DETERMINATION OF WATER DROP CHARACTERISTICS FROM A MEDIUM PRESSURE ROTARY IRRIGATION SPRINKLER

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Charles Carsten Mueller

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FROM A MEDIUM PRESSURE ROTARY
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by

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ABSTRACT

DETERMINATION OF WATER DROP CHARACTERISTICS FROM A MEDIUM PRESSURE ROTARY IRRIGATION SPRINKLER

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With the information gained from water drop energy investigations a more informed basis for irrigation system design is gained. This is of particular interest when working with fragile plants, easily eroded soils, or soils which tend to form impermeable crusts.

The objective of this project was to develop a method that would allow measurement of a water drop's kinetic energy as it approached the ground surface.

After reviewing past efforts to measure drop characteristics it was concluded that photographic techniques provided the advantage of drop size and velocity measurements of individual drops in one operation.

By taking short-interval double-exposure photographs of the drops as they approached the ground the drop energies were determined. Thru varying the sprinkler's operating characteristics and measuring drop energies at several distances from the sprinkler the better operating pressures and nozzle sizes can be selected.

Using the techniques developed, one single-nozzle rotary sprinkler was investigated for variation in drop

characteristics using combinations of three nozzle sizes (1/16, 3/32 and 1/8 inch diameter) and three operating pressures (30, 50 and 70 psi). The manufacturer's recommended pressures for these nozzles in the sprinkler tested was 35-40 psi.

It was concluded that:

(1). The use of photographic techniques for drop energy investigations is feasible.

(2). The accuracy of measurements made with photographic methods is good. The reliability of these measurements is dependent on the number of observations made.

(3). For the sprinkler tested an increase of operating pressure resulted in: (a) a more even distribution of water, and (b) a general decrease in the energy applied to the soil per unit depth of water applied.

Approved E H Kidder
Major Professor

Approved Carl W Hall
Department Chairman

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Credit is due my advisers for helping to establish the scope and direction of this project. I wish to thank Professors E. H. Kidder and F. H. Buelow for their technical advice and stimulating thoughts that they shared with me.

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INTRODUCTION

Knowledge of the sizes, velocities, and energies of water drops that strike the ground from a sprinkler could provide manufacturers with a basis for sprinkler design and evaluation. By comparing the water drop characteristics and the resulting undesirable effect on soil, an irrigation system designer would be able to more readily select sprinklers and operating pressures that would minimize structural changes and erosive damage to a soil.

This project was conducted in an effort to develop a system which can be used to evaluate water drop characteristics. Methods were developed which enabled accurate measurement of drop sizes, velocities, and direction of travel as these drops approached the ground. Using the techniques developed for these measurements, one single-nozzle rotary sprinkler was investigated for drop characteristics using combinations of three nozzle sizes and three operating pressures.

REVIEW OF LITERATURE

As early as 1877, Wollny described the effect of a beating rain in breaking down the soil, washing of the fine particles into tiny crevices and pores, in sealing the soil surface and thereby decreasing porosity, and the effect of a cover crop in decreasing just such tendencies.

Cook (1936) concluded that water drop velocity is one of the variables in the water erosion process. Ellison and Slater (1945) determined that low infiltration rates are associated with a high splash soil content. This was substantiated by Free's (1952) finding that soil crusts resulting from water drop impact had a volume weight of about 30 percent more than the soil immediately below the crusts. Duley and Kelly's (1939) work in this area included the study of the formation of a compact surface layer which greatly reduced infiltration rates, and showed the effect of mulches in preventing a crusted surface. They regarded the surface condition as having a greater influence on infiltration than the combined effects of soil type, initial moisture content and rainfall intensity.

Robert Horton (1940) considered the energy per inch depth of rain as the important property of rainfall that effects infiltration. Laws (1940) came to a similiar conclusion, in that a decrease in infiltration rate followed an increase of drop kinentic energy per unit area of surface. Working with drop sizes of 1 to 5 mm, Laws showed that as drop size increased, infiltration decreased up to 70 percent and the amount of soil in the runoff water increased up to 1200 percent.

In the study of erosion processes of water, Ellison (1944a) grouped the effecting factors into four areas: (1) variables of rainfall, (2) slope of the land, (3) soil characteristics, and (4) protection of the soil against, or its exposure to rainfall impact. In his experiments, Ellison showed that in samples of splash and runoff water, the weight of particle sizes of less than 0.05 mm exceeded that of the original soil, while larger particles were usually not less than in the original soil. Evidence of aggregate breakdown was also found. Ellison disclosed that more soil was splashed when a film of water was on the soil. This was believed to be due to decreased cohesion of the soil particles.

Bilanski and Kidder (1958), Strong (1955), and Wilcox and McDougald (1955) all studied various aspects of sprinkler operation as effected by nozzle size, operating pressure, oscillating arm action, wind, and/or spacing. All showed that large changes in distribution patterns were made by variations in operating procedures or sprinkler characteristics. In regard to water distribution VonBogrell <u>et al</u>. (1959) stated that two different models of sprinklers perform nearly the same if equipped with the same nozzle sizes and operated at similiar pressures and rotation speeds. Both VonPogrell and Christiansen (1941) noted the zone of low precipitation in a normal distribution pattern resulting in a 'doughnut' shaped distribution.

Measurement of Drop Sizes

Two methods of determining drop sizes required the use of blotter paper or flour as a media for measurement. When blotter paper was used the drop size was determined by the area of the wetted portion of the paper where a drop had landed. Anderson (1948), Blanchard (1953), Levine (1952), and Shanks and Paterson (1948) used this method in their investigations. The second method, involving flour, was used by Chapman (1948) and Bentley (1904). Here a tray of smoothed, uniform flour was exposed to the falling drops. The resulting flour and water 'pellets' were then dried and their sizes measured to determine drop sizes.

Several other unique methods for drop size analysis have also been developed. Taylor and Harman (1954) froze their drop samples in a hexane bath cooled to -20° C. Drop sizes were then determined by timing the fall of the frozen pellets through the fluid onto a scale pan and applying Stokes Law for falling bodies.

Smith (1951) allowed drops to fall between two plates and measured the resulting change in capacitance to determine drop size. Cunningham (1951) allowed drops to pass between a light source and a photo tube to determine drop size, the results being read from an oscilloscope. Cunningham also measured the electrical impulses produced by drops impacting on a microphone diaphragm to find drop sizes.

Gardiner (1964) devised a direct measurement method of measuring drop sizes, based on the principle that when a drop of liquid touches an electrically charged body it draws an amount of charge proportional to the size of the drop. His apparatus has a 0.5 mm diameter wire probe, as the charged body, connected to a potential source and an impulse sorting and counting circuit. With this equipment the analysis of 200,000 drops per minute has been recorded.

Measurement of Drop Velocities

To measure the velocity of drops Gunn and Kinzer (1949) electronically measured the time required for a drop carrying an electrical charge to pass through two inducing rings. Drop sizes were determined by weight or by direct measurement with a low-power microscope. Their data provided terminal velocities for drop sizes of .078 to 5.76 mm in diameter.

Green (1952a) studied and evaluated Laws' (1941) data of drop terminal velocities and formulated an emperical equation for determining the terminal velocities of falling drops: V_t = 820 Mgd, where M = drop mass in grams, g = force of gravity, and d = the equivalent spherical diameter in mm.

Measurement of Drop Energies

Several researchers have used one of the above mentioned methods for determining drop sizes and then assumed terminal velocities to find drop energies. Another method to measure drop energies was developed by Neal and Baver (1937). They modified a beam balance, allowing drops to strike one pan which moved a pen across a recording cylinder.

Schleusener (1960) used a styrofoam target mounted on a cantilever beam to measure drop impact energies. Strain gages on the beam detected deflection which was recorded on an oscillograph. However, Brazee's (1963) mathematical analysis of the use of a damped oscillating transducer as a method of measuring random impact energies opened question as to the validity of such procedures.

A few investigators have used photography as a means of studying water drop phenomena. Worthington (1894) used high speed photography to study turbulance created by drop impacts. Green (1952b) worked with photo techniques to measure drop sizes and velocities. He obtained drop sizes from a photo image of a drop made with a short duration flash and measured the drop velocity from the streak length made during the time the camera shutter was open. Green also tried recording velocities by multiple flash exposures, but was limited by his flash unit's maximum flash rate of 20 flashes per second. This allowed drop travel of 1.5 feet or more between successive flashes. With several drops in one picture the successive drop images could not be selected. While taking photos of drops along their travel axis, Green found that drop oscillation was of negligable effect as the drop images were always near perfect circles.

After reviewing past experiences in measuring water drop characteristics it was concluded that photographic techniques offered the advantage of both size and velocity measurements for any given drop in one operation.

Drop Formation

Baron (1947) studied the atomization of liquid jets and droplets. He "treats the deformation of a moving drop as forced vibration with viscous damping. In order to be able to oscillate and still not oppose the drag and interia forces the drop must rotate. The (resulting) centrifugal forces drive the liquid toward the periphery producing a ring having a thin center membrane which will ultimately be blown out, thus disintegrating the drop into particles or greatly differing sizes."

Several ideas have been brought forth on the process of jet break up. Hinze (1946) studied surface disturbances of a jet which developed into ligaments and eventual drop formation. In photographs taken by Haenlein (1931) the waviness of a liquid jet prior to actual break up are shown. Most of the investigators have considered several of the following factors in jet break up: change in potential energy due to surface tension, change in kinetic energy due to the liquids motion, turbulance, nozzle dimensions, liquid viscosity, jet velocity, air viscosity and density, capillary ripples on the liquid surface, and air friction.

DESIGN OF EXPERIMENT

Following Green's (1952b) work, experiments were conducted using the Strobolux and Strobotac flash units for multiple exposure pictures. Even with a maximum flash rate of 100 flashes per second it was questionable if successive drop images could consistantly be determined.

Tests with a high speed motion picture camera also meet with poor results. While drop velocities could easily be determined, individual film images of drops were not defined enough to permit confident measurement of drop sizes. Perhaps the use of a 35 mm movie camera instead of the 16 mm tested would enable drop size measurements from the film image.

Returning to the multiple flash concept, a keying system was developed which allowed consecutive short-interval firing of two separate flash units. By firing the two flash units at a short time interval a double exposure of individual drops was recorded by the camera. Later projection of the film allowed measurement of drop diameter and distance traveled during the flash interval. By comparing the computed drop energy values at various points along a sprinkler radius, a basis for evaluating the soil erosion potential of a sprinkler was established.

Nine combinations of three nozzle sizes (1/16, 3/32 and 1/8 inch diameter) and three pressure levels (30, 50 and 70 psi) were selected for a sprinkler drop energy evaluation. (The manufacturer's recommended pressure for the selected nozzle sizes was 35-40 psi.)

Preliminary tests were conducted to determine the natural rotation speed for the sprinkler with the oscillating arm when operated with the three nozzle sizes and with the three water pressures selected for testing. While rotation rate varied for both nozzle size and operating pressure changes, the effect of nozzle size was dominant. Variation of rotation rate for each nozzle size only was therefore deemed sufficient for the tests. Rotation speeds of 70, 50 and 30 spr (seconds per revolution) were used for nozzle sizes of 1/16, 3/32 and 1/8 inch diameter, respectively.

APPARATUS

The sprinkler tested was mounted in a 55 gallon barrel with an adjustable width slot cut in the side. The slot allowed the stream of water from the sprinkler to emerge in one direction for sampling purposes. A vertical shaft ran from the sprinkler through the barrel top to the sprinkler rotating mechanism. This mechanism consisted of a variable speed motor and speed reduction devices and allowed the sprinkler rotation rate to be varied between 15 spr and several hundred spr. For drop energy and distribution tests the sprinkler was operated without its oscillating arm.

For distribution tests, screen covered frames were laid on the laboratory floor on the radius in line with the sprinkler and barrel slot. Sampling cans were placed along the screening at one meter intervals. The wire window screening eliminated the tendency of drops to ricochet from the concrete floor into the cans.

A 35 mm Leica, Model IIIf, camera with a telephoto lens was used to photograph the drops for velocity, size and travel direction determinations. The 200 mm Telyt camera lens was fitted to a reflex housing and a bellows unit to permit close focusing. Camera-to-subject distance was 1.5 meters (5 ft) and the drop sampling area was approximately 22 by 15 centimeters (9 x 6 in.).

The flash units used for drop illumination were the Strobolume and the Strobolux, manufactured by General Radio Corperation, which provided an intense short-duration flash on the order of 30 microseconds. Each flash unit was keyed by a SPST relay which in turn was operated by a single DPST relay. The single DPST relay was controlled by a micro-switch at the sprinkler rotating mechanism. The time interval between flashes was varied by adjusting the operating voltages of the SPST flash control relays. Two variable DC power supplies were used as a power source. Possible flash time intervals were zero to 0.010 second. Most photos were taken with a flash interval of about 0.0025 second.

An adjustable cam on the vertical sprinkler shaft closed the microswitch which in turn activated the flash control circuit. The cam adjustment allowed the flashes to be fired as any portion of the water stream passed the photographic field.

In the photo subject area background a small motor rotated a disk on which a short radial line was inscribed. The flash time interval was computed from the measured angle formed by the double image of the line and the motors speed.

To allow easy sampling of the water stream along its axis the photographic and flash equipment were mounted on a wheeled platform. The platform was covered with splash and light shields except for a 2 inch slot through which the drop stream entered the photo subject area.

This shielding kept the equipment dry and eliminated the variable of ambient lighting conditions. The 2 inch slot in the splash shield also controlled the depth of field for drops in the photo area. A double row of galvanized sheet metal strips attached to the sides of the opening at 1/2 inch spacing and bent toward the sprinkler at a 45° angle largely eliminated splash from entering the photographic field.

A five horsepower centrifugal pump was used to boost the line water pressure. Fluctuations in the water pressure at the sprinkler were minimized by including a surge tank in the high pressure portion of the system. Needle control valves were used for fine adjustment of the operating pressure.

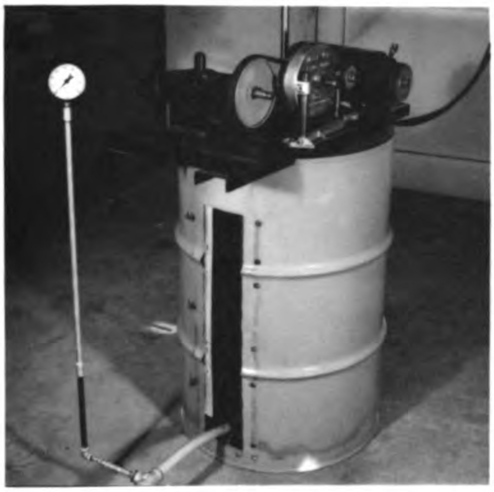

Figure 1. Slotted barrel shield and sprinkler rotating mechanism.

Figure 2. Flash timing microswitch and adjustable cam.

Figure 3. Laboratory where tests were conducted. Sprinkler barrel in background with distribution test equipment in place.

Figure 4. From top, clockwise, Strobolume and Strobolux flash units, camera, flash control relay unit, and variable DC power supplies.

Figure 5. Photo and flash equipment in position for drop energy tests. Most of the light shields have been removed.

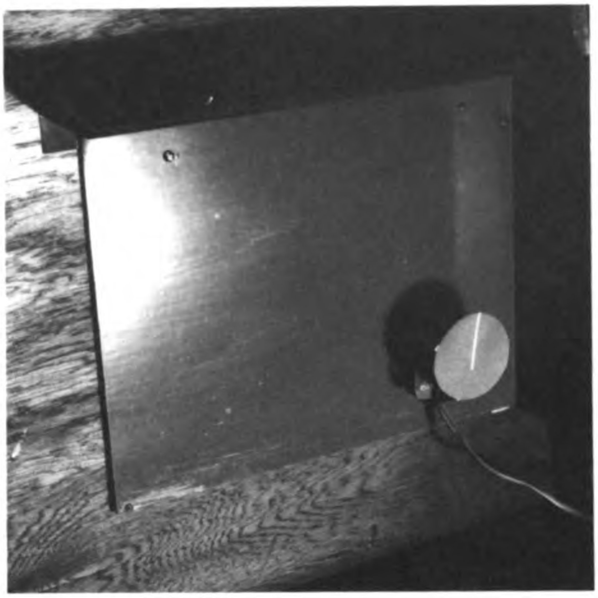

Figure 6. Background of photo sampling field with motor-rotated disk for time interval measurements.

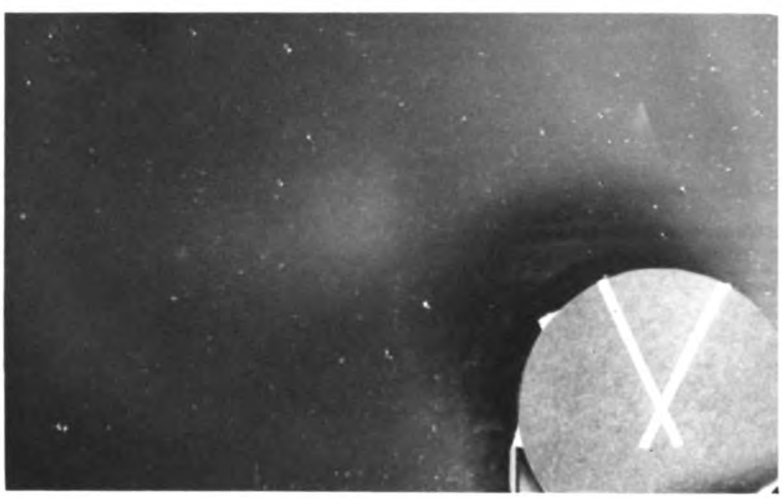

Figure 7. Example of drop data photographs.

EXPERIMENTAL PROCEDURE

Three individual tests were conducted, one for each nozzle size. At the start of each test the wheeled sampling platform holding the photo and flash equipment was placed four meters (13.1 ft) from the sprinkler. The flash timing cam was set so that the flashes were fired just before any drops from the stream entered the photo sampling field. Water pressure was adjusted to 30 psi. With these initial conditions the testing cycles were started.

For each set of conditions three photographs were taken, followed by a Strobotac check on the timing motor rotation speed. After each set of three photos, the water pressure was adjusted to the next higher test pressure. After nine photos were taken - 3 for each of 3 pressures - the water pressure was adjusted to 30 psi and the adjustable flash timing cam was advanced one degree. Again 9 photos were taken followed by another degree of cam advancement. When it was obvious that no water drops were left in the photo field when the flashes fired, the initial conditions were established once again, and the sampling platform was moved away from the sprinkler one meter (3.3 ft) to the next sampling station.

By taking photographs before the sprinkler had rotated enough for the drop stream to enter the sampling area, and continuing to take photos until after the stream had passed beyond the sampling area, it was insured that there was an equal opportunity for sampling all portions of the stream.

The above set of cycles was repeated until it was obvious that the sampling platform had been moved beyond the range of the water stream. Then initial conditions were once again established with the sampling platform at the four meter station, and a new nozzle size was installed for the next test.

At the start of each new roll of film a millimeter scale was mounted in the center of the water drop path photo sampling field and photographed to establish a known dimension and the horizontal plane on each roll of film. All photographs were taken with the camera shutter held open, allowing the flashes to determine the actual instant the drops were recorded.

The exposed film (Kodak Tri-X) was then developed in Kodak D-76 developer with a 100 percent increase in recommended development time to increase drop image contrast.

The resulting negatives were projected onto a smooth surface from which measurements were made of: drop diameter, drop travel distance between flashes, the direction of drop travel with respect to the horizontal, and the angle of the two images of the line on the motor-rotated disk.

Following the photo tests, standard distribution tests were completed for each nozzle size and pressure setting used.

DISCUSSION OF RESULTS

Using the data measured from the photo negatives, mean values were determined for the drop diameter, mass, velocity and kinetic energy at each sampling station for each nozzle size and pressure tested.

By applying the effect of the application rate to the mean drop energies found, a time factor was introduced into the water drop energy data. This was done by finding the time required, for each nozzle and pressure setting, to apply an average of one centimeter depth of water over the circular area normally covered by the sprinkler.

Table 1. Time required for an average accumulation of one centimeter depth of water over the area covered by one sprinkler for nozzles and pressures tested.

nozzle diameter	pressure	time per cm ave. depth
inch	psi	hours
1/16	30	27.2
	50	22.5
	70	16.4
3/32	30	12.8
	50	9.1
	70	7.5
1/8	30	6.5
	50	5.0
	70	4.1

From the mean drop mass the number of drops per cubic centimeter (sq cm area x cm depth) and the energy per cm^3 was determined. The numerical values are given in the Appendix. The following three pages of curves show the energy per cm^2 area per cm ave. depth for the conditions tested. The same data is shown on page 25 in the three-dimensional sketch which can help to visualize the relationships.

Limitations of Testing Method

A 0.5 mm diameter drop was recorded on the film as a 0.067 mm diameter image. Due to this small image size, the optical perfection on the projection system used to read the film, and the inherent grain size in the film, measurement of drops smaller than 0.5 mm in diameter was not attempted. Nearly all of the drops 0.4 mm or smaller in diameter that were observed were at the 4 and 5 meter sampling stations with the 1/16 inch nozzle. Though the omission of these drop energies created a slightly higher energy value at these stations the end effect is thought to be of small difference.

By comparing the curves for energy/cm^2/cm and the distribution for a single nozzle size and operating pressure it will be noted that no energy values are given for the furthest distant sampling station while an application rate is given for that station. Although many

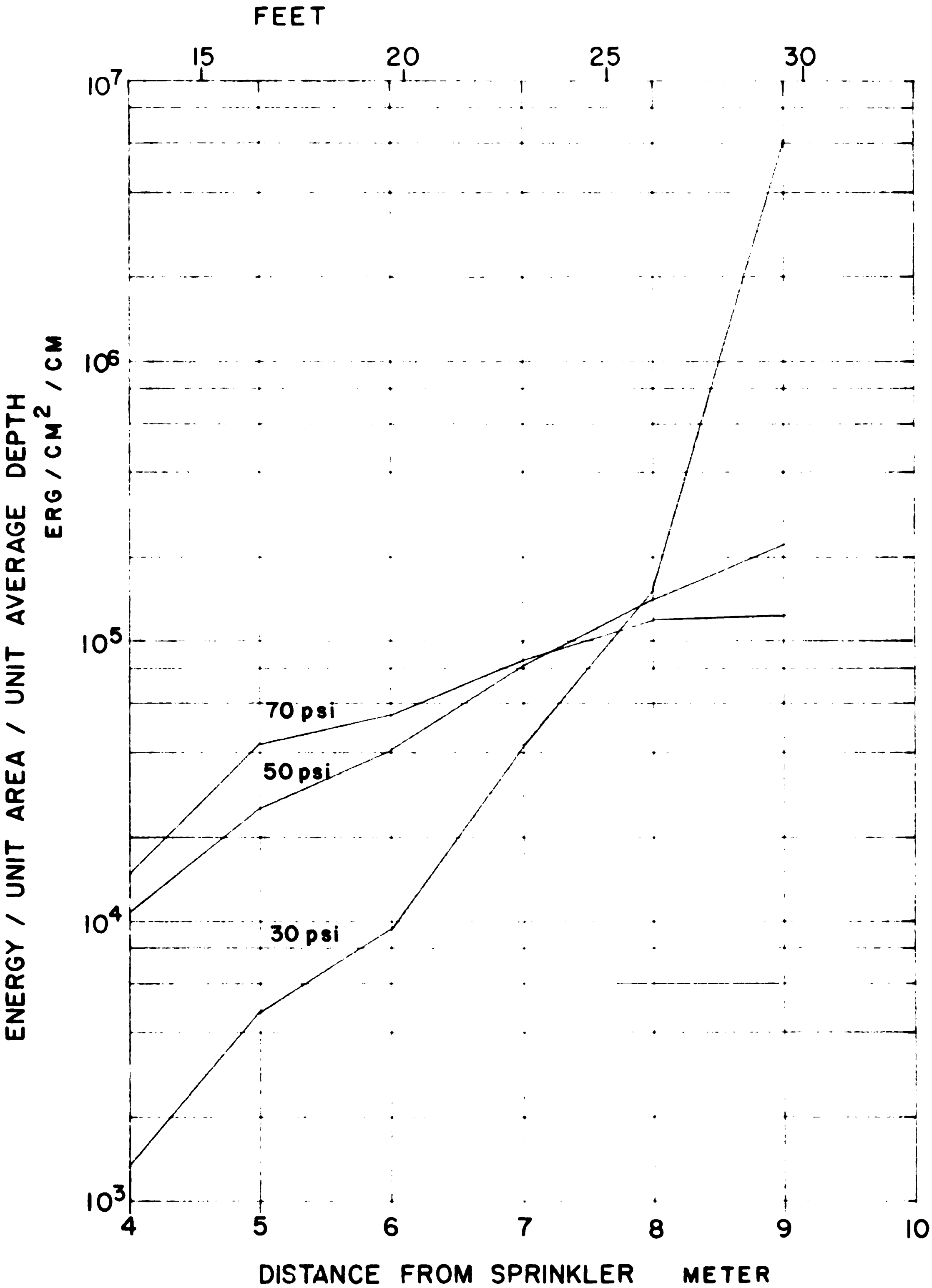

Figure 8. Energy per unit area per average (over total area) unit depth versus distance from sprinkler for 1/16 inch nozzle at pressures tested.

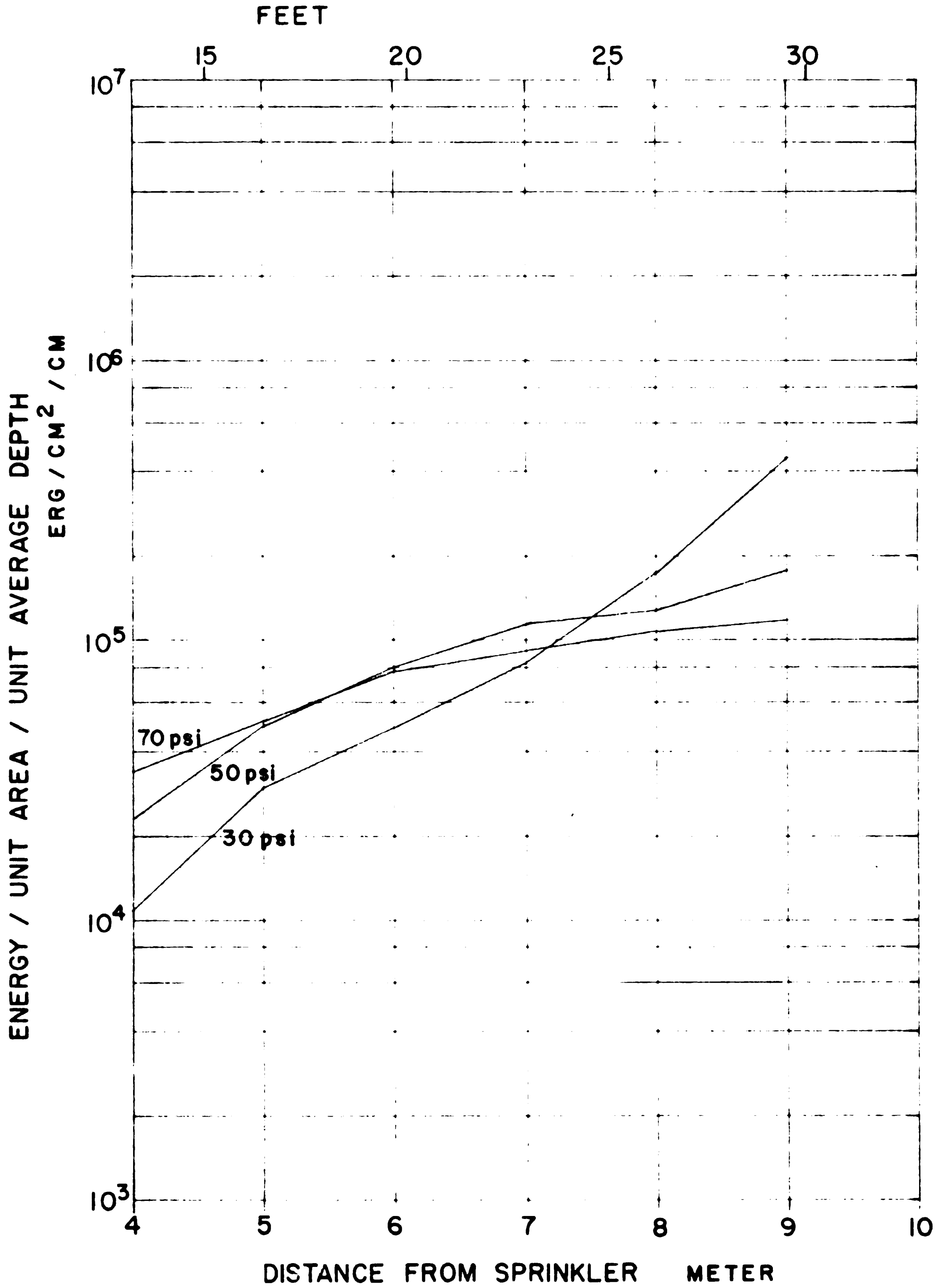

Figure 9. Energy per unit area per average (over total area) unit depth versus distance from sprinkler for 3/32 inch nozzle at pressures tested.

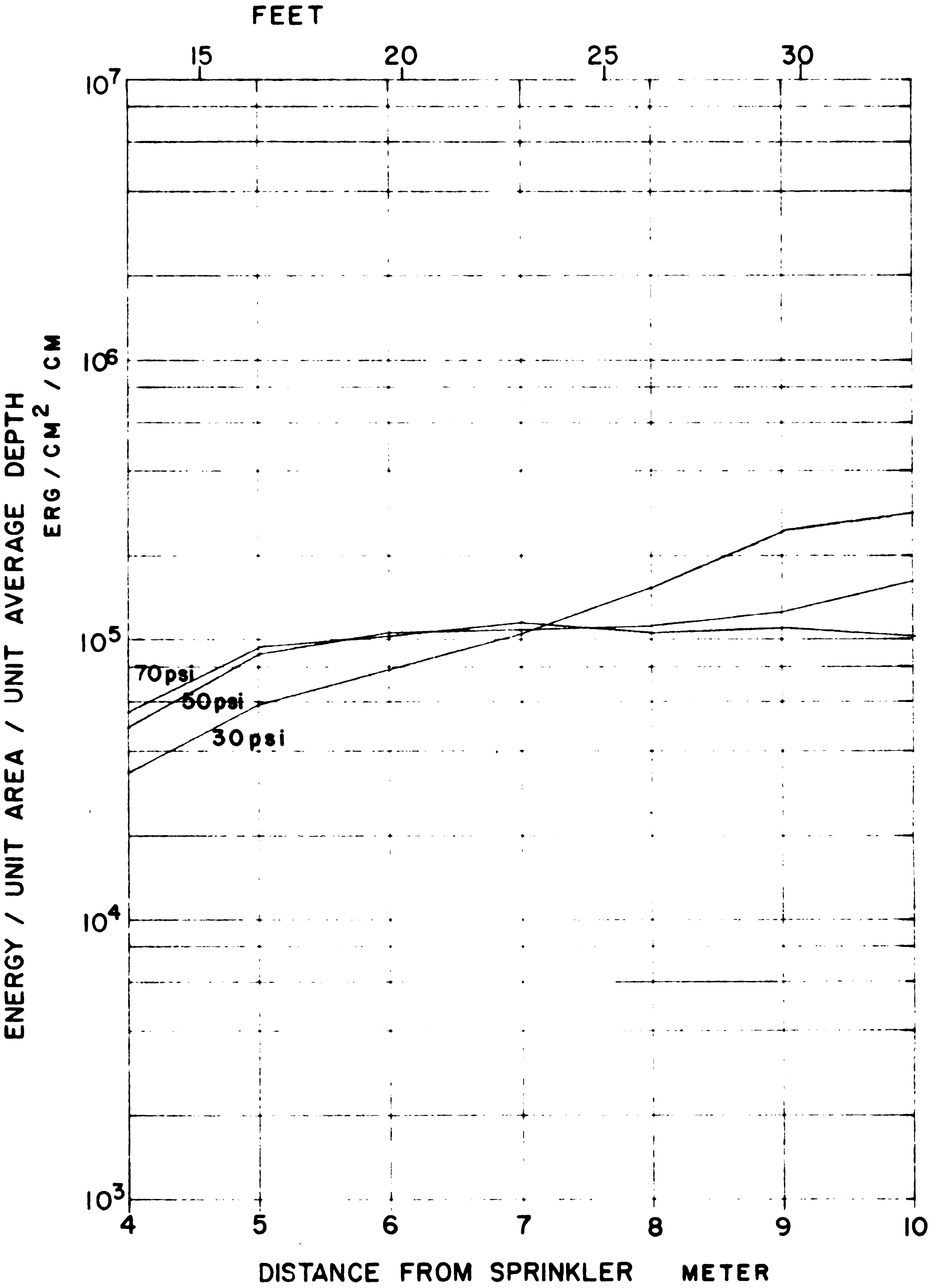

Figure 10. Energy per unit area per average (over total area) unit depth versus distance from sprinkler for 1/8 inch nozzle at pressures tested.

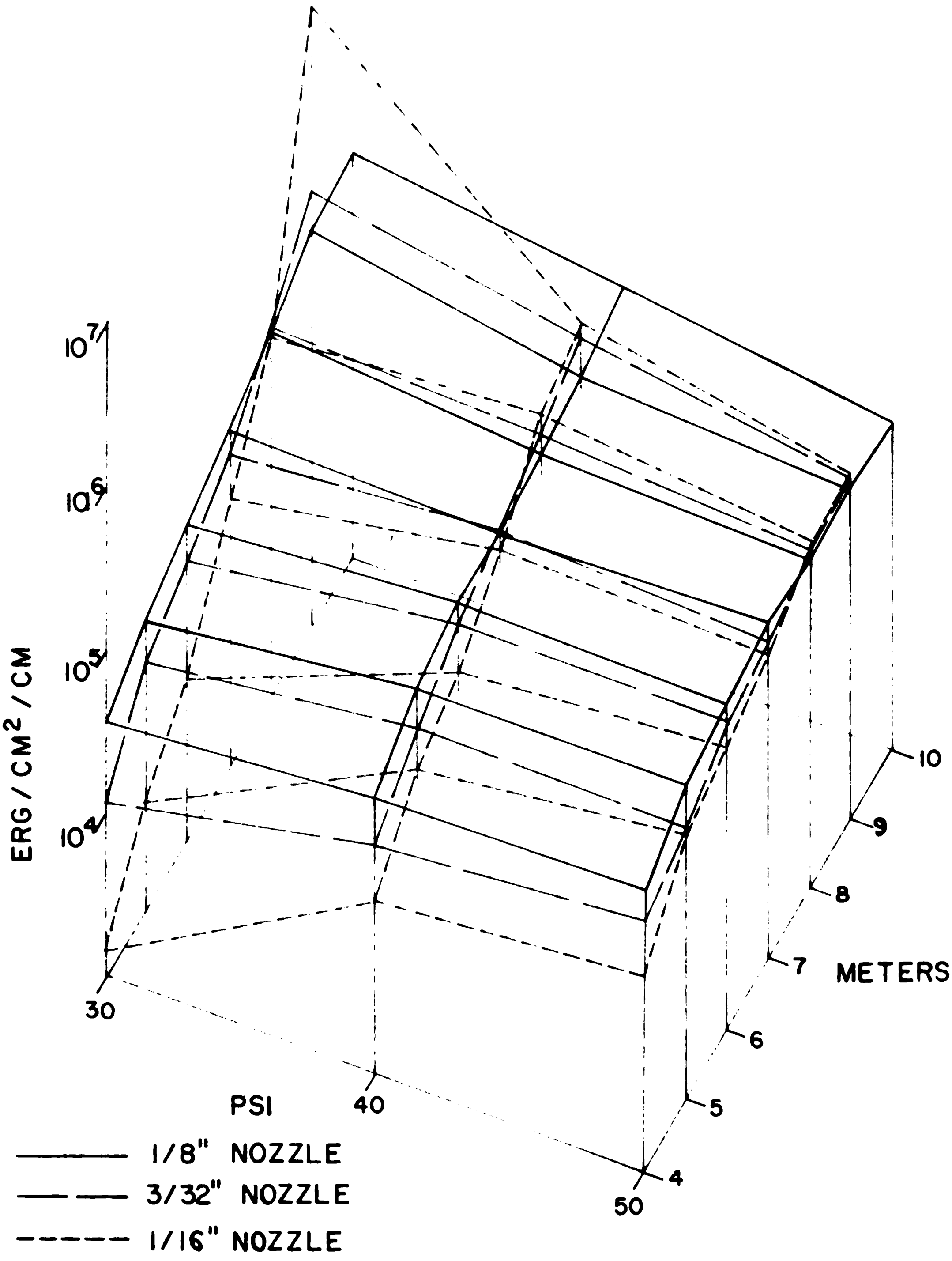

Figure 11. Sketch of energy per unit area per unit depth versus pressure and distance for nozzles tested.

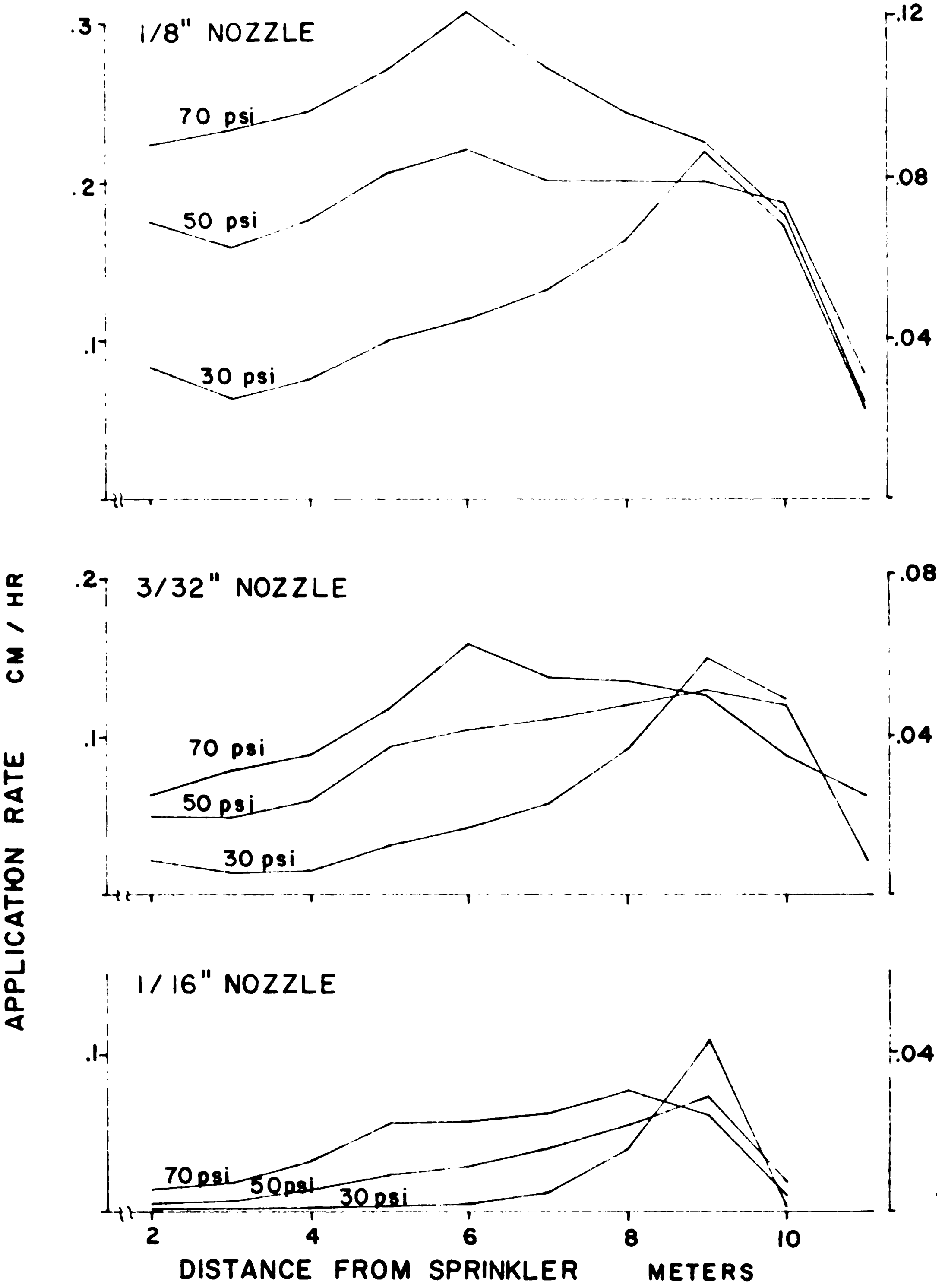

Figure 12. Application rate versus distance from sprinkler for nozzle sizes and pressures tested.

photographs were taken at these stations no drops were recorded. As relatively few drops were landing in these areas it can be assumed that it was only by coincidence that no drops were in the sample field when the flashes were fired.

Another gap in the energy data occurs with the 1/8 inch nozzle when operated at 30 psi pressure. At the 6 meter station no drops were recorded. Although to the eye it appeared that drops were falling in the area this would seem to indicate another region of light precipitation. However, this is not substantiated by any relatively light application rate at that point during the distribution tests. It is thought that this lack of data was caused by an experimental procedure error, but the exact reason has not been determined.

Accuracy of Data

To estimate the accuracy of the energy computations the propagation of error method of combining independent errors was utilized. This method gives an estimate of the approximate maximum error.

From k measurements of (x) and (y) one may compute k values of V:

$$V_1 = V(x_1, y_1),\ V_2 = V(x_2, y_2),\ \ldots,\ V_n = V(x_n, y_n),\ \ldots,\ V_k = V(x_k, y_k)$$

The mean values of the measurements of (x) and (y) will be:

$$\bar{x} = \frac{\sum_{n=1}^{k} x_n}{k} \quad \text{and} \quad \bar{y} = \frac{\sum_{n=1}^{k} y_n}{k}$$

And the most probable value of V will be:

$$V = V(\bar{x},\bar{y})$$

In general each value of V_n differs from our best estimate of V(x,y) by some amount:

$$\delta V_n = V_n - V(\bar{x},\bar{y})$$

which is the absolute error. From differential calculus the approximate maximum error of V_n (δV_n) will be:

$$\delta V_n = \frac{\partial V}{\partial x}\,\delta x_n + \frac{\partial V}{\partial y}\,\delta y_n$$

For drop kinetic energy determinations:

$$KE = \frac{1}{2}\, m\, v^2 = \frac{3\pi \gamma D^3\, d^2\, RPM^2}{A^2}$$

where:
- m = mass of drop in grams
- v = drop velocity in cm/sec
- γ = water density in gm/cc
- D = drop diameter in cm
- d = drop travel distance during flash interval in cm
- RPM = timing motor speed in rpm
- A = disk line image angle.

From the propagation of error method:

$$\delta KE = \frac{\partial E}{\partial D}\,\delta D + \frac{\partial E}{\partial d}\,\delta d + \frac{\partial E}{\partial \gamma}\delta \gamma + \frac{\partial E}{\partial RPM}\,\delta RPM + \frac{\partial E}{\partial A}\,\delta A$$

Solving the partial differentials and simplifying results in:

$$\delta KE = \frac{3\pi \gamma D^3\, d^2\, RPM^2}{A^2}\left[3\frac{\delta D}{D} + 2\frac{\delta d}{d} + \frac{\delta \gamma}{\gamma} + 2\frac{\delta RPM}{RPM} + 2\frac{\delta A}{A} \right]$$

Three sources of error were involved in the linear measurements made. The drop diameters and the drop travel distances were both measured to within 0.005 cm. The linear distance error caused by the drop not being in the same plane as the reference rule created a possible error of 0.00167 cm. Thus the possible variation in the measurements and the real values of both the drop diameter (δD) and the drop travel distance (δd) is 0.00667 cm. The Strobotac unit used to measure the motor speed was accurate to within 5 rpm (δRPM). The angle of the line images on the motor-rotated disk was measured to within 0.5 degree (δA). For computations the density of water was assumed to be 1 gm/cc. Variation in water temperature caused a change in its density of up to 0.000268 gm/cc ($\delta \gamma$).

Using the above formula and error values the following maximum errors were computed for typical energy values.

Table 2. Approximate maximum errors of energy values for typical drop diameters and velocities.

D	d	KE	δKE	error
cm	cm	erg	erg	%
.10	1.0	32.9	7.85	24
.15	1.2	160.0	27.1	17
.20	1.4	516.	69.3	13
.25	1.6	1608.	181.9	11
.30	1.8	2880.	285.	10

The individual error sources were then computed for small and large energy values.

Table 3. Percent of total error of individual error sources for small and large energy values.

source	percent of total error large KE	small KE
δD	4	1
δd	67	84
$\delta \gamma$	8	6
δRPM	3	1
δA	18	8

CONCLUSIONS

Although the manufacturer's recommended operating pressure for this sprinkler with all the nozzle sizes tested is 35 to 40 psi it was found that higher pressures tended to give a more uniform application rate. From the distribution curves given all three nozzles (1/16, 3/32 and 1/8 inch) produced the most uniform results when operated near 70 psi.

From the energy/cm^2/cm versus distance curves it is seen that in all cases an increase in operating pressure resulted in a small increase in energy near the sprinkler and a large decrease far from the sprinkler. The decrease in energy applied is particularly significant with the 1/16 inch nozzle at the 9 meter station.

Specific conclusions of this project are:

(1). The use of photographic techniques for drop energy investigations is feasible.

(2). The accuracy of measurements made with the photographic method is good. The reliability of these measurements is dependent on the number of observations made.

(3). For the sprinkler tested an increase of operating pressure resulted in: (a) a more even distribution of water, and (b) a general decrease in the energy applied to the soil per unit depth of water applied.

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APPENDIX

Table A-1. Drop characteristics for 1/16 inch nozzle.

pressure	sample distance	mean drop diameter	mean drop mass	mean drop velocity	mean drop energy	application rate	energy per unit area per unit depth
psi	m	mm	gr $\times 10^{-3}$	m/s	erg	cm/hr	erg/cm^2/cm $\times 10^3$
30	4	.68	.196	2.45	3.0	.0013	1.4
	5	.83	.345	3.10	18.6	.0032	4.7
	6	1.08	.768	3.72	58.9	.0045	9.4
	7	1.74	3.098	4.64	380.7	.0127	42.4
	8	2.44	8.227	5.22	1181.	.0407	159.0
	9	3.16	17.62	6.25	3622.	.1080	6040.
50	4	.67	.169	2.55	6.1	.0140	11.3
	5	.78	.288	2.97	14.4	.0241	27.1
	6	.96	.516	3.33	31.9	.0292	40.6
	7	1.31	1.306	4.06	116.5	.0400	80.3
	8	1.66	2.586	4.64	297.8	.0584	151.8
	9	2.33	6.701	5.31	959.7	.0711	229.0
70	4	.65	.156	2.41	4.8	.0318	16.0
	5	.81	.319	2.85	14.5	.0578	43.1
	6	.99	.562	3.35	33.8	.0571	56.2
	7	1.28	1.180	3.93	96.3	.0635	84.9
	8	1.45	1.681	4.42	170.9	.0762	127.0
	9	1.93	3.937	5.00	506.8	.0629	132.7

Table A-2. Drop characteristics for 3/32 inch nozzle.

pressure	sample distance	mean drop diameter	mean drop mass	mean drop velocity	mean drop energy	application rate	energy per unit area per unit depth
psi	m	mm	gr $\times 10^{-3}$	m/s	erg	cm/hr	$erg/cm^2/cm$ $\times 10^3$
30	4	.98	.568	2.94	26.6	.0186	11.1
	5	1.21	1.037	3.49	71.5	.0359	31.7
	6	1.48	1.933	3.95	169.4	.0434	48.8
	7	1.70	2.760	4.56	288.8	.0607	81.2
	8	2.21	6.682	5.06	1043.	.0922	184.2
	9	3.18	21.05	6.29	4798.	.1510	441.0
50	4	.95	.492	2.81	21.4	.0635	25.1
	5	1.05	.681	3.27	39.8	.0940	49.9
	6	1.31	1.314	3.81	107.9	.1072	80.0
	7	1.68	2.755	4.45	300.1	.1130	111.9
	8	1.79	3.323	4.74	410.2	.1208	135.4
	9	2.00	4.314	5.45	663.5	.1320	184.3
70	4	.91	.483	2.81	25.1	.0895	35.0
	5	1.01	.592	3.19	32.8	.1206	50.3
	6	1.13	.816	3.48	53.5	.1602	79.2
	7	1.36	1.396	4.05	120.5	.1402	91.2
	8	1.72	2.782	4.61	297.4	.1370	110.4
	9	2.00	4.220	5.00	537.8	.1301	125.0

Table A-3. Drop characteristics for 1/8 inch nozzle.

pressure	sample distance	mean drop diameter	mean drop mass	mean drop velocity	mean drop energy	application rate	energy per unit area per unit depth
psi	m	mm	gr $\times 10^{-3}$	m/s	erg	cm/hr	erg/cm^2/cm $\times 10^3$
30	4	1.12	.806	3.56	56.2	.0762	34.4
	5	1.41	1.697	3.98	148.8	.1027	58.3
	6					.1181	
	7	1.78	3.150	4.74	388.2	.1339	106.7
	8	2.09	5.563	5.11	848.0	.1670	164.8
	9	2.59	9.954	5.83	1765.	.2210	254.0
	10	4.18	43.08	6.99	10790.	.1785	289.0
50	4	1.01	.562	3.24	31.2	.1765	49.0
	5	1.37	1.429	3.99	120.0	.2095	87.8
	6	1.53	1.909	4.32	183.9	.223	107.2
	7	1.55	2.087	4.46	223.9	.201	107.7
	8	1.67	2.652	4.60	306.0	.202	116.2
	9	1.82	3.441	4.94	448.0	.203	132.0
	10	2.52	9.495	5.73	1667.	.188	165.0
70	4	.94	.504	3.05	27.2	.246	54.8
	5	1.27	1.082	3.65	73.5	.273	92.6
	6	1.50	1.767	4.07	146.4	.310	105.9
	7	1.52	1.910	4.52	202.3	.273	119.3
	8	1.57	2.205	4.43	232.7	.244	106.3
	9	1.69	2.870	4.66	339.0	.226	110.9
	10	1.95	4.175	5.19	583.0	.1765	101.7

Table A-4. Sprinkler distribution data.

nozzle size	distance	application rate in cm/hr at			application rate in in./hr at		
inch	meter	30 psi	50 psi	70 psi	30 psi	50 psi	70 psi
1/16	2	.000635	.00508	.0165	.00025	.0020	.0065
	3	.00127	.00635	.0190	.00050	.0025	.0075
	4	.00127	.0139	.0318	.00050	.0055	.0125
	5	.00318	.0241	.0578	.00125	.0095	.0228
	6	.00445	.0292	.0571	.00175	.0115	.0225
	7	.0127	.0400	.0635	.00500	.0158	.0250
	8	.0407	.0584	.0762	.0160	.0230	.0300
	9	.108	.0711	.0629	.0422	.0280	.0248
	10	.00190	.0178	.00889	.00075	.0070	.0035
3/32	2	.0235	.0520	.0647	.00927	.0205	.0255
	3	.0148	.0501	.0800	.00585	.198	.0315
	4	.0186	.0635	.0895	.00733	.0250	.0352
	5	.0359	.0940	.121	.0142	.0370	.0475
	6	.0434	.107	.160	.0171	.0422	.0635
	7	.0607	.113	.140	.0239	.0445	.0552
	8	.0922	.121	.137	.0363	.0475	.0540
	9	.151	.132	.130	.0595	.0520	.0512
	10	.124	.120	.0901	.0488	.0472	.0355
	11		.0216	.0666		.00850	.00262
1/8	2	.0848	.176	.225	.0334	.0692	.0885
	3	.0678	.165	.235	.0267	.0652	.0925
	4	.0762	.176	.246	.0300	.0695	.0970
	5	.103	.210	.273	.0404	.0825	.108
	6	.118	.223	.310	.0469	.0878	.122
	7	.134	.201	.273	.0527	.0790	.108
	8	.167	.202	.244	.0658	.0795	.0962
	9	.221	.203	.226	.0871	.0798	.0892
	10	.178	.188	.176	.0703	.0742	.0695
	11	.0564	.0736	.0576	.0222	.0290	.0227

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