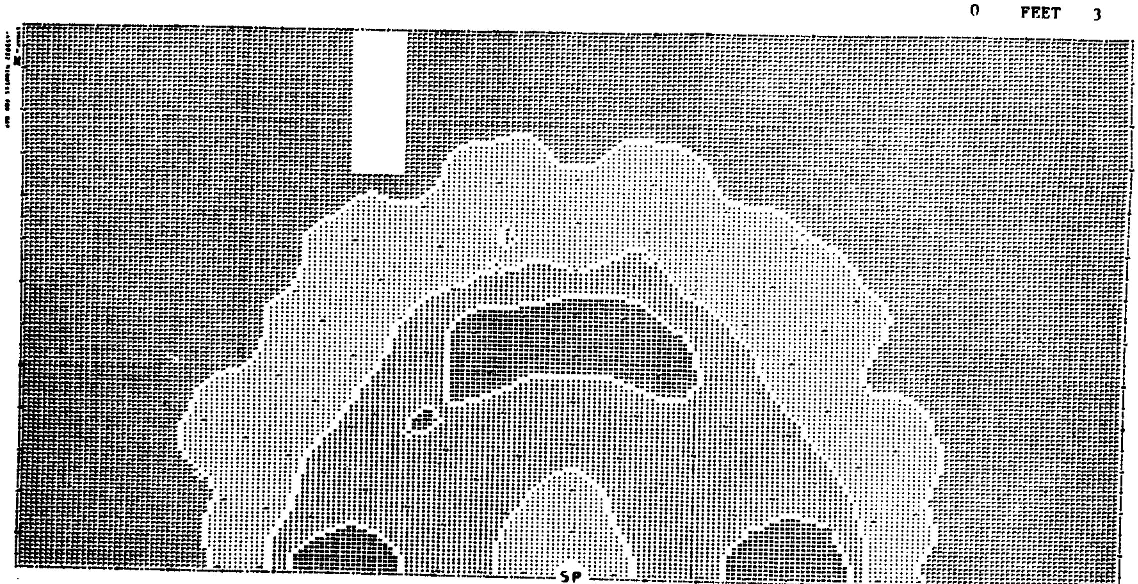
Figure 18

Test #28

Pendent head, flow rate- 10 gpm, size of supply pipe- 1.0 inches, directionality of supply- two, deflector to ceiling clearance- 7.0 inches, sprinkler arms parallel to supply pipe, angle of head- 0 degrees, sprinkler guard not used.

Collection container array- radial

0 METERS 1
0 FEET 3



See Appendix A for explanation of density coding.

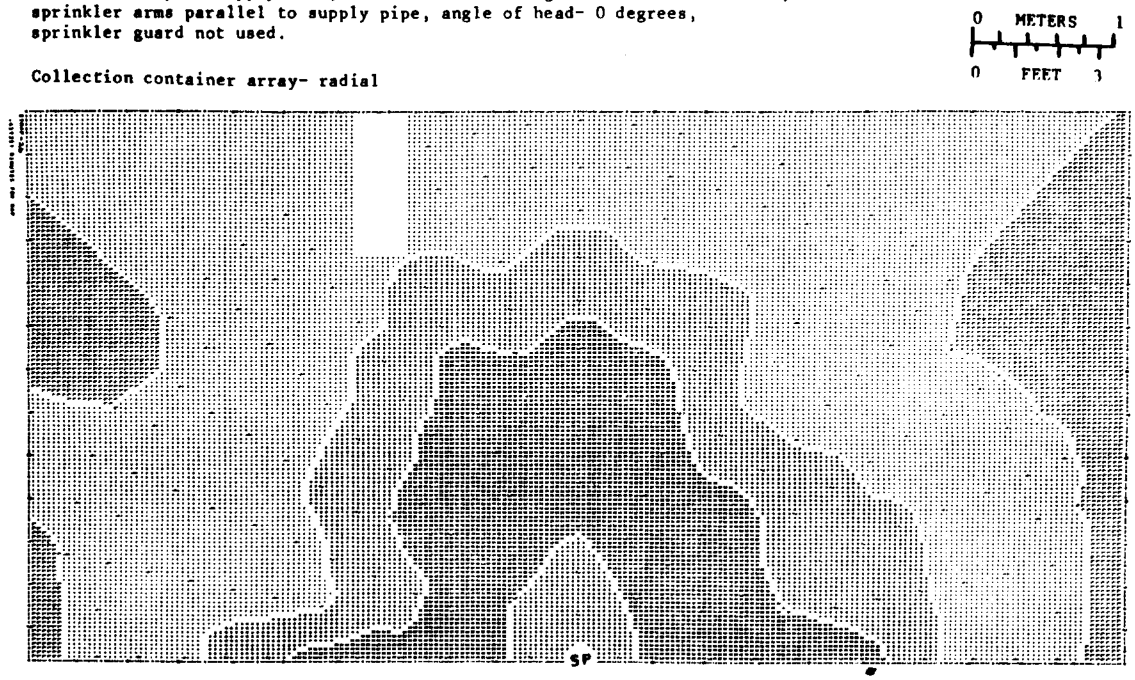
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 19

Test #26

Pendent head, flow rate- 20 gpm, size of supply pipe- 1.0 inches, directionality of supply- two, deflector to ceiling clearance- 7.0 inches, sprinkler arms parallel to supply pipe, angle of head- 0 degrees, sprinkler guard not used.

Collection container array- radial



See Appendix A for explanation of density coding.

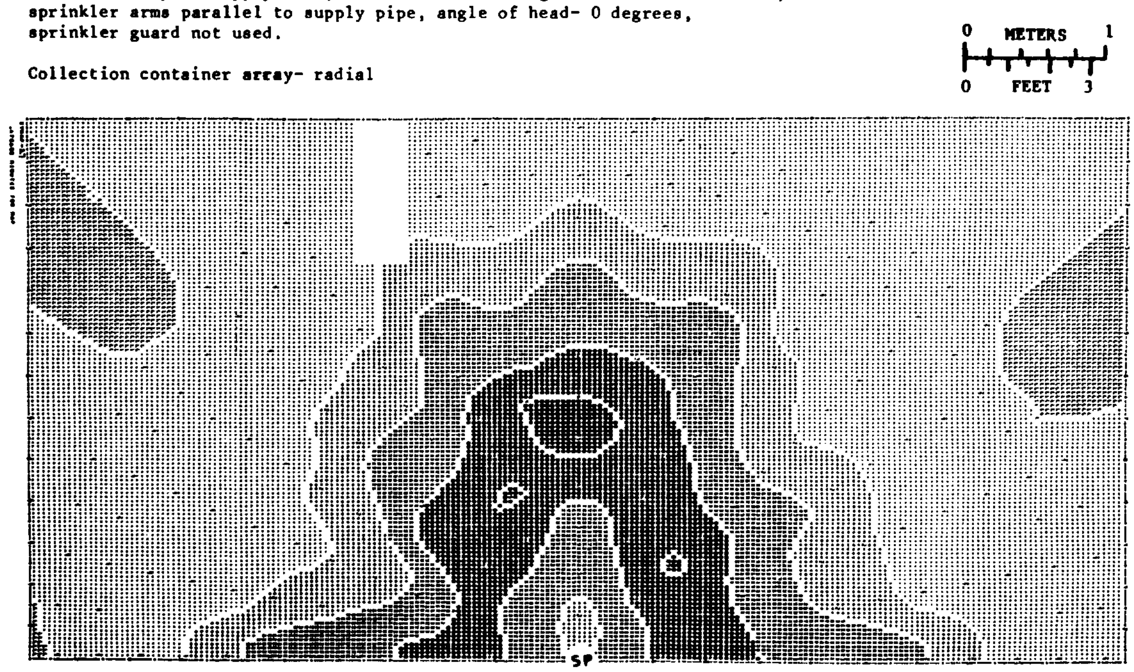
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 20

Test #27

Pendent head, flow rate- 30 gpm, size of supply pipe- 1.0 inches, directionality of supply- two, deflector to ceiling clearance- 7.0 inches, sprinkler arms parallel to supply pipe, angle of head- 0 degrees, sprinkler guard not used.

Collection container array- radial



See Appendix A for explanation of density coding.

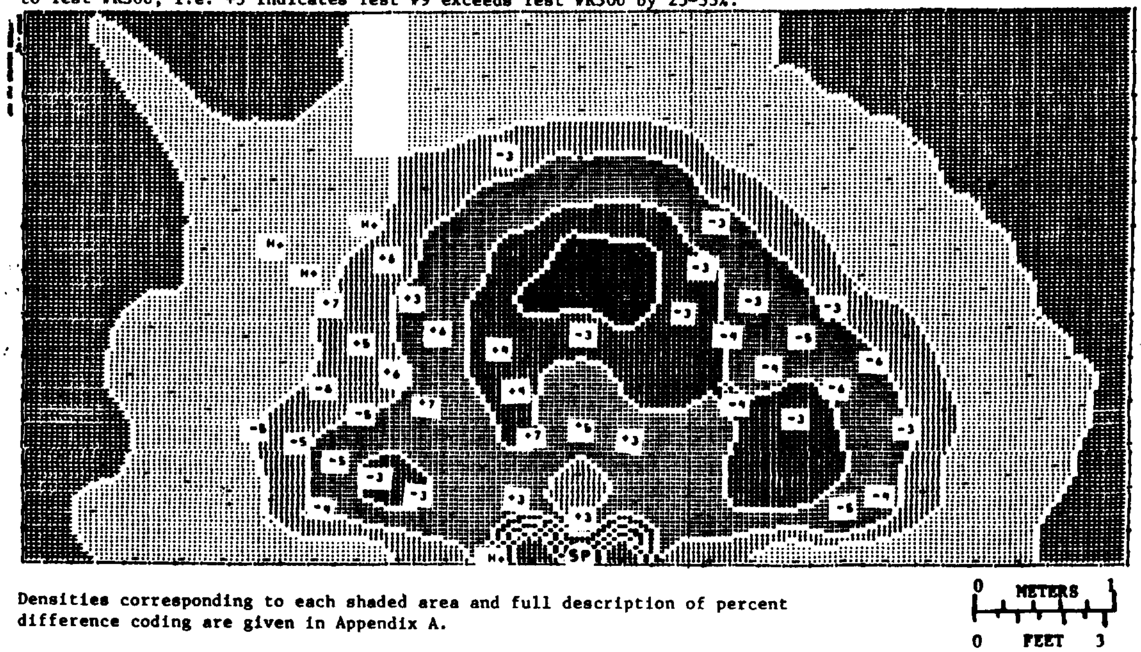
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 21

Comparison #1, PIPE DIAMETER

Variable - Pipe Size, Test #R30U - 1.0", Test #9 - 2.0"
Constant - SSU, 1 Directional Supply 30 gpm, 7" Clearance, Arms Parallel to Pipe

Test #R30U is mapped. Numerical values indicate percent difference of Test #9 relative to Test #R30U, i.e. +3 indicates Test #9 exceeds Test #R30U by 25-33%.



Densities corresponding to each shaded area and full description of percent difference coding are given in Appendix A.

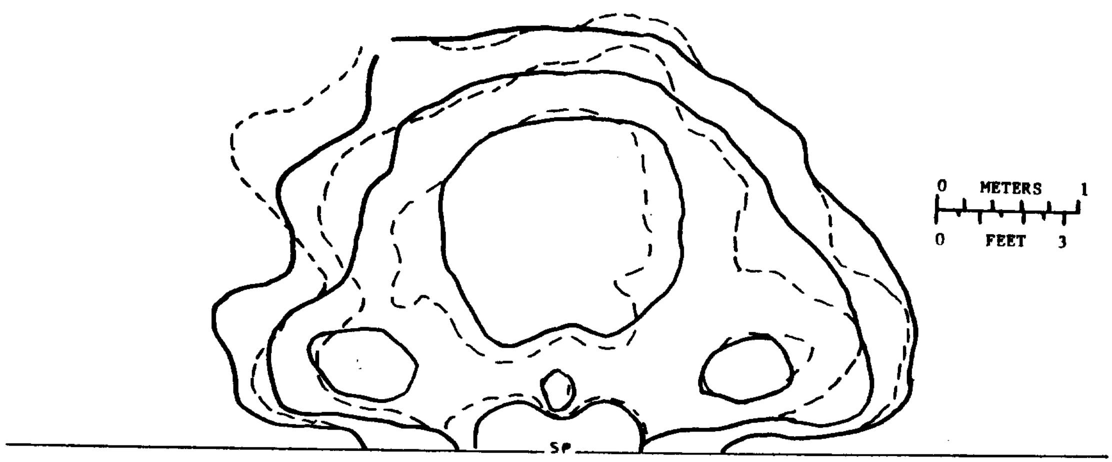
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 22

Comparison #1, PIPE DIAMETER

Variable - Pipe Size, Test #R30U - 1.0", Test #9 - 2.0"
Constant - SSU, 1 Directional Supply 30 gpm, 7" Clearance, Arms Parallel to Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test #R30U and Test #9, respectively.



SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 23

high density gradients found in sprinkler distribution patterns. Thus, in general, comparisons of isodensity line mappings of sprinkler distribution patterns are adequate representations and the overlay method is not needed. This may not be true for multiple head patterns where overlapping reduces the density gradients. The use of both of the described methods in addition to side by side comparison of the distribution patterns yields collectively the clearest view of the effects of variables on distribution patterns.

7. General Observations of Pattern Characteristics

Examination of figures 16 - 21 and 24 - 26 show clear differences in the patterns from upright and pendent heads. The interference of the supply pipe with the pattern from upright heads is clearly illustrated at all flow rates. The high densities below the head are a result of this effect as are the low densities along the pipe at greater distances from the head. Pendent heads on the other hand exhibit a "void" or depression in the density beneath the head. The shapes of the patterns are quite different for the two head types. With the exception of the 37.8 dm^3/min. (10 gpm) flow rate test, the pendent head patterns closely approximate a rectangle. Upright heads maintain a more circular pattern which is in most cases includes an imperfection in the symmetry of the pattern. This imperfection greatly reduces the potential coverage area of the head. An examination of the upright head did not show any visible imperfection in the deflector. The phenomena is unexplained.

8. Results of Test Comparisons

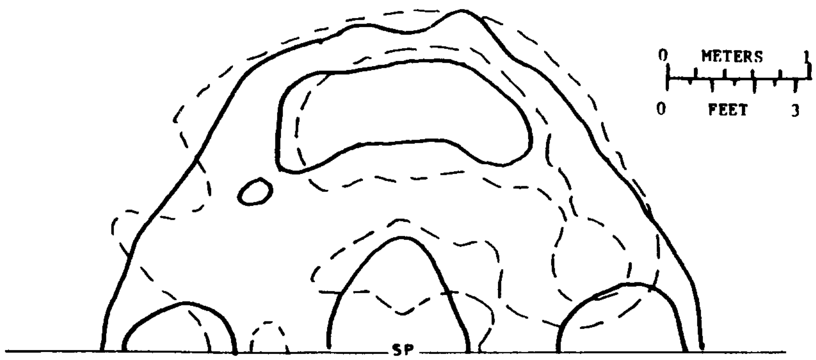
8.1 Flow Rate

The effect of the flow rate on the location of 1.5 and 3.0 mm/min.

Comparison #79, Head Type

Variable- Head Type, Test #R10P- Pendent, Test #R10U- Upright
Constant- Pipe Size- 1.0", 1 Directional Supply, 10 gpm, 7" Clearance, Arms Parallel to Pipe

Solid and dashed lines are 1.5 mm/min. isodensity lines for Test# R10P and Test #R10U, respectively.



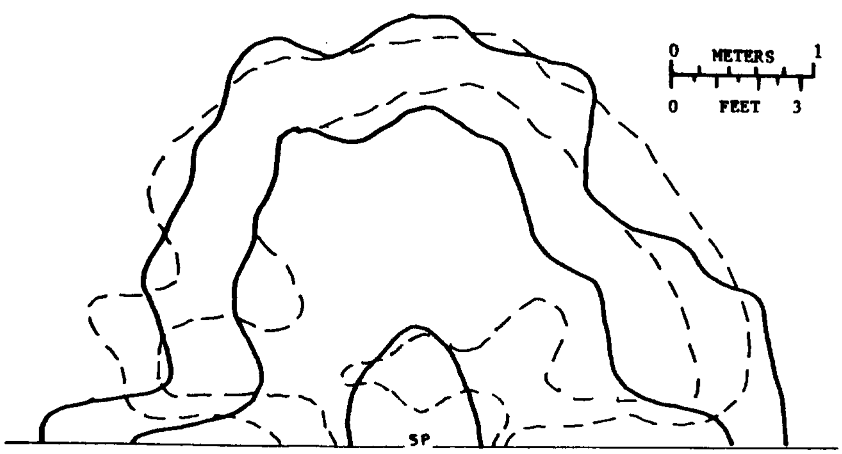
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 24

Comparison #80, Head Type

Variable- Head Type, Test #R20P- Pendent, Test #R20P- Upright
Constant- 1.0" Supply Pipe, 1 Directional Supply, 20 gpm, 7" Clearance, Arms Parallel to Pipe

Solid and dashed lines are 1.5 and 3.0 mm/min.isodensity lines for Test #R20P and Test #R20U, respectively.



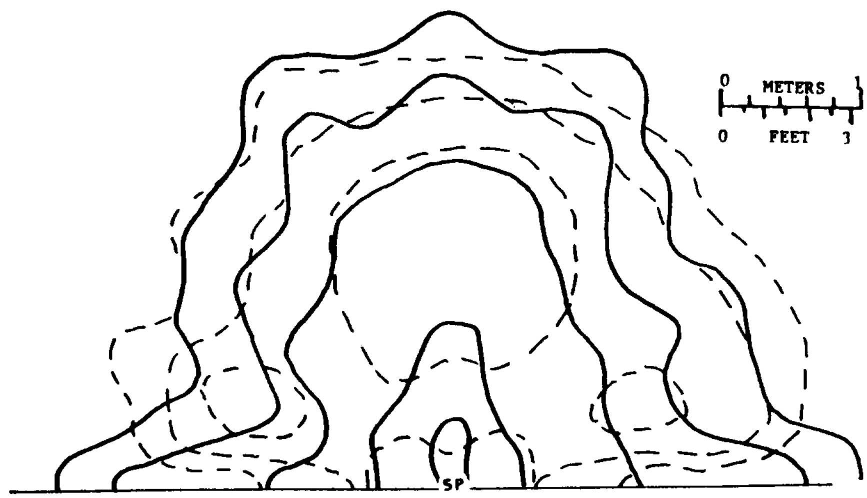
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map

Figure 25

Comparison #81, Head Type

Variable- Head Type, Test #R30P- Pendent, Test #R30U- Upright
Constant- 1.0" Supply Pipe, 1 Directional Supply, 30 gpm, 7" Clearance, Arms Parallel
to Pipe.

Solid and Dashed lines are 1.5,3.0, and 6.0 mm/min. isodensity lines for Test #R30P
and Test #R30U, respectively.



SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 26

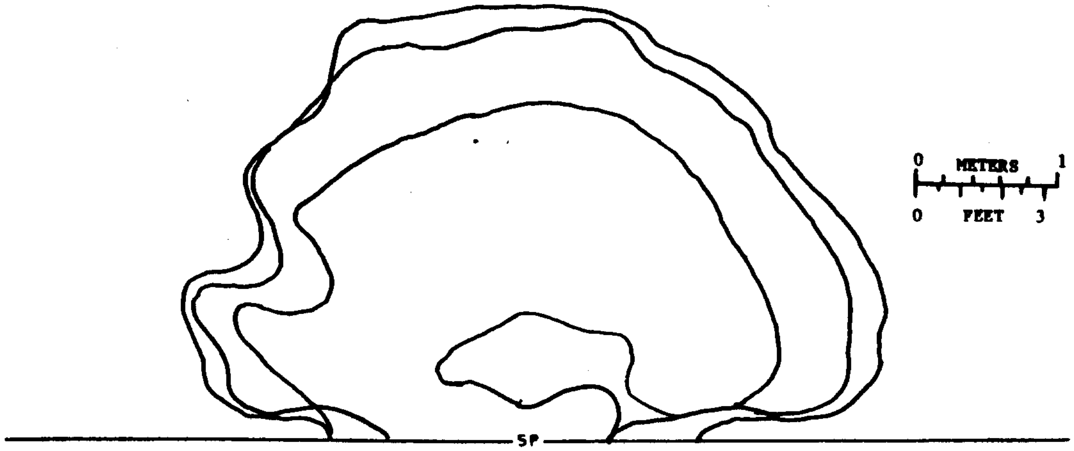
(0.37 and .074 gpm/ft.^{2}) isodensity lines are shown in figures 27 - 30. Figures 27 and 28 indicate that there exists an upper limit on the area within the 1.5 mm/min. (.037 gpm/ft.^{2}) isodensity line which is closely approached at 113.6 dm^3/min. (30.0 gpm). Figures 29 and 30 show a similar trend but indicate the maximum area within the 3.0 mm/min. (.074 gpm/ft.^{2}) isodensity line is approached at a flow rate greater than 113.6 gm^3/min. (30.0 gpm).

By examining figures 29 and 30 first, and then figures 27 and 28, one can trace the development of the area within an isodensity line. The 3.0 mm/min. isodensity line in the 37.8 dm^3/min. (10.0 gpm) tests shows the embryonic stage of development. As one examines the 3.0 mm/min. (.074 gpm/ft.^{2}) isodensity lines at 75.7 (20.0) and 113.6 dm^3/min. (30.0 gpm), and area within the isodensity line develops into what would constitute a feasible

Comparison #75, FLOW RATE

Variable- Flow Rate, Test #22- 10gpm, Test #20- 20 gpm, Test #21- 30 gpm
Constant- SSU, 1.0" Supply Pipe, 1 Directional Supply, 7" Clearance, Arms Parallel to Pipe

1.5 mm/min isodensity lines for each test are shown.



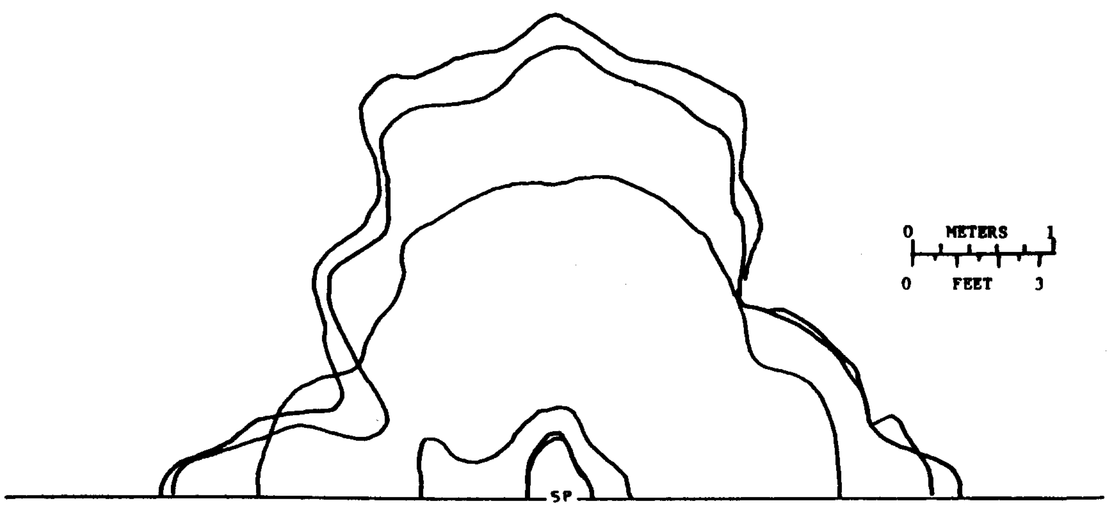
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 27

Comparison #77, FLOW RATE

Variable- Flow Rate, Test #31- 10 gpm, Test #29- 20 gpm, Test #30- 30 gpm
Constant- SSP, 1.0" Supply Pipe, 1 Directional Supply, 7" Clearance, Arms Parallel to pipe

1.5 mm/min. isodensity lines for each test are shown.



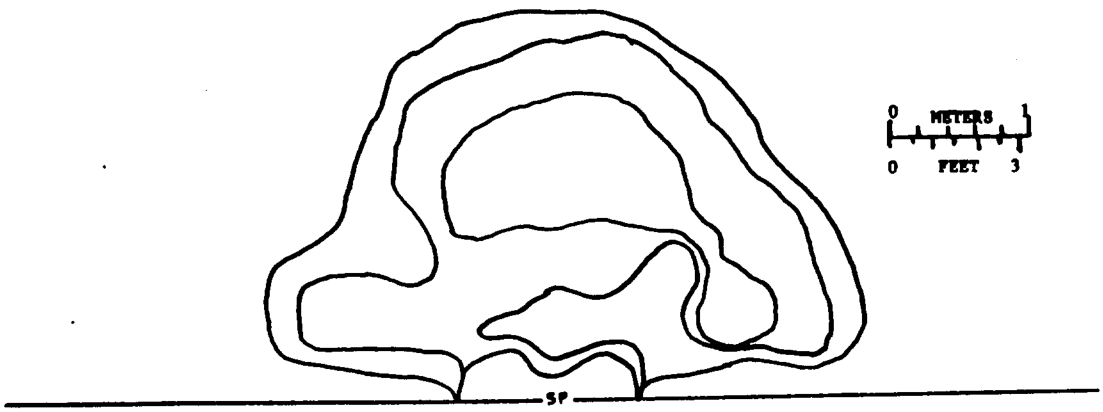
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 28

Comparison #76, FLOW RATE

Variable- Flow Rate, Test #22- 10 gpm, Test #20- 20 gpm, Test #21- 30 gpm
Constant- SSU, 1.0" Supply Pipe, 1 Directional Supply, 7" Clearance, Arms Parallel to Pipe

3.0 mm/min. isodensity lines for each test are shown.



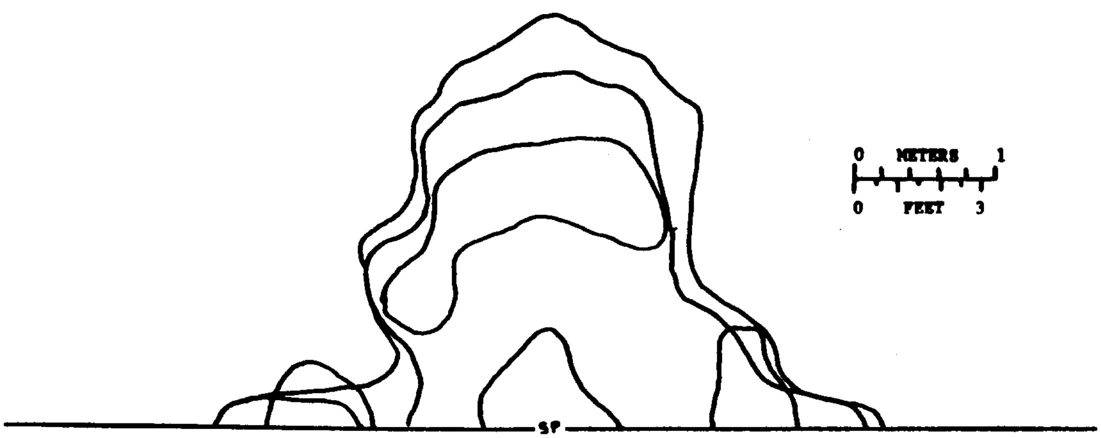
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 29

Comparison #78, FLOW RATE

Variable- Flow Rate, Test #31- 10 gpm, Test #29- 20 gpm, Test #30- 30 gpm
Constant- SSP, 1.0" Supply Pipe, 1 Directional Supply, 7" Clearance, Arms Parallel to Pipe

3.0 mm/min. isodensity lines for each test are shown.



SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 30

coverage area. Looking then at the 1.5 mm/min. (.037 gpm/ft.^{2}) isodensity lines, one sees the final development of the area within the isodensity line as the maximum area is approached.

If one were to define a required density, the area of coverage of a head would be defined by the area within the isodensity line corresponding to the required density. Figures 29 and 30 show clearly that below a given flow rate the coverage area is not yet developed sufficiently to constitute a feasible coverage area. However, figures 27 and 28 show that increases in flow rate beyond the flow which results in the minimum feasible coverage area yield smaller and smaller increases in coverage area. Thus, in terms of efficient use of water the optimum coverage area is the minimum feasible coverage area. This does not mean that the minimum feasible coverage area would result in the least cost sprinkler system since larger coverage areas may allow the use of fewer branch lines. This does mean that using the minimum feasible coverage area will result in the minimum use of water and will allow the smallest pipe sizes to be used. The economic optimum is determined by the relative cost functions for branch lines, alternate pipe sizes, and water supply. The effect of smaller coverage areas on sprinkler actuations will not be discussed, but the effects certainly require consideration.

8.2 Pipe Diameter

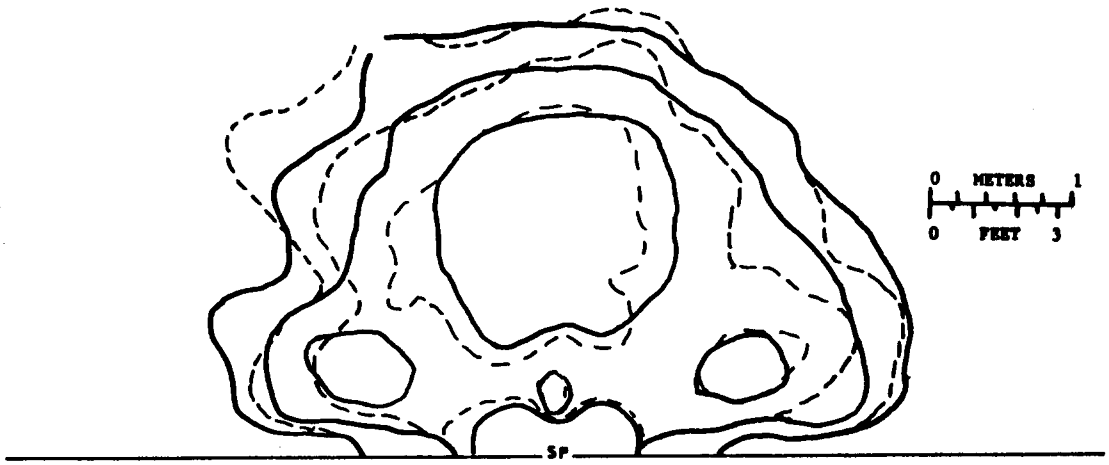
Tests were conducted using black steel pipe of 26.6, 40.9 and 50.2 mm (1.049, 1.610, and 2.067 in.) internal diameter. In all cases increases in pipe size had an adverse effect on the distribution pattern.

Figures 31 and 32 illustrate the effect of pipe size on the distribution pattern from upright heads. The figures indicate that the

Comparison #1, PIPE DIAMETER

Variable - Pipe Size, Test #R30U - 1.0", Test #9 - 2.0"
Constant - SSU, 1 Directional Supply 30 gpm, 7" Clearance, Arms Parallel to Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test #R30U and Test #9, respectively.



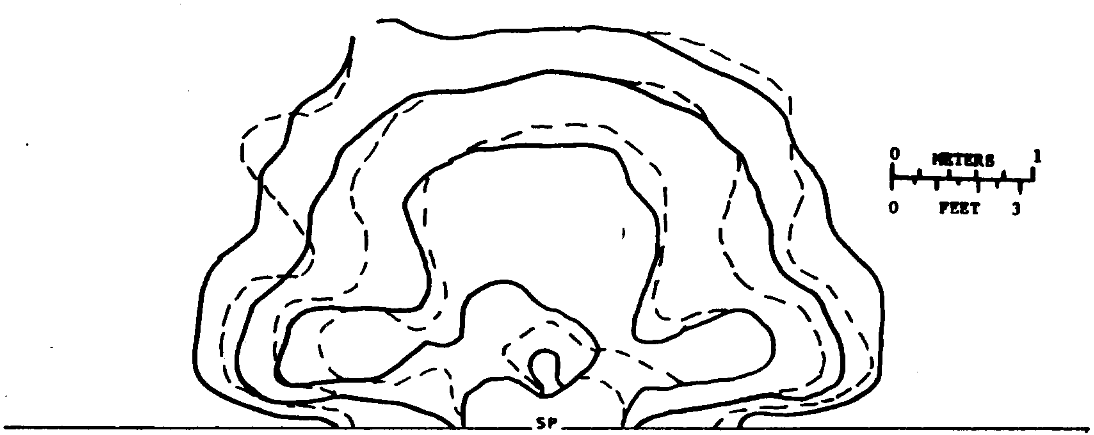
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 31

Comparison #8, PIPE DIAMETER

Variable - Pipe Size, Test #23-1.0", Test #74-1.5"
Constant - SSU, 2 Directional Supply, 30 gpm, 7" Clearance, Arms Parallel to Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test #23 and Test #74, respectively.



SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 32

width of the potential coverage area is reduced by increases in pipe size. While the isodensity lines are never circular, increases in pipe size reduce the circular nature of the isodensity lines.

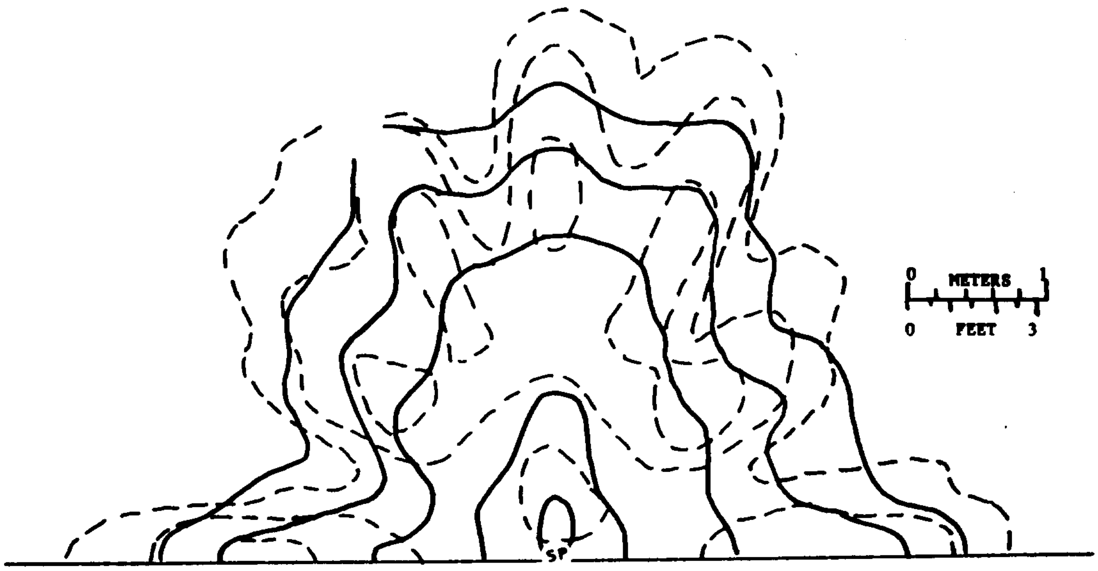
The effect of pipe size on the distribution patterns from pendent heads is far greater than the effect on upright heads. Increases in pipe size from 26.6 mm (1.049 in.) change the whole nature of the distribution pattern. Figures 33 - 36 illustrate the transformation. As a result of increases in pipe size the "void" or area of reduced density below the head is greatly increased in size. At the same time the pattern develops fingers of higher density reaching outward. The distance from the sprinkler where water is distributed is increased. As is the case with both upright and pendent heads, the effect of pipe size changes from 26.6 mm (1.049 in.) to 40.9 mm (1.610 in.) are greater than changes from 40.9 mm (1.610 in.) to 50.2 mm (2.067 in.).

In 26.6 mm (1.049 in.) diameter pipe tests a "spurting" unsteadiness was observed in the stream issuing from the nozzle of the sprinkler of both upright and pendent heads. The phenomena was not observed in larger diameter pipe tests and could not be correlated to the Reynold's Number or the velocity of flow in the supply pipe. The frequency of the "spurting" was related to the flow rate, being very slow at 37.8 dm^3/min. (10.0 gpm) and much more rapid at 113.6 dm^3/min. (30.0 gpm). Given the superiority of the distribution patterns from the sprinklers on 26.6 mm (1.049 in.) diameter supply pipes, it would seem that the unsteadiness of the stream from the nozzle of the sprinkler has an advantageous effect on the distribution. This suggests that sprinkler heads be designed to produce unsteady, highly turbulent streams.

Comparison #13, PIPE DIAMETER

Variable - Pipe Size, Test #27-1.0", Test #14-2.0"
Constant - SSP, 2 Directional Supply 30 gpm, 7" Clearance, Arms Parallel of Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test #27 and Test #14, respectively.



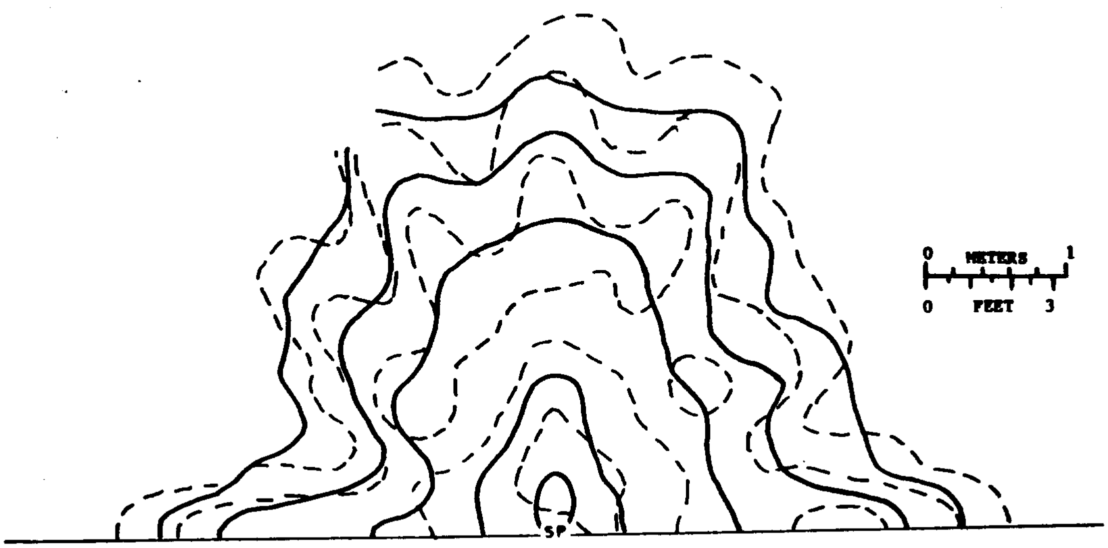
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 33

Comparison #14, PIPE DIAMETER

Variable - Pipe Size, Test #27-1.0", Test #73-1.5"
Constant - SSP, 2 Directional Supply, 30 gpm, 7" Clearance, Arms Parallel to Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test #27 and Test #73, respectively.



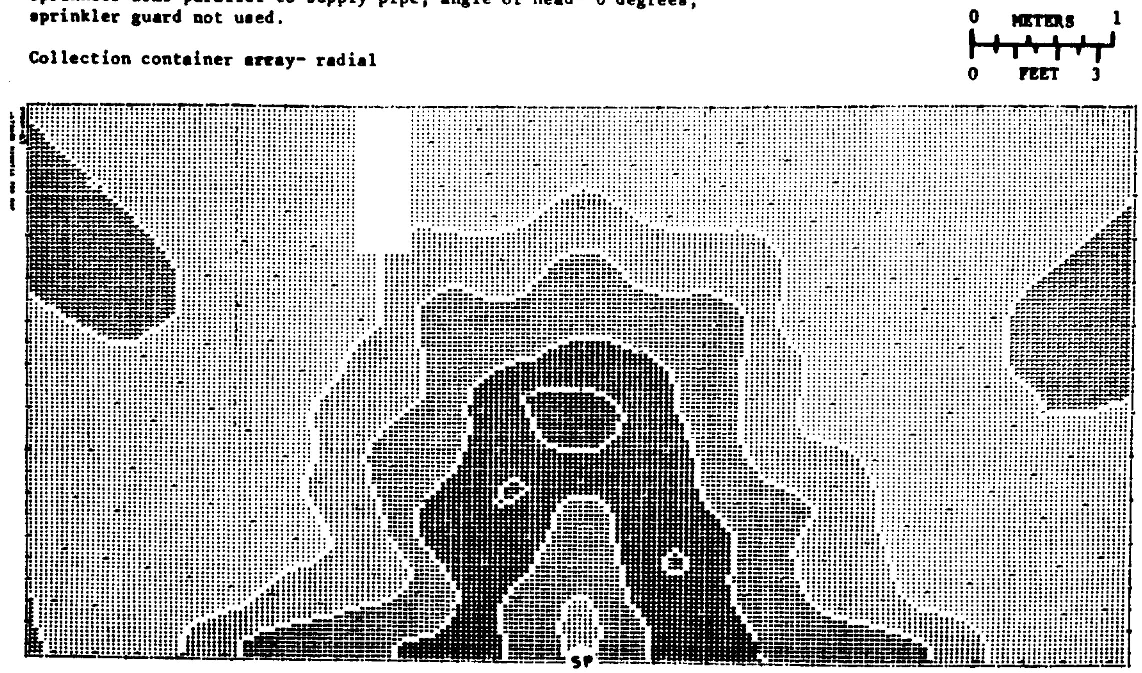
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 34

Test #27

Pendent head, flow rate- 30 gpm, size of supply pipe- 1.0 inches, directionality of supply- two, deflector to ceiling clearance- 7.0 inches, sprinkler arms parallel to supply pipe, angle of head- 0 degrees, sprinkler guard not used.

Collection container array- radial



See Appendix A for explanation of density coding.

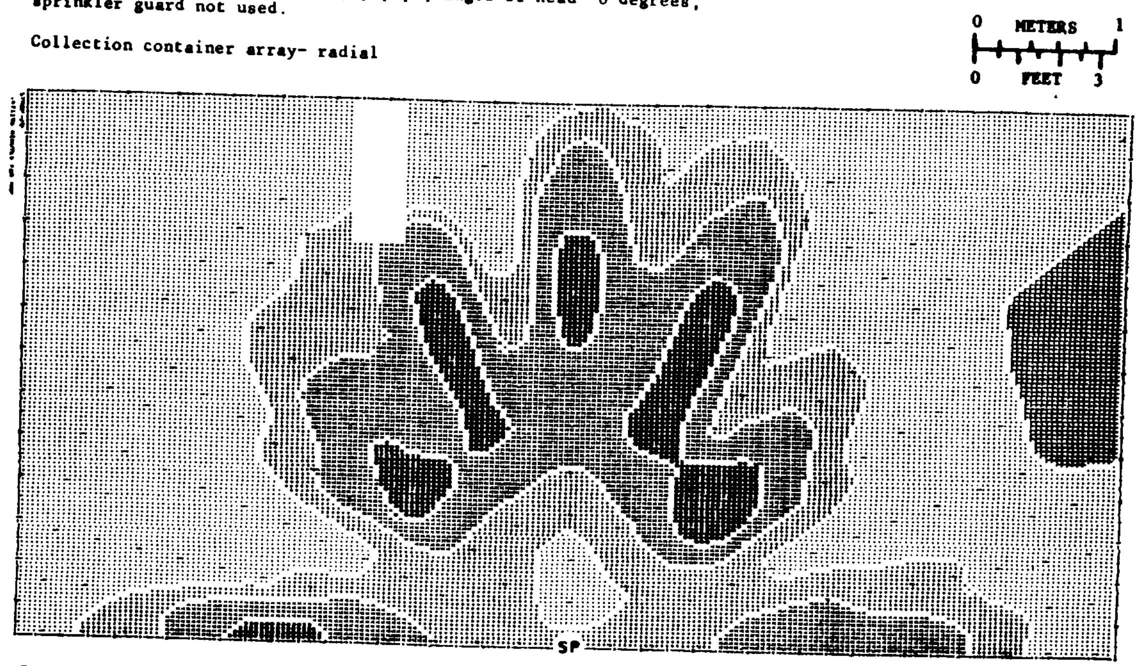
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 35

Test #14

Pendent Head, flow rate- 30 gpm, size of supply pipe- 2.0 inches, directionality of supply- two, deflector to ceiling clearance- 7.0 inches, sprinkler arms parallel to supply pipe, angle of head- 0 degrees, sprinkler guard not used.

Collection container array- radial



See Appendix A for explanation of density coding.

SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 36

8.3 Direction of Supply

One and two directional water supply comparisons were made for 26.6, 40.9, and 50.2 mm (1.049, 1.610 and 2.067 in.) diamter supply pipe tests with upright heads and a 26.6 mm (1.049 in.) diamter supply pipe with a pendent head. In all one directional supply tests the supply was from the right side of the figure.

Figures 37 and 38 illustrate the effect of the direction of supply on the distribution pattern for upright heads. Figure 37 is representative of the 40.9 and 50.2 mm (1.610 and 2.067 in.) supply pipe tests. Figure 38 is representative of the effects of direction of supply on the distribution pattern from upright heads on 26.6 mm (1.049 in.) supply pipes. An explanation of the different effects found for 26.6 mm (1.049 in.) and the large supply pipe tests has not been formulated. However, it is clear the unsteadiness of the stream was greater for 26.6 mm (1.049 in.) supply pipe tests.

Figure 39 represents the effect of direction of supply on the pattern from pendent heads on 26.6 mm (1.049 in.) supply pipes. The area within each isodensity lines was widened and shortened slightly. The "void" beneath the head was also increased slightly for two directional supply. The results for both upright and pendent heads are qualitatively similar to the results found for increasing pipe size. This data indicates the unsteadiness and turbulence in the stream from nozzles appears to be the factor in thest tests as well.

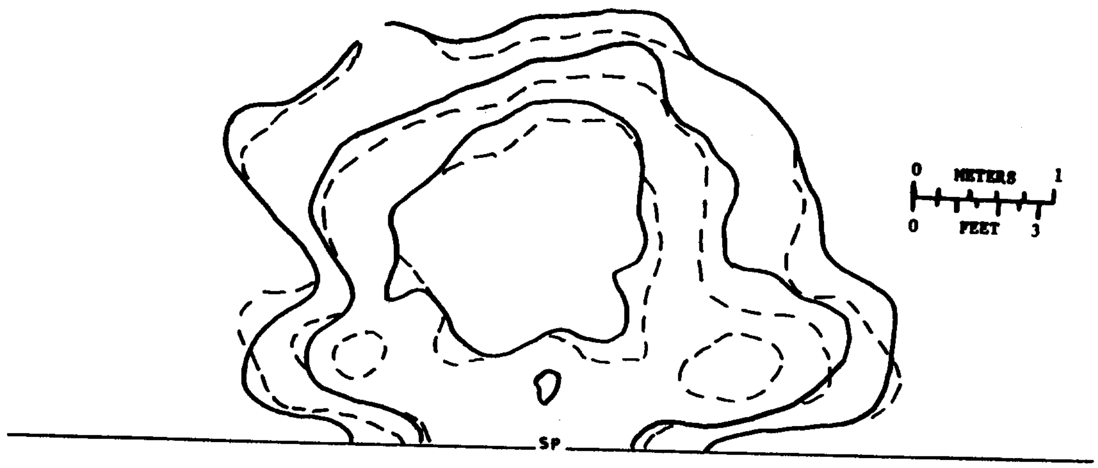
8.4 Hydraulic Considerations

Changes in the size of the supply pipe and in the directionality of supply alter the hydraulic environment of the sprinkler. The examination

Comparison #19, DIRECTION OF SUPPLY

Variable - Direction of Supply, Test 9-1 Directional, Test #11-2 Directional
Constant - SSU, 2" Supply Pipe, 30 gpm, 7" Clearance, Arms Parallel to Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test #9 and Test #11, respectively.



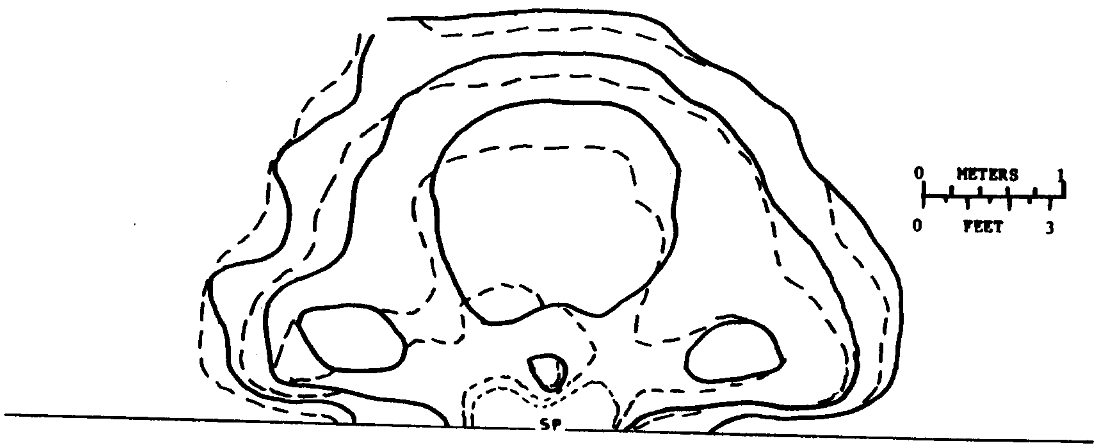
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 37

Comparison #25, DIRECTION OF SUPPLY

Variable - Direction of Supply, Test # R30U-1 Directional, Test #23-2 Directional
Constant - SSU, 1.0" Supply Pipe, 30 gpm, 7" Clearance, Arms Parallel to Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test #R30U and Test #23, respectively.



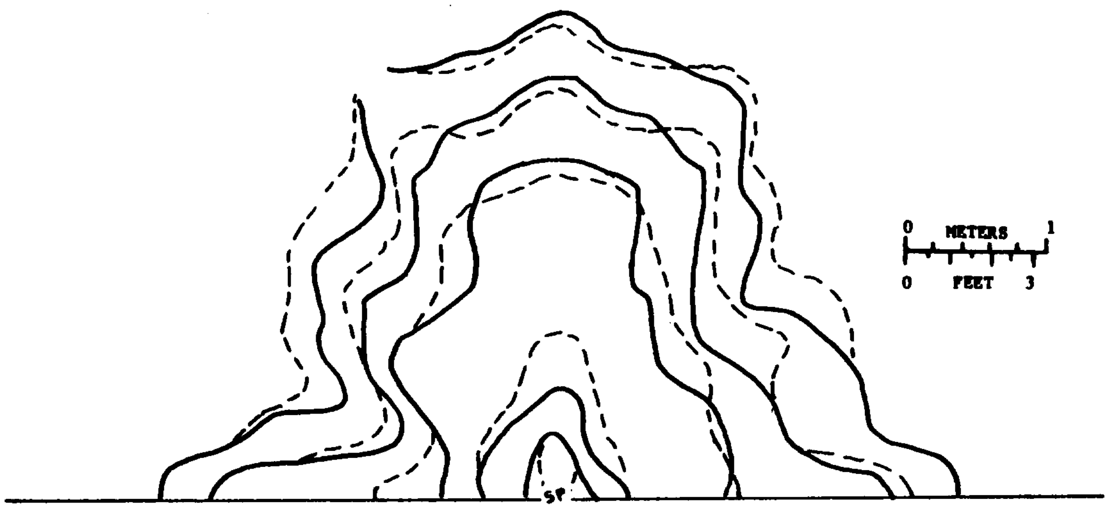
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 38

Comparison #28, DIRECTION OF SUPPLY

Variable - Direction of Supply, Test R30P-1 Directional, Test #27-2 Directional
Constant - SSP, 1.0" Supply Pipe, 30 gpm, 7" Clearance, Arms Parallel to Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min, isodensity lines for Test #R30P and Test #27, respectively.



SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 39

of the effects of these variables have indicated the tests with high Reynolds Numbers in the flow to the sprinkler (small pipe sizes and one directional supply) had improved distribution patterns. The varying spatial location of the effects indicate there is no unique relation between the distribution pattern and Reynold's Number. However, intuitively it would appear the Reynold's Number of the flow in the supply pipe is an important variable. In order to confirm this intuitive observation, the correlation between the degree to which a pattern was modified and the change in Reynold's Number in the supply pipe flow has been evaluated. The measure used to determine the degree to which a pattern was modified was the number of data points where a significant change was noted between the two tests being compared. The comparisons conducted to evaluate the effect of pipe size and the direction of supply with the data points where a significant difference was found were plotted against the change in the Reynold's Number of the flow in the supply pipe. The results are plotted in figures 40 and 41.

These figures support the observation that the Reynold's Number of the supply pipe flow is an important determinant of the distribution pattern. The percent of the variations explained by the change in Reynold's Number for the linear curve fits plotted are shown in Table 2.

These fits include the effects of "spurting" as the "spurting" frequency is a function of the flow rate in the 26.6 mm (1.049 in.) supply pipe and thus is a function of the Reynold's Number. While these curve fits give no indication of the spatial location of the effects of the hydraulic variables they do indicate the expected magnitude of the effect.

Figures 40 and 41 indicate, as have previous isodensity plots, the effects of pipe size on the distribution patterns from sprinklers. It has been observed and collaborated by statistical correlation that the underlying cause of this effect is the turbulence of the supply flow and the resulting stream which is less steady and less coherent. Marshall (1) has indicated that stream breakup is best effected if the stream has begun to collapse just before impacting the deflector. The highly turbulent and less well defined streams resulting from high Reynold's Numbers will collapse more quickly than low turbulence streams. The stream breakup and resulting distributions observed in this study indicate the streams of the pendent heads supplied by large diameter pipes have not yet begun to collapse on impact. Thus, the resulting distribution patterns are less uniform. However, the hydraulic environment of the upright sprinkler head

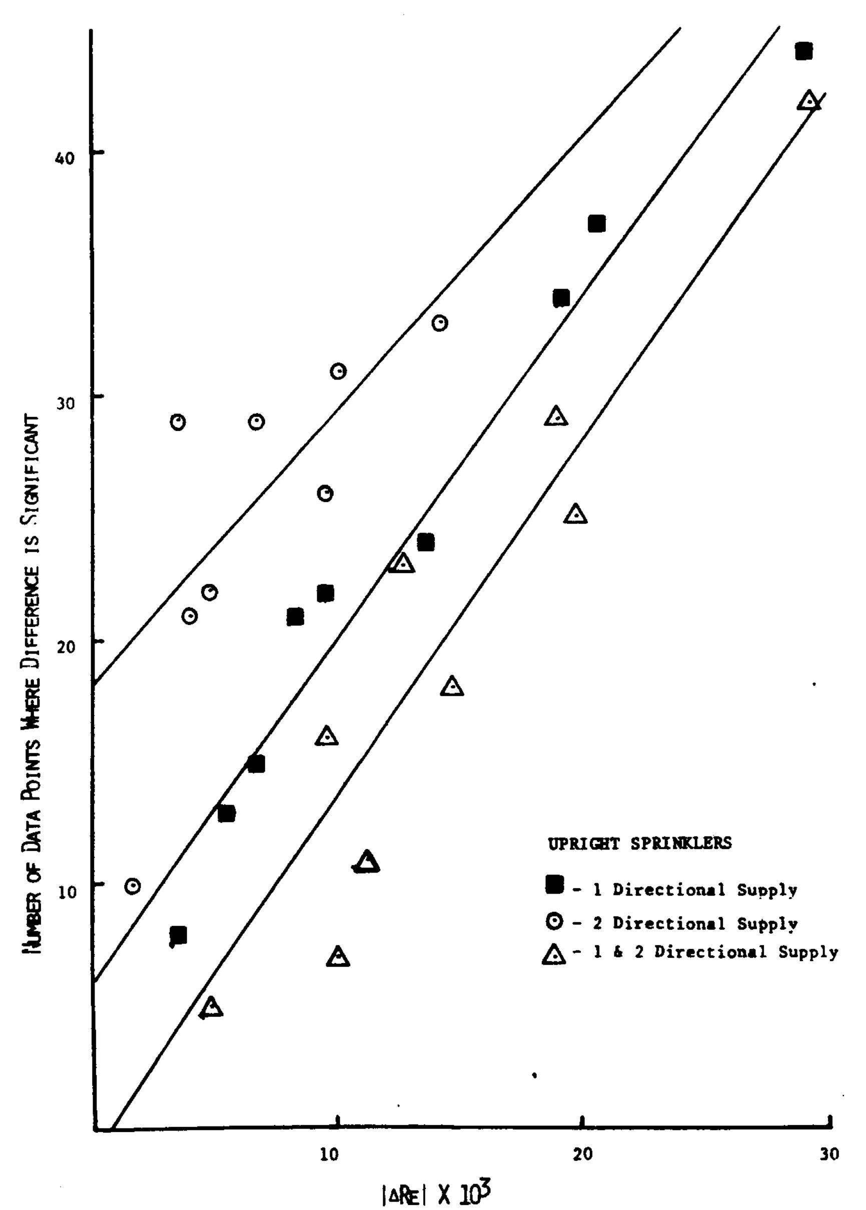


Figure 40

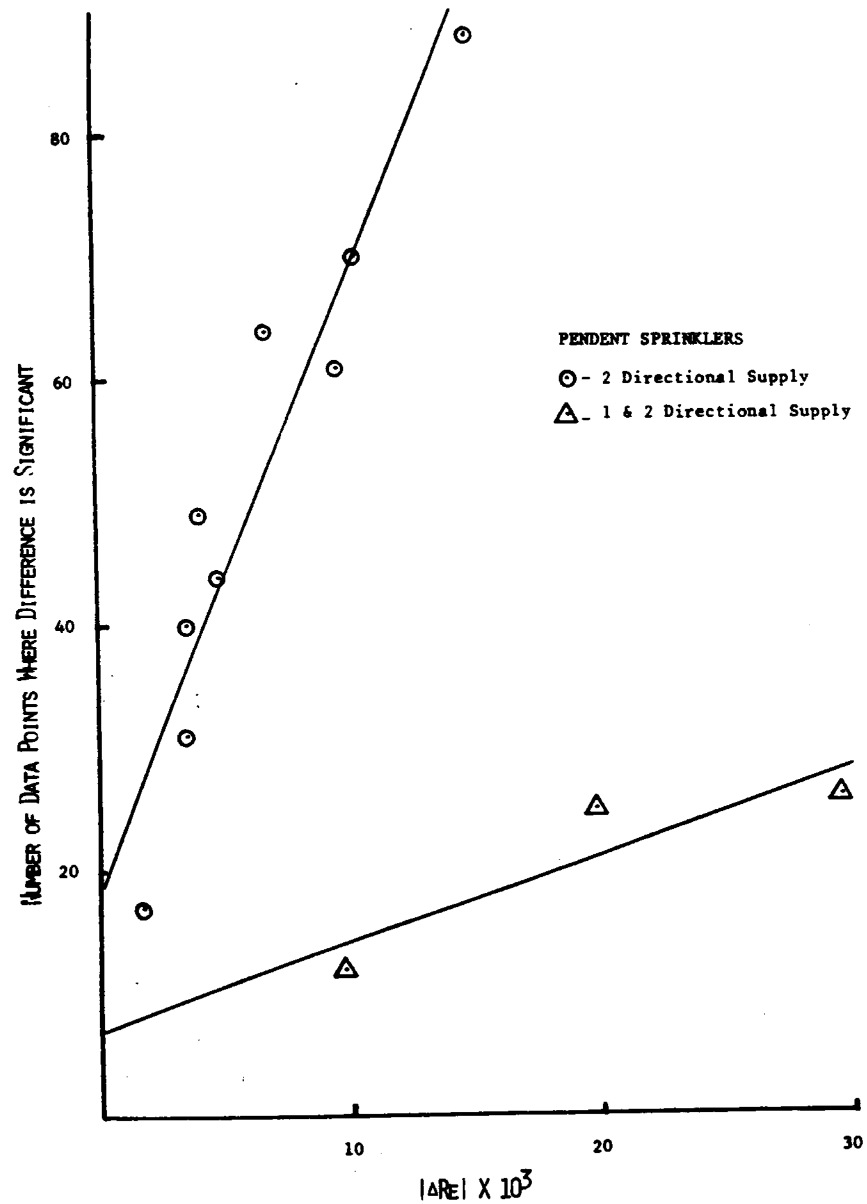


Figure 41

Table 2

Test Group - Variable	% Variation Explained
1 Directional Supply, Upright - Pipe Size	96.5%
2 Directional Supply, Upright - Pipe Size	43.3%
1 & 2 Directional Supply, Upright - Direction of Supply	89.9%
2 Directional Supply, Pendent - Pipe Size	88.7%
1 & 2 Directional Supply, Pendent - Direction of Supply	81.3%

was equivalent to that of the pendent head when tested on the same size pipe at the same flow rate. The nozzles themselves were identical. It would appear some other factor must contribute to the poor pendent head patterns.

The reason for the less uniform patterns for pendent heads relative to upright heads on large diamter pipes appears related to the orientation of the head and the effects of gravity on the stream from the time it leaves the nozzle and the time it impacts upon the deflector. The effect can best be visualized by examination of an analogy. Consider a short rod connected with a pin joint to a small plate. The plate is held horizontally with the rod held vertically above the plate. If the rod is released, it will fall onto the plate. The vertical position is one of unstable equilibrium. Had the plate been turned over and the rod held vertically below the plate on releasing the rod it would remain in place. Thus the orientation of the stream from an upright head is in a position of unstable equilibrium which shortens the collapse length. The stream from a pendent head, however, is in a position of stable equilibrium and gravity does not act to collapse the stream. The explanation accounts for the less uniform patterns resulting from pendent heads. The problem may be alleviated by increasing the turbulence and unsteadiness of the stream or by increasing the distance from the nozzle to the deflector so that collapse of the stream may occur before impact.

8.5 Deflector to Ceiling Clearance

Tests were conducted with deflector to ceiling clearances from 25 mm (1.0 in.) to 457 mm (18.0 in.). Tests run with deflector to ceiling clearances of 25 and 76 mm (1.0 and 3.0 in.) showed modifications in the distribution patterns relative to the pattern found with 178 mm (7.0 in.) clearance test.

Figures 42 and 43 illustrate the effect of reducing the deflector to ceiling clearance from 178 mm to 25 mm (7.0 to 1.0 in.) for upright and pendent heads. It is entirely reasonable to expect when the deflector to ceiling clearance is small, the coverage area of the sprinkler head should increase. This increase in coverage area appears to be due to the reduction in air entrainment caused by the proximity of the ceiling to the spray pattern. The energy which would ordinarily be dissipated in the air entrainment process is maintained by the droplets and results in higher droplet velocities with smaller deflector to ceiling clearances. Therefore, droplets are found at a greater horizontal distance from the sprinkler head at the horizontal plane of the collection containers.

8.6 Orientation of the Sprinkler Arms

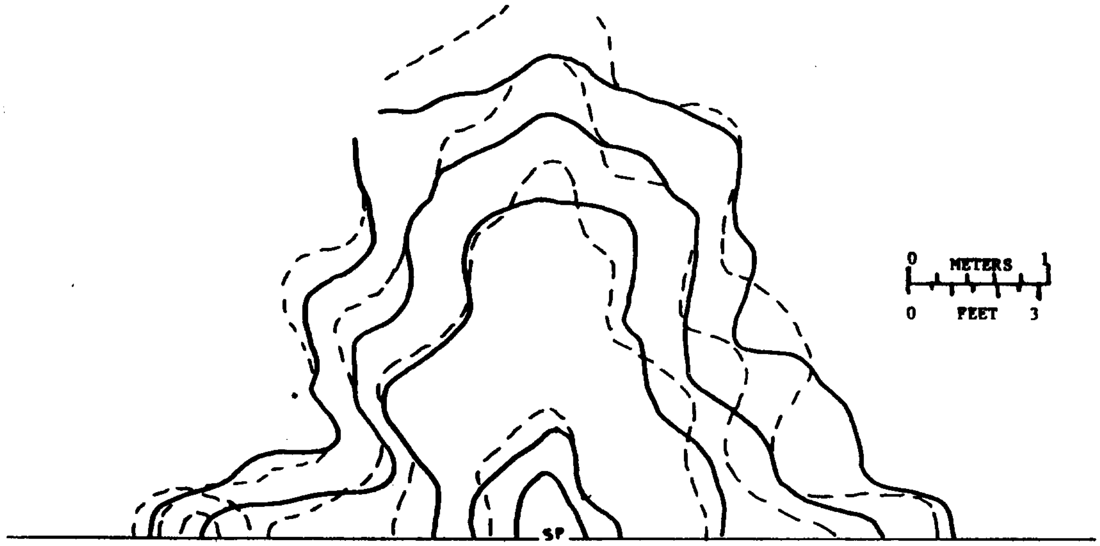
It became apparent early in the study, the deflector arms of the sprinkler heads were important determinants of the discharge pattern. All the distribution patterns at 75.7 and 113.6 dm^3/min. (20.0 and 30.0 gpm) exhibited a major axis perpendicular to the supply pipe and the sprinkler deflector arms. By observation it appeared the location of the major axis was determined by the sprinkler deflector arms rather than the supply pipe.

In order to check this observation, tests were conducted with the deflector arms of both upright and pendent heads perpendicular to the supply pipe. As expected, the major and minor axes rotated 90 degrees

Comparison #31, DEFLECTOR TO CEILING CLEARANCE

Variable - Clearance, Test #R30P-7" Clearance, Test #94-1" Clearance
Constant - SSP, 1.0" Supply Pipe, 1 Directional Supply, 30 gpm, Arms Parallel to Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test #R30U and Test #94, respectively.



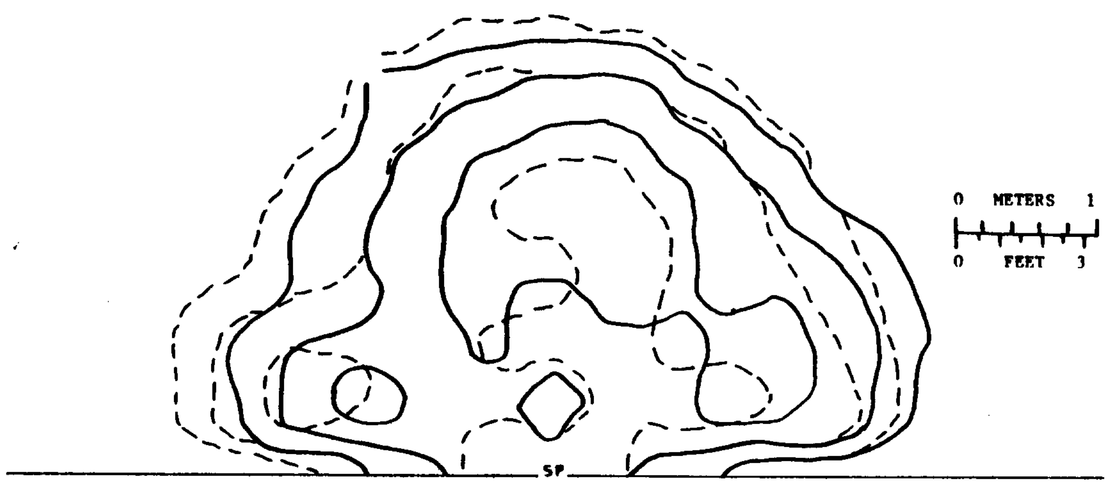
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 42

Comparison #40, DEFLECTOR TO CEILING CLEARANCE

Variable - Clearance, Test #R30U-7" Clearance, Test #52-1" Clearance
Constant - SSU, 1.0" Supply Pipe, 1 Directional Supply, 30 gpm, Arms Parallel to Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test #R30U and Test #52, respectively.



SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 43

with the major axis remaining perpendicular to the sprinkler arms. This is illustrated in figure 44.

8.7 Angle of the Sprinkler Head

In order to assess the effects of the variation of the angle of the deflector from a perfectly horizontal position, tests were conducted with the sprinkler head rotated so that the deflector was at an angle of +5 and -5 degrees from the horizontal. The angle of the deflector was examined both from the standpoint of the need for quality control in the installation of the head and for possible use of an angular installation of the head as a design parameter. Larger angles were not studied because such a test would have required a sloped ceiling designed experimental apparatus.

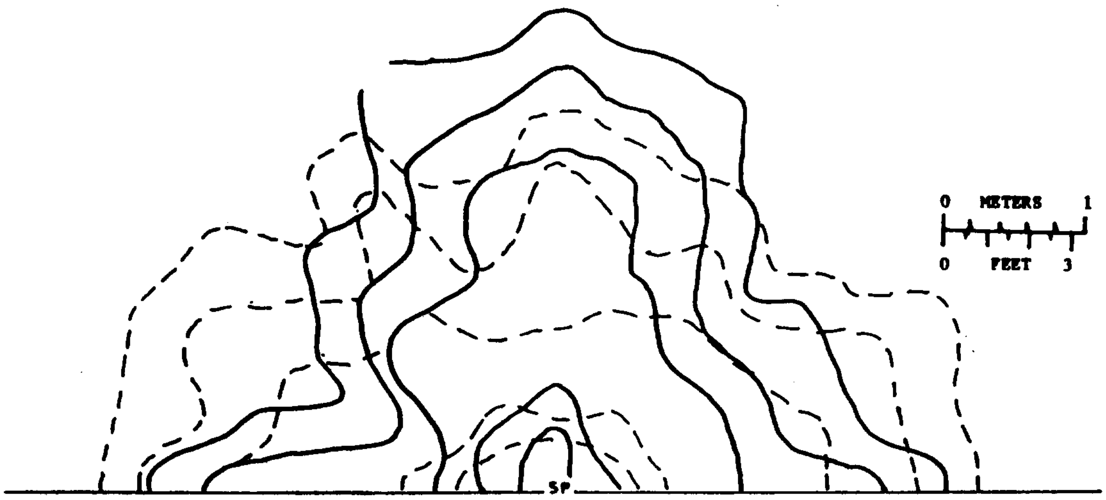
The effects of the +5 and -5 degree angle on the distribution patterns from upright heads are shown in figures 45 and 46. The location of isodensity lines are moved away from the sprinkler and minor decreases in density nearer the sprinkler are a result of the change to a +5 degree deflector angle. The distance that the isodensity lines moved away from the sprinkler was not sensitive to the flow rate. A change in the angle to -5 degrees moved the isodensity lines closer to the head and increased the densities nearer the head. Again, the magnitude of the translation of the isodensity lines was not sensitive to flow rate. The translation was slightly greater at 75.7 dm^3/min. (20.0 gpm) than at 37.8 (10.0 gpm) and 113.6 dm^3/min. (30.0 gpm).

The effect of the angle of the sprinkler on pendent heads was unlike the response of upright heads. The effects are illustrated in figures 47 and 48. For the changes in angle to +5 degrees the isodensity lines moved

Comparison #58 - ARM ORIENTATION

Variable - Arm Orientation, Test #R30P-parallel, Test #68-perpendicular
Constant - SSP, 1.0" Supply Pipe, 1 Directional Supply, 30 gpm, 7" Clearance

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test #R30P and Test #68, respectively.



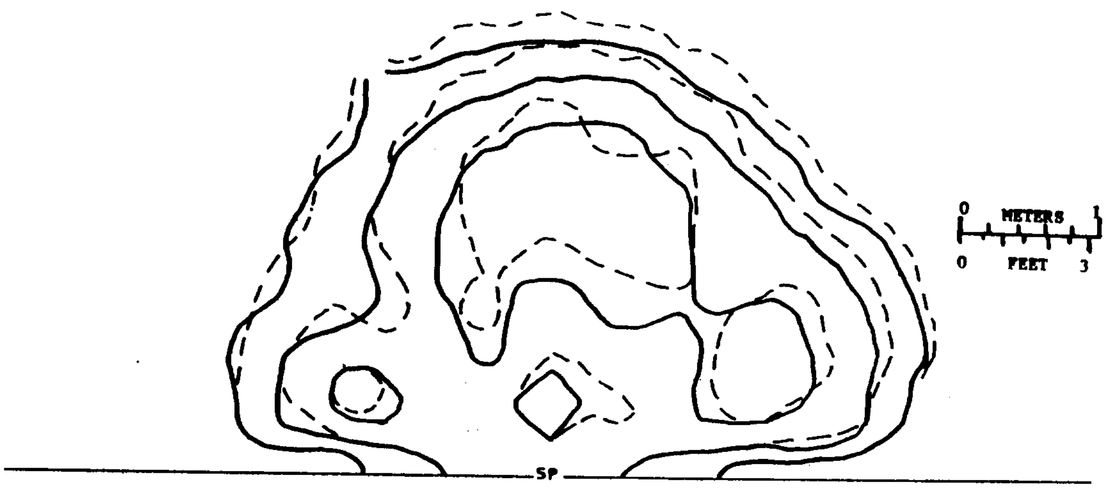
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 44

Comparison #49-A, ANGLE OF HEAD

Variable - Angle of Head, Test #R30U-0 degrees, Test #58-+5 degrees
Constant - SSU, 1.0" Supply Pipe, 1 Directional Supply, 30 gpm, 7" Clearance, Arms Parallel to Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test #R30U and Test #58, respectively.



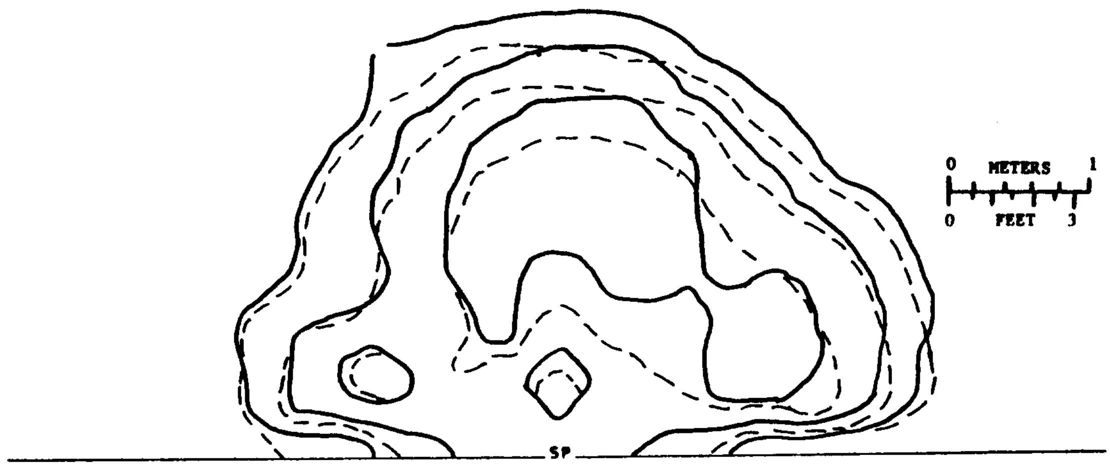
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 45

Comparison #49-B, ANGLE OF HEAD

Variable - Angle of Head, Test #R30u-0 degrees, Test #55- -5 degrees
Constant - SSU, 1.0" Supply Pipe, 1 Directional Supply, 30 gpm, 7" Clearance, Arms Parallel to Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test R30U
and Test #55, respectively.



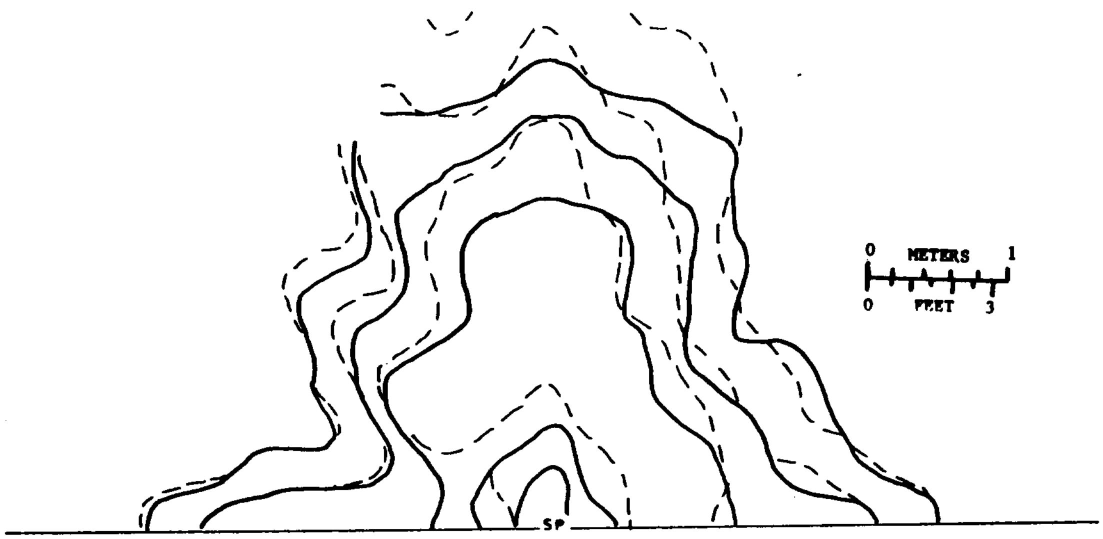
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 46

Comparison #52-A, ANGLE OF HEAD

Variable - Angle of Head, Test #R30P-0 degrees, Test #64- +5 degrees
Constant - SSP, 1.0" Supply Pipe, 1 Directional Supply, 30 gpm, 7" Clearance, Arms Parallel to Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test #R30P
and Test #64, respectively.



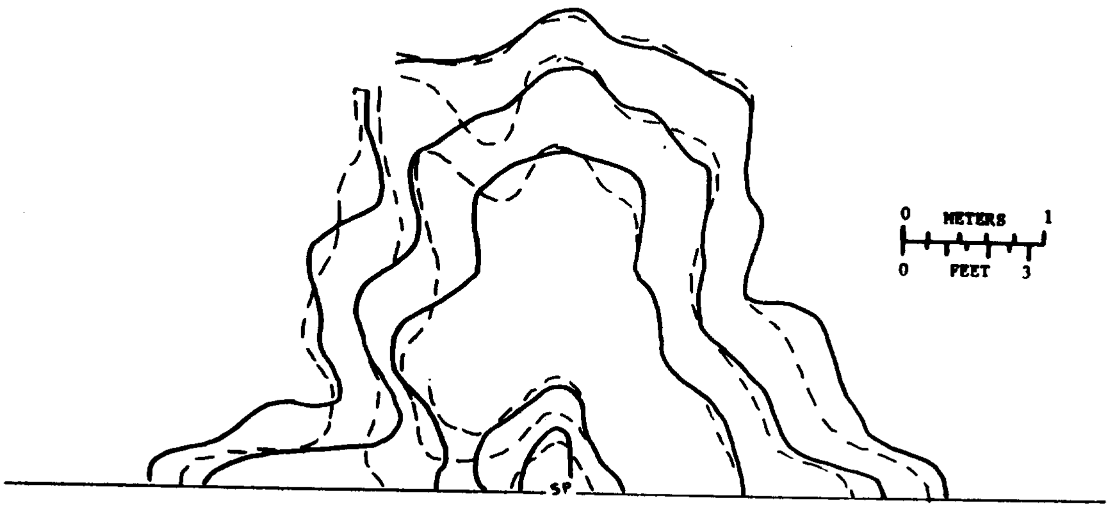
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 47

Comparison #52-B, ANGLE OF HEAD

Variable - Angle of Head, Test #R30P-0 degrees, Test #65- -5 degrees
Constant - SSP, 1.0" Supply Pipe, 1 Directional Supply, 30 gpm, 7" Clearance, Arms Parallel to Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test #R30P and Test #65, respectively.



SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 48

away from the head and minor decreases in density resulted nearer the head. However, the movement of the isodensity lines was a function of flow rate, being greatest at 113.6 dm^3/min. (30.0 gpm). A decrease in the angle to -5 degrees had only very minor effects on the location of isodensity lines. Some small increases in density near the sprinkler were realized.

The tests indicate that alterations of the distribution pattern will result from angles as small as 5 degress. Efforts should be made in installation to insure that the deflector is in fact horizontal. It is not appropriate to attempt to extrapolate these results to larger angels which might be found in installations under peaked roofs. While further testing is necessary these tests indicate the uniformity of the distribution pattern would be expected to be reduced by angular installation.

8.8 Sprinkler Guards

Three tests were conducted with a pendent head equipped with a sprinkler guard. The wires of the sprinkler guard distruped the spray pattern, resulting in reductions in the area within isodensity lines. Figure 49 shows the effect of the use of sprinkler guards. The figure indicates that the coverage area of sprinkler should be reduced when sprinkler guards are utilized.

8.9 Superposition Principle

Tests were conducted with two heads placed 3.2 m (10.5 ft.) apart on a 40.9 mm (1.610 in.) diameter supply pipe. Tests were conducted at 56.8 (15.0 gpm) and 94.6 $dm^3/min.$ (25.0 gpm) for both upright and pendent heads. The series included tests with the discharge from each head individually collected and tests with the discharge from both heads collected. When the discharge from only one head was collected, both heads were flowing in order to maintain the similarity in the hydraulic variables which have been identified to be important. Flow from the sprinklers not being collected was diverted from the collection containers using the apparatus preivously described.

The results of the tests where only the discharge from one or the other head was collected were combined by superposition. The collection array used in this series was rectangular to facilitate superimposing data. The superimposed data was compared to the results of tests where the discharge from both heads was collected. The comparison of the superimposed data and the two head test data is shown in figures 50 and 51.

It is important to note the experimantal procedure was more difficult for this test series and errors in the superimposed data are additive.

Comparison #61, SPRINKLER GUARD

Variable - Sprinkler Guard, Test #73-without, Test #78 with
Constant - SSP, 1.5" Supply Pipe, 1 Directional Supply, 30 gpm, 7" Clearance, Arms Parallel to Pipe

Solid and dashed lines are 1.5, 3.0, 6.0 mm/min. isodensity lines for Test #73 and Test #78, respectively.

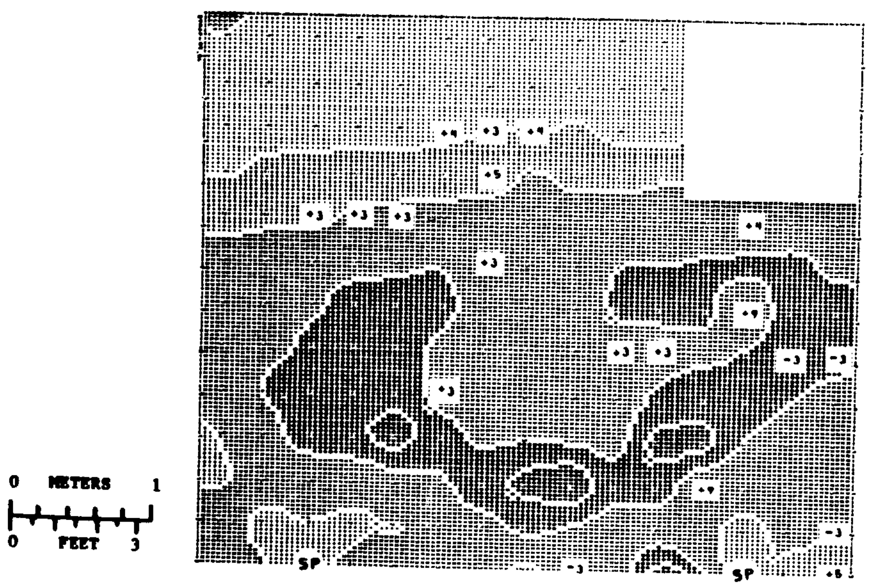
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 49

Comparison #65, SUPERPOSITION

Variable - Superposition, Test #86, 89-Superposition, Test #91 - Actual 2 Head Test
Constant - SSU, 25 gpm/Head, 1.5" Supply Pipe, 7" Clearance, Arms Parallel to Pipe

Test #86, 89 is mapped. Numerical values indicate percent difference of Test #91 relative to Test #86, 89, i.e. +3 indicates Test #91 exceeds Test #86, 89 by 25-35%.



Densities corresponding to each shaded area and full description of percent difference coding are given in Appendix A.

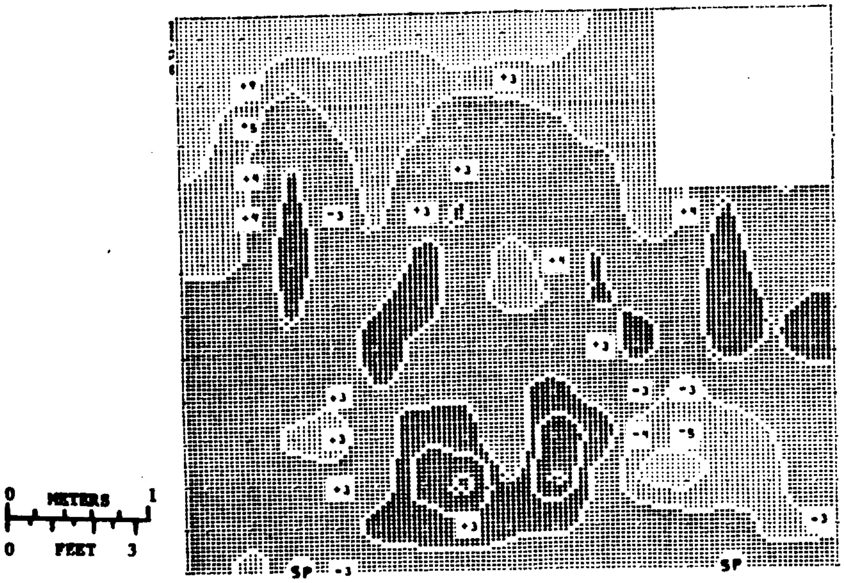
SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 50

Comparison #67, SUPERPOSITION

Variable - Superposition, Tests #80, 83-Superposition, Test #84- Actual 2 Head Test
Constant - SSP, 25 gpm/Head, 1.5" Supply Pipe, 7" Clearance, Arms Parllel to Pipe

Test #80, 83 is mapped. Numerical values indicate percent difference of Test #84 relative to Test #80, 83, i.e. +3 indicates Test #84 exceeds Test #80, 83 by 25-35%.



Densities corresponding to each shaded area and full description of percent difference coding are given in Appendix A.

SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 51

Thus differences in excess of 25% can be attributed to factors other than the validity of the superposition principle. Thus, the superposition principle appears to be an appropriate tool for determining the distribution patterns from multiple heads.

It is apparent that more testing would be required to validate or determine the limitations and errors induced by the superposition principle. Two important factors, the probability of particle collisions and the nature and results of the interaction would cause the predictive power of the superposition principle to be reduced. The probability of particle collisions is directly related to the density of water particles in space. That is, if much of a control volume is occupied by particles, collisions are highly probable. Visual observations of the tests in this series indicated the density was low and the particles from each sprinkler passed without visible collision. Since collisions were not visible, the nature of the particle collisions is unknown. A discussion of droplet collisions and a review of literature is presented by Labes (2).

It appears the density of particles in space will be greater at smaller distances from the sprinkler head. Thus, sprinklers spaced more closely together would tend to violate the assumptions which allow the use of the superposition principle to a greater degree than did the sprinklers in this test series. Further testing at closer spacings could establish the limitations of the use of the superposition principle. The simplicity of the superposition principle is attractive for design purposes. Detailed study could establish appropriate safety factors needed to make use of the superposition principle for determing the density distribution in a design situation.

8.10 Quality Control

Figure 52 illustrates the results of tests of two upright heads of the same model. The figure indicates the differences between sprinklers of the same model and manufacturer can be as great as the effects of some of the variables studied. The lack of symmetry in the two head tests shown in figures 50 and 51 further illustrates the differences in the distribution patterns due to problems of quality control. The analysis of variance due to manufacturing, shipping, and installation requires further study and quantification.

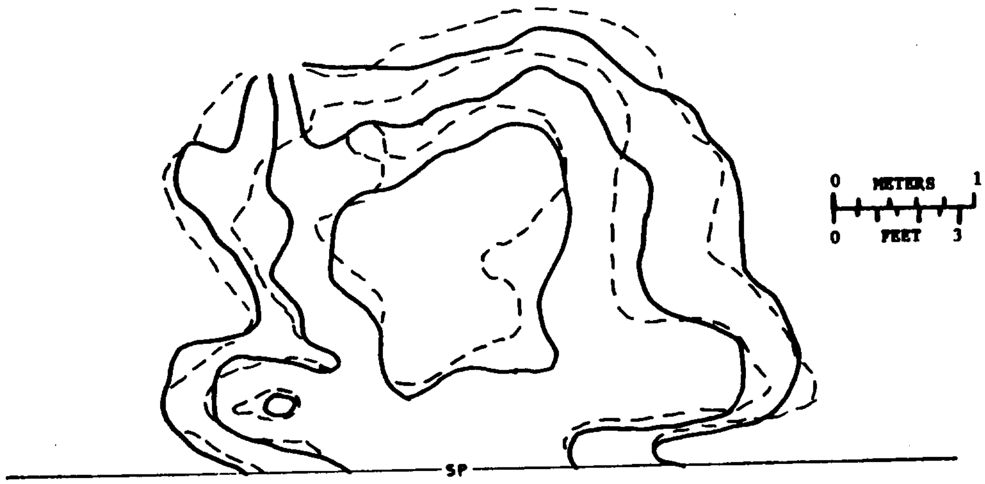
9. Implications for Design

A number of points of interest to manufacturers and fire protection engineers have arisen in the course of this study. These represent design implications for sprinkler heads and system layouts.

Comparison #74, QUALITY CONTROL

Variable - Quality Control, Test #1 and #2 are the same model sprinkler head
Constant - SSU, 2" Supply Pipe, 1 Directional Supply, 7" Clearance, Arms Parallel to Pipe, 30 gpm

Solid and dashed lines are 1.5, 3.0, and 6.0 mm/min. isodensity lines for Test #1 and Test #2.



SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 52

9.1 Implications for Sprinkler Head Design

While not a variable addressed in this study, implications for sprinkler head design have been recognized from the observation of the effects of pipe size and arm orientation on the distribution pattern.

As discussed previously, the uniformity of the distribution pattern is improved by highly turbulent, unsteady flow from the sprinkler nozzle. This turbulence and unsteadiness reduces the collapse length of the stream, which to achieve good stream breakup needs to be less than the nozzle to deflector distance. The importance of this breakup is most clearly shown in large diameter supply pipe pendent head tests.

In this test series the turbulence and unsteadiness of the nozzle stream was caused by shear flow in the supply pipe. Of course the sprinkler head designer cannot choose the size of the pipe which will supply the head. However, he need not depend on external factors to create this unsteadiness. The needed turbulence can be induced by systematically introducing surfaces of velocity discontinuity into the design of the nozzle. In this manner turbulence is induced without dependence on the characteristics of the supply pipe flow.

The effects of the arms of the sprinklers on the distribution pattern illustrate a second result important to the sprinkler head designer. It has been assumed that sprinkler arms constitute an unfortunate structural necessity, which degrade the performance of sprinkler heads. This test series has, however, illustrated the importance and functionality of the sprinkler arms in forming the distribution pattern. Without the arms, a pattern with radial symmetry would be expected, resulting in circular distribution patterns. However, the sprinkler arms modify the pattern to more nearly resemble a rectangle. Clearly, these patterns can more effectively cover the rectangular design coverage areas specified. Experimentation with the position and shape of sprinkler arms would seem to be a potentially valuable venture.

9.2 Implication for System Design

Current design methods take no cognizance of the distribution patterns from sprinkler heads. Figures 53 and 54 relate the distribution patterns from upright and pendent heads to the feasible design coverage areas for ordinary (solid lines) and light (dashed lines) hazard occupancies. Some modification of the spacing rules seems warranted by these figures.

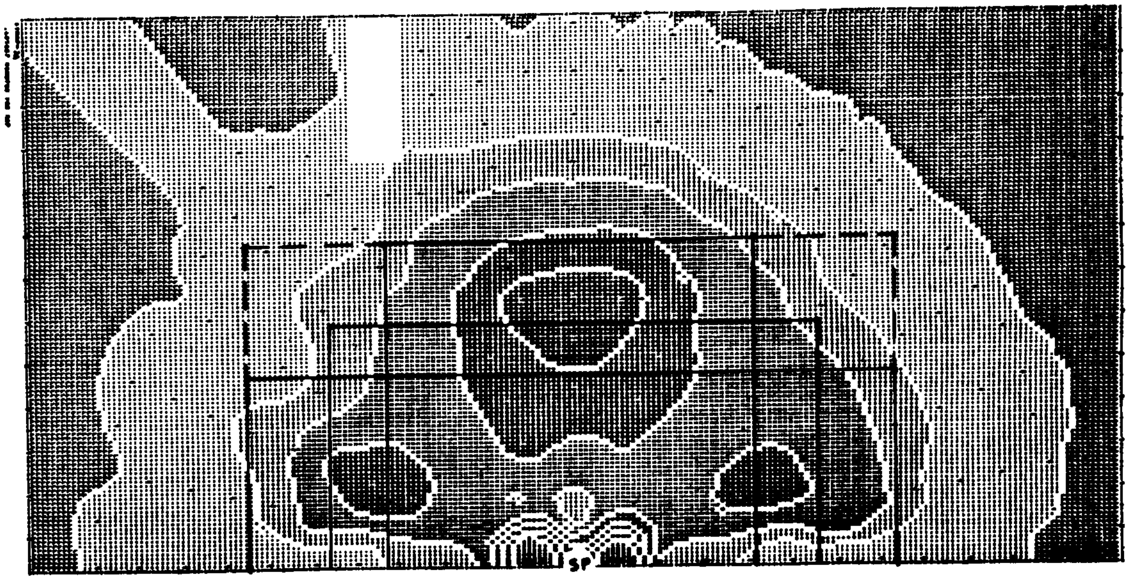
Both figures indicate the distribution patterns more nearly correspond to the design coverage area for ordinary hazards when the minimum spacing allowable (2.65 m) is utilized along the axis of the sprinkler arms and

Test #21

Upright head, flow rate- 30 gpm, size of supply pipe- 1.0 inches,
directionality of supply- one, deflector to ceiling clearance- 7.0 inches,
sprinkler arms parallel to supply pipe, angle of head- 0 degrees,
sprinkler guard not used.

Collection container array- radial

0 METERS 1
0 FEET 3



See Appendix A for explanation of density coding.

SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

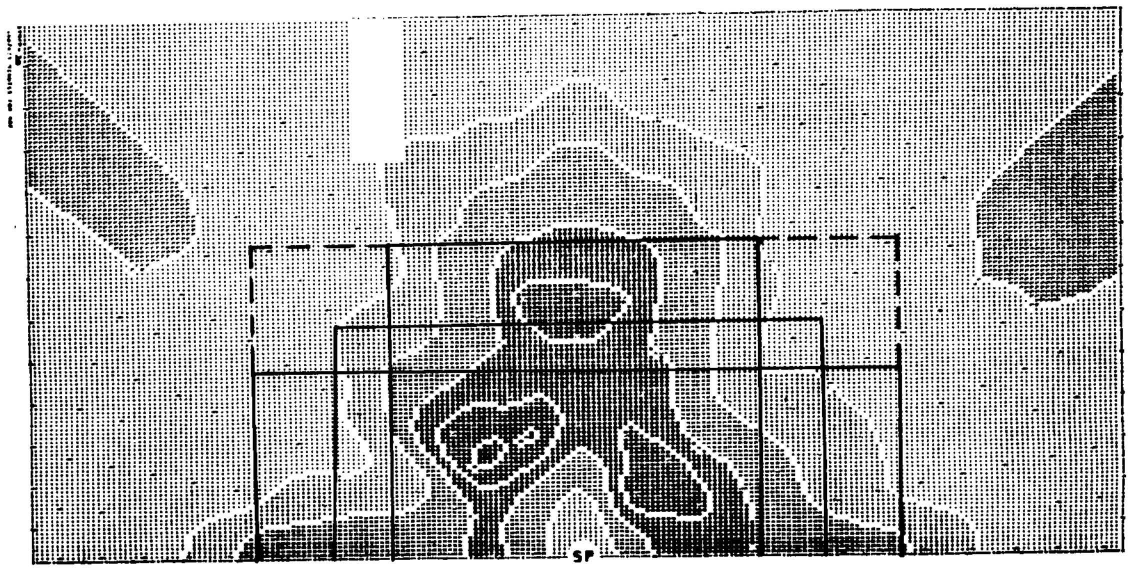
Figure 53

Test #30

Pendent head, flow rate- 30 gpm, size of supply pipe- 1.0 inches,
directionality of supply- one, deflector to ceiling clearance- 7.0 inches,
sprinkler arms parallel to supply pipe, angle of head- 0 degrees,
sprinkler guard not used.

Collection container array- radial

0 METERS 1
0 FEET 3



See Appendix A for explanation of density coding.

SP indicates the location of the sprinkler head. The supply pipe runs along the lower edge of the map.

Figure 54

the maximum spacing (4.57 m) is utilized perpendicular to the arms. These results indicate with the sprinkler arms parallel to the supply pipe the spacing between branch lines can be maximized, thus minimizing piping costs while improving the performance of the system. This simplified approach to the spacing of sprinklers considers only the distribution pattern from a single sprinkler head. Superimposing distribution pattern data for multiple heads indicates the uniformity of the pattern is less sensitive to spacing than the single head case. This is apparently due to the tendency of adjacent head patterns to fill "voids" in the pattern from the initial operating head. However, the improved performance of the initial sprinkler due to proper spacing may alleviate the need for further sprinkler actuations, and thus justified the approach.

Figures 53 and 54 also indicate the design coverage areas allowable for light hazard occupancies are excessive. While this study can provide no evaluation of the density requirement, it appears the coverage area of a sprinkler head cannot approach the allowable design coverage area regardless of the flow rate from the sprinkler head. Distribution patterns developed by superposition of individual distribution patterns of sprinkler heads spaced at the maximum spacing indicate that adjacent heads are unable to fill the "voids" at that spacing. Twenty to thirty percent of the coverage area will receive less than half the design density.

The spacing of sprinklers based on the characteristics of the distribution pattern, coupled with an improved understanding of the actuation of sprinkler heads, and the effect of the water spray on developing fires has the potential for improving the performance of sprinkler systems. This approach requires an improved understanding of both fire development and sprinklers in addition to data concerning the characteristics of sprinklers and their spray patterns not provided by current testing methods.

10. Recommendations for Further Study

The following proposed theories require further study:

1. Gravitational forces have an effect on the collapse length of the nozzle stream and are responsible for the difference in the stream break up between upright and pendent heads on large diameter pipes.

2. The superposition principle is a useful tool for determining the distribution pattern from multiple heads.

3. Significant differences exist in the distribution pattern from sprinklers of the same model and manufacturer.

The following areas are identified as requiring study:

1. Examination of a greater range of flow.

2. Documentation of vertical distribution patterns.

3. Determination of particle size distributions of the water spray.

4. Study of other orifice sizes and sprinkler head designs.

5. Study of distribution patterns of sprinklers under sloped roofs.

6. Study of droplet formation and dynamics.

7. Study to establish the limitation of the superposition principle for high flow rates and small sprinkler head spacings.

11. Conclusions

1. The radial collection container array is an excellent method of collection for single heads. However, when superimposing patterns to generate multiple head distribution patterns, the rectangular array is far simpler.

2. Stopping tests to empty containers directly below the sprinkler head and supply pipe should be avoided because the data points lost are not important and the practice of restarting tests may induce error.

3. Isodensity comparisons, numerical overlay comparisons, and side by side comparisons of distribution patterns are all useful analytic tools.

4. Distribution patterns from upright and pendent heads are dissimilar.

5. The coverage area or area within a given isodensity line of both upright and pendent heads have a maximum which is approached asymptotically.

6. A minimum feasible coverage area can be defined given a required density. At flow rates below that yielding the minimum feasible coverage area, the coverage area is not yet developed and could not provide adequate coverage regardless of sprinkler spacing.

7. Unsteadiness and turbulence in the nozzle stream improves the distribution pattern.

8. The Reynold's Number of the flow in the supply pipe has an important effect on distribution patterns.

9. Sprinkler arms are an important determinant of the distribution pattern.

10. Sprinkler guards reduce the area of coverage of sprinkler heads.

11. Sprinkler spacing rules should be derived from sprinkler distribution patterns to provide for optimum system performance.

12. Acknowledgments

The author gratefully acknowledges the assistance of James M. Thompson, Harry L. Bradley, Robert C. Beller, and Edward B. Douberly for their assistance in conducting the test series.

The author gratefully acknowledges Mr. Jack M. Watts, Jr. and Dr. John L. Bryan of the Fire Protection Curriculum, University of Maryland, for their helpful comments and suggestions through the course of this project.

The author also acknowleges with appreciation the cooperation of Mrs. Eloise McBrier and Mrs. Cindy Silberman who typed the manuscript of this report.

13. References

1. Marshall, Jr., W. R., Atomization and Spray Drying. Monograph Series, American Institute of Chemical Engineers (1954).

2. Labes, W., Evaluation of Fire Protection Spray Devices, The State-of-the-Art, National Bureau of Standards, NBS-GCR 76-72 (June 1976).

APPENDIX A

DENSITY CODING

SYMBOLS

```
==========:
LLLLLLLLL
LLLLLLLLL
LLLLLLLLL
LLLLLLLLL
LLLLLLLLL
==========:
```

\- 0.00 - 0.05 mm/min. (0.00 - 0.0012 gpm/ft^2)

```
==========:
.........
.........
....1....
.........
.........
==========
```

\- 0.05 - 1.50 mm/min. (0.0012- 0.037 gpm/ft^2)

```
==========:
+++++++++
+++++++++
++++2++++
+++++++++
+++++++++
==========:
```

\- 1.50 - 3.00 mm/min. (0.037 -0.074 gpm/ft^2)

```
==========
XXXXXXXXX
XXXXXXXXX
XXXX3XXXX
XXXXXXXXX
XXXXXXXXX
==========
```

\- 3.00 - 6.00 mm/min. (0.074 - 0.147 gpm/ft^2)

```
==========
θθθθθθθθθ
θθθθθθθθθ
θθθθ4θθθθ
θθθθθθθθθ
θθθθθθθθθ
==========:
```

\- 6.00 - 9.00 mm/min. (0.147 - 0.221 gpm/ft^2)

```
==========
█████████
█████████
████5████
█████████
█████████
==========:
```

\- 9.00 - 12.00 mm/min. (0.221 - 0.294 gpm/ft^2)

```
==========:
█████████
█████████
████6████
█████████
█████████
==========:
```

\- 12.00 - 15.00 mm/min. (0.294 - 0.368 gpm/ft^2)

```
===========
HHHHHHHHH
HHHHHHHHH
HHHHHHHHH
HHHHHHHHH
HHHHHHHHH
:==========
```

\- 15.00 mm/min. and greater (0.368 gpm/ft^2 and greater)

PERCENT DIFFERENCE CODING

+3 - 25-35% increase in density of the test relative to the control

-6 - 55-65% decrease in density of the test relative to the control

+H - greater than 95% increase in density of the test relative to the control

-H - greater than 95% decrease in density of the test relative to the control

Percent differences are shown only for points in which the test and/or the control densities are greater than 1.5 mm/min. and less than 9.0 mm/min.

APPENDIX B

Mappings of the distribution of water from sprinklers can be accomplished utilizing a program developed by the Laboratory for Computer, Graphics and Spatial Analysis, Harvard University. The program, known as SYMAP (Synagraphic Mapping System), was designed primarily for use by geographers, planners, geologists, and meteorologists in analyzing spatial data. The program is easy to use and requires no prior knowledge of computer programming unless alterations in input modes is desired. The program will be discussed here only in the context of its use in generating the mappings for this study. A more comprehensive discussion can be found in the SYMAP User's Reference Manual (1).

In this application, SYMAP was utilized to create contour mappings. That is, utilizing inputed data, SYMAP interpolated the density at all locations based on the values and distances to adjacent data points. The density is assumed to vary smoothly between data points, forming a continuous surface. The data and the interpolated data points are assigned to value intervals specified by the user. Each value interval has a unique plotting symbol. The printing of these symbols in a matrix corresponding to the spatial location of the data and interpolated data points constitutes the map.

The input data requirements include the outline of the area being studies (A - Outline), the location of all collection points (B - Data), the density (mm/min) at each collection point (E - Values), and specifications for map characteristics (F - map).

Although the collection area in most of the tests was semi-circular, a rectangular test area outline was specified. This resulted in areas outside the actual test area being assigned densities by extrapolation of the data. These areas outside the real collection area should be ignored.

The location of collection points were easily entered. The coordinates of each point were determined using an origin at the upper left hand point of the map. In the case of the radial experimental set up, this required that the location of the collection points be determined in polar coordinates about the location of the sprinkler. The polar coordinates were converted to rectangular coordinates and the origin was translated to the upper left hand point of the collection area defined in A-Outline.

Input of densities at each collection point required the use of a subroutine, FLEXIN. Raw data in terms of volumes or depths of water collected were input to FLEXIN along with the duration of the test. Using the calibration curve developed for the depth measurements and the appropriate conversion factors, FLEXIN converted the raw data into density data for each collection point in mm/min. This data was returned to the main program for mapping.

The map specifications used in this study were the same for all tests to insure that all test results could be easily compared. The specifications used are listed below.

Map Specifications

Number of value class intervals = 6
Value range minimum = 0.05 mm/min.
Value range maximum = 15.0 mm/min.
Ranges of value class intervals
- 0.05 - 1.50 mm/min.
- 1.50 - 3.00 mm/min.
- 3.00 - 6.00 mm/min.
- 6.00 - 9.00 mm/min.
- 9.00 - 12.00 mm/min.

Map scale 1 inch = 1 foot (on the original output, maps in this report have been photographically reduced.)
Maximum valid data value = 100 mm/min.
Absolute extrapolation minimum = 0.0 mm/min.

The maximum valid data value of 100.00 mm/min. was used so that the points in the two head tests where problems arose due to the test starting methodology would be ignored in the interpolation of the density values between data points. In no tests did actual densities exceed this maximum.

The cost of producing each of the mappings was approximately $4.00.

References

1. Dougenik, J., D. Sheehan, SYMAP User's Reference Manual, 5th edition, Laboratory for Computer Graphics and Spatial Analysis, Graduate School of Design, Harvard University, Cambridge, Mass., 1975.

APPENDIX C

Summary

Test #	Size of Supply Pipe (in.)	Direct of Supply	Head Type	Flow Rate (gpm)	Ceiling Clearance (in.)	Angle of Head	Collection Pattern
1	2	1	u	30	7	0	C
2	2	1	*u	30	7	0	C
3	2	1	u	20	7	0	C
4	2	1	u	10	7	0	C
5	2	1	u	30	7	0	0
6	2	1	u	10	7	0	0
7	2	1	u	20	7	0	0
8	2	1	u	10	7	0	R
9	2	1	u	30	7	0	R
10	2	1	u	20	7	0	R
11	2	2	u	30	7	0	R
12	2	2	u	20	7	0	R
13	2	2	u	10	7	0	R
14	2	2	p	30	7	0	R
15	2	2	p	20	7	0	R
16	2	2	p	10	7	0	R
17	1.5	1	u	30	7	0	R
18	1.5	1	u	20	7	0	R
19	1.5	1	u	10	7	0	R
20	1	1	u	20	7	0	R
21	1	1	u	30	7	0	R
22	1	1	u	10	7	0	R
23	1	2	u	30	7	0	R
24	1	2	u	20	7	0	R
25	1	2	u	10	7	0	R
26	1	2	p	20	7	0	R
27	1	2	p	30	7	0	R
28	1	2	p	10	7	0	R
29	1	1	p	20	7	0	R
30	1	1	p	30	7	0	R
31	1	1	p	10	7	0	R
32	1	1	p	20	7	0	R
33	1	1	p	30	7	0	R
34	1	1	p	10	7	0	R
35	1	1	p	20	12	0	R
36	1	1	p	30	12	0	R
37	1	1	p	10	12	0	R
38	1	1	p	20	18	0	R
39	1	1	p	30	18	0	R
40	1	1	p	10	18	0	R
41	1	1	u	20	10	0	R
42	1	1	u	30	10	0	R
43	1	1	u	10	10	0	R
44	1	1	u	20	7	0	R
45	1	1	u	30	7	0	R
46	1	1	u	10	7	0	R
47	1	1	u	10	3	0	R

Test #	Size of Supply Pipe (in.)	Direct of Supply	Head Type	Flow Rate (gpm)	Ceiling Clearance (in.)	Angle of Head	Collection Pattern
48	1	1	U	20	3	0	R
49	1	1	U	30	3	0	R
50	1	1	U	10	1	0	R
51	1	1	U	20	1	0	R
52	1	1	U	30	1	0	R
53	1	1	U	10	7	-5	R
54	1	1	U	20	7	-5	R
55	1	1	U	30	7	-5	R
56	1	1	U	10	7	+5	R
57	1	1	U	20	7	+5	R
58	1	1	U	30	7	+5	R
59	1	1	U-AP	10	7	0	R
60	1	1	U-AP	20	7	0	R
61	1	1	U-AP	30	7	0	R
62	1	1	P	10	7	+5	R
63	1	1	P	20	7	+5	R
64	1	1	P	30	7	+5	R
65	1	1	P	30	7	-5	R
66	1	1	P	20	7	-5	R
67	1	1	P	10	7	-5	R
68	1	1	P-AP	30	7	0	R
69	1	1	P-AP	10	7	0	R
70	1	1	P-AP	20	7	0	R
71	1.5	2	P	10	7	0	R
72	1.5	2	P	20	7	0	R
73	1.5	2	P	30	7	0	R
74	1.5	2	U	30	7	0	R
75	1.5	2	U	10	7	0	R
76	1.5	2	U	20	7	0	R
77	1.5	2	P-SG	20	7	0	R
78	1.5	2	P-SG	30	7	0	R
79	1.5	2	P-SG	10	7	0	R
80	1.5	2	P(2)	25	7	0	2H
81	1.5	2	P(2)	15	7	0	2H
82	1.5	2	P(1)	15	7	0	2H
83	1.5	2	P(1)	25	7	0	2H
84	1.5	2	P(1&2)	25	7	0	2H
85	1.5	2	P(1&2)	15	7	0	2H
86	1.5	2	U(1)	25	7	0	2H
87	1.5	2	U(1)	15	7	0	2H
88	1.5	2	U(2)	15	7	0	2H
89	1.5	2	U(2)	25	7	0	2H
90	1.5	2	U(1&2)	15	7	0	2H
91	1.5	2	U(1&2)	25	7	0	2H
92	1	2	P	20	1	0	R
93	1	2	P	10	1	0	R
94	1	2	P	30	1	0	R
						0	

U, P - upright, pendant
C, O, R, 2H - conventional, offset, radial, 2 head
* - head used was identical to the head used in all other upright tests - U(2) used in two head tests.
SG - sprinkler guard used
AP - Arms of sprinkler perpendicular to supply pipe

APPENDIX D

Volumetric Calibration Curve

If $82 < x \leq 103.7$

$V = 4000 + 92.5\ (x - 82.0)$

If $103.7 < x \leq 146.1$

$V = 6000 + 94.2\ (x - 103.7)$

If $146.1 < x \leq 188.1$

$V = 10{,}000 + 95.4\ (x - 146.1)$

If $188.1 < x \leq 228.5$

$V = 14{,}000 + 98.9\ (x - 188.1)$

If $228.5 < x \leq 269.1$

$V = 18{,}000 + 98.6\ (x - 228.5)$

If $x > 269.1$

$V = 22{,}000 + 101.0\ (x - 269.1)$

Where x = depth reading, mm

V = volume, ml

NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBS-GCR-77-105	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

EFFECT OF SELECTED VARIABLES ON THE DISTRIBUTION OF WATER FROM AUTOMATIC SPRINKLERS

5. Publication Date

June 1977

6. Performing Organization Code

7. AUTHOR(S)

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8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

University of Maryland
College of Engineering
Department of Fire Protection Engineering
College Park, MD 20742

10. Project/Task/Work Unit No.

11. Contract/Grant No.

6-9008
4-36092

12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*

National Bureau of Standards
Department of Commerce
Washington, DC 20234

13. Type of Report & Period Covered

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

HEW-NBS Fire/Life Safety Program

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The effects of flow rates, supply pipe size, direction of supply, deflector to ceiling clearance, orientation of sprinkler arms, angles of the sprinkler head, and sprinkler guards on the distribution of water from upright and pendant sprinkler heads have been studies. Three collection arrays were used to measure densities from one or two sprinklers. To evaluate the effects of the above variables data from tests were used in conjunction with a Synagraphic Mapping System (SYMAP) computer program to produce isodensity mappings of sprinkler discharges.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Collection arrays; density; distribution patterns; flow rate; mapping; superposition; sprinkler heads; sprinkler systems; spray patterns

18. AVAILABILITY [X] Unlimited

[ ] For Official Distribution. Do Not Release to NTIS

[ ] Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13

[X] Order From National Technical Information Service (NTIS) Springfield, Virginia 22151

19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
UNCLASSIFIED	70
20. SECURITY CLASS (THIS PAGE)	**22. Price**
UNCLASSIFIED	$5.25

USCOMM-DC 29042-P74