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Effects of Wind on Falling Drops

Charles Russell Umback

EFFECTS OF WIND ON FALLING DROPS

BY

CHARLES RUSSELL UMBACK

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EFFECTS OF WIND ON FALLING DROPS

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Adviser | Date

Head, Agricultural Engineering Department | Date

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CHAPTER I

INTRODUCTION

Soil erosion studies have proceeded along two basic paths in-so-far as erosion by water is concerned: (1) the measurement of soil loss and runoff caused by natural rainstorms, with pertinent characteristics of those storms; and (2) the measurement of such losses when caused by artificially-produced storms of arbitrarily-selected characteristics. Both are important research methods. The first provides a measure of the magnitude and variability of storms as they actually occur in a given area, as well as accurate measurement of losses produced by a particular storm type and intensity on a given condition of plots. However, it has one costly disadvantage: a particularly important type of condition and storm might not occur except at rare intervals. The second type of storm can be produced almost any time and has the advantage, therefore, of greatly decreasing the time involved in getting an answer. A disadvantage is the great difficulty in accurately simulating any given storm type. Meyer and McCune (14) describe a rainfall simulator which probably is the most accurate of any devised on the basis of storm energy per unit quantity of rain, and the development of simulator design has been reviewed by Mutchler and Hermsmeier (21).

Meyer (17) defines the following criteria as being important to the accurate simulation of rainstorms: rainfall intensity, raindrop size distribution, raindrop fall velocity, and to lesser degrees or in ways less understood, drop temperature, shape, impact angle, and the effect of wind.

Wind may have several effects on the simulation of rainfall or, for that matter, on natural rainfall.

(1) It distorts the location of the drop impact from the intended target area to some point downwind. Logic and experience would indicate, furthermore, that smaller drops will drift much further than larger drops.

(2) Because drops drift in the wind, they gain a horizontal velocity. This velocity is combined with vertical velocity at some point along the fall path of the drop to determine the resultant velocity and direction of fall at that point. Logic indicates that the limiting factors would be still-air terminal velocity in the vertical direction and wind velocity in the horizontal direction. Van Heerden (28), citing references, indicates the actual horizontal component is somewhat less than mean wind velocity. However, the resultant impact force of individual droplets will be at some angle different from the vertical. This would be expected to give a net splash movement of soil materials in a downwind direction. According to Van Heerden (28), total splash erosion increases with increasing angle of deviation (from a

vertical direction). Wind in itself does not appear to account for soil movement, other than to the extent that it changes the angle of impact of the rain.

(3) Within a small plot area, wind drift may be sufficient to remove appreciable quantities of water from the test area, as a wind-borne mist of fine droplets.

Quantitative data concerning these effects is minimal. To gain this information, this study was conducted.

CHAPTER II

STATEMENT OF PROBLEM

The displacement of falling water drops by wind is of particular interest to those studying the mechanics of soil erosion.

Drops subject to wind drift may commonly occur under one of these basic conditions:

1. They may be formed high in the air, as a rainstorm, falling until they attain vertical terminal velocity, as in still air. More commonly, they may fall through a moving air mass, so that actual drop velocity and direction is a resultant of the vertical velocity attained (produced by the downward force of gravity and limited by air resistance), and the horizontal velocity attained (limited to the velocity of the wind acting on the side of the drop).
2. Drops may be formed by a nozzle, a capillary tip, or a piece of yarn, so as to fall vertically, either with initial velocity or accelerated by gravity alone; but formed sufficiently close to the ground that the force of the wind on the side of the drop would not accelerate the drop sufficiently to bring its horizontal velocity up to the wind velocity.
3. Drops may be produced by a nozzle, projected at some angle from vertical, so the drops have some initial horizontal

velocity. This might be to provide dispersion of the sprinkler pattern over a large area, thereby reducing intensity to a tolerable level.

The "Rainulator" described by Meyer and McCune (14) uses a spray from a Veejet nozzle, directed vertically downward. A small portion of this spray would be typified by case 2. Most of the spray consists of drops of various sizes and projected at various angles from the vertical, within an included angle of 80 degrees.

This particular study is limited to the second case. This situation would typify a rainfall simulator from which all drops are projected vertically downward at a velocity approaching terminal velocity. Such equipment operating in this area would be expected to encounter more or less windy conditions. Wiersma (29) reviewed 52 years' data from Huron, South Dakota and found that the average wind during the irrigation season (defined as April 15 to October 1) was 10.8 miles per hour (15.8 feet per second). Further, he pointed out that this included all hours of the day, and that wind velocity was greatest between the hours of 2 P. M. and 4 P. M. (CST). He concluded that during many hours of sprinkling time a wind velocity of greater than 10.8 miles per hour would be encountered.

Drop displacement was considered to be the dependent variable in this study, with drop size, wind velocity, and fall distance considered to be independent. Other factors investigated were drop velocity and impact angle.

CHAPTER III

THE WIND TUNNEL

Design Principles

Wind tunnels of many different designs and configurations have been developed over the years. Prandtl and Tietjens (24) described a tunnel built in Moscow in 1906: ". . . the air was also sucked in by a blower since it had been shown by previous experiments that an air stream of this kind is far less turbulent than one blown into the tunnel." Further, "The vorticity of the air was diminished by arranging a rather large intake nozzle at the entrance of the tunnel and also by installing a number of honeycomb grids, with the result that the air velocity had variations less than 4% of the mean."

This tunnel, built by Riabouchinsky, was about 4 feet in diameter; about 45 feet long; and yielded velocities of 3-20 feet/second. It was an open-wind tunnel; that is, recirculation was through the atmosphere rather than through a closed loop of ductwork.

Other tunnels described by these authors were closed wind tunnels and free-jet wind tunnels, both types being recirculating. The free-jet tunnel has the rather important advantage, for model studies, of eliminating wall effects in the test area. However, for droplets, this should not be an important factor, as the throat width is much larger than any characteristic dimension of the largest drop concerned.

Most wind tunnels found in the literature are of round or square cross-section in the test throat. Because this study was concerned with two-dimensional travel of water drops, a large vertical dimension (12 feet) was needed, but the lateral dimension could be left quite small. After some investigation (see Appendix I) of the velocity uniformity which could be expected across throats of various widths, the throat width was set at 8 inches. This allowed the use of a crop-drying fan which was already available in the department.

Features of This Tunnel

Construction details of the tunnel are shown in Appendix I. Several design features were incorporated to give velocity uniformity.

1. A smooth, parabolic-wall entrance section was constructed to provide smooth air-flow lines into the tunnel. By providing smooth flow here, turbulence within the tunnel was suppressed and a uniform velocity profile was obtained in the initial reaches of the test section.
2. A transition section was used to couple the downwind end of the test section, 12 feet vertical by 8 inches in width, to the inlet of the fan shroud, which was 2.5 feet in diameter. Because of this marked change in dimension it was believed to be desirable to provide some pressure drop at the juncture of test section and transition. By giving a more uniform negative potential across the entire vertical

section of the tunnel, more uniform velocities could be expected. Ordinary window screen was placed between the test section and the transition section to give this pressure drop.

3. The fan was mounted in a raised position, so its horizontal axis was 6 feet off the floor. This allowed symmetry in the transition section.

Some means was needed to vary the air velocity. Since the transition section was constructed of polyethylene film over a framework of iron rod, the simplest method was to open the transition and bleed air directly to the fan, thereby reducing flow through the test section. The degree of opening was adjusted until a pitot-tube, located directly in the center of the wind tunnel, indicated velocity to be at nearly the desired level. Then the polyethylene was taped in place, a detailed velocity profile was obtained, and the test procedures were resumed.

Calibration Results

Several velocity distributions were obtained in checking uniformity. Figures III-1 and III-2 show the distributions 12 feet and 20 feet, respectively, downwind from the entrance of the test section, for a nominal 20 feet/second velocity. Very good uniformity was obtained across the throat, especially within the center 2-inch section, through which virtually all the drops observed passed. By far the

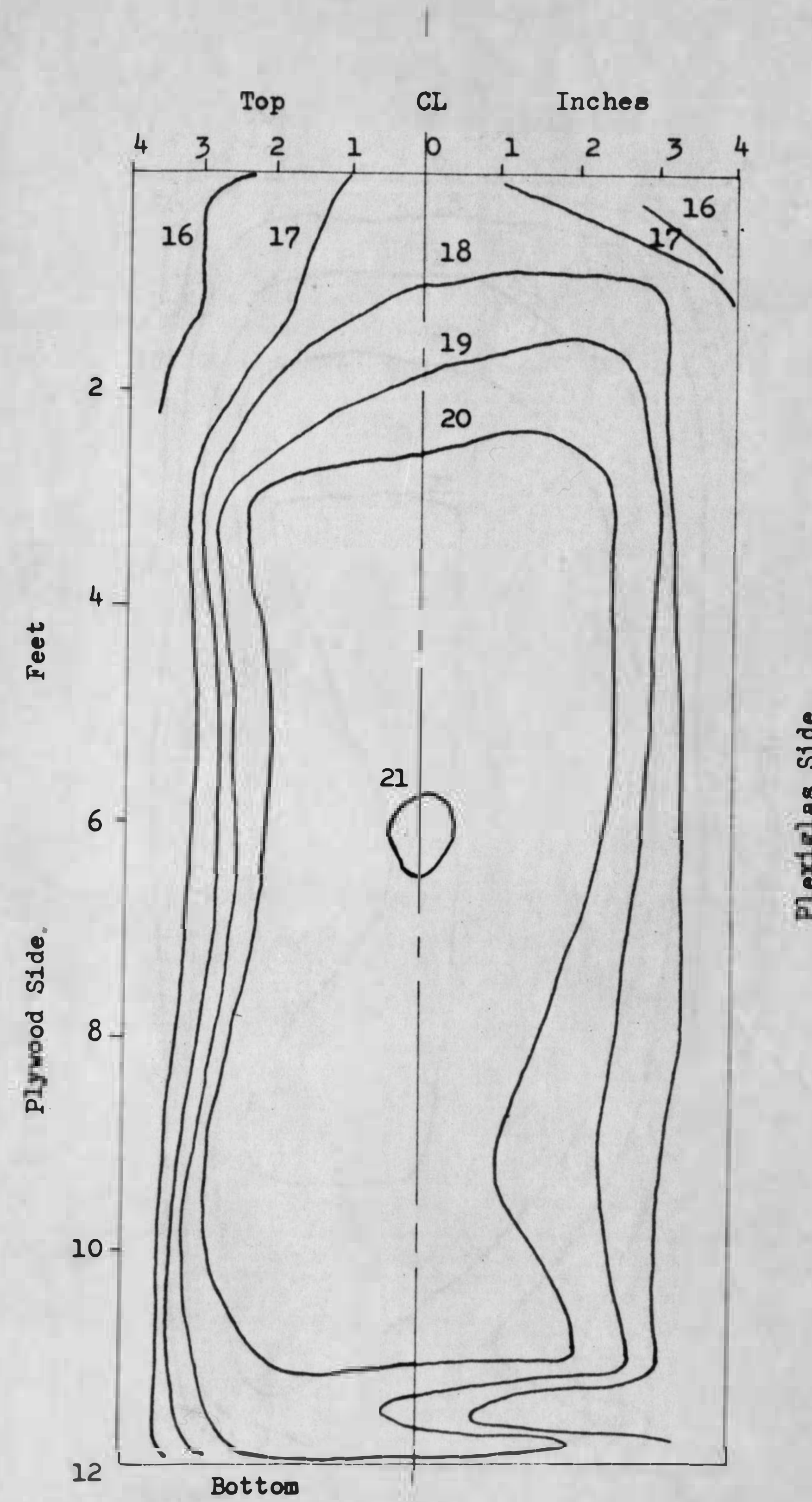


Figure III-1. Velocity Profiles 12 Feet Down Throat
Scale: 1" = 20" Vert. 1" = 2.5" Horiz.

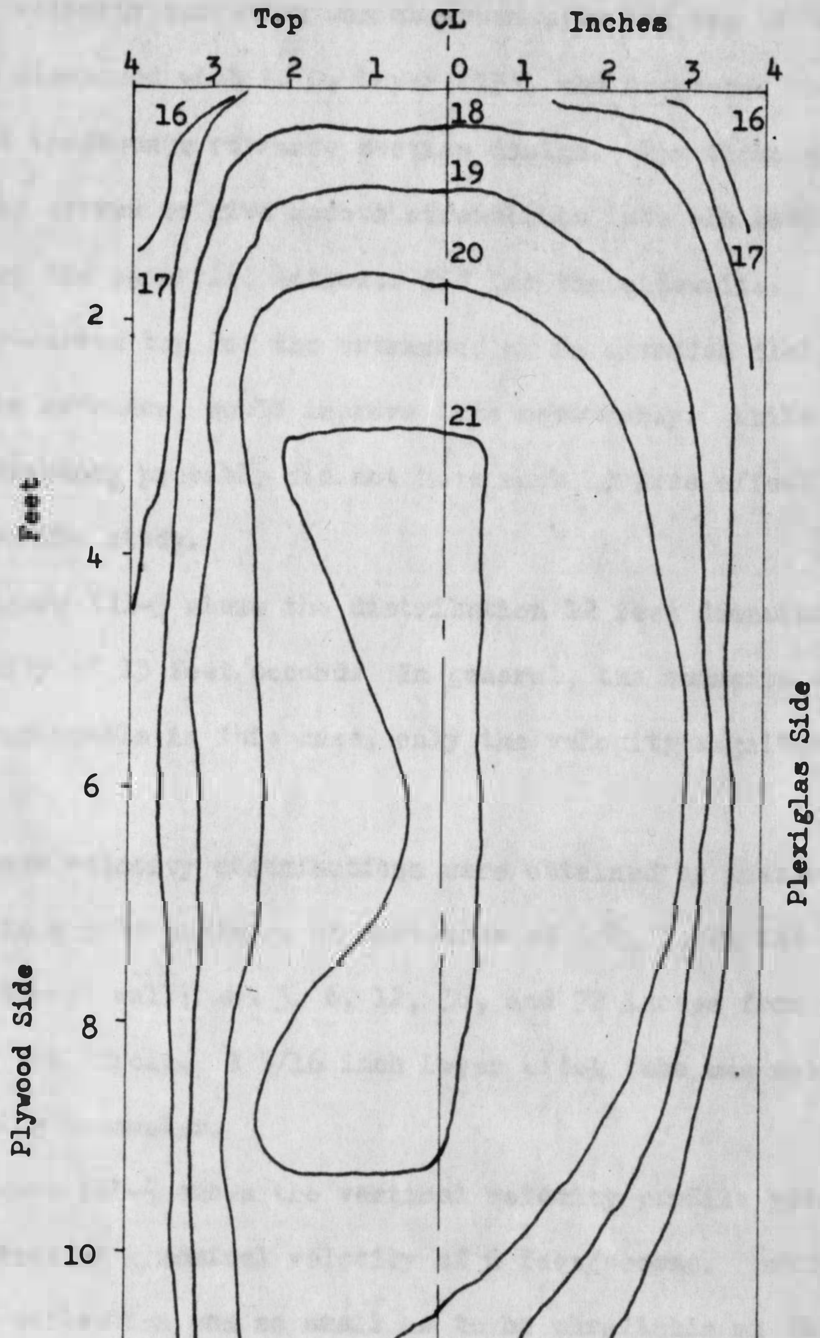


Figure III-2. Velocity Profiles 20 Feet Down Throat
Scale: 1" = 20" Vert. 1" = 2.5" Horiz.

greatest velocity variation was observed near the top of the tunnel. This was discussed with L. D. Meyer (13), who suggested that it indicated inadequate entrance section design. The floor of the laboratory served to give smooth streamlines into the bottom of the tunnel, as the parabolic entrance did for the sidewalls. Either a similarly-curved top for the entrance, or an extended flat plane on beyond the entrance, would improve this measurably. While undesirable, this discrepancy probably did not have much adverse effect on the conduct of the study.

Figure III-3 shows the distribution 12 feet downwind for a nominal velocity of 15 feet/second. In general, the comments above are equally applicable in this case, only the velocity magnitudes being less.

These velocity distributions were obtained by measuring wind velocity in a grid pattern, at distances of 1/2, 1, 2, and 4 inches from the tunnel wall; and 3, 6, 12, 36, and 72 inches from the top and bottom of the throat. A 5/16 inch Dwyer pitot tube was used, connected to a sloping manometer.

Figure III-4 shows the vertical velocity profile through the tunnel throat at a nominal velocity of 6 feet/second. Because the manometer deflection was so small as to be unreliable at this velocity, a K & E fan-type anemometor was used instead.

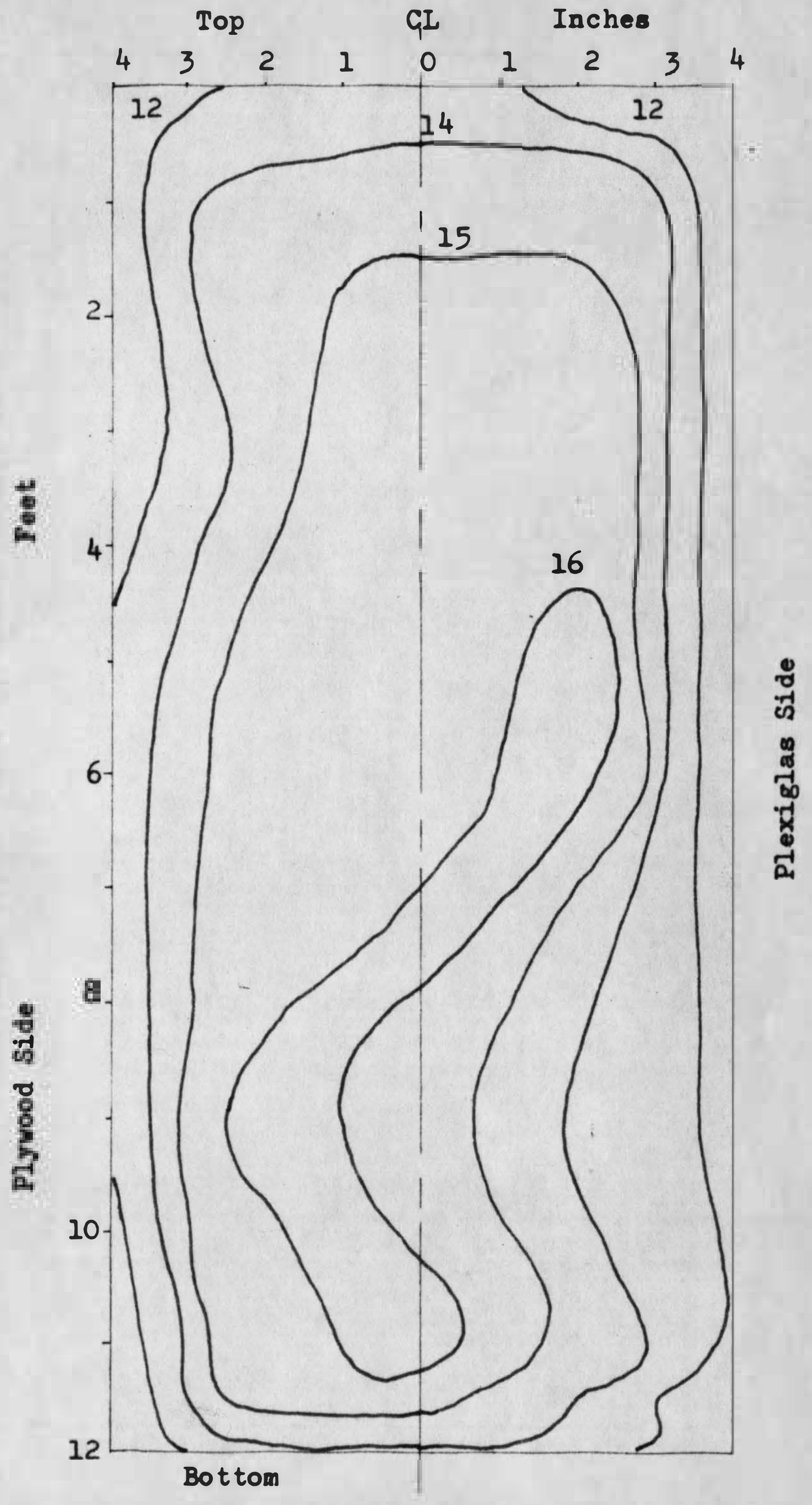


Figure III-3. Velocity Profiles 12 Feet Down Throat
Scale: 1" = 20" Vert. 1" = 2.5" Horiz.

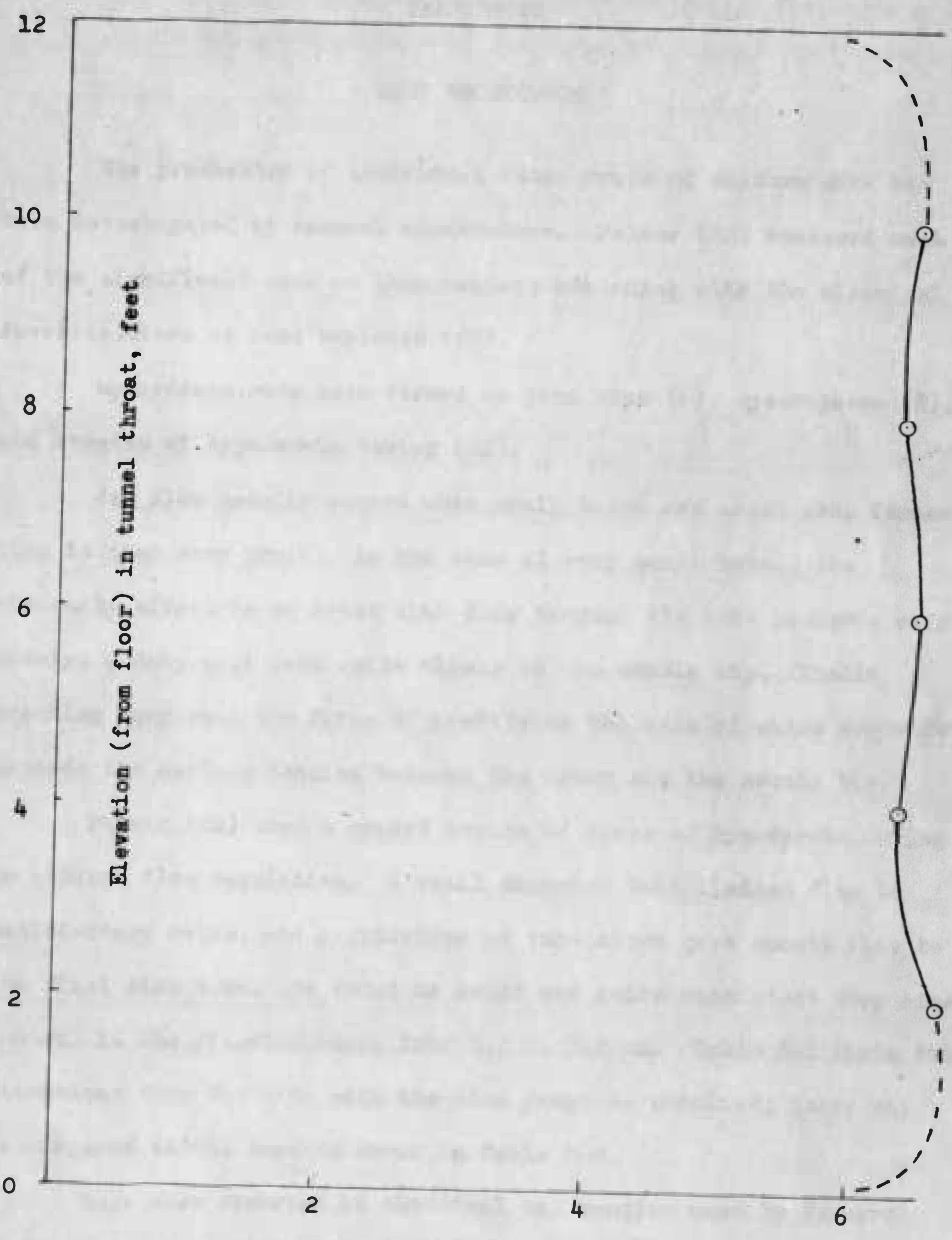


Figure III-4. Wind Velocity Versus Height in Tunnel

CHAPTER IV

DROP PRODUCTION

The production of individual water drops of uniform size has been investigated by several researchers. Palmer (22) reviewed much of the significant work on this subject beginning with the classical investigations of Lord Rayleigh (25).

Waterdrops have been formed on yarn tips (6), eyedroppers (2), and lengths of hypodermic tubing (22).

Jet flow usually occurs when small tubes are used; drop formation is then very rapid. In the case of very small tubes, the viscosity effect is so great that flow through the tube proceeds very slowly; a drop will form quite slowly on the nozzle tip, finally breaking away when the force of gravity on the mass of water suspended exceeds the surface tension between the water and the nozzle tip.

Palmer (22) used a graded series of sizes of hypodermic tubing to achieve flow regulation. A small diameter tube limited flow to satisfactory rates, and a gradation of tube sizes gave smooth flow to the final size tube. He found he could get quite consistent drop size control in the diameter range from 3.2 to 5.2 mm. Table 4-1 lists tube dimensions from his data with the size drops he obtained; these may be compared to the results shown in Table 4-2.

Gage size reported is the final tip section used by Palmer: smaller diameters were used above the tip section to control the flow, as already described.

Table 4-1. Drop Size Compared to Tube Diameter Used. From Palmer (22)

Nominal Diameter Gage	O.D. Inches	Drop Size, mm.
11	0.120	4.6
13	0.095	4.3
22	0.028	2.9*

*Estimated by visual extrapolation

Blanchard (2) formed drops on the tip of an eyedropper and was able to continue to inject water into the drop until it reached the desired size, because his drops were held suspended on a vertical column of air. The rate of drop formation, under such circumstances, could not be considered a factor in his investigations.

Ellison and Pomerene (6) supported cloth over a wire mesh. A length of yarn was suspended from the cloth in the center of each mesh opening. When a nozzle was directed so as to spray over the surface of the apparatus, water would collect in the pockets thus formed and would be conducted down the yarn, from which it would drip. The rate of drop formation with this system could be regulated by the spray intensity on the cloth surface. Drop size was a function of yarn size and was reported to vary about ± 6 percent for a given size yarn.

For this study, it was necessary to produce drops singly, at intervals of several seconds. The drops had to be quite uniform in size, and consistent in size from day to day. A range of sizes was needed.

Table 4-2. Drop Former Data: Tip Diameters and Drop Sizes Produced By Them

Tip Material	Nominal Size	O.D. Inches	Drop Diameter mm.
Glass		0.011	2.2
Steel	22 ga.	0.028	3.0
Steel	13 ga.	0.095	4.2
Glass		0.125	4.6
Steel	1/4" X 27 ga.	0.252	5.5

With the smallest tips used, the viscosity effect was sufficient to provide flow regulation suitable to this study. When using larger tips, an adjustable clamp was used on a rubber supply hose to reduce the flow rate.

Drops formed on the tip of a hypodermic tube appeared to be very uniform in size if flow rate, temperature, and water quality remained constant.

Steel hypodermic tubing was used for three of the five drop sizes, and glass tubing was drawn to appropriate diameters for two more sizes. The dimensions of these tips, and the drop sizes produced by them, are given in Table 4-2.

Comparisons between the sizes of drops obtained by Palmer and those obtained by the author appear to be favorable.

Drop size was determined in this study by catching a known number (100 drops of the largest sizes, 200 of the smaller ones) in a bottle, the weight of which had previously been determined, and by weighing the sample thus obtained. Knowing the average drop weight, mean spherical diameter was then calculated. A drop diameter versus drop weight curve was prepared to facilitate calibrations, and is shown in Appendix II, Figure AII-1.

The steel drop-forming tips were prepared by cutting them to length and then truing them to squareness in a valve-grinding machine. The glass tips were made from 1/4" O.D. glass tubing. A length of this was cut off, chucked in a drill press to provide support, and heated with a torch. The drill press was slowly rotated by hand to give uniform heating around the circumference of the tube. When the flame began to show yellowish-red from the sodium given off by the glass, and a slight reduction in diameter of the tube indicated it was slumping from its own weight, the flame was quickly removed; the rotation was stopped; and the end of the tube was quickly pulled so as to greatly lengthen it, thereby effecting a great reduction in diameter. (It was necessary to do all three things simultaneously. Because some experience was necessary, the first few tips so produced, especially in the smaller sizes, were not satisfactory.)

Once a satisfactory diameter was obtained, it was allowed to cool and was then snapped in two at the point where the desired diameter occurred (usually the minimum diameter). It was impossible to true this end completely; however, it was possible to carefully run the end of the tube over a piece of abrasive paper and break off the larger projections. This process produced a long, gradual taper to the final minimum diameter; this should have produced smooth flow lines, but it also served to trap any flaky materials which might be in the water. Clean, deionized water was used; the author found it necessary, even so, to run the water through Whatman No. 5 filter paper in a filter funnel to minimize plugging of the smallest tip. In most cases, the drop forming equipment was adjusted to a frequency of 6-10 drops per minute. No variation in size, within this frequency range, was detectable. In the case of the smallest glass tip, it was not possible to maintain even this rate of flow.

An illustration of the drop-forming apparatus is shown in Appendix II, Figure AII-2. The complete assembly was suspended from the ceiling, over the wind tunnel, during runs, as indicated in Figure AII-3 of Appendix II.

CHAPTER V

DROP VELOCITY

The velocity of falling water drops has been determined by several methods and by numerous workers. Meyer (15), in a detailed literature review, listed the following methods:

(a) Photographing drops during fall (seven citations)

(b) Electronic measurement of time for drop to pass consecutive points (four citations)

(c) Stopwatch timing (one citation)

(d) Upward velocity of air stream required to suspend drops (three citations)

(e) Computation (three citations)

For the purposes of this study, either of the first two methods was suitable. The photographic method was chosen, and techniques were developed based on the work by Doering (4). Figures V-1 and V-2 illustrate the basic photographic setup which was used. A Graphlex "23" camera with 101 mm lens was used with an aperture setting of f/4.5. Kodak Tri-X 120 roll film, "pushed" in development, provided an adequate image. Two photofloods were used to backlight the drop during the early part of the study, as shown by Figure V-2. Because this was a continuous light source, the camera recorded continuous "streaks" of reflected light from the two sides of the drop. The distance between the pair of streaks gave an estimate of the drop width or diameter.

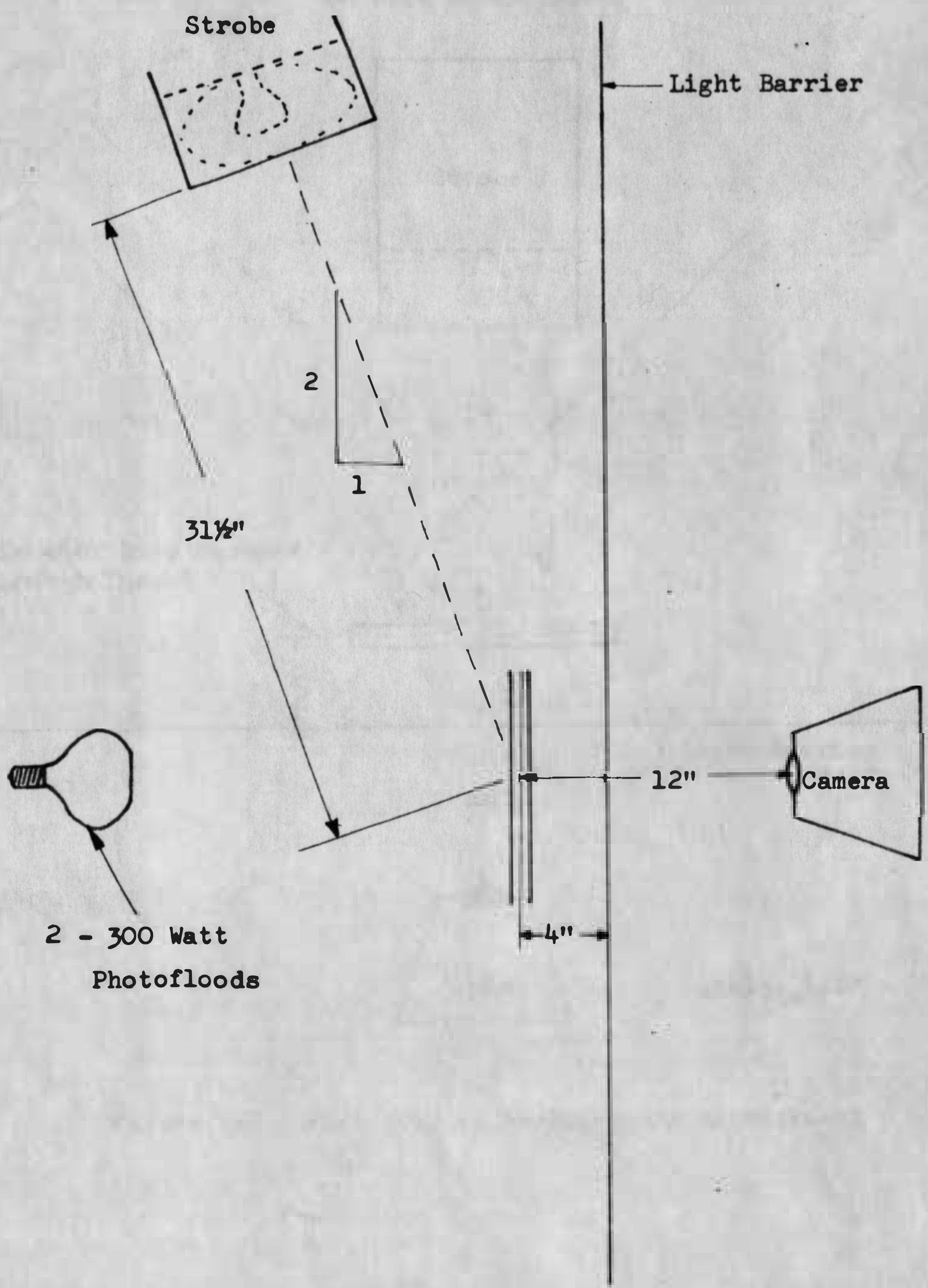


Figure V-1. Elevation View of Photographic Arrangement.
Scale: 1/8" = 1"

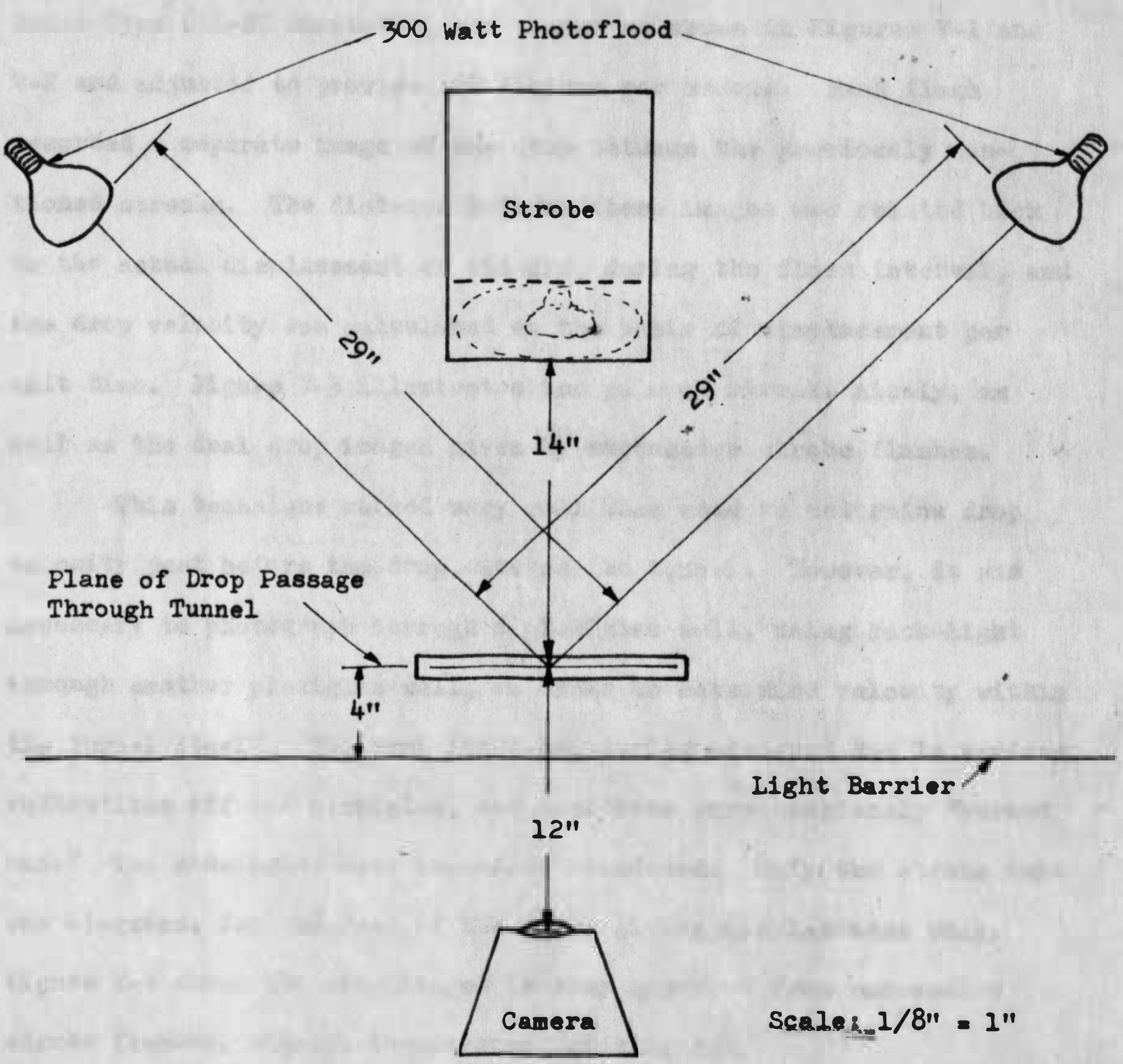


Figure V-2. Plan View of Photographic Arrangement

A General Radio Type 648-A Strobolux, triggered by a General Radio Type 631-BL Strobotac, was placed as shown in Figures V-1 and V-2 and adjusted to provide 100 flashes per second. Each flash recorded a separate image of the drop between the previously mentioned streaks. The distance between these images was related back to the actual displacement of the drop during the flash interval, and the drop velocity was calculated on the basis of displacement per unit time. Figure V-3 illustrates the pair of streaks nicely, as well as the dual drop images given by successive strobe flashes.

This technique worked very well when used to determine drop velocity just before the drop entered the tunnel. However, it was necessary to photograph through a plexiglas wall, using back-light through another plexiglas wall, in order to determine velocity within the tunnel itself. Too much light-scattering occurred due to surface reflections off the plexiglas, and negatives were completely "burned out." The sidelights were therefore abandoned. Only the strobe unit was operated, for the rest of the work, giving displacement only. Figure V-4 shows two drop images as they appeared from successive strobe flashes, without incandescent sidelights.

The drop was formed approximately twelve feet above the top of the tunnel. An assistant watched the drop break free and signaled the author, who then triggered the shutter. A delay of two human reaction times thus was involved, which was less than the fall time

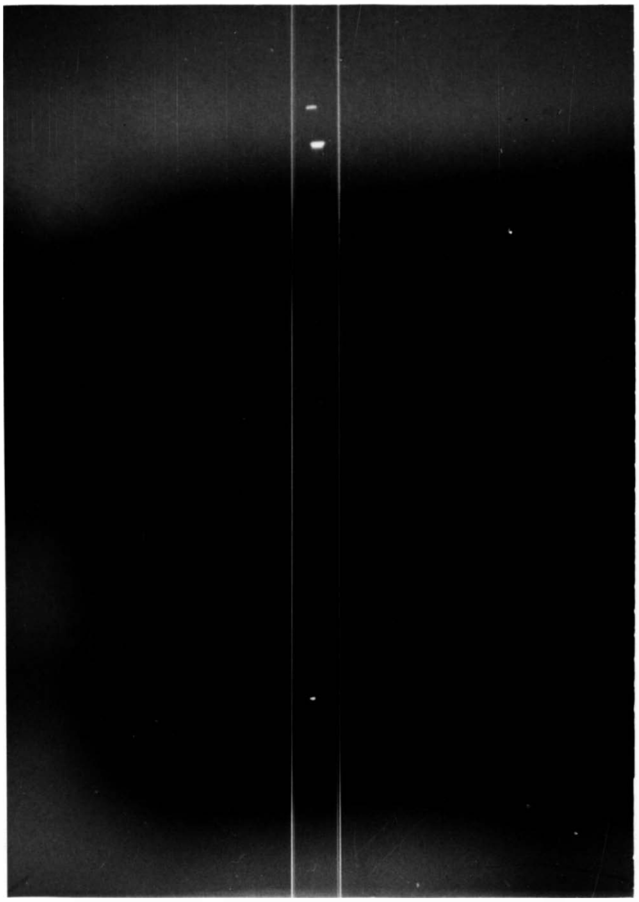


Figure V-3. Successive strobe-illuminated images of a falling drop. Streaks on each side are reflections from continuous light sources (incandescent bulbs) as drop moves through camera field.

Figure V-4. Successive strobe-illuminated images of a falling drop. No continuous light source used. Note horizontal displacement of second image, indicating drop to be falling in a slanting direction due to wind drift.

for the drop. The shutter remained open a half second, during which time the drop fell past the camera and its image was recorded twice on the film.

Drops in the size range used in this study could be expected to attain velocities of the order of 25 ft/sec. At this velocity a drop would fall three inches in 1/100 second (the interval between strobe flashes). Therefore the camera-to-subject-plane distance was adjusted to give a camera field of about six inches. This would usually give two drop images within the field of view. Many of the drops appeared on either side of the field, due to drift. It was usually necessary to expose an entire roll of eight frames to get two or three good pictures.

A 2" X 2" grid pattern was inked on white drawing cardboard to provide a means of checking camera alignment. This was suspended in the center plane of the tunnel while setting up the camera. Focus and alignment were examined on the ground glass of the camera before installing the roll film adapter. In addition to the grid pattern, a scale, computed to give feet per second directly from displacements for 100 flash-per-second exposures, was also inked. A photograph of the grid pattern and scale was made periodically to give easy reference values for velocity measurements and to give a record of camera alignment as proof it had not been altered. Figure V-5 is an example.

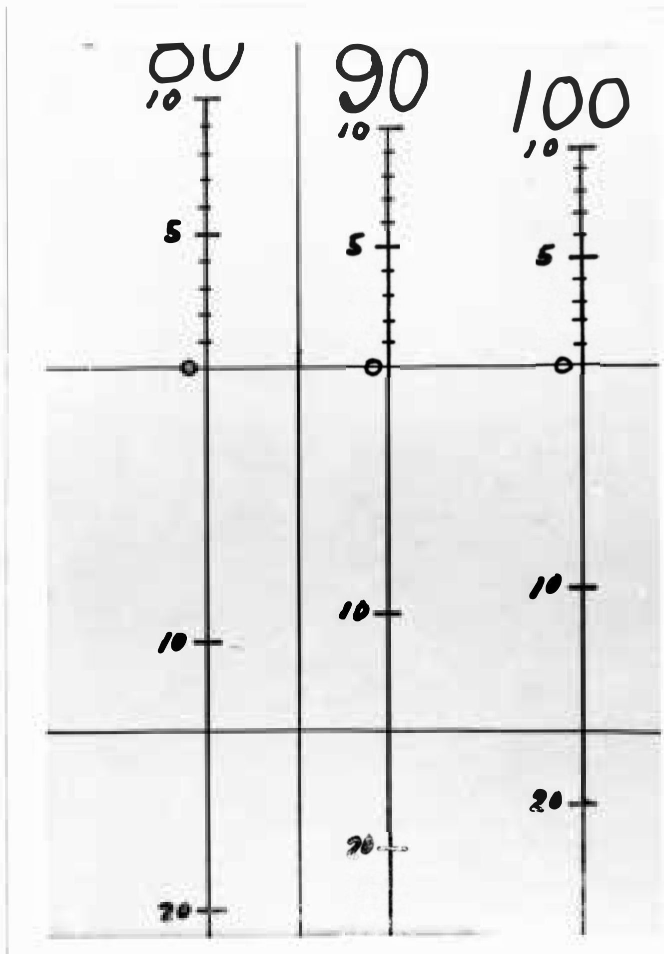


Figure V-5. Grid pattern used for checking camera alignment with and focus on the plane through which drops fell. Note the velocity scales for various strobe-light frequencies. Displacement between successive images as in Figures V-3 and V-4 were compared to the appropriate scale on a photo such as the one above to determine velocity.

Errors and Precautions

Several types of error may occur due to the nature of this method. Their nature, and methods used to minimize them, are discussed below.

1. The camera may have been out of alignment with the plane of the tunnel, thereby recording a false image of the drop's location. To minimize such errors, camera alignment was checked periodically and also whenever the camera was moved, using the grid pattern as previously discussed. The camera was rigidly mounted on a tripod. The film was supplied in a roll adaptor; with care, it could be advanced without disturbing the camera position. The roll film adaptor was easily removed from the camera to change rolls of film. The shutter was tripped by a solenoid and the flash attachment (without use of flashbulbs), so that no disturbance was likely while the shutter was open. The shutter was cocked manually, with efforts to assure lack of disturbance at this time also.
2. An error of systematic nature could have occurred due to the strobotac operating off frequency. However, the unit had been factory calibrated within the past year. In addition, a built-in vibrating reed was used as a guide in adjusting the frequency, after warmup, to frequencies

of 900 and 3600 flashes per minute. The unit seemed to hold frequency very well and did not cause any observable errors during this work.

3. Some latitude in drop-to-camera distance was possible, and could account for some error in individual measurements. Those drops which were photographed above the tunnel to estimate velocity upon entering the tunnel would be the most likely to be in error. The smaller drops, in general, showed greater wander than did the larger sizes.

The drops which were photographed within the tunnel, two feet off the tunnel floor, were more closely confined, because it was necessary for them to fall through a narrow slot (one inch wide), parallel to the film plane, to enter the tunnel. They were therefore limited to a zone somewhat less than one inch in thickness.

In either case, such errors should be nearly random in nature, so that meaningful results could be expected by averaging the results of several measurements.

Results Obtained

The fall velocity of drops of several sizes was determined under three conditions: (a) just above the wind tunnel, to determine approximate entrance velocity after twelve feet of free fall; (b) two feet above the tunnel floor, under still conditions, to determine drop

Table 5-1. Average Fall Velocities for Water Drops

Drop Diam. mm.	Wind Vel. ft/sec	Drop Velocity, ft/sec (1)*	(2)	(3)	(4)	(5)
5.5	0	24.2	24.0	30.0	27.8	30.0
5.5	20			29.9		
4.2	0	22.7	23.0	28.5	26.9	29.2
4.2	20			28.5		
3.0	0	21.5	21.3	26.2	24.9	26.4
3.0	20			26.4		
2.2	0	19.3	19.5	23.6	22.3	22.6
2.2	20			25.2		

*Note: Column (1) is the drop velocity as measured just above the tunnel entrance after falling 12 feet.

Column (2) is the velocity interpolated from the curves given by Laws (10) for 12 feet of fall.

Column (3) is the velocity as measured 2 feet above the tunnel floor, either with or without horizontal wind acting upon it; measured after drop has fallen 22 feet.

Column (4) is the velocity interpolated from Laws (10) for 22 feet of fall.

Column (5) is the terminal velocity for the respective drops as given by Gunn & Kinzer (8).

velocity after approximately twenty-two feet of fall; (c) two feet above the tunnel floor, with a twenty ft/second wind, to determine the resultant velocity as caused by the combined forces of wind and gravity. The results shown in Table 5-1 are the average values from several measurements for each drop size and measurement location.

Discussion

Drop velocities measured after 12 feet of fall agree very closely with values from curves published by Laws (10). Average values vary no more than 0.3 ft/sec from Laws' curves, and it must be emphasized that some error in this interpolation is also likely, on the order of ± 0.1 fps.

After 22 feet of fall, however, the data obtained appear to be 5-8 percent higher than values taken from Laws. For the 5.5 mm drops, the velocity measured equals that given by Gunn and Kinzer for terminal velocity. For the 2.2 mm drops, the velocity measured actually exceeds their terminal velocity value by 1.0 fps. Since they employed an electronic method of velocity measurement, capable of very good accuracy, their values would seem to be definitive.

This would cast doubt on the accuracy of the results obtained after 22 feet of fall. Table 5-2 gives the individual values obtained from separate photos, as an indication of uniformity of measurement from one picture to the next. All values shown were for drops exposed to 20 ft/sec of wind.

It can readily be seen that the measurements were somewhat variable. This may be attributed to any of the several errors previously discussed. The variance of individual values from their respective means was calculated according to the methods suggested by Mills (18), and amounted to ± 0.4. Since the variation between actual velocities recorded and values given by Laws (3) in every case exceeds

Table 5-2. Individual Drop Velocities After 22 Feet of Fall

Date	Drop Diam. mm.	Measured Velocity ft/sec	Average for Size
22 May 64	5.5	29.7	29.9
22 May 64	5.5	30.1	
15 May 64	4.2	29.1	28.5
19 May 64	4.2	27.8	
28 July 64	4.2	28.0	
28 July 64	4.2	28.5	
28 July 64	4.2	28.8	
28 July 64	4.2	29.0	
22 May 64	3.0	25.8	26.4
22 May 64	3.0	24.8	
22 May 64	3.0	27.3	
22 May 64	3.0	26.8	
22 May 64	3.0	27.2	
21 May 64	2.2	25.0	25.2
21 May 64	2.2	24.8	
21 May 64	2.2	25.9	

this several-fold, it is very unlikely that this difference could be attributed to a random effect. It can only be concluded, therefore, that (1) drops fall more rapidly at this distance than has generally been shown, or (2) some consistent error was present during the entire series of measurements at the greater fall distance. Because the studies of velocity by Laws (10) and Gunn and Kinzer (8) were much more thorough than was the author's study, the latter conclusion must be accepted as the likely explanation.

However, despite this distrust of the absolute values obtained in this study, comparison of the results for wind and no-wind conditions near the bottom of the tunnel would still seem valid.

Based on the averages shown in Table 5-1, it seems safe to conclude that the larger drops showed no effect of the vectorial addition of gravitational force and wind force in determing drop velocity. Only in the case of the 2.2 mm drops does a difference of any real magnitude appear.

CHAPTER VI

WIND DRIFT

Rain falls in a slanting direction when accompanied by wind. The slant is related to the wind velocity and to average drop size. This is described in more detail in the next chapter (Chapter VII). It is sufficient here to say that the horizontal-component velocity of the raindrops will approach the velocity of the wind acting upon them.

Rainfall simulation equipment of current usage produces drops projected downward at an appreciable initial velocity from a few feet above the ground surface. This has two important effects:

(1) the drops strike the ground with impact energy approaching that of natural rainfall.

(2) the drops fall only a short distance through air in motion, thereby minimizing horizontal drop acceleration and resulting wind drift.

Both are desirable traits. They promote realistic and uniform storm characteristics over a series of trials. Differences in results obtained can then be attributed to differences in plot characteristics (e.g. soil type, slope, cover, tillage treatment, etc.) under similar storm conditions. Meyer (17) discussed at some length the criteria for obtaining realistic information by means of such equipment. Characteristics stated to be important are:

(1) Drop size distribution and fall velocities near those of natural rainfall at comparable intensities.

(2) Intensities in the range of storms producing medium to high rates of runoff and erosion.

(3) Application area of sufficient size for satisfactory representation of treatments and erosion conditions.

(4) Complete portability.

(5) Accurate reproduction of storms.

(6) Satisfactory operation in winds of appreciable velocity (field research equipment).

(7) High uniformity of application intensity and drop characteristics throughout the study area.

(8) Angle of impact not greatly different from vertical for most drops.

(9) Rainfall application nearly continuous throughout the study area.

It seems clear that any appreciable wind drift might alter the uniformity of application intensity and the uniformity of drop characteristics throughout the study area. Small drops could be expected to drift much further than large drops. No criteria for acceptable performance in these regards have been offered; none could reasonably be established without at least some quantitative knowledge of wind drift of the drops involved. Impact angle will also be affected by wind drift.

Beyond establishing criteria for acceptable performance, such information should enable the appraisal of changes in the design of equipment to allow more perfect storm simulation.

Wischmeier and Smith (30) found they could best predict soil erosion from a given storm by an interaction between storm kinetic energy and the maximum 30-minute intensity of the storm. Since with simulation equipment intensity is usually held constant, the only variable would be kinetic energy. While maintaining other criteria - drop size distribution, intensity and uniformity of intensity - at desired levels, Mayer (15) was able to find one nozzle arrangement which produced a "storm" giving kinetic energy equal to 77% of that from a natural rainstorm at an intensity of 2.5 inches/hour. The nozzle chosen is operated at a height of eight feet.

Increasing this height would increase somewhat the kinetic energy of the "storm" produced, since the larger drops have not yet reached terminal velocity. Criteria for evaluating a nozzle on this basis are available (15), if the drop-size distribution characteristics are known.

However, increasing operating height exposes drops to a greater time of fall, making them more susceptible to wind drift. Any rational method of deciding a best balance between operating height, storm energy and allowable wind drift must be based upon achieving a "best balance" for the particular situation. Knowledge of the relationships between drift and drop size, drift and operating height and drift and wind velocity is needed.

Some idea of the effect of wind on sprinkler irrigation patterns may be gained by studying the work done by Wiersma (29). However, irrigation sprinklers cover a large area by projecting a stream horizontally outward and slightly upward while rotating. Individual drops therefore are exposed to wind for a much longer period and consequently tend to drift greater distances. Furthermore, irrigation investigations are primarily concerned with getting uniform intensity over the area involved. Energy is regarded as detrimental because of its effect in packing the ground surface (7).

This study was planned and conducted to obtain data of the kind needed to aid in selection of nozzles and operating conditions for more accurate rain simulation. Drops of five sizes, from 2.2 mm to 5.5 mm diameter, were allowed to fall into a wind tunnel operating at three wind velocities (6, 15, and 20 feet/second). In order to determine wind drift at various heights in the tunnel, a board was placed horizontally in the tunnel in the drop path. Paper toweling was taped to the top of the board, since it was found that drops could be seen much more readily against an absorbent background. The board was supported on eighth-inch welding rods across the test section, at two-foot height increments. To obtain "average impact point," the location of one splash was first noted with an aiming device. The device was then moved one-half the distance to the next impact point, one-third the distance from there to the next, then one-fourth, one-fifth, etc., until the movements became too small to be made reliably. The aiming device as illustrated in Figure VI-1, and was made of one eighth-inch welding rod, formed into two triangles so their intersection is perpendicular to the plane of their bases. This was held against the transparent side of the tunnel. The location of the splash from the drop former was first determined with the fan not running, then wind drift was determined at each height as the net displacement from this index after the fan was started. The average splash location for a given drop size-wind velocity-fall distance condition was recorded from three separate runs made on different days.

Data obtained are summarized in Tables 6-1, 6-2, and 6-3. These data were subjected to statistical analysis in an effort to find an expression for drift (in inches) dependent upon fall distance (H, feet), wind velocity (V, feet/second), and drop diameter (D, millimeters). A multiple correlation which explained 80% of the variation in drift was obtained when drift was correlated with H, H^2, V, V^2, 1/D, and $1/D^2$. Reciprocal values for diameter were used because drift increases with a reduction in diameter. It was found that the multiple coefficient of correlation did not drop significantly when up to three of the six independent variables were omitted from consideration, these being V^2, H, and 1/D. This analysis resulted in the

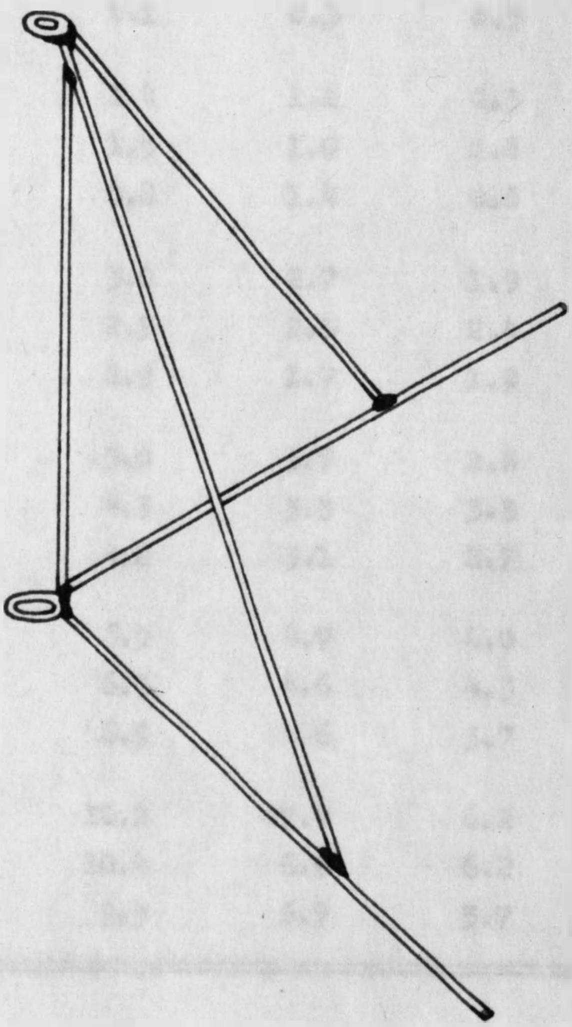


Figure VI-1. Aiming Device For Determining Drop Impact Point in Wind Tunnel. Scale: 1/2" = 1"

Table 6-1. Drift of Water Drops of Various Diameters, Falling Various Distances, Exposed to Wind at 6 feet/second

Fall Distance Feet	Drop Diameter, Millimeters 2.2	3.0	4.2	4.6	5.5
2	0.3 in.	0.6	0.2	0.2	0.2
	0.2	0.1	0.3	0.3	0.1
	0.1	0.3	0.5	0.5	0.4
4	1.4	1.1	0.5	0.8	0.6
	1.5	1.0	1.8	0.5	0.5
	0.8	1.4	0.8	1.1	0.6
6	3.0	2.7	1.9	1.6	1.3
	2.5	2.5	2.4	1.1	1.5
	2.9	1.7	1.9	1.5	1.3
8	5.0	3.7	2.8	2.6	2.0
	4.3	3.3	3.3	2.2	1.8
	4.2	3.1	2.7	2.4	2.1
10	6.9	4.7	4.0	3.3	3.0
	6.9	4.6	4.3	3.3	3.0
	6.9	4.6	3.7	3.5	3.2
12	10.2	7.9	6.2	5.4	4.3
	10.4	6.9	6.2	5.0	4.7
	9.9	6.7	5.7	5.1	4.7

Table 6-2. Drift of Water Drops of Various Diameters, Falling Various Distances, Exposed to Wind at 15 feet/second

Fall Distance Feet	Drop Diameter, Millimeters 2.2	3.0	4.2	4.6	5.5
2	1.3 in.	1.0	0.4	0.6	0.6
	0.4	0.6	1.0	0.7	1.0
	1.2	0.8	0.6	0.6	0.8
4	4.4	2.6	2.1	1.9	1.9
	3.1	2.8	2.6	2.2	1.6
	3.6	3.2	2.4	2.1	2.2
6	9.0	6.6	4.9	4.7	5.2
	8.2	6.3	5.6	5.4	4.7
	8.9	6.6	5.3	4.9	4.9
8	15.4	10.4	7.9	8.7	7.9
	14.3	11.0	9.1	8.5	8.1
	14.8	10.8	8.3	8.3	8.2
10	22.0	15.3	12.6	12.4	12.1
	21.2	16.9	13.5	12.3	11.9
	22.6	15.9	13.0	12.3	11.9
12	31.6	22.4	18.2	17.5	16.9
	29.1	22.6	18.8	18.2	16.7
	30.4	23.4	17.8	17.5	16.8

Table 6-3. Drift of Water Drops of Various Diameters, Falling Various Distances, Exposed to Wind at 20 feet/second

Fall Distance Feet	Drop Diameter, Millimeters 2.2	3.0	4.2	4.6	5.5
2	1.6 in.	1.5	0.7	0.9	1.3
	1.4	0.8	1.0	0.9	1.1
	1.2	1.0	0.9	0.5	0.8
4	5.7	4.3	2.9	3.2	4.0
	5.1	3.6	3.2	3.1	3.4
	5.4	4.1	3.1	3.9	3.6
6	13.1	9.0	7.9	7.0	7.0
	11.9	9.5	7.5	7.0	7.1
	12.2	9.2	7.4	7.3	6.9
8	20.7	15.1	11.9	11.6	11.7
	21.1	15.5	12.5	12.0	11.9
	21.7	15.2	12.1	14.4	10.9
10	34.7	22.6	18.3	17.9	18.0
	32.1	24.6	18.8	18.2	17.9
	32.1	23.7	18.0	21.4	17.1
12	47.0	32.1	25.6	24.8	25.0
	45.1	32.1	26.3	25.5	25.0
	44.6	33.0	25.9	26.6	24.1

regression equation

$$\text{Drift} = -12.97 + 0.757V + 0.134H^2 + 33.4/D^2. \qquad \text{(VI-1)}$$

An equation of such form is based on an assumption that the effects of the independent variables are additive.

A second analysis was made, correlating the logarithm of drift with the logarithms of wind velocity, fall distance, and drop diameter.

The resulting equation explained over 95% of the variation in drift and when retransformed to the form of the original variables, gave

$$\text{Drift} = H^{1.83}\ V^{1.21}/50.5\ D^{0.69} \qquad \text{(VI-2)}$$

Such an equation indicates a multiplicative effect between the independent variables.

Figures VI-2, VI-3 and VI-4 illustrate the fit of these two regression equations, compared to actual data for wind velocities of 6, 15 and 20 feet/second.

Discussion of Results

Equation VI-1 ($\text{Drift} = -12.97 + 0.757\ V + 0.134\ H^2 + 33.4/D^2$) plots as a family of curves (Figures VI-2, VI-3 and VI-4) of identical shape, translated up or down the inches-of-drift axis depending upon values of velocity or fall distance inserted. Study of the three sets of graphs indicates that this equation fits very well for 8 feet of fall through wind at 15 feet/second. However, the inflexibility of curve shape leads to poor prediction of drift either for the smaller

Figure VI-2. Drift Vs. Drop Size (6 feet/sec wind)

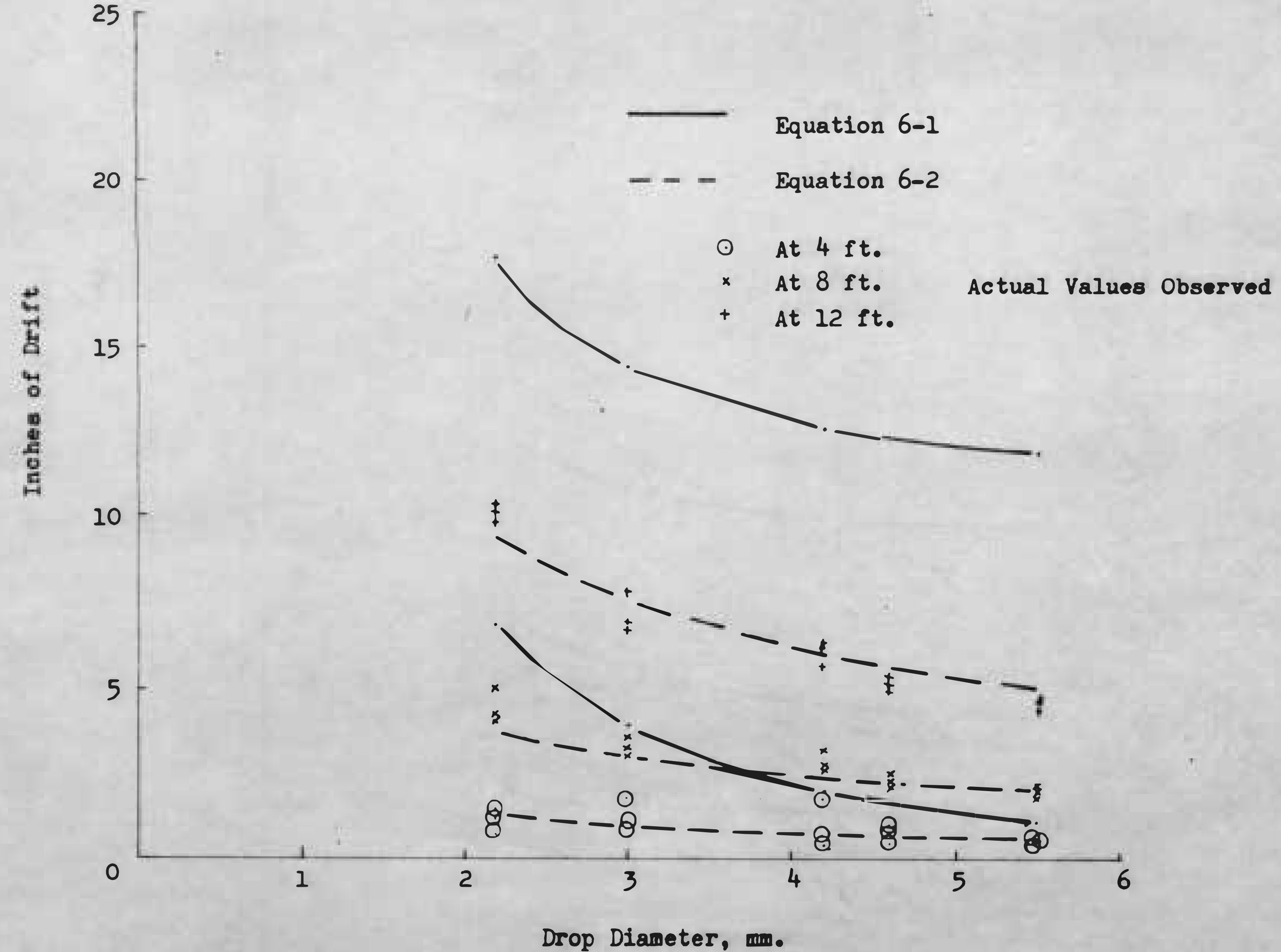


Figure VI-3. Drift Vs. Drop Size (15 feet/sec wind)

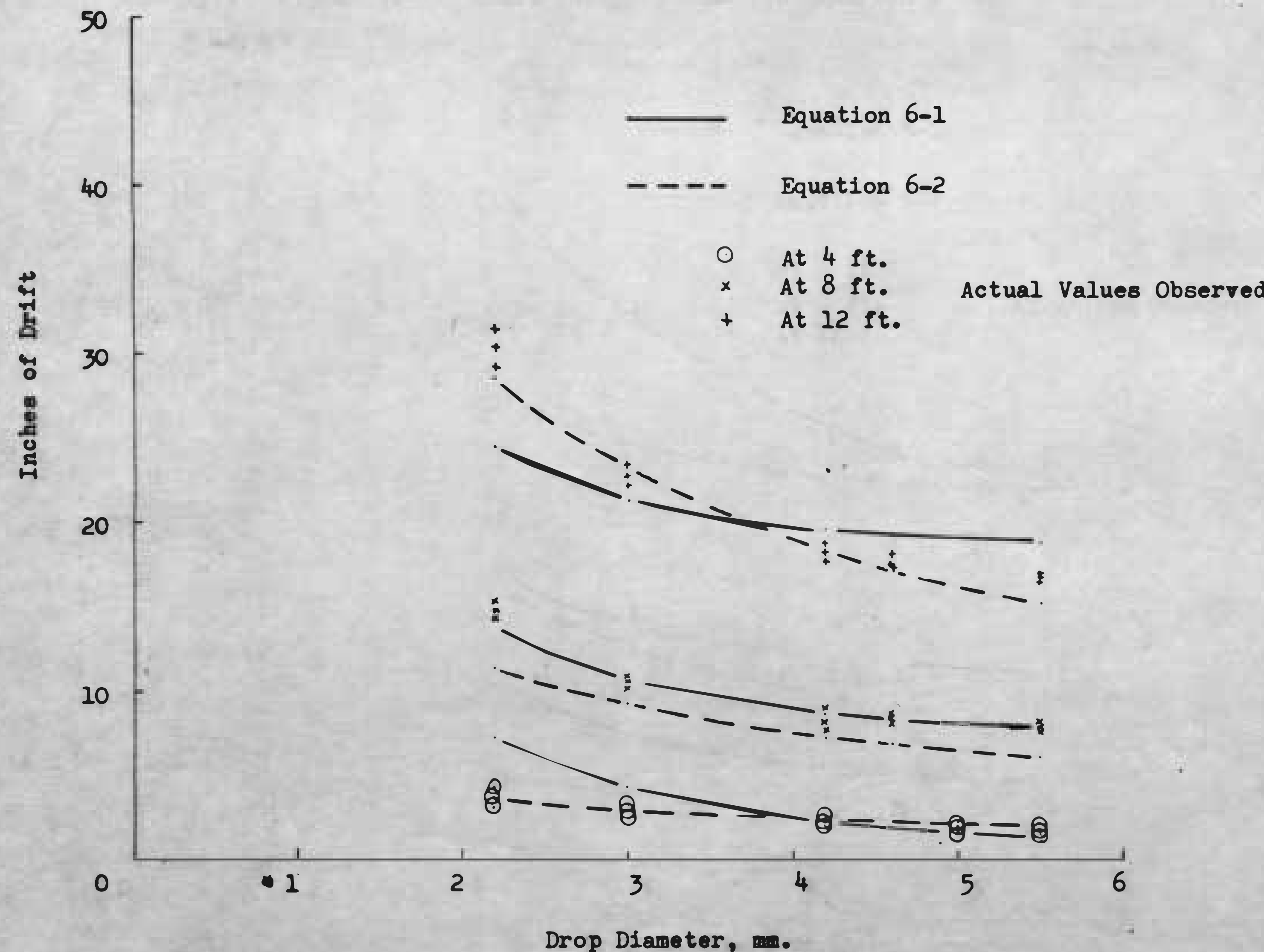
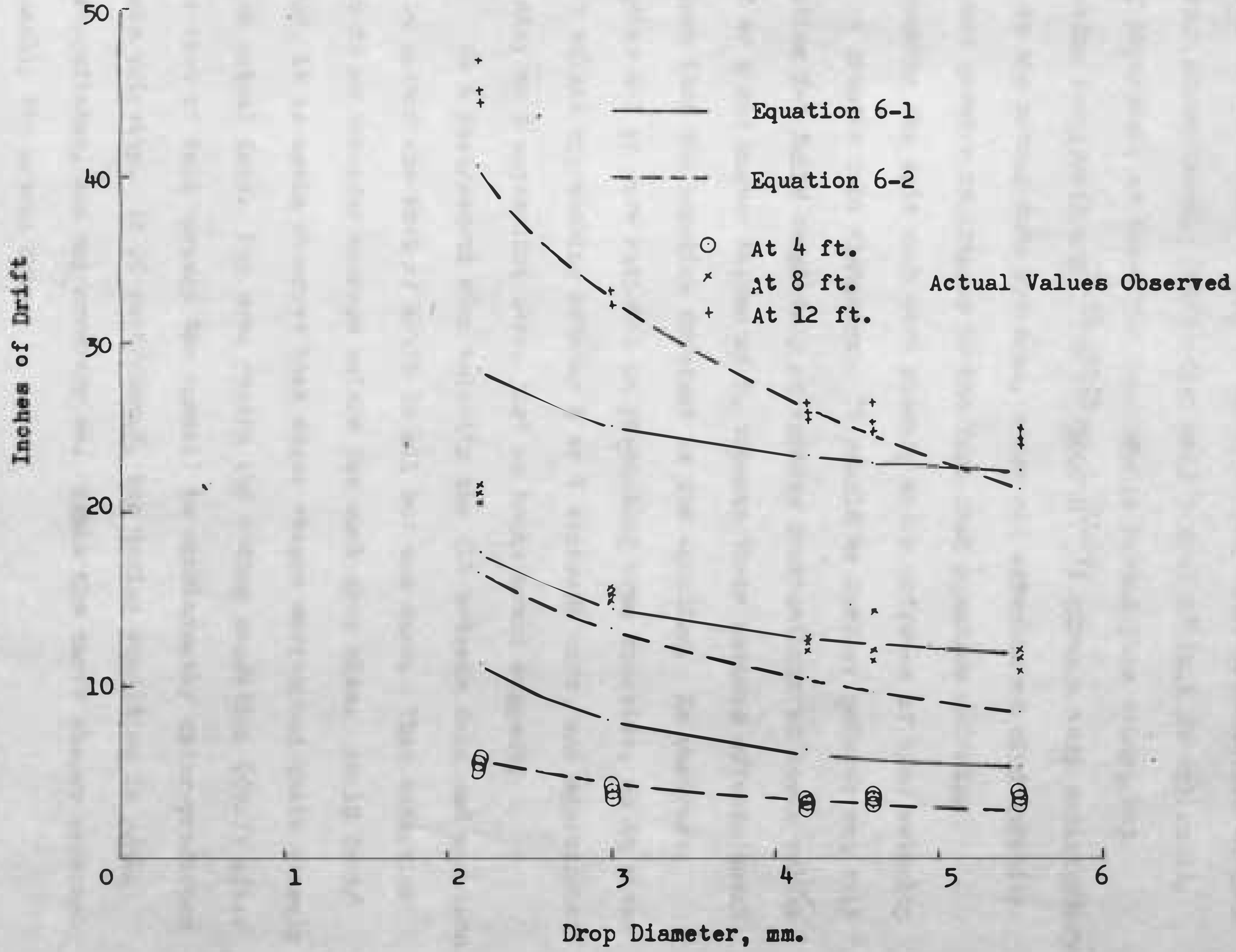


Figure VI-4. Drift Vs. Drop Size (20 feet/sec wind)

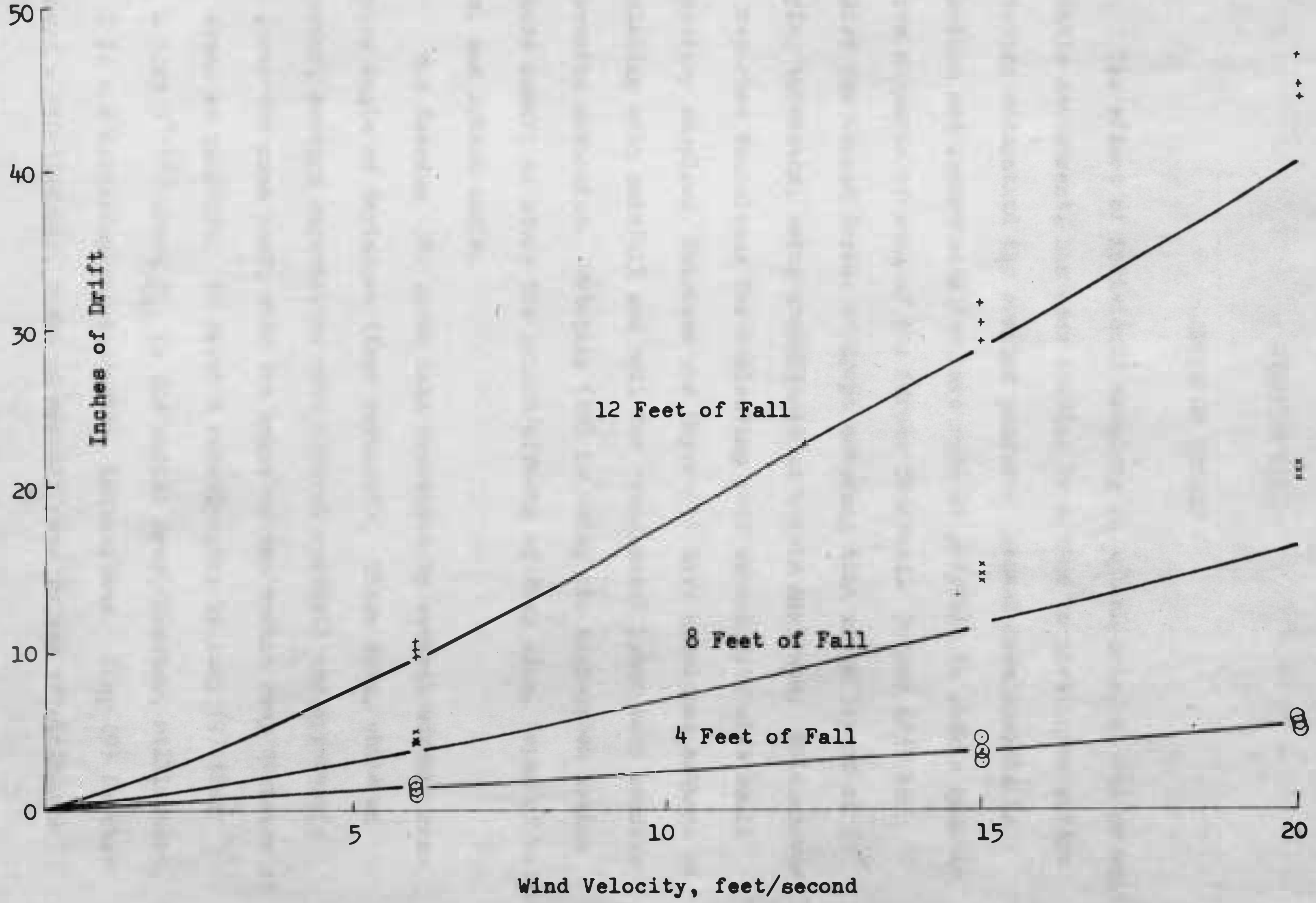


drops, or the larger drops, or both, at any other combination of conditions encountered. Drift after only 4 feet of fall is not really very important, at least for the purpose behind this study; but equation 6-2 (Drift = $H^{1.83}\ V^{1.21}/50.5\ D^{0.69}$) gives a very satisfactory fit to the actual data obtained, under all extremes of wind velocity. Of much greater importance is the fact that equation 6-2 also approaches the data much more closely under extremes of wind velocity and at greater fall distances. It should be further pointed out that equation 6-1 fails completely at various combinations of lower values of V or H and higher values of D, because their various effects total to less than the negative constant in the equation. In contrast, equation 6-2 is more rational in predicting true behavior, as it gives drift values approaching zero as H or V approach zero, and approaching infinity as D approaches zero, just as logic would suggest.

At 6 feet/second wind velocity the fit between data and equation 6-2 is within one inch of drift in all but one case. That exception falls if we consider average values for each drop size. At 15 feet/second, it is again observed that curve shapes correspond quite closely to the actual data. For some reason the medium condition (drift after eight feet of fall through the tunnel) is consistently under-predicted at this velocity. At 20 feet/second, the medium condition is again under-predicted, but not severely so. Again the curve shapes approach reasonably the actual data.

It may be noted that the drift of extremes of drop sizes are under-predicted in several cases; in no case is there a tendency to over-predict the drift of the smaller drops, and only in the case of the largest drops exposed to only 6 feet/second of wind for 12 feet of fall does the equation over-predict the observed drift. Figure VI-5 illustrates clearly the tendency to under-predict drift for smaller drops.

Figure VI-5. Drift Vs. Wind Velocity, 2.2 mm. Drops



CHAPTER VII

ANGLE OF IMPACT

The effect of individual droplets on splash erosion, and on soil particle detachment, has been studied from time to time in an effort to better understand the erosion process. Recent developments in technique and instrumentation have made it possible to obtain quantitative measures of some of the forces involved. Palmer (23) has studied the impact forces of drops entering thin water layers of varying thickness, using straingages on a thin membrane. Moldenhauer (19) has reported techniques for evaluating soil erodability with small laboratory samples. Bubenzer and Meyer (3) have developed methods of simulating both rainfall and soil for fundamental laboratory studies of erosion mechanics. Mutchler (20) is using the high-speed motion picture camera to study the splash effects of drop size, depth of water film, and splash angle.

Van Heerden (28) cites data presented by several workers concerning angle of deviation (from vertical). These data, while of interest, concern experiences with natural rainfall and apparently deal, for the most part, with the angle of the median drop diameter of the storm in question. He cited a relationship by Lacy (9) that $D_{50} = 2.23\ I^{0.182}$ where D_{50} is the median drop diameter, millimeters, and I is the instantaneous intensity, inches/hour. Lacy (9) further offered a relationship, based on monthly mean values of windspeed (miles/hour) V, and angle of deviation (degrees); tan i = -0.04 + 0.14 V.

Since natural raindrops have fallen a sufficient distance to approach or achieve terminal velocity vertically and a balance with windspeed horizontally, the impact angle or angle of deviation should be expected to exceed those experienced under a rainfall simulator.

As more is learned about the influence of splash angle on such things as splash transport, surface sealing, and splash agitation of surface-impounded runoff water, existing data on impact angles under a variety of conditions are likely to become more valuable. It is quite simple to determine approximate impact angle under a range of drop sizes, fall distances, and wind velocities.

Procedure

Data for drop drift (as reported in Chapter VI, Wind Drift) under varying heights and wind velocities were plotted (Figures VII-1, VII-2, and VII-3). To determine the impact angle at a particular point on the trajectory of a given drop size, the slope of a tangent to the trajectory curve was determined from these plotted data. A protractor was held tangent to the curve and the apparent angle from vertical was read off, to the nearest degree. Since these curves were not drawn to the same scale on both axes, it was necessary to calculate the true angle from vertical at that point. This correction was made by first looking up the tangent-function of the angle involved, then

Figure VII-1. Drift Vs. Fall Distance With 6 Feet/Second Wind

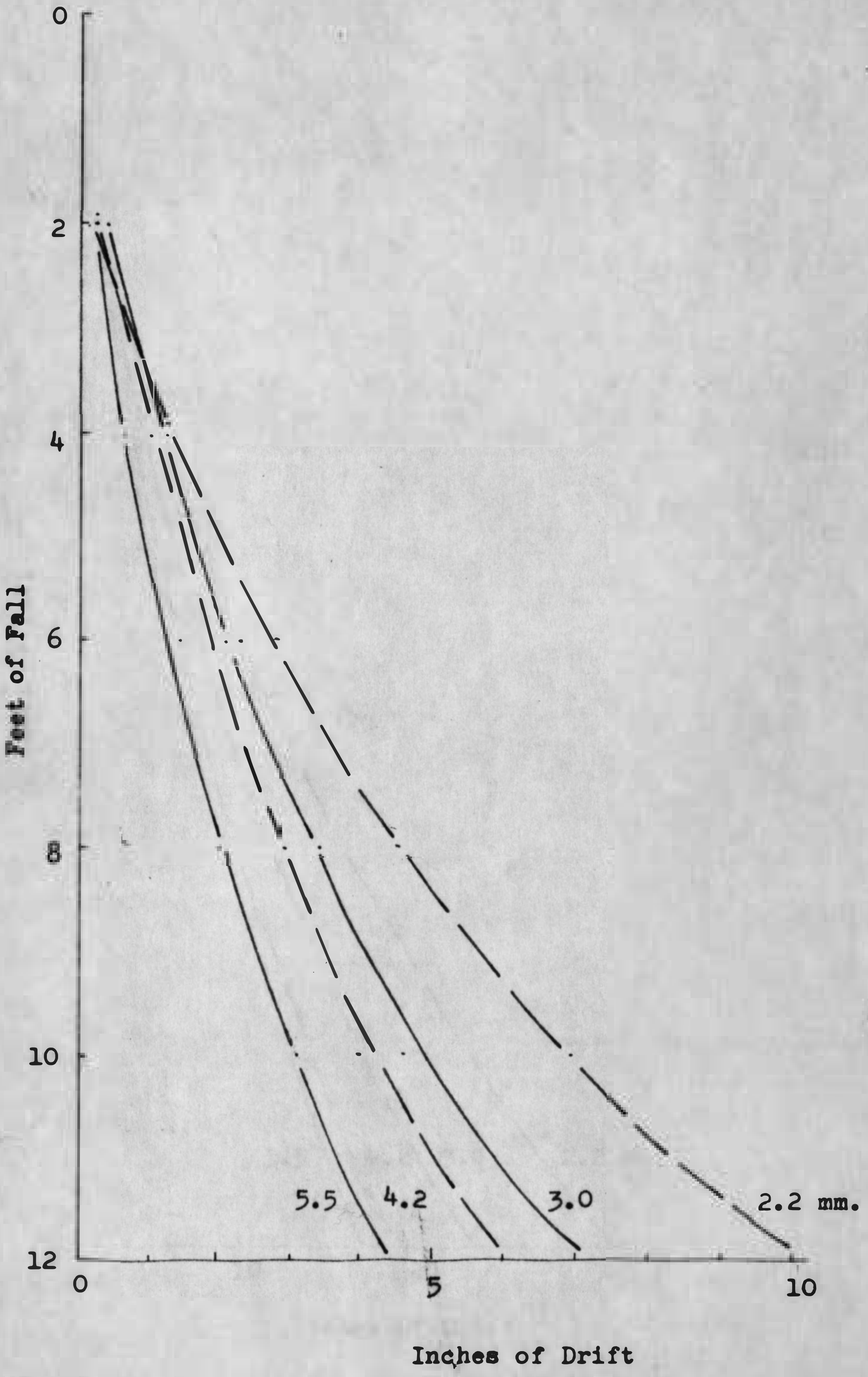


Figure VII-2. Drift Vs. Fall Distance with 15 Feet/Second Wind

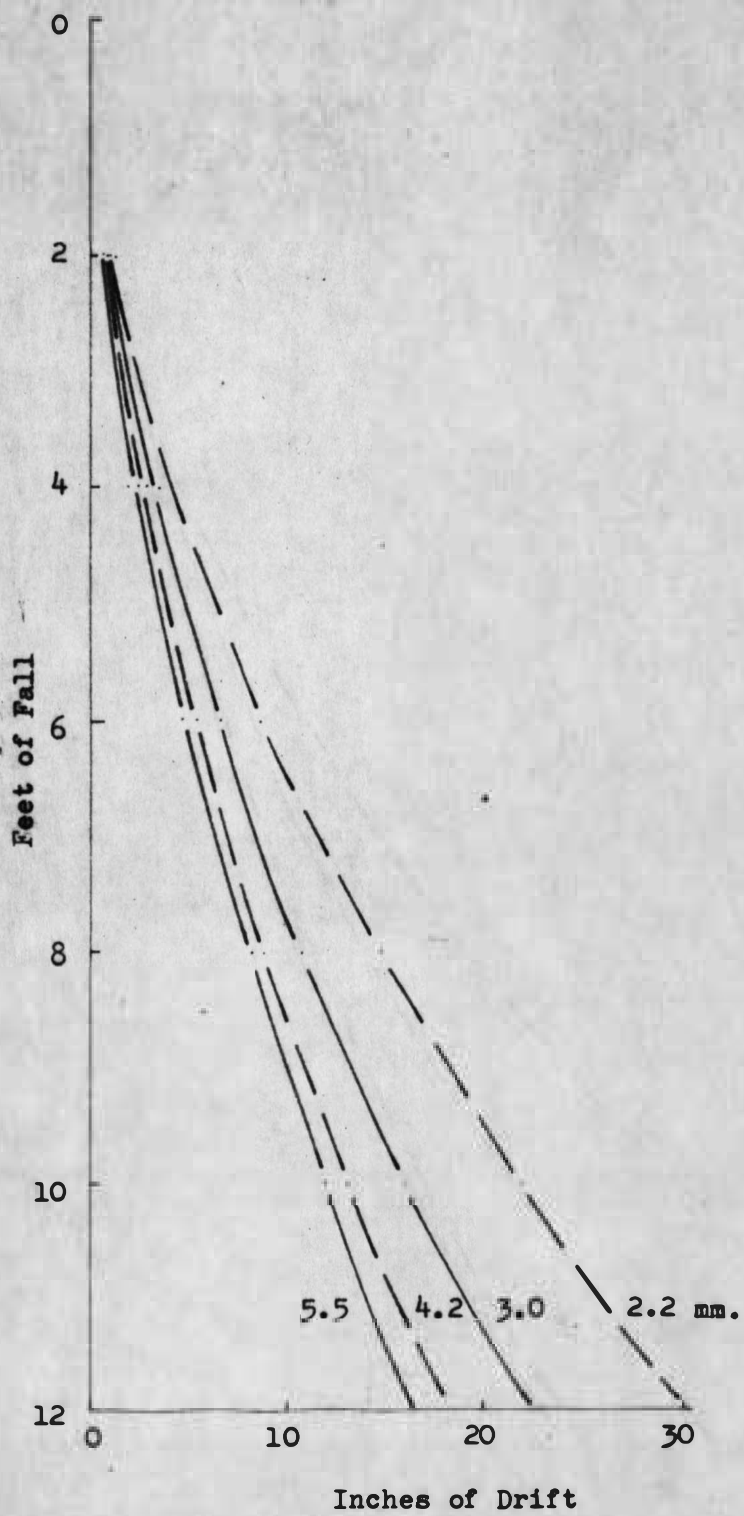
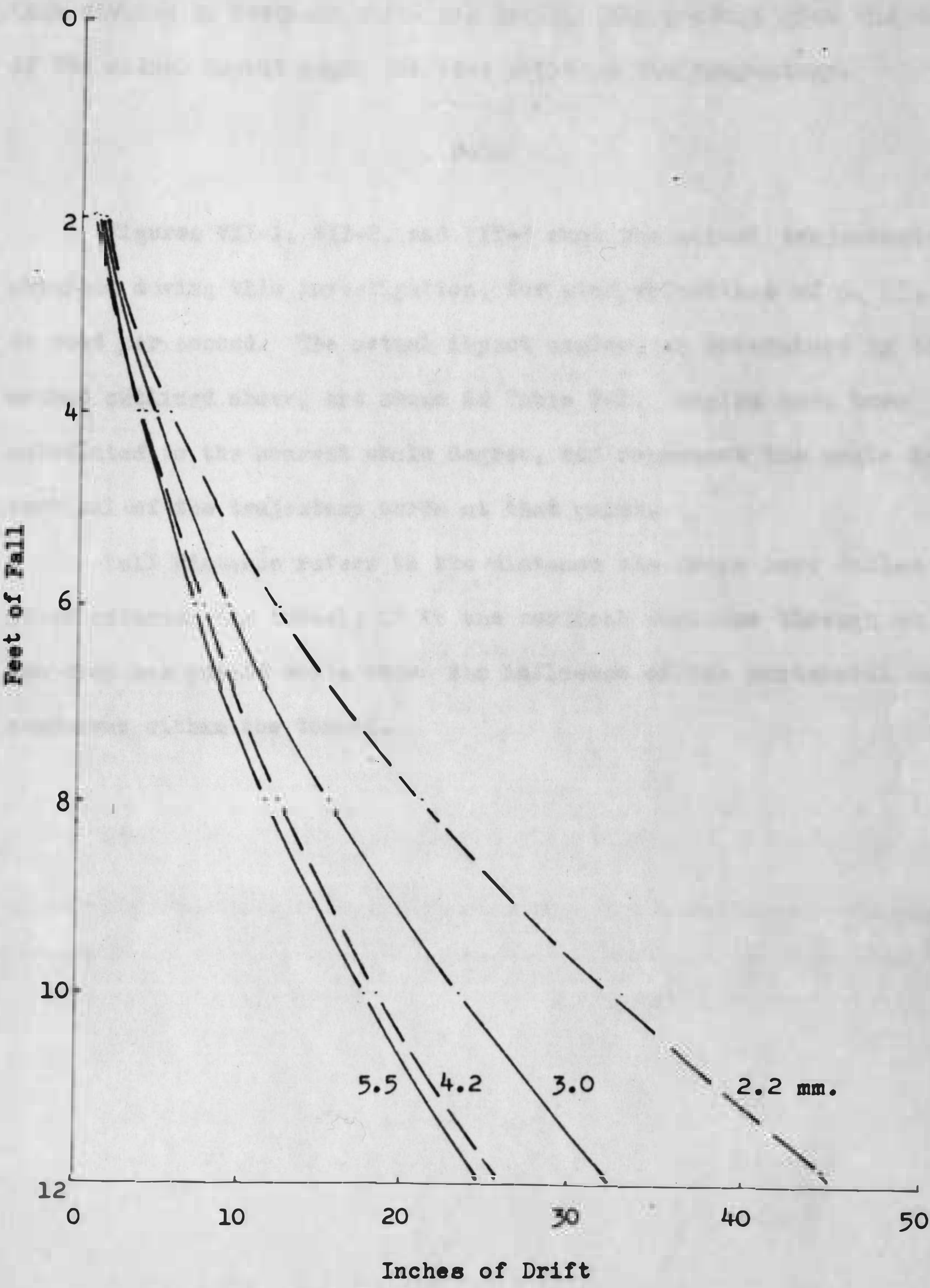


Figure VII-3. Drift Vs. Fall Distance With 20 Feet/Second Wind



multiplying it by the ratio of the two scales (horizontal units per inch divided by vertical units per inch). The product gave the tangent of the actual impact angle for that point on the trajectory.

Data

Figures VII-1, VII-2, and VII-3 show the actual trajectories obtained during this investigation, for wind velocities of 6, 15, and 20 feet per second. The actual impact angles, as determined by the method outlined above, are shown in Table 7-1. Angles have been calculated to the nearest whole degree, and represent the angle from vertical of the trajectory curve at that point.

Fall distance refers to the distance the drops have fallen after entering the tunnel; it is the vertical distance through which the drop has passed while under the influence of the horizontal wind component within the tunnel.

Table 7-1. Impact Angles of Several Sizes of Drops

Drop Diameter mm.	Fall Distance, Feet 2	4	6	8	10	12
			6 fps wind			
2.2	2 deg.	3	4	5	7	10
3.0	1	2	3	4	5	7
4.2	1	2	2	3	4	5
5.5	1	1	2	2	3	4
			15 fps wind			
2.2	4	9	13	16	18	20
3.0	3	7	9	12	14	17
4.2	3	6	7	9	12	14
5.5	2	5	7	9	11	12
			20 fps wind			
2.2	5	11	19	23	26	28
3.0	4	9	13	17	20	22
4.2	4	8	10	13	17	19
5.5	3	8	10	13	16	18

CHAPTER VIII

DROP BREAKUP

Surface tension forces tend to hold a drop of water in the shape of a sphere. A falling drop, however, is deformed to a greater or lesser degree, due to the pressure of air against the leading surface, and the reduction in pressure against the trailing surface. Blanchard (1) pointed out that the internal pressure due to surface tension varies inversely with the radius of the drop. At the same time, terminal velocity increases with increasing drop diameters; with increased velocity, external forces also increase. This deformation is nicely illustrated in some of the flash photography by Edgerton (5). As drops increase in size, therefore, they tend to become more and more flattened in shape until instability is reached and the drop is broken to form several smaller drops. Blanchard (1) was able to illustrate the oscillation in shape which takes place prior to the drop breakup. Figure VIII-1 illustrates by successive flashes (1/10 sec intervals) the initiation of this oscillation as a drop is formed on a large (1/4 inch) drop former. However, Blanchard's work demonstrated that this oscillation would occur due to instability of the larger drops; it is not apparently due to initial disturbances at the time of formation.

Blanchard stated (1) "Drops below 4.6 mm in diameter have been found to be quite stable when subjected to shock as described above.

Instability begins to set in at 4.6 mm diameter and increases until at drop sizes of 5.4 mm diameter, all drops subjected to shock will break up." In his experiments drops were supported stationarily upon an upward-directed air stream. The shock to which he refers was caused by passing the hand quickly across this air stream. He cited Lenard (11) as having concluded that drops above 5.5 mm cannot exist for more than a few seconds.

During the early portion of the drift investigations, reported in Chapter VI, a close similarity in trajectories of the 4.2 mm and 5.5 mm drops was noted. The possibility existed that the larger drops might be splitting into two drops about 4.2 mm in diameter. Such break up might be due to the shock of being abruptly subjected to a horizontal wind at 20 feet/second. This would not be important with the present rainulator because the upper limit of drop sizes produced, as reported by Meyer (15), is about 3.5 mm. However, should these data be later used in evaluating other drop-forming systems for simulation work, it might be an important effect.

To determine whether this was occurring, it would be necessary to either (1) observe or photograph simultaneous multiple drops, or (2) determine at least relatively the diameter of drops passing through the tunnel.

During the determination of representative drop velocities, the instantaneous images of single drops, illuminated by the Strobolux unit at 100 flashes/second, could be seen with the naked eye. On

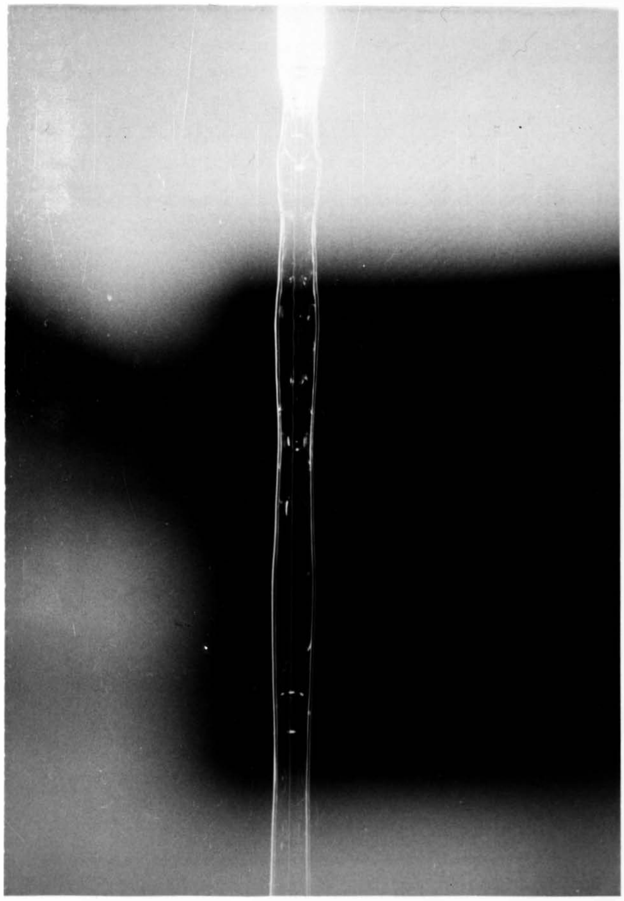


Figure VIII-1. Successive images at 1/10 second intervals of drop forming on 1/4 inch tubing and then breaking loose to fall at rapidly increasing velocity. A new drop formed in approximately 1.5 seconds. Note the alternate lateral contractions and expansions as shown by the continuous streaks, indicative of the oscillation between oblate and prolate shape as the drop falls.

one occasion, it was noted that a cluster of drops, descending more slowly than usual, was seen. No photograph of this turned out: either the multiple drops drifted to one side of the field of view of the camera, or their slower rate of descent allowed sufficient time for the camera shutter to close, or both.

Meyer (15) cited several methods of determining drop size by indirect means: among these is the correlation of known size with the size of spot produced on some material such as treated paper. A rough adaptation of this method was made during the drift measurements. Each drop was allowed to fall on paper towelling taped to a board in the tunnel. Since precise drop size need not be measured for this purpose, it was only necessary to note whether a given drop produced a spot similar to that normally made by a 5.5 mm drop, or a spot much smaller. A drop of 4.2 mm diameter was found to produce a spot on the order of an inch or less in diameter immediately after landing on the paper, while a 5.5 mm drop produced a spot roughly twice this size. It was only necessary to note whether a series of drops, nominally 5.5 mm diameter, all produced substantially the same size spots when subjected to the 20 feet/second wind in the tunnel, to be reasonably sure that breakup was not occurring.

No evidence was obtained suggesting that breakup was occurring, other than the one breakup previously mentioned. It is very possible this occurred as a result of impact of the drop against the side of the slot in the roof of the tunnel.

In conclusion, it does not appear likely that the force of a 20 feet/second wind acting on the side of a 5.5 mm drop, already travelling at a velocity of 24 feet/second, is sufficient to cause it to break up, at least during the split second it takes for it to fall another ten feet. Smaller drops could also be assumed to be stable under these conditions.

CHAPTER IX

APPLICATION OF RESULTS

In Chapter VI it was stated that a need existed for knowledge of the relationships existing between drift and drop size, operating height, and wind velocity. Such knowledge would allow optimum selection of nozzles for rain simulation under various conditions and would be helpful in establishing operating criteria for windy conditions. Two applications of this information follow.

1. Shown on Figure IX-1 are two curves representing drift at 8 and 12 feet of fall, respectively, plotted against drop size, assuming a wind velocity of 20 feet/second. These were plotted to points calculated from equation 6-2. Such a velocity represents a wind of 13.6 miles/hour, about the upper limit for satisfactory operation of the Meyer-McCune "Rainulator," according to Young (31).

   Assuming the wind to be blowing across the plots, one could conclude that the border area outside the plots must be about 40 inches wide for 8 feet of fall, or about 90 inches wide for 12 feet of fall, if a uniform rate of water application and energy application to the soil were to be maintained, given this wind velocity.

2. Meyer (15) presented calculations by which he determined the kinetic energy of various portions of the spray produced

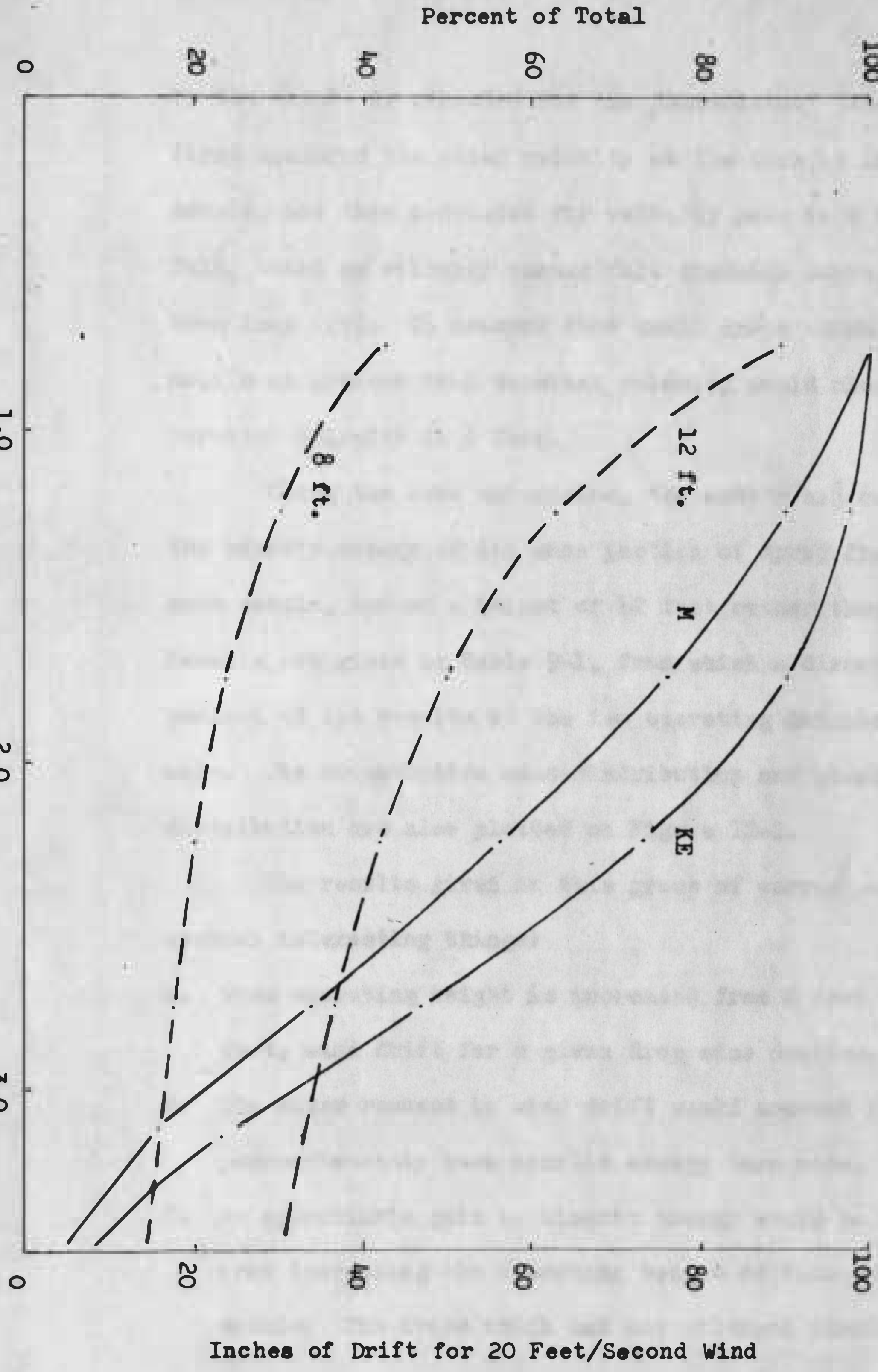


Figure IX-1. Drift Vs. Drop Size and Accumulative Mass and Kinetic Energy by the nozzle he selected for the "Rainulator" (14). He first measured the water velocity at the time it left the nozzle, and then corrected for velocity gain in 8 feet of fall, based on velocity versus fall distance curves derived from Laws (10). He assumed that small drops which left the nozzle at greater than terminal velocity would slow to terminal velocity in 8 feet.

Using the same assumption, the author has calculated the kinetic energy of the same portion of spray from the same nozzle, but at a height of 12 feet rather than 8 feet. Results are given in Table 9-1, from which a direct comparison of the results of the two operating heights may be made. The accumulative mass-distribution and kinetic-energy distribution are also plotted on Figure IX-1.

The results given in this group of curves point up several interesting things:

1. When operating height is increased from 8 feet to 12 feet, wind drift for a given drop size doubles.
2. The water removed by wind drift would account for proportionately less kinetic energy than mass.
3. No appreciable gain in kinetic energy could be expected from increasing the operating height of this particular nozzle. The drops which had not attained terminal

Table 9-1. Sample Evaluation of Spraying Systems Company 80100 Veejet, Operating at 6 Psi
Data From Center of Pattern, Nozzle Velocity 22.3 fps

* Drop Size Group, mm	* Per-cent by Wt.	Accu-mula-tive From Larg-est	* ½ Mass per Ac-In	Velocity, fps * Term-inal	* @ 8'	@12'	V^2 * 8'	12'	KE, ft-lb/Ac-In * 8'	Accum %		12'	Drift, In. 8'	12'
0.5-1.0	10.0	100.0	352.2	10.1	10.1	10.1	102.0	102.0	35,924	100.0	100.0	35,924	41.0	85.9
1.0-1.5	14.0	90.0	493.1	15.9	15.9	15.9	252.8	252.8	124,656	97.8	97.8	124,656	28.8	60.4
1.5-2.0	19.5	76.0	686.8	19.9	19.9	19.9	396.0	396.0	271,973	89.9	90.1	271,973	22.9	48.0
2.0-2.5	22.5	56.5	792.5	23.0	22.8	23.0	519.8	529.0	411,942	72.5	73.4	419,232	19.2	40.3
2.5-3.0	18.0	34.0	634.0	25.5	24.3	24.8	590.5	615.0	374,377	46.5	47.7	389,935	16.7	35.1
3.0-3.5	11.5	16.0	405.0	27.3	25.1	26.0	630.0	676.0	255,150	22.8	23.8	273,780	14.9	31.2
3.5+	4.5	4.5	158.5	28.6	25.8	26.9	665.6	723.6	105,498	6.7	7.0	114,692	14.0	29.4
							Total		1,579,520			1,630,192**		

* Indicates data tabulated by Meyer (15)
** Represents kinetic energy gain of 3.3 percent

> velocity after 8 feet of fall did not accelerate enough in an added 4 feet of fall to effect any significant energy gain.
>
> Such a study forces the conclusion that nothing would be gained, and much lost, by increasing the operating height of this particular nozzle.

Similar comparisons could, of course, be as easily made between a number of different nozzles. Another nozzle might be found which produced larger drops than did this one, but at the cost of too great an intensity. Increasing the operating height would spread out the pattern, reducing intensity, while at the same time allowing gravity to accelerate a large drop and give a more impressive boost to kinetic energy. Working from Laws (10), a 4 mm drop leaving the nozzle at 22.3 feet/second would reach a velocity of about 26 feet/second in 8 feet and about 27 feet/second in 12 feet; a 5 mm drop would reach velocities of about 26.7 and about 28 feet/second, respectively, under the same conditions. The significance of these velocities in determining storm kinetic energy would be determined by their frequency of occurrence as well as by their velocity. Such investigations would have to weigh all the factors given by Meyer (17) in Chapter VI. This information should be helpful in evaluating his objective 6.

CHAPTER X

CONCLUSIONS

1. A wind tunnel of eight-inch width was found adequate for studying wind-drift characteristics of vertically falling water drops. Individual drops were assumed to be small enough that edge effect would not become a valid consideration. Uniformity in velocity profile obtained was quite good with this wind tunnel, in the velocity range studied.
2. Drops from 2.2 to 5.5 millimeters diameter, having very good size uniformity, were produced at a controlled rate by regulating flow rate to the tubing upon which the drop was formed. Drop size obtained was a function of tubing size. Moderate variation in rate of production did not appear to cause change in drop size.
3. Drop velocities appeared to conform well with values given by sources in the literature, except at greater fall distances. Measurements after twenty-two feet of fall did not appear to be consistent with values given by other workers. Comparison of measurements obtained under wind and no-wind conditions indicated that impact velocity of drops larger than 3.0 mm was not affected by 20 feet/second wind, if those drops fell no more than 10 feet through the wind. Smaller drops were affected, however, as 2.2 mm drops showed a velocity gain of almost seven percent.

4. A regression equation (eq. 6-2) was developed which explained more than 95 percent of drop drift, depending upon wind velocity, drop size, and fall distance. Wind drift was shown to be the result of a multiplicative, rather than an additive, effect of these variables. Within the range of conditions studied, the equation tended to under-predict, indicating it to be a conservative estimator. Drift was found to be almost a linear function of wind velocity, but an exponential function of fall distance, and an inverse function of drop diameter.
5. Impact angles were measured under a variety of fall distances, wind velocities, and drop sizes. Impact angle, like drift, increased with fall distance and wind velocity, and decreased with increasing drop size.
6. Drops up to at least 5.5 mm diameter were shown to be capable of withstanding the shock of a 20 feet/second wind without breaking up. Drops of this size were travelling 24 feet/second vertically when first exposed to the horizontal wind force. Literature sources indicate breakup to be a function of time and that drops larger than 4.6 mm are unstable. However, greater fall distance, or a more intense wind force, or both, would seem to be necessary to cause breakup of these large drops under simulation equipment.

CHAPTER XI

SUGGESTED FURTHER RESEARCH

The effect of wind in displacing small-arms projectiles has been rather well investigated by ordnance engineers and experimenters both amateur and professional.

Lowrey (12) presented the relationship usually used in predicting such drift as

$$D = 12\, v\, (T - R/V_o)$$

where

D = drift in inches

v = cross wind velocity, feet/second

T = time of flight, seconds

R = range, feet

V_o = muzzle velocity of the bullet, feet/second.

He explained the reasoning behind this equation by an analogy, which follows:

Suppose that two railways are parallel, a distance R apart. Two trains travel the same direction and velocity, even with each other, down the two railways. A rifleman on the first train aims at a target on the second train. His firing the rifle directs a bullet towards the second train, the bullet having a velocity V_o towards the target train and a velocity v parallel to the trains. If the bullet travelled at constant velocity it would strike the center of the target at a time equal to R/V_o, just as though the trains had been standing still.

However, because the bullet slows down in flight due to air resistance, at time R/V_o the bullet is still a short distance away from the target. Because the target continues to travel at a velocity v, by the time the bullet gets to the second train the target has moved an additional distance, equal to v times the "lag time." Lag time is the difference between actual flight time T and the time given by R/V_o. The same relationship between these factors has been shown to hold true if v be considered the wind velocity with target and rifle stationary.

The same relationship may hold true for the drift of falling water drops, if "lag time" is correctly defined. In this case, the actual flight time, or fall time, may be determined from either existing measurements of velocity for different drop sizes and distances, or by additional measurements of drop time from drop forming device to final impact area. This might well include drops produced by numerous types of nozzles which project drops at some angle from vertical, including irrigation sprinklers, cone- and flat-spray nozzles, etc. The value corresponding to "R/V_o" in the analogy above would be derived from the idealized equations of motion, based on initial velocity and direction and the force of gravity. Initial investigations might well be based on existing data from this and other sources, disregarding the material involved. If feasible, it could then be applied to more complex situations.

Additionally, more information on drift of falling drops is needed for drops smaller than those investigated in the present study. Fully half the water making up the spray under the Meyer-McCune simulator, for example, is in drops smaller than 2.2 mm (15), and they account for a third of the storm kinetic energy.

Such small drops cannot be produced by the method used in this study. Meyer (15) indicated that they can be produced by blowing moist air past the drop former to oppose surface tension and allow the drop to fall before its size grew sufficiently for the force of gravity alone to pull it from the drop former. He reported that drops smaller than 1.0 mm could thus be produced.

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APPENDIX I

DESIGN DETAILS OF TUNNEL

When the tunnel was being planned, a good deal of concern existed that throat width be kept adequate to provide a uniform flow of air within the desired velocity range of 0-25 feet/second. On the basis of a fan available, a Habco 3 horsepower (Model J-127) unit, it seemed that an 8-inch throat width would provide velocities up to about 24 feet/second.

Evaluation of this throat width was based on criteria suggested by Schlicting (26). Meyer (16) pointed out that air would enter the test section at a velocity initially uniform across the throat. It would then gradually accelerate in velocity at the center while decelerating along the wall, until a parabolic profile resulted. According to Schlicting (26), the parabolic profile is developed at a distance from the entrance given by $l_E = 0.04(2a)R$, where l_E is the distance (in throat widths) from the entrance; 2a is the throat width; and R is the Reynolds number. Reynolds number is given by the equation

$$R = u l \rho / \mu$$

where u = velocity (8, 16, 24 feet/second were checked)

l = characteristic length (8 inches, or 12 feet)

ρ = mass density (0.0807 lb/ft^3)

μ = viscosity (4 X 10^{-7} lb-sec/ft^2)

Values were checked in both axes and are tabulated in Table I-1. Also

Table I-1. Characteristics of 8-Inch by 12-Foot Tunnel Throat Section

Velocity	Reynolds Number		l_E* for Parabolic Development	
ft/sec	8" dimension	12' dimension	8" dimension	12' dimension
8	1.077×10^6	19.39×10^6	2.85×10^4	9.3×10^6
16	2.154×10^6	38.78×10^6	5.74×10^4	18.6×10^6
24	3.231×10^6	58.17×10^6	8.59×10^4	27.9×10^6

*With the intended tunnel length of 24 feet, actual lengths, in units of l_E would be 36 (8" units) and 2 (12' units)

given is the number of throat lengths for the parabolic velocity profile to develop.

In the words of Schlicting, "...at R of 2000 to 5000 the inlet length extends over 80 to 200 channel widths. Consequently, the flow does not become fully developed at all if the channel is short or if the Reynolds number is comparatively large." Study of the velocity profiles actually obtained, as shown in Figures IV-1, IV-2, and IV-3 substantiate this statement satisfactorily: the parabolic velocity profiles did not develop to any extent.

With the establishment of throat dimensions, it became necessary to design an entrance section to provide smooth flow into the throat section. Because of space limitations, it was decided to limit the entrance section to a length of 4 feet. An assumption was made that air would accelerate uniformly from zero velocity, at a distance of 4 feet from the throat, to the full velocity of 25 feet/second, at the throat. It was further assumed that because of the relatively low velocity, the air would not undergo sufficient expansion to change its density appreciably and that it could therefore be assumed to flow as an incompressible fluid. From the equation of motion, as given by Sears and Zemansky (27), $v^2 = v_o + 2\,a\,s$, where

v = final velocity

v_o = initial velocity (zero in this case

a = acceleration

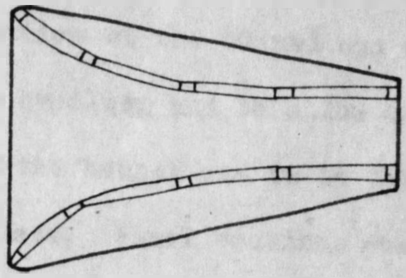
s = displacement

Since $s = 4$ feet, $a = 25^2/8$ or 78.12 ft/sec^2. From this equation a series of throat cross-section widths were calculated, as given in Table I-2.

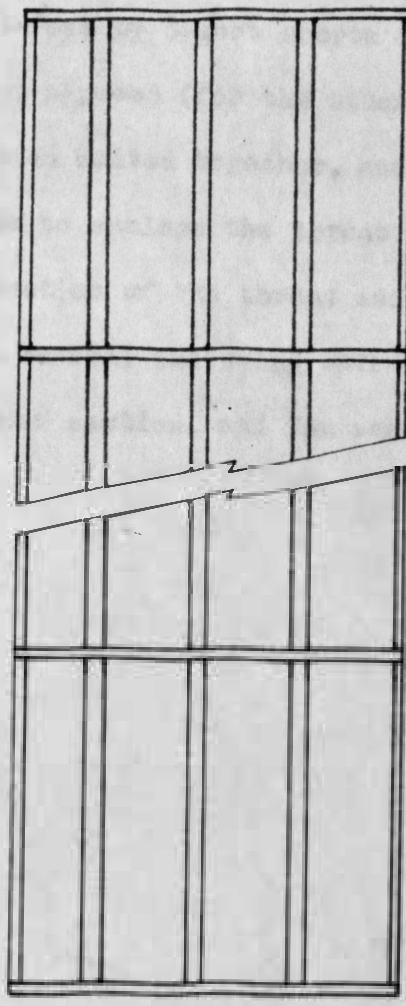
Table I-2. Tunnel Entrance Cross-Sections

Distance from Tunnel Throat, feet	Velocity, ft/sec	Throat Section Width, Inches
0.5	23.4	8.55
1.0	21.6	9.3
2.0	17.7	11.4
3.0	12.6	15.9
3.8	5.6	35.7

These dimensions were plotted to scale, connected to form a smooth curve, and the necessary structural members were drawn on to scale and critical dimensions scaled from the sketch for fabrication. The entrance section is illustrated in Figure AI-1.



a. Plan View of Entrance Section



b. Elevation View of Entrance Section

Figure AI-1. Entrance Section of Wind Tunnel. Scale: 1/2" = 1'0"

The throat section of the tunnel was constructed as a series of panels to facilitate handling and to allow easy disassembly for storage in the event the tunnel was to be taken out of the laboratory and used at a later date. Panel sections measured 8 feet by 12 feet. Figure AI-2 illustrates the basic framing of one panel. The frame was made of nominal 1-inch by 4-inch pine around the outside, with nominal 2-inch by 4-inch interior sections. Each panel was then covered with three 4-feet by 8-feet sheets of 1/4-inch plexiglas (for one side) or 3/8-inch plywood (for the other).

Panels were then bolted together, and 3/8-inch plywood bolted to the top and bottom to enclose the throat section. Figure AI-3 represents a cross-section of the throat and Figure AI-4 is a side view of the complete tunnel, including entrance section, test throat section, fan transition section, and fan assembly.

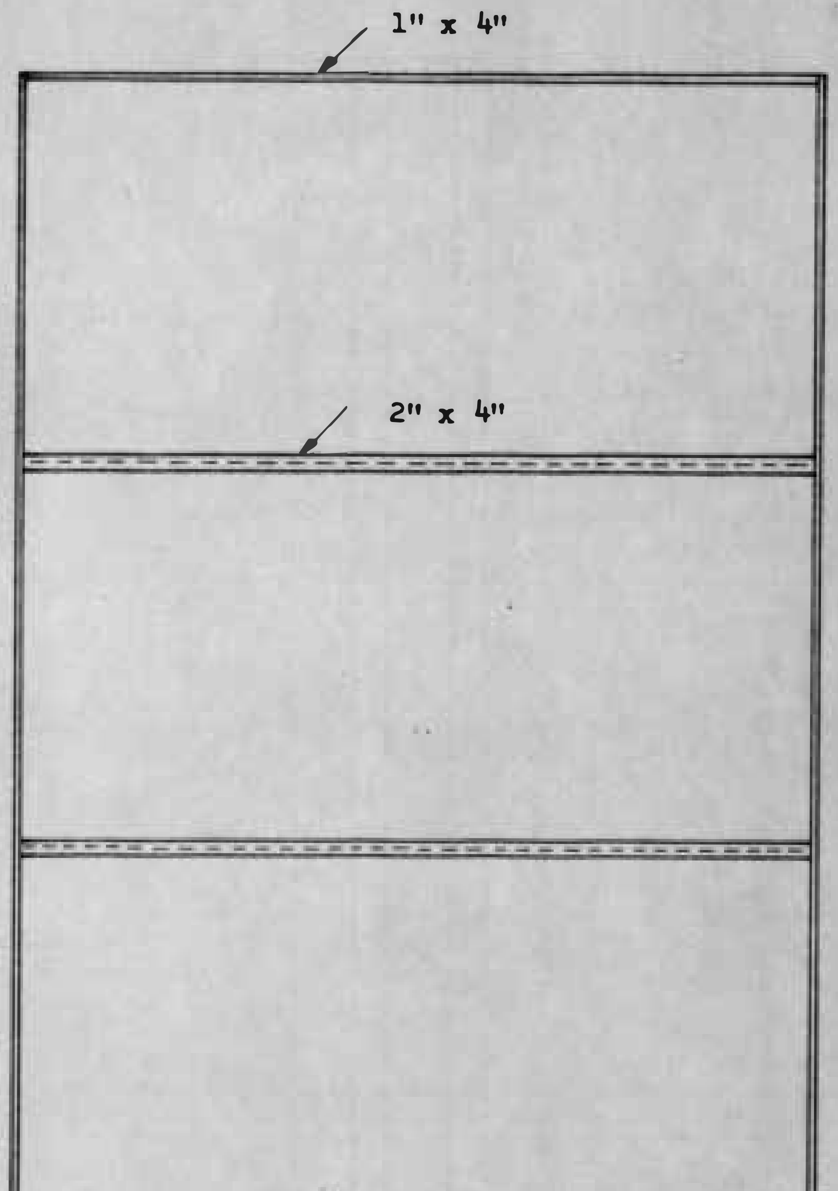


Figure A I-2. One 8' x 12' Panel of Wind Tunnel. Frame Was Covered With Three 4' x 8' Sheets of 1/4" Plexiglas or 3/8" Plywood. Scale: 1/2" = 1'0"

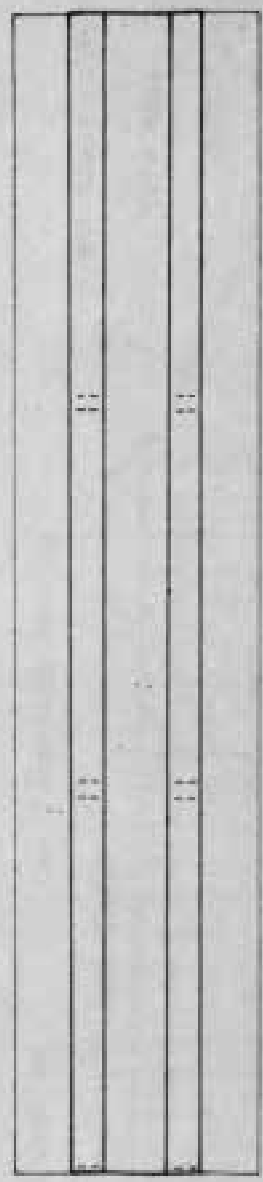
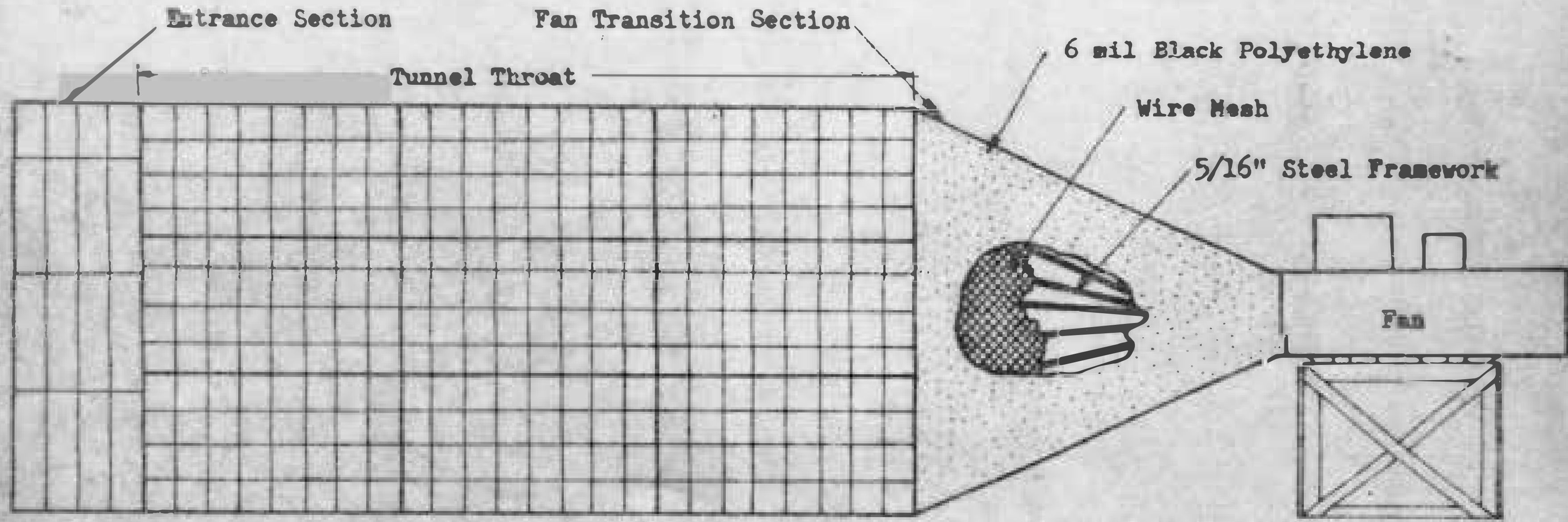


Figure AI-3. End View of Tunnel. Scale: 1/2" = 1'0"

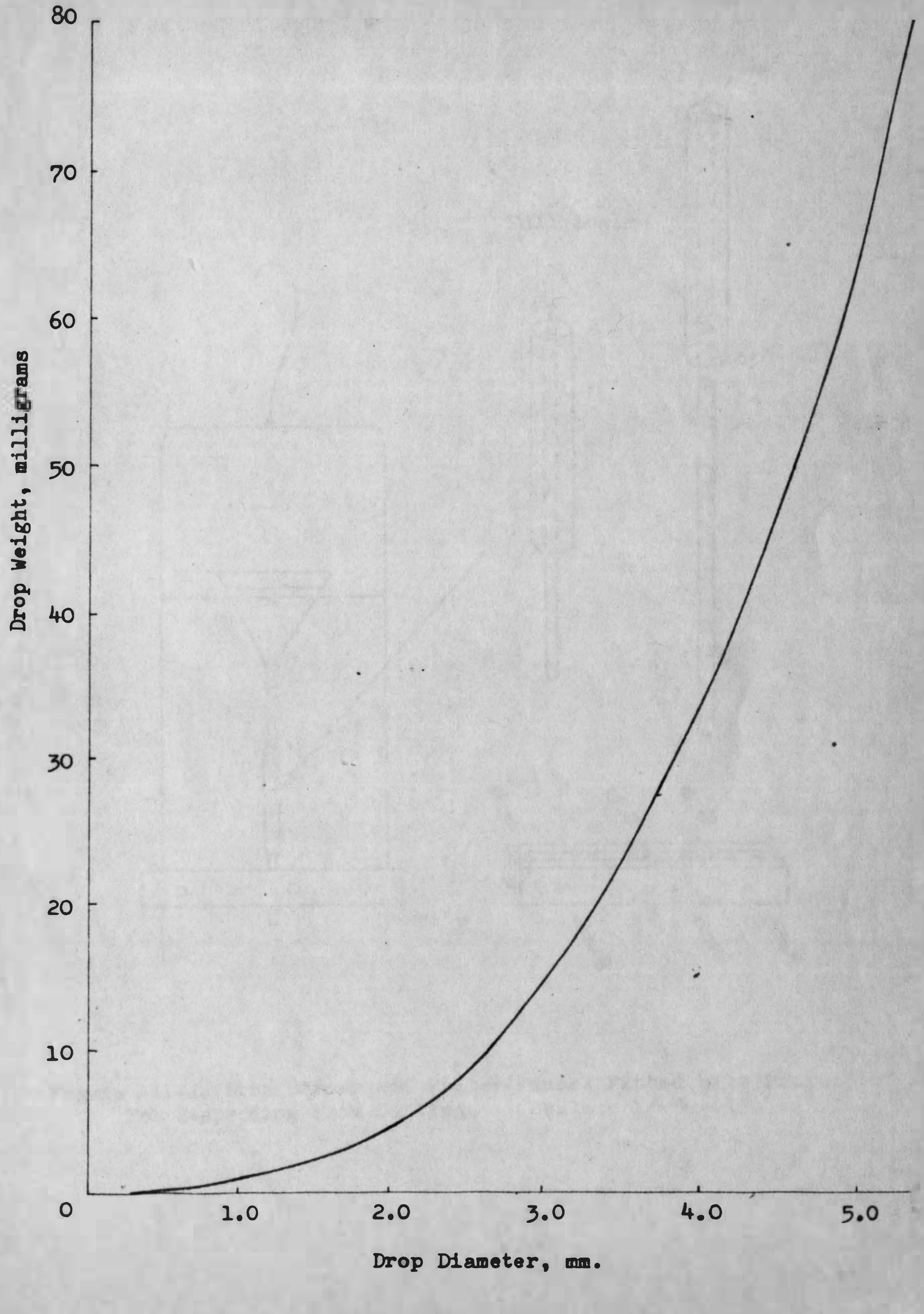


Scale: 3/16" = 1'0"

Figure A I-4. Elevation View of Complete Tunnel

APPENDIX II: ILLUSTRATIONS OF DROP FORMING APPARATUS

Figure AII-1. Drop Weight Vs. Diameter



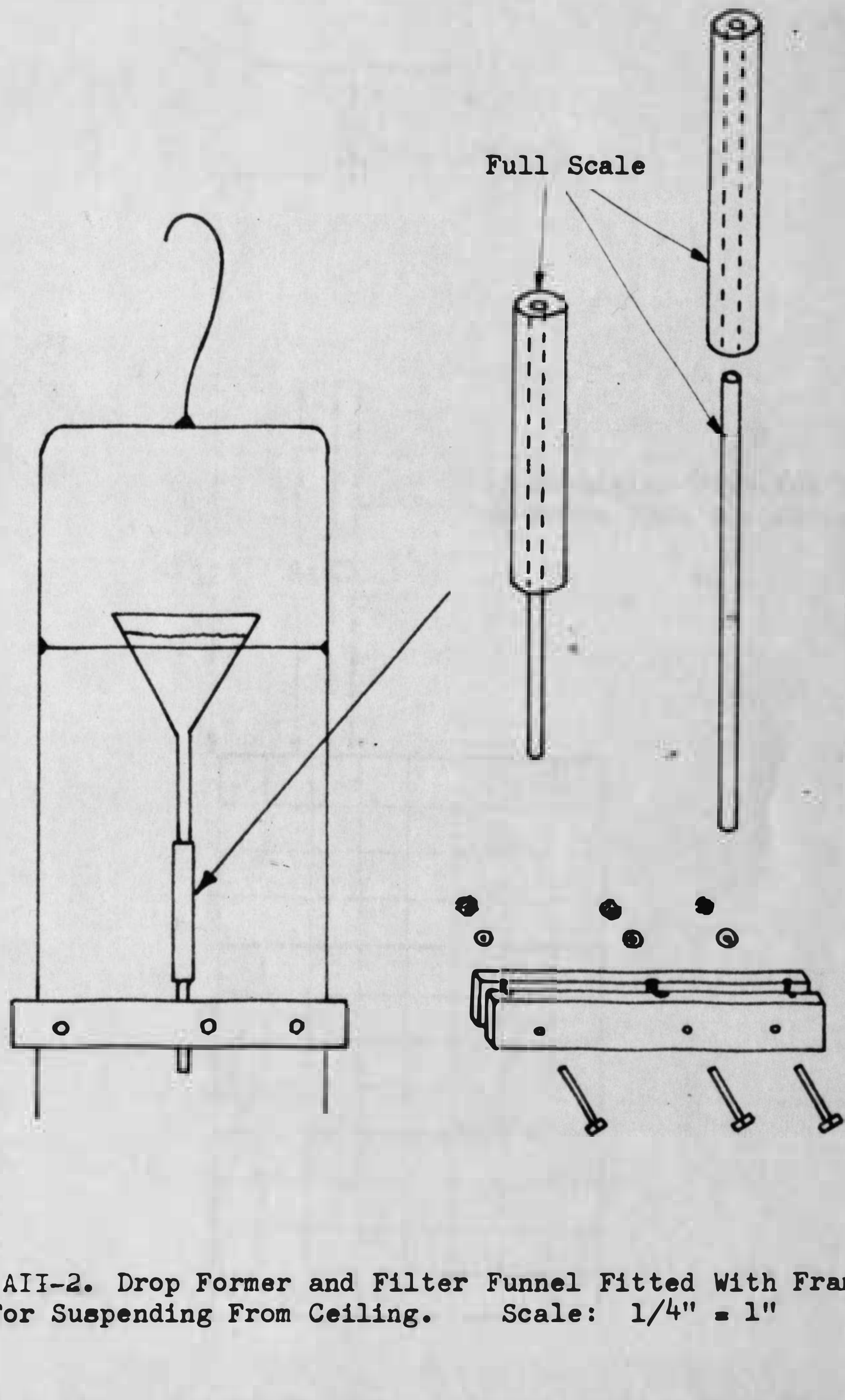


Figure AII-2. Drop Former and Filter Funnel Fitted With Frame For Suspending From Ceiling. Scale: 1/4" = 1"

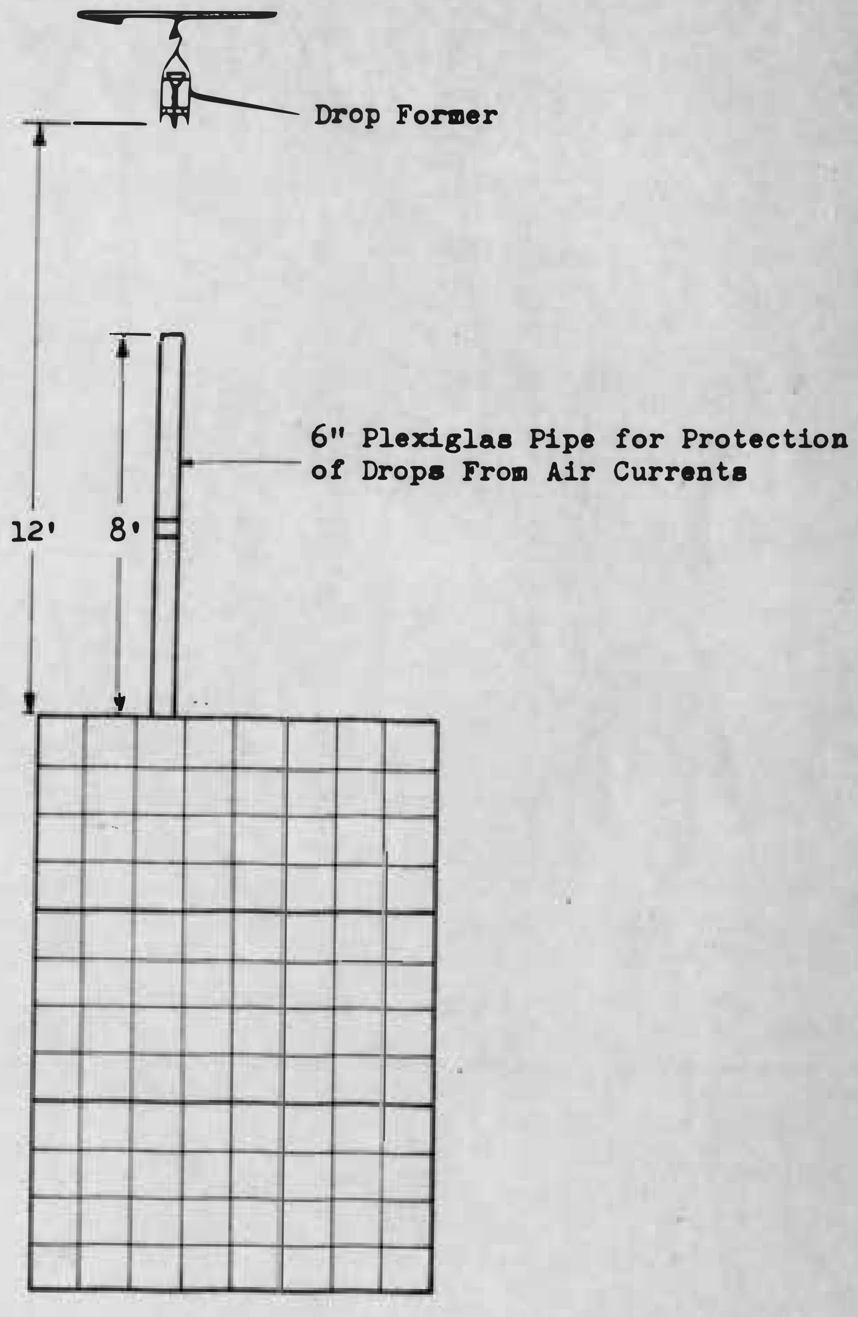


Figure AII-3. Elevation View of Throat Section With Drop Former in Place. Scale: 1/4" = 1'0"