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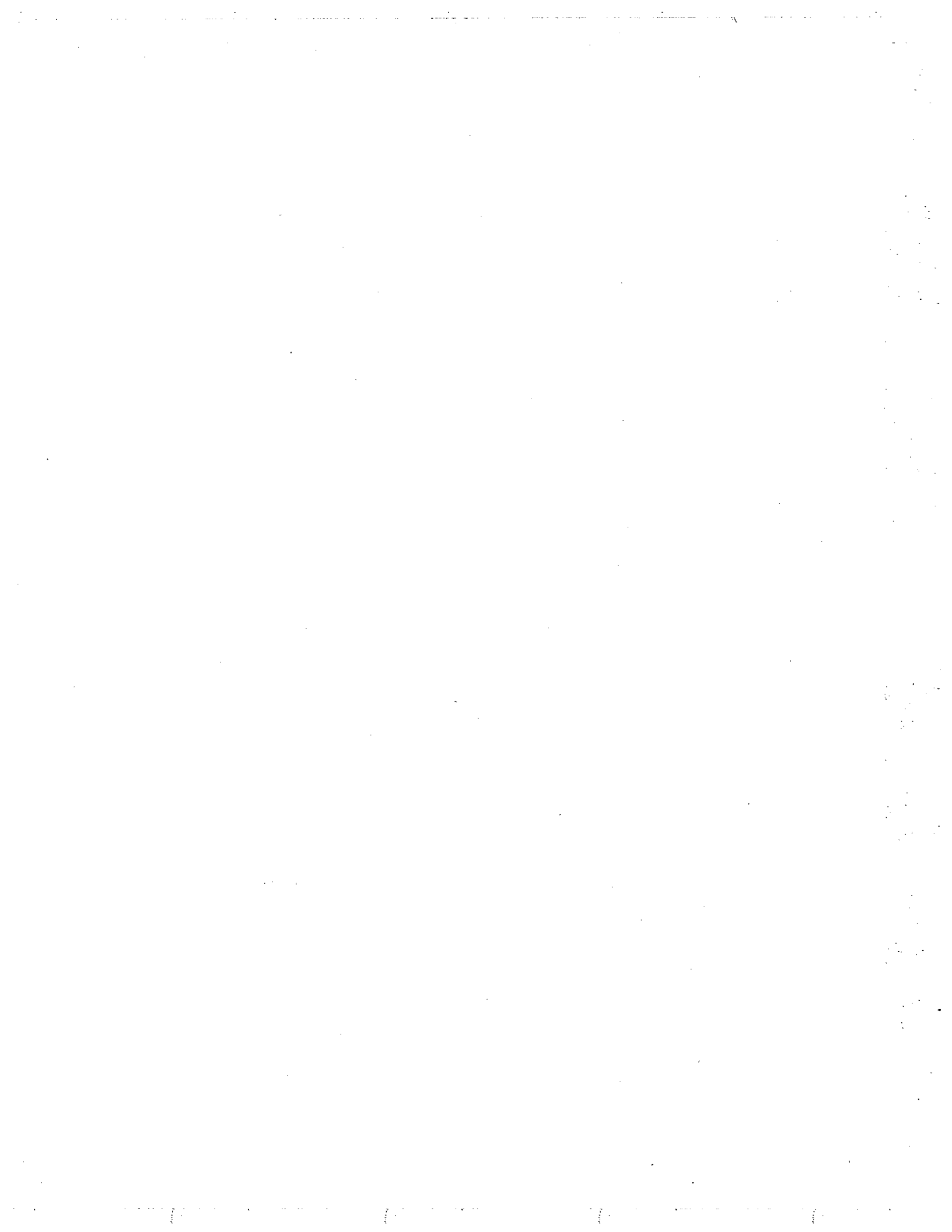
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ON THE MEASUREMENT OF DROP SIZE
AND LIQUID WATER CONTENT
IN FOGS AND CLOUDS

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ABSTRACT

I. A short critical review of possible methods for the measurement of the size of fog particles is presented. It is concluded that the only suitable method of obtaining the distribution of drop sizes present in a given fog consists in the microscopic measurement of large numbers of drops which have been collected on a properly surfaced slide. A method for surfacing microscope slides with a thin, uniform layer of petroleum grease is described. The important problem of obtaining a representative sample of drops on a slide is next considered. Experimental results indicate that slides no larger than 5 mm square will collect satisfactory samples if exposed facing the wind. Larger slides are found to discriminate against the smaller drops. Special fog microscopes which have been constructed for observing droplet samples are described, and typical results obtained in natural fogs are presented. Although forty sets of data have been procured in sixteen different fogs, it has not been possible to correlate the drop size data with any of the accompanying meteorological conditions. There is no evidence of mass grouping, such as Köhler observed in clouds; however, definite conclusions cannot be drawn from such a relatively small amount of data.

II. The usefulness of fog water data is indicated and possible methods of procuring them are reviewed. An investigation of the sampling problem encountered in the operation of most fog measuring instruments is described. The method of avoiding sampling difficulties in a new fog water instrument is explained and the constructional features and operation of the apparatus are discussed.

The essential part of the new instrument is a unit comprising a succession of ordinary wire screens through which a motor driven fan forces foggy air at a measured rate. The central portion of this screen unit is removable for weighing. Liquid water determinations are made from the weight increments of this unit corresponding to the passage through it of a known volume of air as indicated by a vane anemometer. The outer section of the screen unit serves as a guard ring for the central measuring unit, thereby avoiding sampling errors, and at the same time functions as the collector of samples of fog water for chemical analysis.

From the results of numerous measurements it has been determined that in the typical advection fogs which occur at Round Hill the liquid water content may range up to approximately 0.25 g/m^3 . Total dissolved salt contents of from 8 to 480 mg/l have been observed. The number of drops per cc of foggy air has been found to be usually less than five.

I. MICROSCOPIC MEASUREMENT OF THE SIZE OF NATURAL FOG PARTICLES*

BY

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The size distribution of the particles comprising a fog is one of its most significant physical characteristics. Knowledge of the size distribution is important in the theoretical treatment of problems relating to visibility and the transmission of radiant energy through fog. Recently the size of fog particles has been of interest in connection with the development and application of a method for the local dissipation of fog.¹ Data on particle size as well as on all other significant physical properties of fog are of considerable meteorological importance insofar as they contribute to a better understanding of fog structure and the processes of fog formation.

A paper published by one of the authors in 1932² described the development of a method for the microscopic measurement of natural fog particles. The particles were collected on a grease-coated glass slide and were measured either visually, with the aid of an eyepiece micrometer, or by the subsequent measurement of photomicrographs. Typical particle size distribution curves obtained in natural fog were presented and some tentative conclusions were drawn. The development of this method has continued since that time and it is the purpose of the present paper to describe the improved apparatus and technic and to present typical examples of the results which have been obtained. A brief review of the general problem of the determination of fog and cloud particle sizes is also included.

AVAILABLE METHODS OF SIZE MEASUREMENT

Various methods of fog and cloud particle measurement have been employed by different observers. Probably the best known is the corona method which has been used extensively by Köhler³ and also by Barus,⁴ Wagner,⁵ Mecke,⁶ Werner,⁷ Hartmann,⁸ Richardson,⁹ and others. This method is based on the optical theory of the coronal rings observed around light sources viewed through fog or cloud. As usually applied, it yields only an average or predominant particle size. For the solution of most problems concerning fog it is necessary to know not only the predominant size but also the actual range and distribution of the drop diameters. Numerous attempts have been made to

* Although the research reported here was begun as part of a light scattering investigation, it was continued also as a phase of the Fog Dissipation project supported in part by a grant from the Penrose Fund of the American Philosophical Society and through joint contracts with the Bureau of Aeronautics of the U. S. Navy Department, the U. S. Army Air Corps, and the Bureau of Air Commerce of the U. S. Department of Commerce covering several years.

The work was carried out at the Institute laboratories on the Round Hill estate of the late Colonel E. H. R. Green whose foresight and generosity made the project possible. Not only did Colonel Green offer the natural facilities of his estate to the Institute for use as a laboratory, but he also aided by numerous gifts, financial and otherwise. Through the courtesy of Mrs. H. Sylvia A. H. G. Wilks, sister of Colonel Green, we have been enabled to continue work at Round Hill so as to complete our projects.

Round Hill is at South Dartmouth, Massachusetts, on the west shore of Buzzards Bay, about six miles south of the city of New Bedford.

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apply the corona method to Round Hill fogs but the results have been uniformly unsatisfactory, presumably because of the rather wide range of drop sizes always present. Apparently the corona method is suitable only for fogs or clouds comprising particles of a very uniform size. It is interesting to note that in a recent theoretical study of optical methods of measuring small water drops, Wilson¹⁰ concludes that the corona method is not applicable to drops smaller than about 20 microns in diameter and further states that there is no reliable optical method for drops having diameters between about 3 and 20 microns.

Another possible procedure of size measurement is the sedimentation method whereby, in general, the particle sizes are determined with the aid of Stokes' law from observed rates of settling under gravitational or electrical forces. This method is simple in theory but difficult in practice and does not seem to be well suited to measurements in natural fog because of the inherent difficulties of avoiding errors resulting from evaporation of the droplets during the sedimentation period. Adaptations of this method have been used in artificial fogs by Fuchs and Petrianow¹¹ and also by Heubner¹² and by Rohmann.¹³

A third possible means of determining fog particle sizes is by direct photography of the individual drops contained in a small volume of foggy air. Although some preliminary development work has been done on it at this laboratory, so far as is known, the method has not yet been successfully applied to natural fog. The method purposes to illuminate only those drops which are in focus, by employing a very thin transverse sheet of light. To obtain photographs of the normally rapidly moving drops it would be necessary to use as a light source an electric spark of high speed and intensity. The illuminated volume would be so restricted by any optical system having sufficient resolving power that it has been estimated that only about one drop would be photographed per exposure. Because of this, and other difficulties inherent in the design of the apparatus, further development of the method has been deferred.

Findeisen¹⁴ has employed a somewhat indirect photographic method of measuring fog particles in their natural state. He used low magnifications (1 to 5 diameters) and shutter speeds of 1/2000 sec with an arc light source. He made no attempt either to resolve individual drops or to have the photographed drops in focus, but simply obtained photographs of the diffraction rings produced by the drops. From the size and density of these images he was able to deduce the size of the fog drops by a somewhat intricate method. It is interesting to note that the distribution curves which he obtained all show a predominance of particles less than 5 microns in diameter and that many of them have no maxima.

It appears that the only other method of fog particle size determination of importance is the microscopic method described in the previous paper by one of the authors.² Variations of this method have been used independently by a number of observers working with both natural and artificial fogs. In conjunction with his corona measurements Köhler¹⁵ made a few microscopic measurements of frozen drops and of liquid drops which he caught on fine wires. Häusser and Strobl¹⁶ made measurements of atomized droplets which they collected on slides covered with a thin layer of oil. Heubner¹² measured drop sizes of sprayed liquids using unsurfaced slides and observing both the height and diameter of the drops on the slide. Kinoshita and Uchiyama¹⁷ measured the size of artificial fog particles which they forced into a film of oil. They made interesting corrections for the rate at which the droplets evaporated into the oil. More recently Hage-

mann¹⁸ applied a similar method to natural fog drops and obtained about 67 size distribution curves having peaks ranging from 9 to 24 microns particle diameter. Fuchs¹⁹ and Petrjanoff²⁰ have made microscopic measurements of fog and rain drops which were collected on slides covered with a mixture of vaseline and light mineral oil. They found natural fog particles ranging in size from 12 to 60 microns diameter.

The use of an oil layer on the slide to envelop the impinging drops has certain advantages over the use of a thin vaseline layer such as is described in this paper. If the oil is properly saturated with water the evaporation of the drops can be prevented, even when the slide is brought indoors, and if the proper oil mixture is used the drops will retain their spherical shape. However, the oil composition must be varied to suit the prevailing temperature, and also the oil tends to flow to the bottom of the slide when the slide is exposed in the vertical position (which the authors have found to be desirable). From published photomicrographs of drops in an oil film¹⁹ it appeared that the photographic contrast was very poor, especially in the case of the smaller drops, but preliminary investigations at this laboratory have indicated that satisfactory contrast can be obtained if a proper dark field illuminator is used. It is apparent from the photomicrographs which appear in this paper that excellent contrast is obtained when the drops rest on a greased surface.

Since the fog microscopes here described are always used out in the fog the evaporation problem is of no great importance. Normally, no evaporation is observed during periods very much longer than are required for taking the photomicrographs. Also, when a flattened drop partially evaporates its apparent diameter as observed from above usually does not change. It is often possible to determine the original diameter after the complete evaporation of the drop simply by observing the ring which remains on the greased surface. The flattening of the drops on the slide is a disadvantage, since a correction factor must be applied to obtain the original drop diameter, but errors due to variations in this factor, with the present technic, are now less than those from other causes. It may be concluded that both the oil and grease methods of slide surfacing have definite advantages and that the choice of the one or the other should depend on the requirements of the individual problem.

SLIDE SURFACING

Proper surfacing of the slides used for the collection of the fog drops is of the utmost importance. When fog drops rest on a horizontal surface they are more or less flattened by their own weight, the extent of the flattening depending upon the contact angle between the drop and the slide surface. On the basis of capillary theory it may be shown that the free surface of such a flattened drop is approximately spherical for drops smaller than about 1 mm diameter. Thus if the contact angle is known it is possible to determine the original diameter of the drop from its apparent diameter on the slide. For a given contact angle the ratio between the true diameter and the observed diameter is a constant which is independent of the drop size. The contact angle must be maintained constant over the entire slide surface and this may be accomplished by completely covering the glass surface with a uniform layer of clean grease. The surface must be smooth to avoid distortion of the drops and to provide a suitable background against which their outlines will be sharply defined.

The original method of slide surfacing consisted simply in wiping a thin film of petroleum grease (white vaseline) on the surface of a clean slide. The surface so formed,

when viewed under dark field illumination, was found to be streaky and irregular so that some of the drops were always distorted and the contrast was poor. Subsequently, the technic of slide surfacing was improved resulting in the production of much more uniformly surfaced slides. The improved method finally selected after considerable experimentation consists in spreading a moderately heavy coating of vaseline on the surface of a perfectly clean slide and then placing the slide in a vertical position in an oven at a temperature of 300°F for three minutes. It is absolutely essential that the slide surface be clean before the grease is applied as otherwise the grease may collect in spots instead of spreading uniformly. It has been found that the slides can be adequately cleaned by first scouring them with concentrated chromic acid, then thoroughly rinsing them in distilled water and finally allowing them to dry in a dust free atmosphere. Slide surfaces carefully prepared in this manner are so uniform that they are practically invisible when viewed with intense dark field illumination. The degree of uniformity of slide surfacing by the improved method is such that flattening variations cause no more than a 5% error in the determination of the original drop diameters from the observed diameters of the flattened drops.

Determinations of the coefficient by which the diameters of the flattened drops must be multiplied to obtain the original drop diameters have been made by two methods. One method involved the measurement of the height and diameter of individual flattened drops, which were viewed from the side. The "flattening coefficient" could then readily be computed. In the second method an average value of the flattening coefficient was obtained by determining the total weight of a number of flattened drops resting on a slide and then measuring the diameters of the individual drops. Rather large drops were used for most of these measurements in order to obtain convenient weights, but in one case this procedure was applied to natural fog particles and a result was obtained which was in close agreement with the results of the other determinations of the flattening coefficient. From numerous measurements it has been found that the flattening coefficient for water drops resting on a vaseline surface is 0.80 ± 0.04 .

THE SAMPLING PROBLEM

In order to obtain the true drop size distribution of a fog or cloud it is evidently desirable to collect a representative sample of the drops on the slide, or if the sample is not truly representative the law governing the departure should be known. A proper sample will be obtained if all of the droplets from a given volume of foggy air are deposited on the slide. Theoretically this might be accomplished by isolating a portion of the foggy air in a tube and allowing all of the drops to settle onto a slide located at the bottom, as suggested by Fuchs and Petrjanoff.²⁰ However, such a procedure is impractical because, in the considerable time required for all of the particles to settle, the ambient conditions can easily change enough to greatly modify the size of the drops. Also, the isolation of a true sample of the foggy air would be extremely difficult, particularly if there were an appreciable wind.

It has been our practice to expose the slides either horizontally in the fog microscope slide holder or vertically facing the wind. When the wind velocity is very low it has been found necessary to move the slide broadside through the foggy air. On numerous occasions when fog conditions were quite stable, successive slides were exposed horizontally in the microscope slide holder and facing the wind vertically. The samples obtained by the two methods of exposure were found to be identical within the limits of accuracy of

the measurements. Tests made in calm foggy air indicated that a sample obtained by moving a slide through the air at about 1 m/sec was substantially the same as one secured at a velocity of about 20 m/sec.

Hagemann¹⁸ obtained his samples by placing slides behind the small end of a tapered opening through which the foggy air was drawn at a velocity of about 15 m/sec. A similar arrangement was tried at this laboratory and slides so exposed were compared with slides exposed facing the wind. It was found that there were fewer large drops on the slides exposed in the model of Hagemann's apparatus than on those exposed facing the wind. Because of their greater kinetic energy some of the larger drops were evidently deposited on the walls of the tapered opening and it was concluded, therefore, that this is not a suitable method for obtaining a true sample of the fog particles.

In another attempt to learn something of the manner in which the drops are deposited on a slide the total volume of the drops collected on a slide held facing the wind was determined. This quantity was then compared with the total amount of liquid water contained in the foggy air which would have passed through the area occupied by the slide surface during the time of exposure. (This latter value was computed from the average wind velocity normal to the slide and the liquid water content of the fog as measured by a "fog separator."*) It was found that the two quantities were nearly equal indicating that the drops which comprise the bulk of the liquid water were deposited on the slide. The results of this experiment suggest the use of this method of slide exposure to determine the number of fog drops in a unit volume of foggy air, as well as their size.

Notwithstanding the results of the investigations described above it has been suspected for some time that a truly representative sample is ordinarily not obtained. Because of the great difference in kinetic energy between the large and the small drops there is reason to believe that the small drops may be discriminated against. This question can be properly settled only by making a comparison with samples obtained by a method of known reliability, such as the sedimentation method mentioned above. The practical difficulties which preclude the application of this method to natural fog have been pointed out. It was decided, therefore, to make the comparison in an artificial fog formed by atomizing a salt solution of such concentration that the droplets would be in size equilibrium with the surrounding atmosphere. Artificial fog was introduced into a vertical pipe of 10 cm diameter through which an appropriate air flow could be maintained. A short section of the pipe was equipped with shutters so that a portion of the foggy air could be isolated to allow the drops to sediment onto a slide. Sedimentation samples so obtained were compared with impact samples collected by introducing a slide faced normal to the air flow.

As anticipated, it was found that the sedimentation samples comprised a much greater proportion of small drops than the impact samples. However, the method by which the sedimentation samples were obtained is not considered very satisfactory because of the turbulence induced by the closing of the shutters. This factor probably caused some of the larger drops to be deposited on the wall of the pipe. For this reason the results should probably be regarded only as qualitative. Nevertheless, it was quite definitely established that the method which heretofore has been used for the collection of samples of natural fog particles discriminates against particles smaller than about 20 microns in diameter. Since this effect becomes more pronounced as the drop size is reduced, an almost negligible proportion of the drops smaller than 5 microns is collected. Prac-

* See Part II.

tically all of the liquid water contained in the fogs which have been observed at Round Hill is in the form of drops having diameters greater than 20 microns so that the data presented in this paper are not subject to much modification as a result of the findings just outlined. However, it is planned to develop a better method of obtaining sedimentation samples in artificial fog so that quantitative correction factors can be determined which may be applied to the size data procured from impact samples of natural fog particles on slides 25 mm square.

The application of correction factors to take care of the sampling difficulty is not entirely satisfactory, particularly in the case of fogs having a predominant particle diameter less than 20 microns, and a means for obtaining a more representative sample has therefore been sought. From a simplified analysis of the factors influencing the deposition of the droplets on the slide, which include the kinetic energy of the drops, the resisting force when the drops deviate from the streamlines and the nature of the velocity field in front of the slide, it was decided that a smaller slide may be expected to collect more of the smaller drops. Accordingly, 5 mm square slides were substituted for the standard 25 mm square slides and, using the same artificial fog apparatus described above, samples for comparison were collected by impact and by sedimentation. Again the results could not be considered to be quantitative, but it appeared that representative samples were obtained on the small slides exposed by impact for drops down to about 5 microns in diameter. It was definitely demonstrated that the 5 mm slides obtained a much truer sample of the fog than did the 25 mm slides. The use of the small slides is therefore indicated in all cases where drops less than about 20 microns in diameter are of importance.

THE IMPROVED FOG MICROSCOPES

Since the publication of the paper already referred to² describing the first fog microscope constructed at Round Hill, two greatly improved models have been built. The first of these, which was constructed in the fall of 1935, has been used extensively for routine observations in fog and also for numerous measurements of the sizes of drops formed by spray nozzles. The other improved microscope, constructed in the spring of 1936, has been used satisfactorily in the field for over a year by another observer.* Due to improvements in their optical and mechanical features, and the use of better surfaced slides, the new instruments yield photomicrographs which are vastly superior to those obtained with the original apparatus. To prevent the evaporation of the fog drops while they are being measured, the microscopes have been designed to be used out in the fog. They are much more compact than the original instrument and are also more convenient to operate because of the simple external controls which are provided. Standard incandescent lamps are used which may be operated either from a single storage battery or other convenient source. With the new microscope, it is readily possible to obtain several photomicrographs within a minute.

Fig. 1 is a photograph of the microscope which was constructed in 1935. This instrument utilizes a simple system of bright field illumination including a water cell which reduces to a minimum the amount of radiant heat reaching the slide. This model is arranged primarily for photographic observation and is equipped with a 16 mm Micro-Tessar lens giving a magnification of 25.4 \times . The standard 9 \times 12 cm film pack holder and a

* Mr. Alan C. Bemis has generously cooperated with us in obtaining data in fogs and clouds at various locations. It is expected that some results of this work will be published in the near future.

ground glass and hood are mounted on a sliding carriage to facilitate focusing. A convenient toggle-type shutter automatically gives the proper film exposure. The slide holder is constructed so that any desired portion of the slide surface can be observed.

Fig. 2 is a photograph of the later and somewhat improved model. This instrument employs dark field illumination and is equipped with a 16 mm, 10 \times microscope objective mounted in a microscope tube of standard dimensions. Any of a number of oculars may

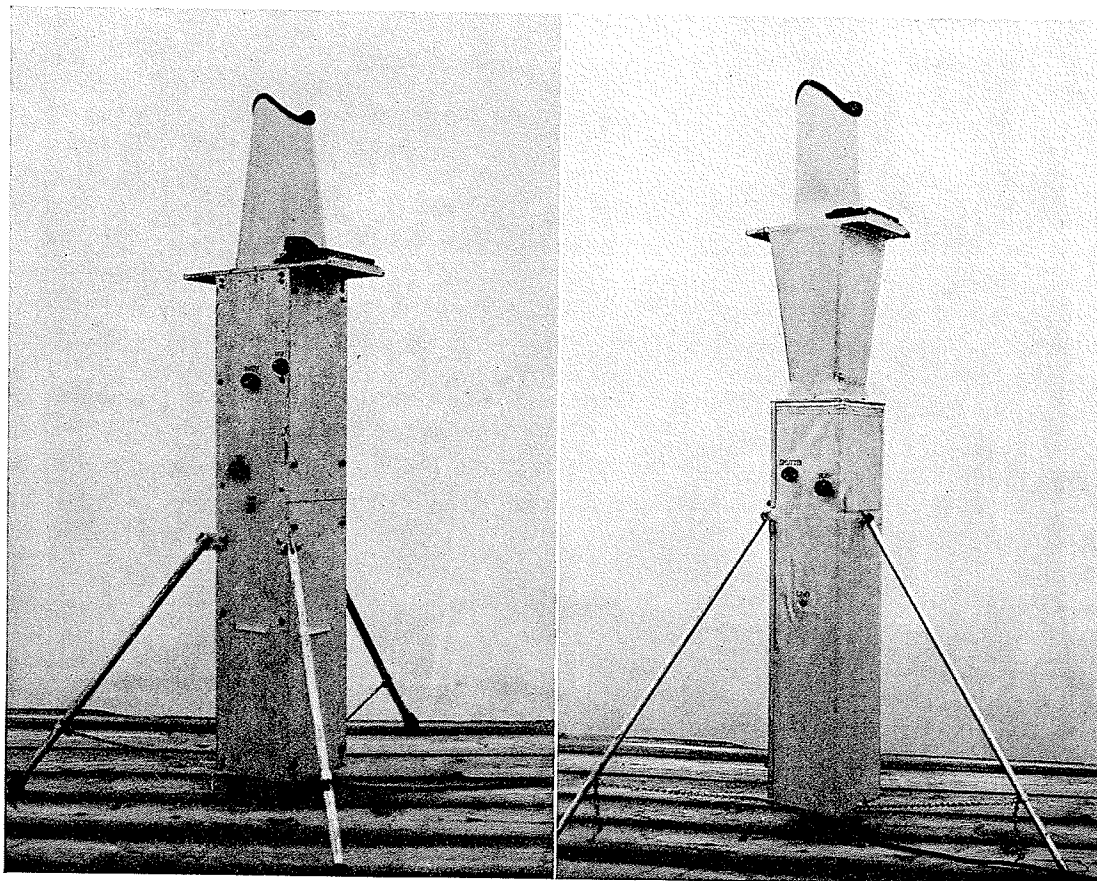


FIG. 1.—The 1935 model of the fog microscope. This instrument has bright field illumination and is equipped for photographic use. Three of the four control knobs can be seen in the illustration. The framework of the instrument is of angle iron and the covering is of sheet metal. One side is removable to provide easy access to the interior.

FIG. 2.—The 1936 model of the fog microscope. This instrument uses dark field illumination and is equipped with standard microscope optics. The upper portion of the instrument, comprising the camera, is removable. The framework is of welded steel tubing and the covering is of fabric and sheet metal.

be used, depending on the overall magnification desired, about 80 \times usually being employed for photographic observations. The upper portion of the instrument, which comprises the camera, is removable so that this microscope can also be used for direct visual measurements. Other essential features of this instrument are similar to those of the bright field microscope described above.

Considerable experience with these two fog microscopes has revealed the superiority of the dark field model. With bright field illumination the contrast is very poor for the

