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# PHOTOGRAPHIC ANALYSIS OF SPRAYS

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# PHOTOGRAPHIC ANALYSIS OF SPRAYS

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## ABSTRACT

This paper describes an experimental method for determining the size distribution and velocities of drops in a spray. Photographs are taken of a small known volume of the spray, and the images of the drops are counted and measured to give the size distribution. Velocities are determined by taking two exposures on the same film and measuring the displacement of the drops in the interval between exposures. Since a photographic method does not require any objects in the spray, the results are free of bias from disturbances of the flow pattern. The technique is applicable to sprays in which the diameters of drops range from 15 to 500 microns and gives results which differ by less than 20 per cent from the metered values of total flow rate.

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Introduction. The study of sprays and their properties has been hampered by difficulty in obtaining trustworthy measurements of the number, sizes, and velocities of drops at various locations within a spray. Many attempts to evaluate the character of a spray have been concerned only with the distribution of the flow and give no information about the drops. An example is the patternator, which operates with cups placed at various locations in the spray. After the spray fills the cups, the contents of each cup, for some period of time, can be measured to evaluate the flow rate at that location. Other methods of analysis attempt to measure the number and size of the drops of a spray. Most of these depend on physical sampling of the spray or on the scattering of light by the spray. Physical sampling is usually accomplished by having drops impinge on cups or microscope slides in the spray or by sucking them out of the spray through a tube. The captured sample can then be analyzed leisurely for number and size of drops. These procedures are untrustworthy because it is questionable if the sample analyzed is representative of the original spray. The work of Langmuir and Blodgett (4)*, Sell (5), and others, (1), (2), (3) indicates that any impingement process discriminates against capturing small drops. Analyses based on light scattering are free of the bias arising from impingement, but the interpretation of light scattering data is extremely difficult when the drops of the spray are not in a very narrow range of sizes. Furthermore, any interpretation depends on a long chain of theory containing questionable assumptions. None of these methods give any information about drop velocities.

The photographic method of spray analysis here described was developed to give spray measurements which are not biased by physical sampling and which are susceptible to direct interpretation in terms of number, sizes, and velocities of the drops.

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*Numbers in parentheses refer to similarly numbered references in bibliography at end of paper.

The Principle. In the photographic technique of spray analysis pictures are taken of a small volume in the spray without disturbing the flow pattern with any objects. The drop images on the film are measured and counted, giving the size distribution of drops in the small volume of the spray (the spatial distribution). For most applications, however, the information desired is the size distribution of drops passing a cross-sectional area in a unit time (the temporal distribution). Since the temporal distribution is the product of the spatial distribution and the average velocity of drops of each size, it is necessary to measure drop velocities to obtain the temporal distribution. We therefore take double exposures of regions in the spray with a small known interval between exposures. The resulting photographs show a pair of images for each drop, one image made at each exposure. The velocity of each drop can be calculated from the distance between images and the interval between exposures.

The Camera. The camera is a light-tight wooden box with a receptacle for film holders and a viewing screen on the back and a threaded fitting for a lens in front. The lens is an Argus Coated Cintar with a 50-mm focal length and f/3.5 aperture. Although the lens and front part of the camera are wet by the periphery of a wide-angle spray no special precautions have proved necessary to prevent the entry of water. The lens fittings are normally lubricated with a heavy grease, and this has evidently been a sufficient barrier to the water. The optical properties of the lens are not seriously distorted by the water on the front surface.

The distance from the lens to the film is such that there is a magnification of 10 (about 20 inches). This magnification produces images of a convenient size and also gives virtually the best resolution obtainable with a given lens.

The Film. We have used Kodak Contrast Process Ortho film because it has high contrast and high resolution. The high contrast makes close control of the illumination necessary.

The Illumination. The open-shutter method is used in all photographs: the camera shutter remains open, and the length of exposure is determined by the duration of the illumination. For the light source we have used a General Electric Photolight*, which produces light by the discharge of a capacitor through an arc, the duration of useful illumination being about 1 microsecond. In the early stages of the development of this technique we placed the Photolight so that the light reflected from the drops into the camera. The photographs taken with this arrangement showed images which were reflections of the light source in the surface of the drops. The size of the image was not easily related to the size of the drop and we abandoned this arrangement in favor of one in which the light shines directly into the camera giving a silhouette picture with the background illuminated and the drops appearing as shadow. In the arrangement we now use, the light from the Photolight passes through a water cell onto a ground-glass diffusing screen, then through the spray and into the camera as shown in Fig. 1. Fig. 4 shows the resulting photograph. The water cell is a lucite vessel with flat sides containing a solution of nigrosin to control the intensity of illumination.

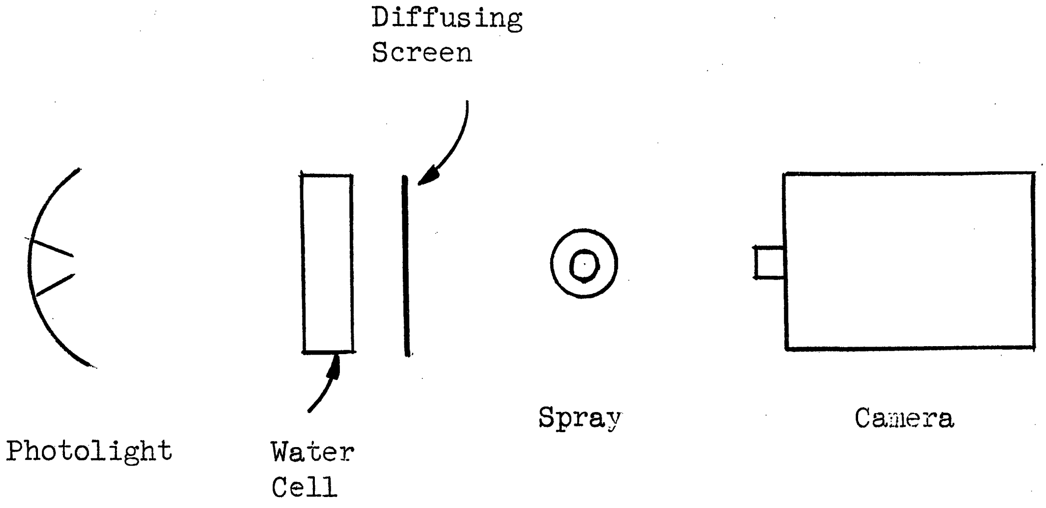

Fig. 1
Arrangement of Elements

The concentration of nigrosin required for correct exposure will vary as different parts of a spray are photographed. The concentration can be adjusted

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*General Electrical Photolight, Catalog 9364688G1.

by trial exposures, but this procedure is inconvenient since the result of each adjustment is not known until after the film is processed. A photoelectric cell cannot be used directly for immediate measurements of the intensity of the illumination because it will not respond to the high intensity and short duration of the light from a Photolight. We have therefore used the following method to permit immediate measurements with a photoelectric cell to adjust the nigrosin concentration. By a series of trial exposures we established the correct nigrosin concentration for one point of a spray. Leaving the spray and nigrosin unchanged we placed a photoelectric cell at the plane of the film and an incandescent light so that it would shine through the water cell, spray and into the camera. The reading of the photoelectric cell was taken as a measure of correct exposure conditions, and for any other photographs the nigrosin concentration is adjusted to give the same reading. The diffusing screen makes the illumination of the spray more uniform.

The Method of Counting Drops. After the films are processed the negatives are placed in a Jones and Lamson bench comparator and projected onto a ground-glass screen. The projection produces a magnification of 10; hence, the image on the screen is 100 times the size of the drop. An operator then classifies the drops by sizes and counts the drops of each size. This gives the spatial distribution.

The volume of the spray which is photographed with one exposure is bounded in two dimensions by the view of the camera and in the third dimension by the depth of field of the optical system as shown in Fig. 2. The extent of depth of field is not as sharply defined as is the extent of field of view. The images of drops that are successively further from the object plane are more and more blurred. The operator who sizes and counts the images must judge from the amount of blur whether a drop is within the arbitrary limits of the depth of

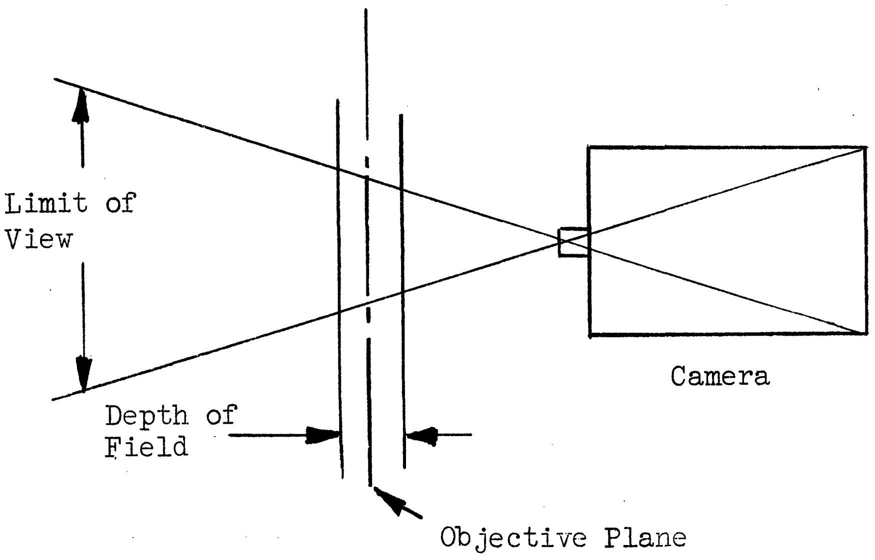


Fig. 2
Limits of Known Volume Photographed

field. In the early stages of the development of this technique, judgments of various operators did not agree, and the judgment of a single operator changed over a period of time. To coordinate the judgments of various operators over a period of time, we made "standard images". These are images of various sizes of drops known to be at the limit of field depth. They are projected on the screen along with images of the drops to be sized and counted. Thus an operator needs to judge only whether a given image is more or less blurred than a standard image of the same size.

The standard images were selected by comparison with a series of photographs of glass fibers having diameters in the same range as the diameters of the drops of the spray. Between photographs, the lens of the camera was advanced on a screw toward the fibers. The photographs thus showed the fibers at successive locations in the field of the camera. Since the movement of the lens was known, the photographs indicated the degree of blur corresponding to a certain distance from the object plane. A convenient limit of field was chosen and the corresponding images of fibers provided a measure of permissible blur for each diameter. Drop images with the same amount of blur were then chosen as standard images for each size.

The depth of field for any fixed blur depends on the lens aperture. If the depth of field is to be maintained constant for a series of photographs, the aperture must remain unchanged and the illumination must be controlled some other way. This is why a water cell is used rather than a variable aperture.

Measurement of Velocities. Drop velocities are measured by means of double exposures, necessitating two flashes of light. Since the interval between flashes must be less than the recovery time of a Photolight, two are necessary, one firing after the other. The light beams are brought into the spray from the same direction by using a half-silvered mirror as a beam splitter. Otherwise, the optical arrangements are the same as when single exposures are made. Fig. 3 shows the arrangement and Fig. 5 a typical photograph. The interval between flashing of the first photolight and the second is controlled by an electronic delay unit. The circuit diagram for this is given in Fig. 6. The exact length of the interval is not critical, but it must be reproducible. If the delay is very long it becomes difficult to associate the two images of a single drop. If the delay is very short the movement of the drops is difficult to measure, and small uncontrollable delays inherent in the flash units themselves become significant. A delay of 25 microseconds proved reasonable for the optical arrangement described here and drops moving about 20 feet per second.

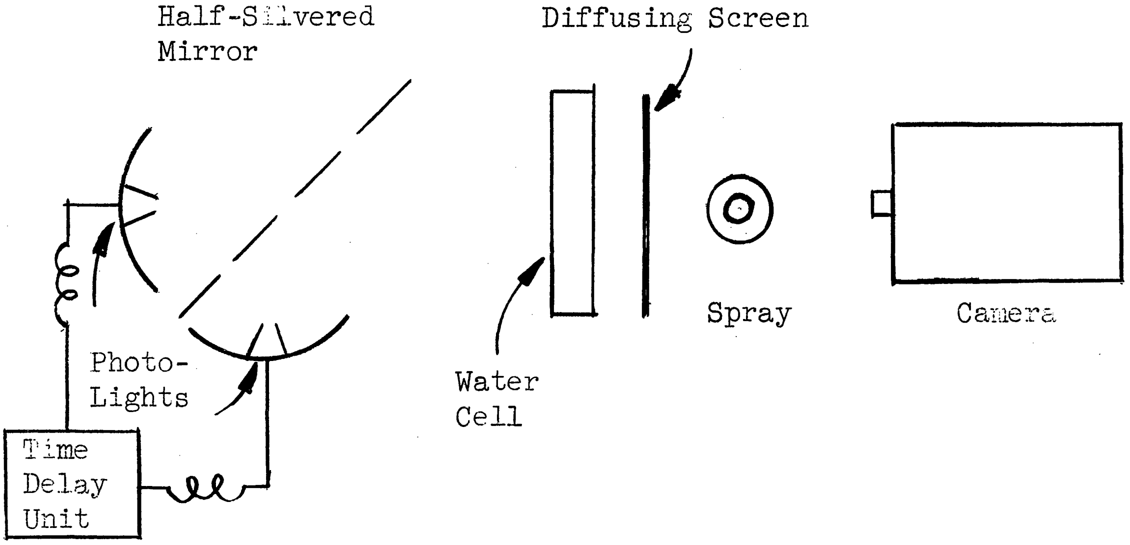


Fig. 3
Arrangement for Double-Exposure

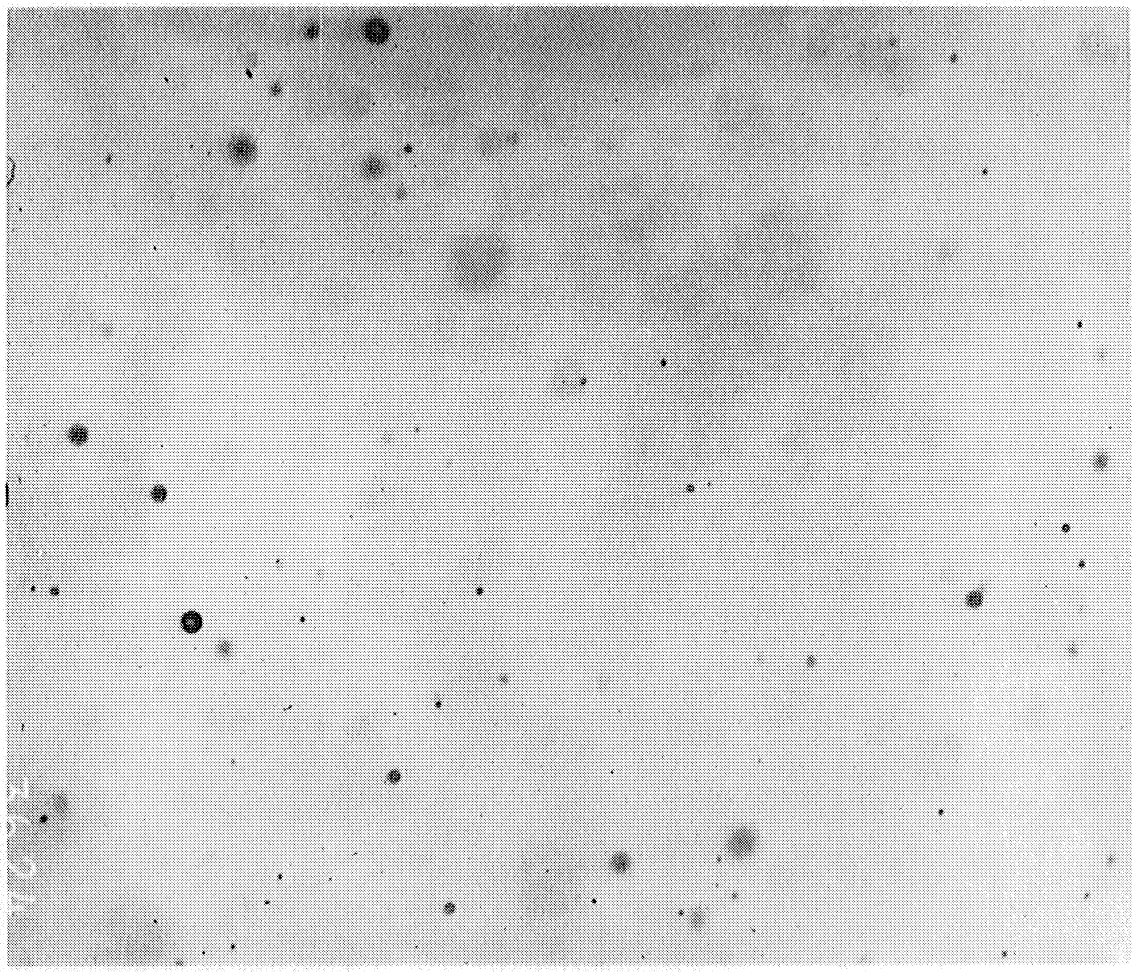


Fig. 4 Typical Silhouette Photograph

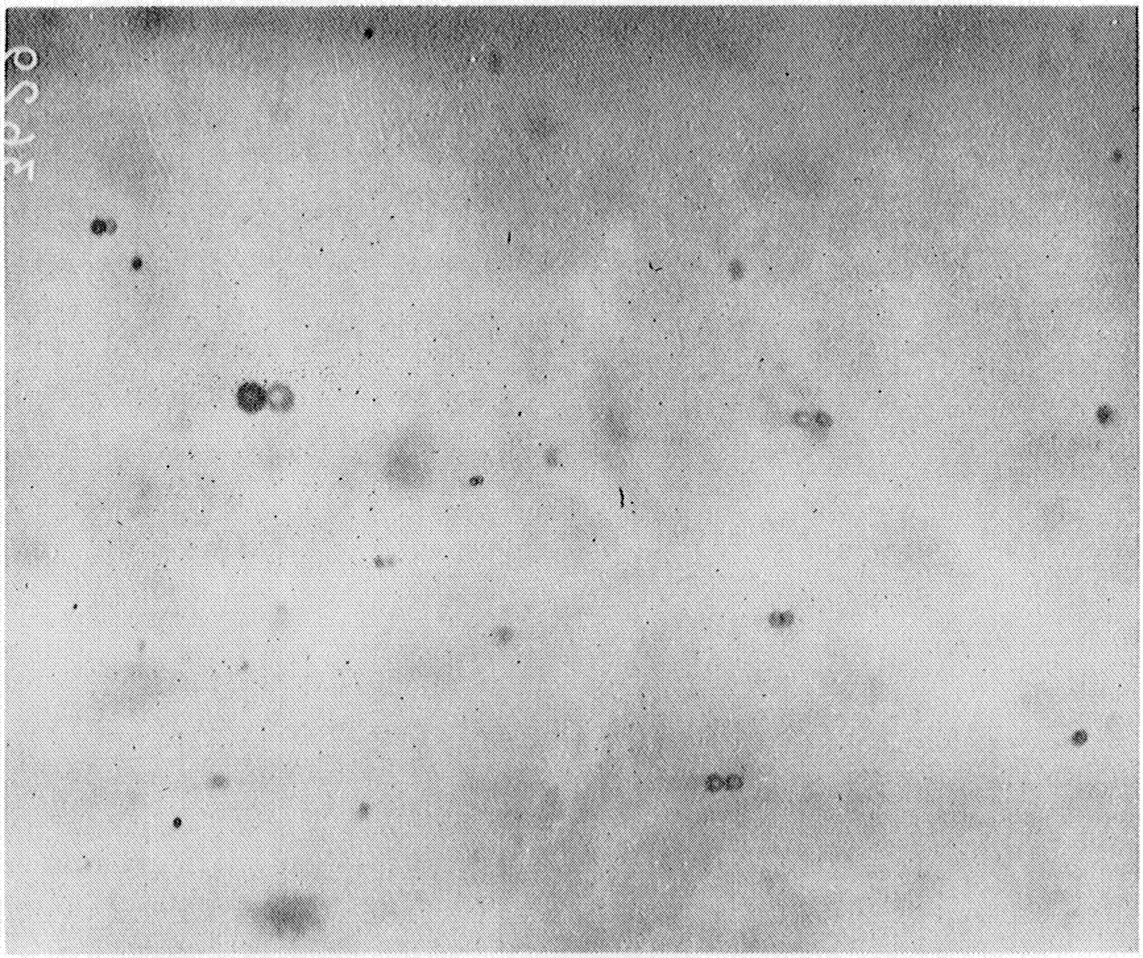
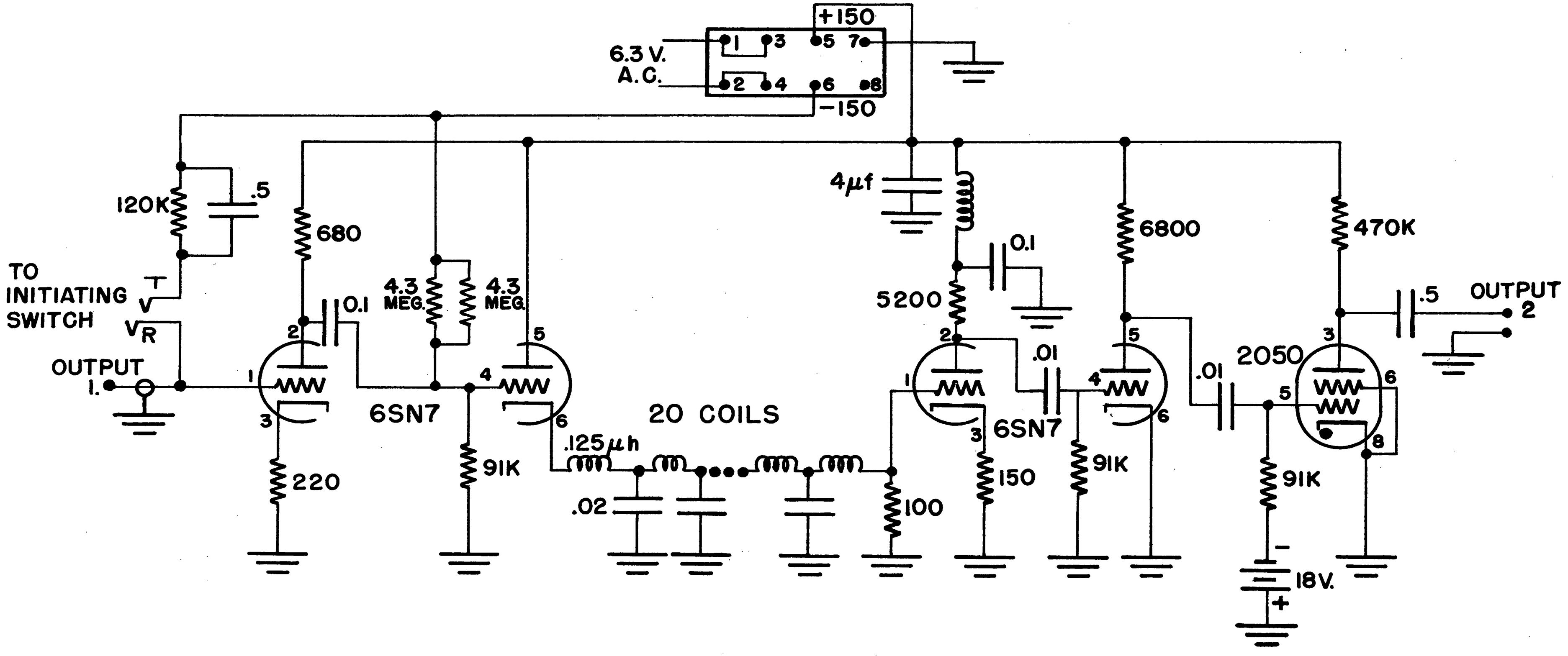


Fig. 5 Double Exposure for Velocity Measurement



RESISTORS IN OHMS
CAPACITORS IN μF

FIG. 6
TIME DELAY CIRCUIT

After making several unsuccessful attempts to calibrate the delay unit using electronic timing equipment, we turned to a mechanical calibration which has been quite successful. In this method a double-exposure photograph is taken of a rotating saw blade. The arrangement is exactly the same as shown in Fig. 3 except that the rotating saw blade replaces the spray. By measuring the angular velocity of the saw and the distance a tooth moves between exposures, the interval between flashes can be calculated.

The negatives with the double exposures of drops are placed in the comparator and the displacement of pairs of images is recorded as a function of drop diameter. From this information the average velocity in each size range is obtained and then this is used to calculate the temporal drop-size distribution.

By repeating the whole procedure described above at successive locations in the spray, the character of the whole spray can be determined.

Results of Analysis of a Spray. The results of this analytical method as applied to a Monarch Simplex Nozzle spraying water at the rate of 200 pounds per hour are shown graphically in Figs. 7, 8, 9, and 10. This nozzle has a hollow-cone spray that is symmetrical about an axis. The character of the spray six inches from the nozzle tip and at different angles from the axis is shown.

Fig. 7 shows the average drop-velocity pattern. At a distance of six inches from the nozzle tip the velocity is far from uniform. This indicates that the drops are moving at velocities considerably different from that of the surrounding air. Fig. 8 shows the temporal drop-size distribution. In this figure the number of drops per centimeter per steradian per cubic centimeter of flow is plotted against size of drop for various locations in the spray. Such a plot is not of immediate use in spray applications but it is of interest in making complete comparisons between nozzles and in design of nozzles. The ordinate $\underline{f}$ in this plot at diameter $\underline{x}$ and angle $\underline{a}$ is

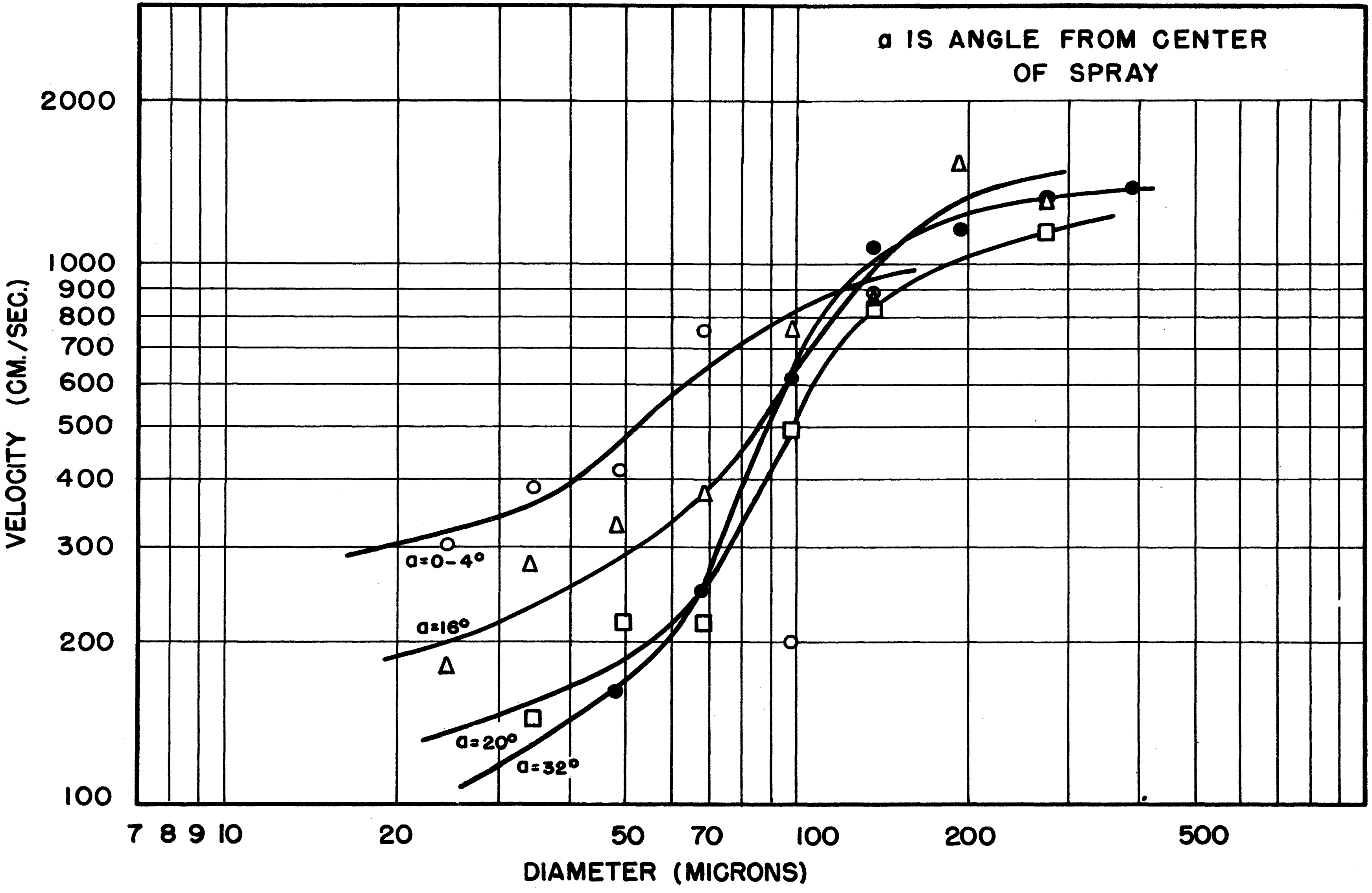


FIG. 7 AVERAGE DROP VELOCITY

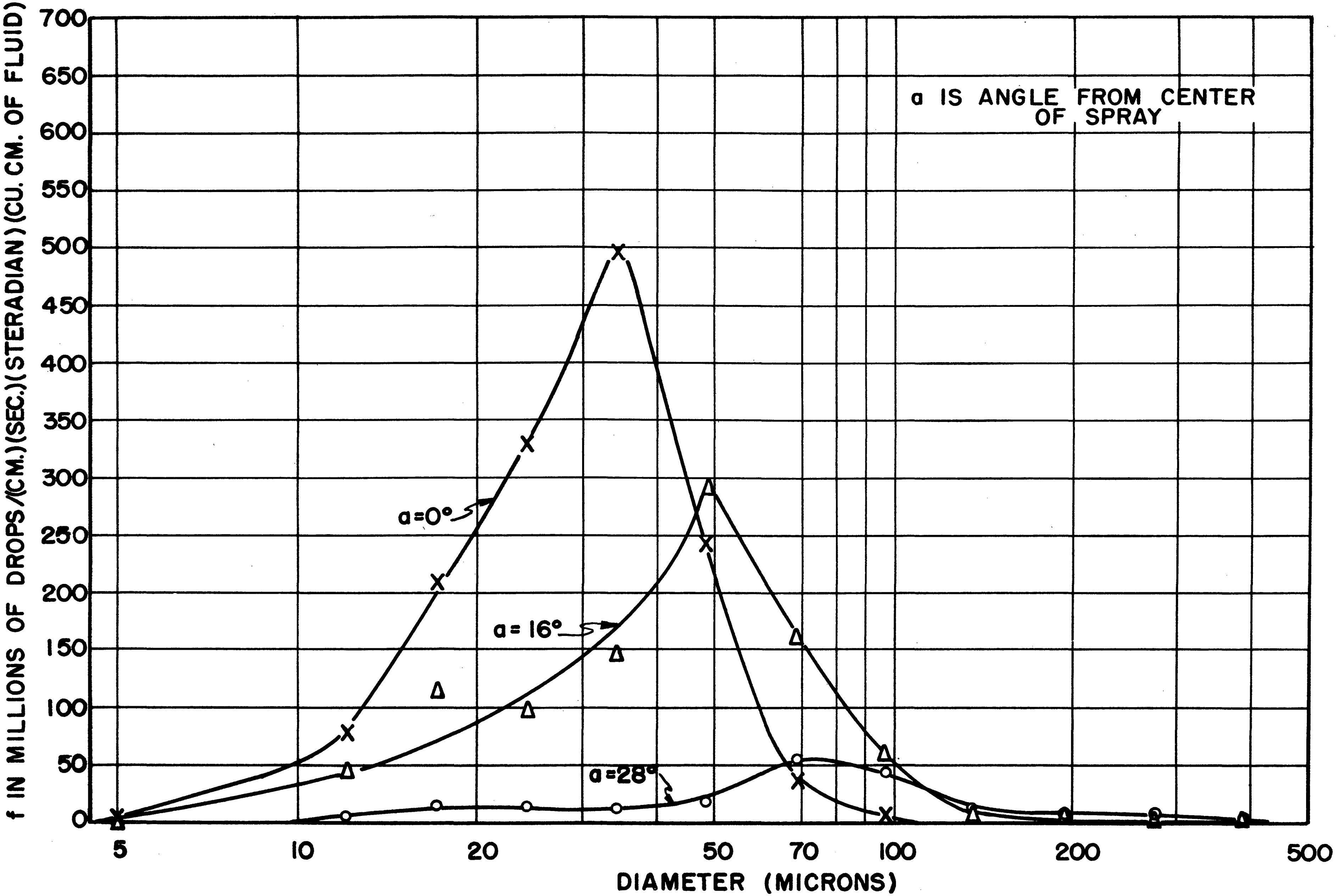


FIG. 8 DISTRIBUTION FUNCTION

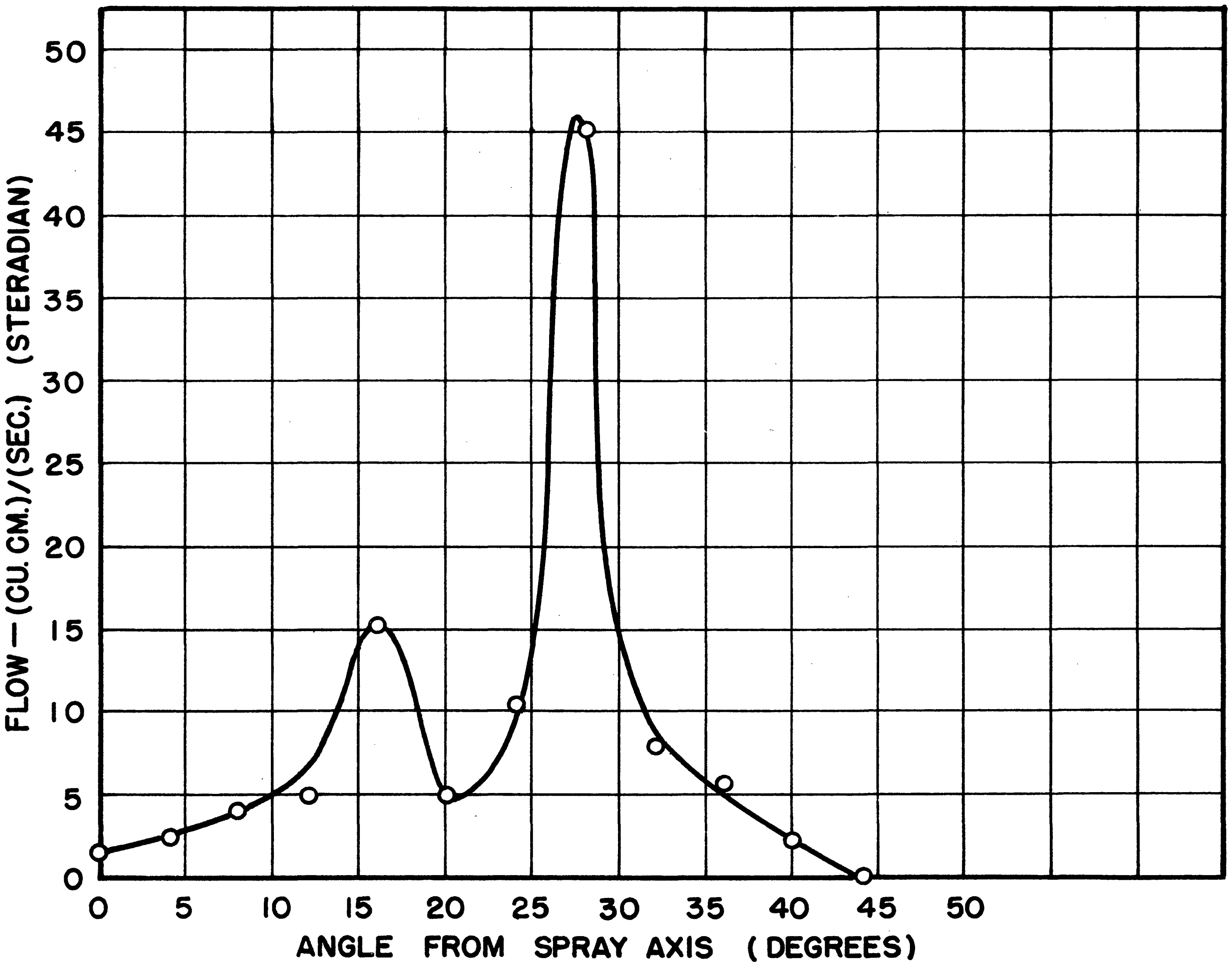


FIG. 9 FLOW DISTRIBUTION

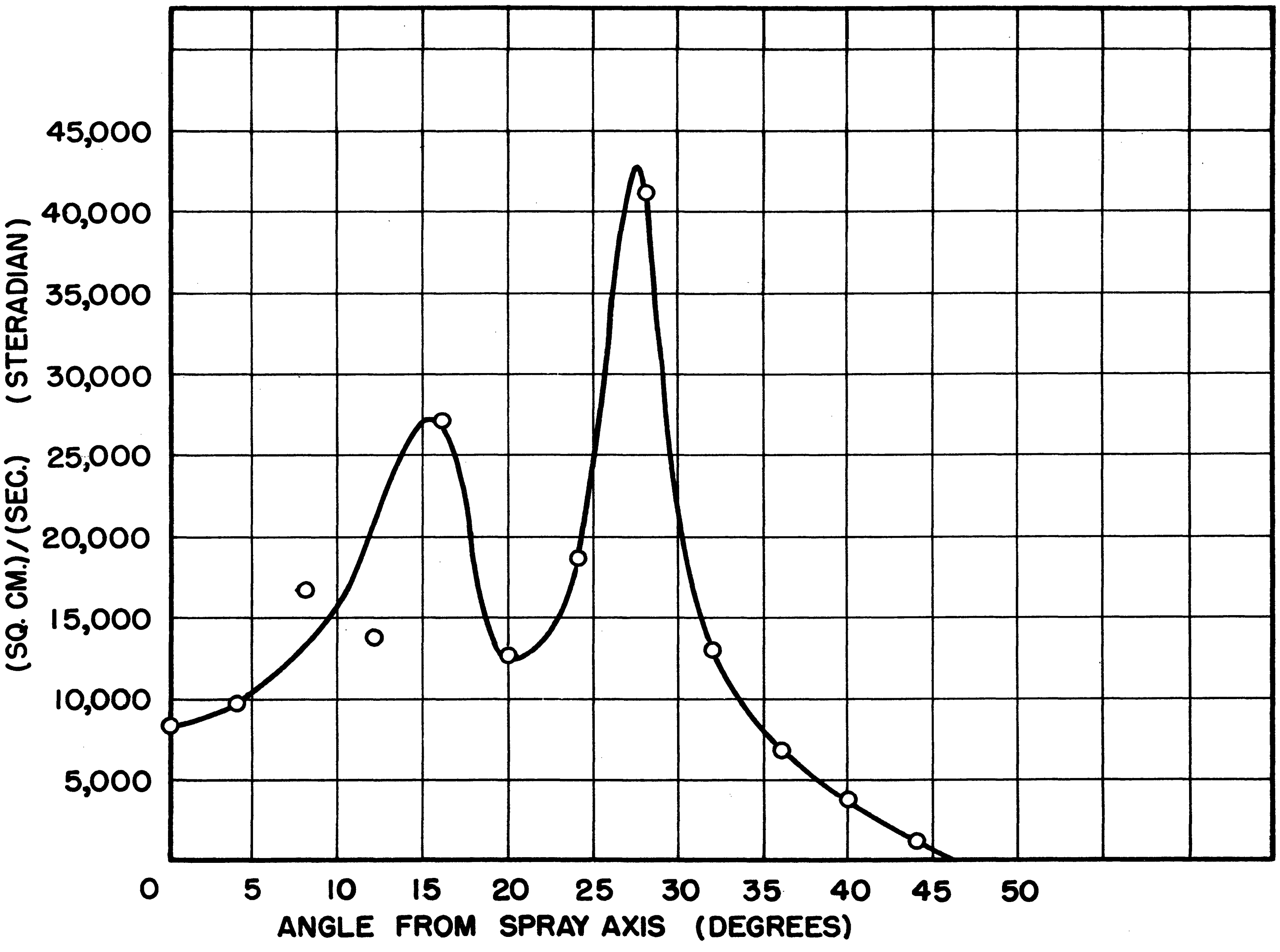


FIG. 10 SURFACE DISTRIBUTION

$$= \frac{1}{q} \lim \frac{1}{(\Delta x)\ (\omega)}$$

as $\Delta x$ and $\omega$ approach zero. n is number of drops with diameter between x and $x + \Delta x$ passing across a surface having solid angle $\omega$ with respect to the tip of the nozzle while the quantity of fluid q is sprayed through the nozzle. If the function f is integrated over all drop sizes and all solid angles, the result will be the total number of drops produced in the spray for each cubic centimeter of fluid sprayed.

We have chosen to present this plot and the succeeding ones in terms of unit solid angles rather than in terms of unit cross-sectional area. If the functions plotted were in terms of cross-sectional area, they would change radically as the distance from the nozzle changes, reflecting the divergence of the spray instead of any fundamental change in the character of the spray. When the functions are expressed in terms of solid angle it is possible to compare directly data taken at different distances from the orifices of nozzles.

Fig. 8 contains all the distribution information about the spray. From it can be derived the mass or surface distribution throughout the spray, the specific surface, the total surface, or any other distribution information desired. Some of the information derivable from the distribution curves is given in Figs. 9 and 10.

By integrating the surface and volume distributions over the whole spray, values can be obtained for the total surface and volume produced in the spray in a unit of time. Since the volume per unit time entering the nozzle can be obtained independently by metering the flow, it is possible to check the overall accuracy of the analysis by comparing the two values. For this analysis the discrepancy was less than 20 per cent.

Discussion. We have determined drop velocities and the spatial size distribution from different series of photographs because the double exposure necessary for velocity measurement tends to obscure the smaller drops. This effect is less objectionable in velocity measurements, since a fraction of the small drops will suffice to determine the average velocity of such drops. For a spray which diffuses little light and consequently gives very sharp drop shadows, or if only larger drops (over 50 microns) are of interest, it might be feasible to use double exposures for both distribution and velocity measurements.

The number of photographs which must be taken and drops which must be countedrises sharply as the desired accuracy increases. The problem is a statistical one.

Even though a large part of the work of an analysis can be made routine, and does not require highly trained personnel, it is still quite laborious to apply the technique described in this paper to a large number of points throughout a spray. In many applications it may not be worth while to obtain the detailed quantitative analysis of which the method is capable. Often the effort can be better spent getting semiquantitative information at a few points of a spray which would be sufficient to indicate the trends and general nature of the spray. Adaptations of this method might also be used to examine the mechanism of formation of a spray or its behaviour as it impinged on an object or at some other point of special interest.

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