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# COMPARISON OF THREE MULTICYLINDER ICING METERS AND CRITIQUE OF MULTICYLINDER METHOD

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## SUMMARY

Three multicylinder cloud meters, fundamentally similar but differing in important details, were compared in use at the Mount Washington Observatory. Determinations of liquid water content were found to agree within the limits of the probable error, but the two instruments designed by the National Advisory Committee for Aeronautics indicated larger drop sizes than did the Observatory's instrument, apparently because of spurious ice catch on the rather rough surface of the larger cylinders. Comparisons of drop-size distribution were largely indeterminate.

In a critique of the method, the probable error of determination of liquid water content was found to be ±8 percent; of drop size, ±6 percent; and of drop-size distribution, about ±0.5 unit of the modulus of distribution. Of the systematic errors, run-off of unfrozen water is most important, blow-off and erosion seldom being hampering.

Revision of collection-efficiency computations for cylinders in clouds with distributed drop sizes was found necessary and also revision of one of the correction-factor graphs heretofore used. The assumption of constant ice density in deriving cylinder size was found to be permissible for cylinders 1 inch or more in diameter.

## INTRODUCTION

Three different multicylinder icing meters, fundamentally similar but differing from each other in important details of design, were compared in actual use at the Mount Washington Observatory. The purpose was to compare the relative functional effectiveness of the instruments, to evaluate the observational errors, to study the effects of detailed differences in design, and to recommend further improvements of design. The instruments used were one built for the Observatory in 1944 by the General Electric Company and two provided specifically for the comparison by the National Advisory Committee for Aeronautics.

Evaluation of the multicylinder method is concerned jointly with the validity of the theoretical basis and with the degree to which the instrument and the technique of its use permit accurate determination of the physical measurements involved. Limitations of time and equipment prevented repetition of the droplet-trajectory computations, but the application of their results in the multicylinder method has been carefully reviewed, resulting in two revisions of the theoretical data heretofore in use. The analysis of errors is based entirely on experience at the Observatory with the techniques and equipment in use there.

The work described in this report was made possible by the sponsorship and the financial assistance of the National Advisory Committee for Aeronautics and by the cooperation of the icing research staff of the Lewis Flight Propulsion Laboratory.

The observational work was supervised and largely carried out by Mr. Robert B. Smith. He was assisted by Mr. Norman E. Turner and on occasions by Messrs. Charles Harrington, Rudolph Honkala, Paul Oyler, and James Rosenberry of the Observatory staff. The meteorological observations were provided by the cooperation of the United States Weather Bureau

## SYMBOLS

| | |
|---|---|
| $d_d$ | drop diameter, microns |
| $D$ | diameter of cylinder, centimeters |
| $D_K$ | diameter at which $K = 1$, centimeters |
| $E_M$ | collection efficiency |
| $K$ | dimensionless parameter $\left(\rho_w d_d{}^2 V / 9\eta D\right)$ |
| $L_w$ | liquid water content of air, grams per cubic meter |
| $m$ | modulus of drop-size distribution |
| $R_U$ | Reynolds modulus $\left(\sqrt{K\phi}\right)$ |
| $s_d$ | drop-size distribution according to Langmuir's letter designation |
| $V$ | wind speed, meters per second |

| | |
|---|---|
| W | weight of ice accumulated on cylinder, grams |
| $\eta$ | viscosity of air, grams per cubic centimeter |
| $\rho_a$ | density of air, grams per cubic centimeter |
| $\rho_i$ | density of ice, grams per cubic centimeter |
| $\rho_w$ | density of water, grams per cubic centimeter |
| $\phi$ | dimensionless parameter $\left(9\rho_a{}^2 DV/\eta\rho_w\right)$ |

## COMPARISON OF THREE MULTICYLINDER ICING METERS

### Description of Instruments

The multicylinder instrument used by the Observatory is the one described by Schaefer (reference 1). For brevity it will be referred to as set "O." It has six cylinders graduated in diameter from 0.065 inch up to 3 inches, the two smallest ones being about 12 centimeters long (so that ice samples 10 cm long can be cut from the collection on them), while the other four cylinders are brass shells 7.45 centimeters long. Between the cylinders are reducing segments that change the diameter without a sudden break and are intended to provide undisturbed air flow about the measuring sections. The outline of the assembly is smooth, without flanges or plates separating the measuring sections from the reducing segments. The surfaces of the cylinders are machined smooth but not highly polished and they have become strongly hydrophobic by being handled with gloves contaminated with silicone. The cylinders are rotated at 6 rpm.

The two instruments provided by the NACA are referred to here as sets "A" and "B." Set A is similar to the one described by Jones and Lewis (reference 2) and has five cylinders graduated in diameter from $\frac{1}{8}$ inch to $4\frac{1}{2}$ inches and separated by flat end plates $5\frac{1}{2}$ inches in diameter. The cylinders are all 4 inches long. The two largest cylinders are aluminum shells having a moderately rough-machined finish on the outside. The B set is of a later design having five cylinders graduated in diameter from $\frac{1}{8}$ inch to $4\frac{1}{2}$ inches, 2 inches long, and separated by reducing segments quite similar to those of the O set. The cylinders, however, are provided with flanges that terminate the measuring sections, these flanges being about 1/8 inch high. The cylinders are aluminum, with a moderately rough-machined finish.

The lower end of the NACA multicylinder assemblies is a rod that can be set in a socket on the upper end of a drive shaft and held in place with a setscrew, the drive shaft extending some 30 inches from a box containing the driving motor and reduction gears which turn the shaft at about 24 rpm. The box is set on a jointed mount that fits on the standard anemometer taper used at the Mount Washington Observatory as a universal instrument mount.

The long drive shaft of the NACA instrument proved unwieldy at Mount Washington because of severe whipping of the multicylinders in strong, gusty winds and a tendency for the whole assembly to rotate on the mounting taper. The drive shaft was therefore shortened 18 inches, eliminating these difficulties. Before then, the NACA multicylinder, when mounted in position for an exposure, extended about a foot higher than the 0 set.

## Exposure Site

The instruments were exposed on the tower of the Mount Washington Observatory, 6300 feet above sea level. The tower is 6 feet square and 30 feet high, standing 8 feet above the peak of the Observatory roof at the northeast end of the building. The exposure is unobstructed from east-northeast to south-southwest. To the southwest it is obstructed by the lower bridge work of a 150-foot radio tower 75 feet away, to a degree dependent on the amount of rime on it. From west-southwest and west the exposure is unobstructed. From west-northwest through northeast it is partially obstructed by nearby buildings on the summit so that small-scale turbulence and the amount of snow carried in the air are increased.

Anemometer-mounting tapers of standard Weather Bureau pattern are fixed at several points around the tower rail, so placed that at least two and usually three are always on the windward side. The instruments were set on these tapers with jointed mounts so that they could be tilted forward or backward. The tilt was adjusted to place the instruments as nearly normal to the wind as possible, frost feathers usually being used as indicators of the upslope of the wind over the railing. Frost feathers forming on the instruments themselves provided a further indication so that faulty settings could be noted and allowance made.

Two pairs of tapers, one on the southwest and one on the northwest side of the tower, were used in over 90 percent of all exposures. On these mountings, the two instruments being compared were about 1 foot apart. A pair of multicylinders is shown in figure 1 in the southwest exposure position.

There were a few occasions when the wind direction was such that one instrument somewhat obstructed the exposure of the other. These observations were eliminated from the analyses.

## Observational Procedure

Before observations with the multicylinders were begun, a test was made of the uniformity of the wind speed and liquid water content in the air space above the tower railing where the instruments were to be placed. The test was made by mounting a cylindrical brass rod 30 inches long on the NACA apparatus in place of the multicylinder assembly and exposing it, under various wind conditions, in the positions to be occupied by the multicylinders. The ice deposits on the rod were measured and examined to determine whether the amount or character of the ice varied along the length of the rod. No variation was found. A similar result was obtained by Howell (reference 3) in a study of observations made with the uniform cylinder on the parapet of Tip Top House, about 150 feet north-northwest of the Observatory tower and about 10 feet above the ground. The earlier observations showed a decrease of $2\frac{1}{2}$ percent in the average length of frost feathers at 57 centimeters above the railing as compared with 117 centimeters above it, attributed to the combined effect, inseparable by the method used, of wind and water-content gradients near the ground. In the subsequent analyses, the conditions of exposure were therefore considered uniform over the length of the multicylinders.

Observations with the O set were made every 3 hours during icing weather. Comparative observations with the NACA instruments were made at these times. The exposure was usually begun about an hour before the indicated synoptic hour, but a later start was sometimes made, up to a few minutes after the synoptic hour, when a period of icing began. After the instruments had been assembled in preparation for the observation and the selected exposure positions cleared of ice, the O set was put in position. A measured time later, usually 30 seconds, the NACA instrument was put in position. The cylinders were already rotating when set out. There were a few times when the delay in exposing the second instrument exceeded 30 seconds; the few for which it exceeded 2 minutes were eliminated from the analyses. Final adjustment of the angle of inclination was made, if necessary, the two instruments always being made as nearly parallel as possible. The angle was generally correct within $\pm 10^{\circ}$ and suitable corrections were made in the computation.

The exposures were continued until a measurable collection of ice had accumulated on as many of the cylinders as possible without incurring an excessive collection on the smallest one and the cylinders were then brought in with the same time interval and in the same order as they were set out. They were taken immediately to the cold laboratory within the Observatory tower, where they were disassembled, and the ice accumulations were weighed and measured. The procedure used with the O set has been described in detail by Clark (reference 4) and Howell (reference 5). A similar procedure was used with the NACA sets except that the ice samples were not trimmed to length in the same fashion, the length being fixed by the flanges or end plates. The difficulties experienced in preserving the true ice sample will be described in a later paragraph.

Computation of each observation of the pair was made independently except that the same values of wind speed, air temperature, and air pressure were used for both. The wind speed was read from the chart of the recording anemometer in the Observatory which is connected to an electrically heated, vaned pitot tube atop an iron pipe 6 feet above the railing of the tower. The only deviation from the computational procedure previously described is that the theoretical collection-efficiency graph with the $K\phi$-value closest to the true $K\phi$ was always used in making the final determination of $L_W$ and $D_K$.

## Results of Measurements

Between February 22, 1949, when the first NACA instrument was received at Mount Washington, and May 28, 1949, when rising temperature ended the season, 36 comparisons were made with the A set of which 32 were suitable for analysis, and 44 comparisons were made with the B set of which 30 were suitable for analysis. The data obtained are summarized in table I. For brevity, observations made with the A set are called "A" runs and simultaneous observations with the O set are called "OA" runs. "B" and "OB" runs refer similarly to observations with the B set and paired ones with the O set.

The reliability is the only quantity tabulated that is not described in the references. It is a guide to the internal consistency of the observation, based on the number of cylinders on the instrument, the number having a measureable ice accumulation, and the number of computed data points falling along the theoretical collection-efficiency curve within a 5-percent margin of error. It is defined by the equation

$$\text{Reliability} = \sqrt{\frac{n^2}{CN}}$$

where $n$ is the number of points falling along the curve, $C$ is the number of cylinders collecting measurable ice, and $N$ is the number of cylinders on the instrument.

There were a few observations for which two or more theoretical collection-efficiency curves might with equal validity have been selected as most nearly matching the data points. These ambiguous observations were eliminated from the analyses.

Liquid water content.- The means of the liquid water contents determined with the NACA instruments are almost exactly 1 percent less than those determined with the O set. Figure 2 is a correlation diagram of liquid-water-content observations. The root-mean-square deviation from exact equivalence is 0.025 gram per cubic meter for the A set and 0.044 gram per cubic meter for the B set, which are 6.5 and 9 percent, respectively, of the mean liquid water contents. These deviations are only slightly greater than what would be expected from the probable errors (see the section "Critique of Multicylinder Method"). They indicate that, at the present state of refinement of the observational method, there are no significant differences among the three instruments with regard to the determination of liquid water content.

Drop size.- The means of the drop sizes from the observations with the NACA instruments are greater than those with the O set. The correlation diagram is shown in figure 3. The root-mean-square deviation from the best-fitted line of unit slope is 0.82 micron for the A set and 0.92 micron for the B set, both very nearly 6 percent of the means. The deviations are somewhat larger than the known probable errors, possibly because of variations of collection efficiency of the rough cylinders, as will be discussed later in this report. There is, further, a systematic difference, the NACA instruments yielding a larger drop size than the O set, arising from the same cause.

Drop-size distribution.- In the present report it is presumed, following Howell (reference 6), that water-volume distribution with the drop size is a Gaussian distribution, the breadth of which may be characterized by a modulus of distribution $m$ that is defined by the relation

$$m = \sqrt{2}\sigma / \bar{r}$$

where $\sigma$ is the standard deviation and $\bar{r}$ is the volume median radius. The distributions postulated by Langmuir (reference 7) and used in the multicylinder method may be given numerical values as follows:

| Langmuir letter | A | B | C | D | E | F | G | H | J |
|---|---|---|---|---|---|---|---|---|---|
| Modulus $m$ | 0 | 0.50 | 0.75 | 1.00 | 1.25 | 1.50 | 1.75 | 2.00 | 2.50 |

Comparison of the means of the moduli obtained from the NACA and O instruments shows that the A set yields a smaller modulus and the B set a larger one than the O set. Correlation diagrams are shown in figure 4. If the scatter of these data is taken as the measure of their precision, the difference between the A runs and the OA runs is $1\frac{1}{2}$ times the probable error of the mean; the other difference is twice the probable error of the mean. Conclusions based on these data, however, can be no more than tentative.

A further study of the collection efficiency of the larger cylinders and the effect it has on the indicated drop diameter and liquid water content was made by the following method. A piece of tracing paper was marked with coordinates corresponding to those of the collection-efficiency curves, $E_M$ and $1/K$. The origin was located successively over the origin of each of the data graphs obtained from the A runs and the data points were all marked on the tracing paper. A similar tracing was made of the data points from the OA runs. Each tracing showed a scatter of points along a mean curve, the scatter being due in part to errors and in part to variations of the drop-size distribution and the Reynolds modulus $R_U$.

When the two tracings were coordinated, very little difference could be seen between them. There was some indication that the data points for the next to the largest cylinders of the A set were displaced slightly toward low collection efficiency relative to the mean curve of the OA runs. These displacements would result in indication of a narrower drop-size distribution by the A set, confirming the tabulated means of the distribution moduli.

The coordinates of the two tracings were then displaced by amounts corresponding to the ratios between the means of the liquid water contents for each group of observations and the means of $D_K$. Thus placed, they were in a common relation to nature if the exposures were identical. The result was then that the mean collection efficiency of the A cylinders exceeded that of the O cylinders, for the values of $K$ less than 2, by a factor of about 1.2 at $K = 1$, increasing up to 3 or so at $K = 0.5$.

When the B and OB runs were similarly treated, the result was different. The first coordination showed substantial agreement all along the curve except that the A curve is very slightly flattened at the lowest values of $K$, corresponding to the broader mean drop-size distribution arrived at. With the coordinates displaced by the ratios described, the points from the two largest B cylinders appear displaced toward higher collection efficiency by a factor of about 1.2 at $K = 0.5$.

The possibility that the greater collection efficiency of the larger NACA cylinders could be explained by the action of the end plates or flanges, by the factor rate of rotation of the NACA cylinders as compared with the Observatory's, or by the vibration of the former in the wind, were all considered and rejected. It is not clear whether a hydrophobic or hydrophilic state of the surface may play a part; all the cylinders were more or less hydrophobic, the O set being the most hydrophobic and the B set the least. Since the greatest contrast was between the O set and the A set, both strongly hydrophobic, such an effect must be doubted. The roughness of the surface remains the most probable cause of the difference in collection efficiency. This conclusion is in harmony with that reached in experience with the instrument at Mount Washington.

## Experiences with the Instruments

End plates and flanges.- In experience at the Observatory so far, each method of separating the desired ice sample from the rest of the ice has its drawbacks. The flush joint of the O set between the measuring sections of the cylinders and the reducing segments often caused irregular fracture of the ice when the parts were separated and occasionally it was necessary to trim the sample with a heated knife. The end plates obstructed the exposure of the cylinders with which they were used whenever the instrument was tilted even slightly from the normal to the wind. The degree of obstruction was in most cases describable within the accuracy of measurement by the geometric relation:

$$S_{eff} = S(\cos \theta - F \tan \theta)$$

where $S_{eff}$ and $S$ are the effective and actual lengths, respectively, of the measuring section, $F$ is the distance that the end plate extends beyond the cylinder, and $\theta$ is the angle between the wind and the normal to the cylinder axis. There were a few times, however, when the ice deposit on the larger cylinders was shorter than on the small ones, even though the end plates overhung the former less. In any event, when the length of the ice deposit was affected by the end plates, the effective length of the cylinder could be determined only within an error of $\pm 2$ millimeters. Further uncertainty arose at times when the ice on the cylinder adhered to the end plates, breaking or chipping unevenly when the instrument was disassembled.

The flanges on the B set were more satisfactory than the end plates on the A set. Usually the ice on the outer edge of the flange could be removed with the thumbnail without disturbing the ice on the measuring section. Even so, it was obvious from visual inspection that the ice accumulated on the flange obstructed the exposure of the part of the cylinder next to it, shortening the effective length of the cylinder. When this occurred, which was frequently, the effective length could be established only to about the nearest millimeter. Further difficulty arose at times when the ice deposit bridged across the flange completely from one side to the other. When this happened, the ice on the measuring section was likely to become chipped or broken in disassembling the instrument and removing the ice from the flange.

The most reliable method of obtaining a good sample was that used with the two smallest O cylinders, where the cylinder is longer than the desired sample and the sample is cut on a pair of heated knives set a fixed distance apart. In general, neither of the NACA instruments proved as satisfactory in regard to ice-sample length as the O set, and the former were considered by the observers to be slightly more difficult to manipulate.

Accumulation of ice on cylinders.- No significant difference in the appearance of the ice on the smaller cylinders could be noted from one instrument to another. When the icing on the larger cylinders was moderate or heavy, so that the surface was soon coated with a sheath of ice, there likewise appeared to be no difference in the amount or character of ice accumulated on like-sized cylinders of different instruments. However, when the icing was light, so that the ice began to form as minute feathers that remained separate or grew to join each other like the kernels of corn on the cob, the NACA cylinders appeared to have a greater accumulation than the O cylinder of the same size. These appearances reported by the observers are confirmed by the data of table II, which show the collection efficiency of the NACA and O 3-inch cylinders for 12 such occasions. The collection is almost 50 percent greater on the NACA cylinders for those occasions.

Boundary effect.- No boundary effects of consequence were recognizable with any of the instruments except that the top of the smallest cylinder frequently exhibited a slight bulb of ice. The effect was more pronounced on the NACA instruments, the smallest cylinders of which are larger than their O counterpart. The effect is presumably caused by the end of the cylinder acting as a hemisphere, which has a higher collection efficiency than a cylinder of the same radius. It is most easily overcome by cutting the ice sample from the part of the cylinder below the bulb.

## CRITIQUE OF MULTICYLINDER METHOD

### Random Errors

The numerical results of the multicylinder observations are the liquid water content of the air, the mean effective drop size in the cloud, and the drop-size distribution. The measured quantities enter into these results in complex fashion. Measurement of the weight $W$ of ice caught on each cylinder is combined with measurement of its mean area, the wind speed, and the duration of the exposure to give for each cylinder the product of its collection efficiency and the liquid water content of the air. These products are plotted as ordinate on logarithmic graph paper against the mean diameter $D$ as abscissa, resulting in an array of data points that is compared directly with a theoretically computed curve to find the coordinates of asymptotes from which the liquid water content may be obtained directly and the drop diameter by further computation involving measurement of the wind speed, pressure, and temperature. The disposition of the data points with respect to the asymptotes is determined by the design of the instrument and the conditions of its use.

The errors that enter into determination of $L_w$ are therefore those of the measurement of the weight, length, and mean diameter of the ice sample; the wind speed; duration of exposure; and the errors of plotting the data on a graph and matching the theoretical curve.

The ice-covered cylinders were weighed on a triple-beam balance having a nominal accuracy of ±0.01 gram; but under the conditions of use at Mount Washington, where the cylinders must be weighed quickly and the air even inside the cold laboratory becomes turbulent when the wind is very strong, the probable error has been estimated by the observers as ±0.02 gram for gross weights up to 25 grams, increasing to ±0.05 gram for gross weights over 100 grams. Since net weights of ice vary from 2 to 4 grams on the smaller cylinders, becoming very variable, from 1 to 10 grams or more, on the larger ones, the probable error may be reasonably taken as ±2 percent for the small cylinders and ±4 percent for the large ones.

The length of the ice sample on the O cylinders is fixed for the larger cylinders by the length of the shells and for the smaller ones by the distance between the fixed heated knives used to trim the specimen; the lengths are accurate within ±1 percent. With the A cylinders, the lengths are established by the distance between the end plates, but correction must be made whenever the end plates obstruct the cylinders; this obstruction always occurs to a greater or lesser extent and the resulting error is estimated at ±2 percent. The shorter length of the B cylinders, even though its flanges are much narrower than the end plates of the A set, results likewise in an error of ±2 percent.

The diameters of all three sets of cylinders were measured by identical techniques. The errors arise principally from the irregularity of the ice accumulation and its fragility, making it difficult to obtain precise measurements with a micrometer. The errors are about ±4 percent for the smaller cylinders and ±2 percent for the larger ones.

The probable error in measuring the duration of exposure, amounting to a few seconds out of an average duration of 20 minutes, is of small order and may be neglected. Accurate measurement of the wind speed is difficult because of the gustiness and the error is of the order of ±6 percent, but this does not enter into the comparisons because the same wind speed is assumed for both instruments when exposed together. Errors in measurement of temperature and pressure are unimportant in magnitude and do not enter into the comparison.

When the errors described above were combined according to the root-sum-square rule, it was found that the probable error of the data points on the collection-efficiency graph is ±5 percent in $E_M L_W$ and ±2 to ±4 percent in D, the larger error in D occurring where the curve approaches unit collection efficiency and the error is therefore least objectionable.

Under the conditions prevailing at Mount Washington the data points are usually disposed from a place where the curve makes an angle of 15° or so with the $E_M L_W$-axis through an arc of about 45° toward the other asymptote. The effect of averaging several data points in matching them to the theoretical curve combines with the slope of the curve and the probability that errors cause selection of a wrong theoretical curve, with the result that the final error in determining liquid water content is about 6 percent (wind-speed error omitted), while $D_K$ is determined within 3 percent. These are the probable errors that apply to pairs of observations as they are compared in this study. When a single observation is taken alone, considering also the error of wind speed, temperature, and pressure measurements, the probable errors are 8 percent for liquid water content and 6 percent for drop size.

The drop-size distribution is inferred from relative displacements of the data points that amount to only about 6 percent for a unit change of the distribution modulus. The amount of error accruing through the data points and the curve-matching is difficult to estimate, and the problem is treated in greater detail elsewhere in this paper. It is probably of the order of 0.5 unit of m.

## Systematic Errors

Blow-off.- If the collection efficiency of a particular cylinder is very low, the ice deposits on it may be quite fragile. Parts of it may be blown off by the wind as the cylinder rotates, or it may be eroded by snow driven against it by the wind. This loss is termed "blow-off" and causes a negative error in the weight of ice on the larger cylinders. Clark (reference 8) has determined that blow-off is likely to occur when the cloud drops are smaller than 11 microns in diameter and with somewhat larger drops when the temperature is below -12° C. It is favored by a low rate of ice accumulation. It occurs on any given occasion over a rather narrow range of cylinder sizes between a size so large that icing is too light to measure and one a half to a third as large, where the ice becomes dense enough to resist blow-off.

Blow-off causes a characteristic displacement of the affected data points toward low collection efficiency. It can usually be easily recognized and it does not contribute materially toward the error of the method except under very unusual circumstances when only the smallest cylinders are unaffected. It may be noted that the problem of blow-off is almost never encountered at the airspeeds at which multicylinder observations from aircraft are ordinarily made.

There is no direct evidence of the part that may be played by erosion of the ice deposit by wind-driven snow. Comparison of collection-efficiency graphs of runs with and without snow, when blow-off occurred, fails to show any notable effect of snow. Erosion, attacking fragile ice most severely, would cause symptoms of blow-off at higher collection efficiencies than it would otherwise occur, but examination of the Mount Washington data leads one to believe that erosion, like blow-off, operates through only a narrow range of cylinder sizes on any given occasion and hence may be similarly recognized. Since evidence of blow-off from aircraft observations is lacking, it may be presumed that erosion is unimportant there.

Run-off.- When the temperature is only slightly below freezing and water impinges rapidly on the cylinders, some of it flows around to the leeward side and runs or is blown off before it freezes fast. This loss is generally irregular in its effect, with some tendency to affect the smaller cylinders more than the larger ones. It occurs only at temperatures above $-5^{\circ}$ C and is favored by large drop size and rapid accumulation of water. It affects about 5 percent of all observations made at Mount Washington. The value of an observation affected by run-off is very difficult to estimate. Observations so affected were eliminated from the comparisons reported in this study. Errors of unknown magnitude may remain, however, in a few observations when run-off may not have been recognized or when it may have occurred during a part of the period of exposure.

A very similar error occurs, even without run-off, when the temperature is near the freezing point, for it is then very difficult to weigh and to measure the ice samples before they begin to melt. Several observations have been lost or rejected on this account.

Angle of tilt.- For the O set, which has no end plates or flanges, Howell (reference 3) has shown that tilt relative to the wind causes the liquid-water-content determination to be in error by a factor of the cosine of the angle between the axis of the cylinders and the normal to the wind, while the error factor for the drop size is about 25 percent of the secant of that angle. For angles less than $10^{\circ}$ the error due to tilt is less than 1 percent and even for a $15^{\circ}$ tilt it is less than 4 percent. For the NACA A multicylinder the angle of tilt has more significance, since the cylinders are more or less shielded by the wide end plates when the instrument is tilted relative to the wind.

## Revisions of Fundamental Computations

In the course of the present study, it was noticed that the computed drop size depended upon the choice of collection-efficiency graph used to match the observed data, even when the appropriate correction according to the method of Clark (reference 4) was applied. A further check showed that the same difficulty existed when the corrections given by Cunningham (reference 10) and Downie (reference 11) were applied.

It was found that the quantity termed by Clark as the "exact $K\phi$" was actually an approximate value, derived from an approximate determination of K, and itself required correction. When the necessary correction of K was accomplished by successive approximations, the inconsistency described above nevertheless remained. This led to a review of the derivation of the correction factor.

Three conflicting sets of data were obtained. The first is given by Langmuir and Blodgett on page 33 of reference 12; the second is derived by careful comparison of Clark's collection-efficiency curves with one another; and the third was obtained from figure 1 of Langmuir and Blodgett's paper by constructing therefrom a graph of K plotted against $K\phi$ at a fixed representative value of collection efficiency (50 percent) and interpolating to obtain the ratios of K corresponding to the ratios of $K\phi$ represented by successive pairs of theoretical collection-efficiency graphs. The data are shown in table III.

Figure 5, a revision of Clark's (reference 4) figure 5, was prepared by plotting the points from the bottom line of this table and connecting them with smooth curves. The manner of its use is as follows. Entering with the approximate $K\phi$ at the left, the intersection with the curve labeled with the $K\phi$ value of the collection-efficiency graph used is found and the drop-size correction factor is read directly beneath it. The correction factor to be applied to the approximate $K\phi$ is the square of the drop-size correction factor. Alternatively, the corrected $K\phi$ may be found from the figure by moving from the intersection described previously to the line of unit correction factor along a line parallel to the nearest one of the set marked $K\phi$-correction curve and reading the corresponding value of $K\phi$ on the scale at the left.

Since any given set of collection-efficiency graphs will have minor errors of draftsmanship that affect the correction, weight should be given to values of the K-ratios obtained by direct comparison of the particular graphs in use. The dotted curves on figure 5 are those recommended for use with Clark's collection-efficiency graphs.

In the course of earlier work on the physical origin of the drop-size distribution in clouds, the volume distribution diagram of Houghton and Radford (reference 13) for fog drops was redrawn in the form shown in figure 6 and the volume distribution found by Vonnegut, Cunningham, and Katz (reference 14) in clouds was plotted on the same chart. Upon comparing this chart with Langmuir's tables (reference 7), it was found that his selections of the representative radii for the various subdivisions of the volume were in error. The matter was not pursued further at the time, but as a part of the present study it was decided to investigate the effect this error might have on the collection-efficiency graphs, based on Langmuir's data, that have been used by virtually all workers with the multicylinder method. Accordingly, table IX of Langmuir's paper was revised and expanded to include the broader distributions that had been added later by Clark, and is presented here as table IV. The collection efficiencies corresponding to the revised volume distributions were computed at $K\phi = 1000$ and are shown in table V and figure 7.

Sample computations appeared to show that Langmuir had computed the collection efficiency for distributed drop sizes by adding the weighted collection efficiencies that were appropriate to the several radii at a fixed value of $K\phi$. However, consideration of drop trajectories of different sized drops about a cylinder of fixed size shows that the value of $\phi$, rather than $K\phi$, should be held constant. This procedure was followed in the present instance and it is possible that further differences from previous computations resulted thereby.

It is difficult to make a simple comparison of the revised collection-efficiency graph with the one previously in use because the curves differ in several respects and the actual effect of the revision upon computation of an observation depends on the span of K-values represented by the data. In general, the effect of distributed drop sizes on the shape of the collection-efficiency curve is somewhat less than previously indicated, so that the breadth of size distribution has probably been slightly underestimated in data heretofore computed. When $K$ is greater than 3, the new J curve is most nearly like the old G curve; when $K$ is less than 3, it is most like the old H curve. The determinations of the liquid water content and drop size are affected by less than 10 percent, even for the broadest distribution, when the smallest cylinder of the instrument operates at a $K$ greater than 10; only at smaller values of $K$ does this revision become greater. More will be known about the effects of the revision when a complete set of revised collection-efficiency graphs has been produced and a body of data has been corrected.

## Determination of Drop-Size Distribution

In a cloud of uniform drops the collection efficiency of a cylinder is 0 when $K = 0.125$ and increases regularly toward 1 when $K$ becomes very great. When the drops are not uniform in size, drops larger than the mean effective size still strike the cylinder when $K = 0.125$; while at high values of K, the drops much smaller than the mean effective size still have a collection efficiency significantly less than 1. The shape of the collection-efficiency curve is therefore modified, becoming less sharply curved. This change in the shape of the curve is the basis for determining the breadth of drop-size distribution by the multicylinder method. Collection-efficiency curves corresponding to postulated drop-size distributions have been computed and used for this purpose.

The accuracy of the observational data determines the accuracy with which the drop-size distribution can be determined. When distribution of the drop sizes changes the shape of the collection-efficiency curve but slightly, the accuracy of size-distribution determination is correspondingly poor. This is the situation when K is roughly greater than 3. When K is smaller, the shape of the curve is more greatly affected by drop-size distribution.

The practicability of obtaining significant measurements of drop-size distributions therefore depends upon the design of the multicylinder instrument used and the conditions of its employment. If the cylinders are small and the speed of flight is high, very great accuracy of observation will be required to yield any significant values of drop-size distribution; at low airspeeds and with large cylinders, the determination should be relatively good.

Direct evaluation of the multicylinder method is possible only by comparison with an independent and relatively precise method of determining the drop-size distribution. This was attempted by the Mount Washington Observatory in 1945 by comparison with sooted-slide determinations of cloud droplet size, but was not completed at that time. The data were recently reviewed in relation to the present problem and a correlation coefficient of 0.43 $\left(5\frac{1}{2}\right.$ times the probable error$\left.\right)$ was obtained between the modulus determined by the sooted-slide method and that determined by the multicylinder method. The relative accuracy of the sooted-slide method is difficult to evaluate; many times the presence of a single large drop on the slide greatly affected the computation so that perfect correlation is not to be expected.

Direct comparison of different methods has been attempted more recently by Lewis and Hoecker (reference 15) by comparison of multicylinder data with determinations of the maximum effective drop diameter, but their results were negative. With regard to the latter comparison, it should be pointed out that the multicylinder instrument used, the flight speed employed, and the accuracy of observation (where, for instance, an average ice density is assumed in arriving at the diameter of the ice-covered cylinder) were all unfavorable and, furthermore, it has not been demonstrated that the maximum effective diameter, as determined by the method described by Lewis and Hoecker, bears the presumed relationship to the volume median diameter and the drop-size distribution. The number of drops exceeding the volume median diameter is much smaller than the number below it.

There remains the possibility of evaluating the method indirectly. If the variations of size-distribution breadth as determined by the multicylinder method can be shown to have statistical significance, then the reality of the observations is confirmed. For this purpose the observed breadth of size distribution was expressed in terms of the modulus of distribution m, defined in the section "Results of Measurements."

The possibility of demonstrating the reality of a diurnal period in the drop-size distribution was first investigated, since Conrad (reference 16) had concluded that marked diurnal periods were present in both drop size and drop concentration in clouds at Mount Washington. Correlations of the diurnal variations of drop-size distribution among the three seasons 1945 to 1946, 1946 to 1947, and 1948 to 1949, failed to show significance, but an independent correlation of the diurnal drop-size variations likewise failed to have significantly high values so that the only conclusion reached was that the diurnal period in cloud characteristics lacked regularity from year to year.

It was then decided to investigate the relation of drop-size distribution to other physical variables that have been found to affect cloud characteristics. Accordingly, the variation of drop-size distribution with temperature was tabulated independently for the 1946 to 1947 and 1948 to 1949 seasons; the two series gave a correlation coefficient of 0.85, which is 8.8 times the probable error of the coefficient and hence may be considered significant. Data at temperatures below -21° C were neglected because of the small number of observations. When the same data were divided according to wind direction (which at Mount Washington is roughly tantamount to dividing them by air masses), the correlation coefficient was found to be 0.61, which is 3.8 times the probable error of the coefficient and hence of doubtful significance.

Another opportunity of indirectly evaluating the multicylinder method is offered by determining the internal consistency of two series of observations with identical instruments under similar conditions. Such a series of 12 simultaneous pairs of observations was made at the Mount Washington Observatory during the 1945 and 1946 season by Clark. Correlation of the two series of drop-size distributions from these observations yields a coefficient of 0.88, which is 38 times the probable error. The details of the variations are shown in table VI.

It is therefore apparent that the drop-size distribution determined by the multicylinder method has reality in the Mount Washington series of observations and, therefore, that significant measurements of it can be made when the multicylinder instrument is of suitable design and observational errors are minimized. The same impression is gained from the fact that, although many sets of observed points fall on curves deviating in one sense from the curve for uniform drops, deviation in the other sense is very rare except where it is expected because of loss of fragile rime from the larger cylinders, a deviation that is usually pronounced and easily recognizable. Nevertheless, the probability remains that the determinations of drop-size distribution are often inaccurate, the probable error increasing as the K-value of the largest measurable cylinder decreases and as the accuracy of weight and dimension measurements decreases.

## Density of Ice Accumulation

Some workers, including Lewis (unpublished method) and Downie (reference 11), have deduced the diameter of the ice-covered cylinders from the weight of the ice accumulated by assuming that the density of the accumulation is constant. This practice simplifies the observational procedure but contributes to the probable error of the observed quantities. Under some conditions the contribution is negligible, under others it is considerable.

In order to establish the least cylinder size on which ice may be assumed to have constant density without significantly increasing the probable error, the measured diameter of each cylinder for a number of observations at Mount Washington was compared with the diameter that would have been deduced by assuming a constant ice density equal to the mean density of the ice observed on the smallest O cylinder over a long period. The result is illustrated in figure 8 and shows that the probable error in the determination of diameter incurred by the assumption of constant density is 1 percent or less for cylinders with a diameter greater than about 2 centimeters, but that the probable error exceeds 3 percent for cylinders smaller than about 1 centimeter in diameter. As a result of this finding, the procedure being adopted at the Mount Washington Observatory is that the diameters of all cylinders will be measured directly when this can be done with the micrometer in use (opening to 2.5 cm). Cylinders too large to be accommodated by the jaws of this micrometer will be assumed to have ice with a density of 0.60 gram per cubic centimeter, the long-period mean density on the large cylinders at Mount Washington. A similar procedure, using a value of mean density appropriate to the conditions of exposure, is recommended for others using the multicylinder method.

Alternatively, it has been suggested that perhaps the density of ice may be well enough expressed by an empirical function of temperature, airspeed, liquid water content, or other variables, so as to make the measurement of even the smallest cylinders unnecessary. Empirical functions have been proposed by Langmuir (reference 7) and Loughborough, Greene, and Roush (reference 17), both based on data taken at the Mount Washington Observatory. Further investigation of these functions with series of data other than those on which they were based showed them, however, to be little better as a means of predicting the ice density than an assumption of mean density.

In an attempt to improve on previous empirical formulas, the correlation of ice density with other variables was undertaken and the following correlation coefficients were obtained. The data on which the correlations are based are the 95 0 runs for January 1949, using the smallest cylinder.

The correlation coefficient between air temperature and computed density was 0.49, which is 9.4 times its probable error.

The computed ice density was compared with the density computed according to the formula of reference 17. Though the densities were not computed by the procedure recommended, the differences are probably slight. The correlation coefficient was 0.82, 36 times its probable error. Thus slightly over two-thirds of the ice-density variation can be ascribed to collection-efficiency variation. The constants given in reference 17 are in error, however, since the mean Observatory density was equal to 0.68 gram per cubic centimeter, whereas it equaled 0.82 gram per cubic centimeter according to reference 17.

A correlation of temperature with collection efficiency gave a correlation coefficient of 0.52, 10 times its probable error, for the same data.

The study was not carried further for lack of time and because it seemed likely that no relationship would be found simple enough to justify using it instead of the recommended procedure for determining cylinder size.

## RECOMMENDATIONS

Design of the multicylinder instrument.- Details of recommended changes in the multicylinder instrument are illustrated in figure 9. In addition to the changes shown, the design should provide a motor for rotating the cylinders that has adequate reserve power to assure reliable operation under extreme conditions and the motor and reduction gears should be lubricated with silicone.

The flanges used to set off the measuring sections should be made part of the fairing segment rather than part of the measuring section.

They should be flared slightly away from the measuring section and the side of the flange toward the measuring section should be kept painted with a light coat of grease to prevent adhesion of ice.

The measuring sections should be made as thin and light as possible and the outer surface should be smooth. In order to avoid doubt as to the state of the surface, it should be maintained in a hydrophobic state. The length of the measuring sections should not be made less than 7.5 centimeters unless tests of the newly recommended flange design shows the effective cylinder length to be satisfactorily determinate.

The instrument should have a minimum of six cylinders embracing as wide a range of diameters as the conditions of design and exposure can permit. The smallest cylinder should not be larger than 2 millimeters in diameter and the largest not smaller than 10 centimeters. A diameter of 15 centimeters for the largest cylinder is strongly recommended for use in flight.

With the smallest cylinders, with diameters less than 6 millimeters, the use of flanges is not recommended. Instead, the cylinders should be overlength and the ice samples should be cut to length with fixed heated knives.

Computational procedures.- Revision of the collection-efficiency computations, already completed for $K\phi = 1000$, should be carried out for the other values of $K\phi$ in routine use. Past observations where broad drop-size distributions are indicated should be reworked or their results otherwise corrected.

The diameters of the smaller cylinders, up to 2 centimeters in diameter, should be measured directly rather than being deduced on the basis of assumed density of the ice.

## CONCLUSIONS

From a comparison of three multicylinder icing meters and a critique of the multicylinder method, the following conclusions may be drawn:

1. There is no significant difference among the three instruments tested in the determination of liquid water content of the air. The NACA instruments indicate drop sizes 0.5 to 1.5 microns larger than the Observatory's, believed to be due to spurious catch of ice on the larger NACA cylinders because of their roughness. Determinations of the drop-size distribution agree within the probable error, but the latter is so large that the comparison is not definitive.

2. Flanges and end plates bounding the measuring sections of the NACA instruments were found to cause uncertainty as to the effective length of the measuring section, especially when the wind was not absolutely perpendicular to the cylinder axis. Cylinders without flanges performed about as well as those with flanges and better than those with end plates. The Observatory instrument (without flanges or end plates) was considered by the observers to be slightly easier to manipulate. Trimming of a long ice sample with fixed heated knives was found the most satisfactory way of obtaining a sample of determinate length.

3. The probable error due to random errors was found to be ±8 percent for liquid water content, ±6 percent for drop size, and about ±0.5 unit of modulus for drop-size distribution. The probable errors when comparison is made between two instruments exposed together and the same values of wind speed, air temperature, and air pressure are used for both is ±6 percent for liquid water content and ±3 percent for drop size. These probable errors are based on the techniques and equipment in use at the Mount Washington Observatory.

4. Systematic error due to blow-off or erosion of fragile rime affects only a narrow range of cylinder sizes on a given occasion. It is easily recognizable and affects the accuracy of only a very small proportion of observations. Loss of catch by run-off of liquid water before it freezes occurs only at temperatures above $-5^{\circ}$ C and is favored by large drop size and a high rate of accumulation. It affects about 5 percent of observations made at Mount Washington and causes indeterminate errors. Correction for the effect of tilting the instrument relative to the wind can be accurately made.

5. Revision of collection-efficiency computations for cylinders in a cloud with distributed drop sizes was found necessary because of an error in the previous computations. The determinations of liquid water content and drop size are affected by less than 10 percent under most conditions, even for the broadest drop-size distributions. The graph for correction of drop size due to approximate determination of $K\phi$ was also revised.

6. It was established that the drop-size distributions as determined at Mount Washington by the multicylinder method have reality, even though individual determinations are often inaccurate because of the large probable error of the method.

7. It was found that the cylinder diameter arrived at by assuming the ice accumulated on it to have a density equal to the long-term average density has a probable error of ±1 percent or less for cylinders larger than 2 centimeters in diameter and an error of ±3 percent or more for cylinders smaller than 1 centimeter in diameter.

Mount Washington Observatory,
Gorham, N. H., Nov. 9, 1949

## REFERENCES

1. Schaefer, Vincent J.: Demountable Rotating Multicylinders for Measuring Liquid Water Content and Particle Size of Clouds in Above and Below Freezing Temperatures. Tech. Rep. No. 5539, Air Materiel Command, Army Air Forces, Jan. 24, 1947, pp. 59-67.

2. Jones, Alun R., and Lewis, William: A Review of Instruments Developed for the Measurement of the Meteorological Factors Conducive to Aircraft Icing. NACA RM A9C09, 1949.

3. Howell, Wallace E.: Contribution to the Evaluation of the Multicylinder Icing Meter. Tech. Rep. No. 5676, Air Materiel Command, U. S. Air Force, June 22, 1948, pp. 269-296.

4. Clark, V. F.: The Multicylinder Method. Mt. Wash. Observatory Monthly Res. Bull., vol. II, no. 6, June 1946.

5. Howell, Wallace E.: Instructions for Making Icing Observations by the Multicylinder Method. Mt. Wash. Observatory Monthly Res. Bull., vol. II, no. 12, Dec. 1946.

6. Howell, Wallace E.: The Growth of Cloud Drops in Uniformly Cooled Air. Jour. Meteorol., vol. 6, no. 2, April 1949, pp. 134-149.

7. Langmuir, Irving: Super-Cooled Water Droplets in Rising Currents of Cold Saturated Air. Contract W-33-016-sc-65, U. S. Army and General Electric Co., 1944.

8. Clark, Victor F.: Conditions for Run-Off and Blow-Off of Catch on Multicylinder Icing Meter. Tech. Rep. No. 5676, Air Materiel Command, U. S. Air Force, June 22, 1948, pp. 190-218.

9. Howell, Wallace E.: Effect of the Vertical Gradients of Wind Speed and Water Content on Measurements with the Multicylinder Icing Meter. Tech. Rep. No. 5676, Air Materiel Command, U. S. Air Force, June 22, 1948, pp. 297-303.

10. Cunningham, R. M.: Instructions for Calculating the Liquid Water Content, Effective Drop Size and Effective Drop Distributions from Rotating Cylinder Data Obtained from Average Speed Aircraft. Informal rep., De-Icing Res. Lab., Dept. of Meteorol., M.I.T., 1945.

11. Downie, C. S.: The Rotating Cylinder Method for Obtaining Icing Intensity Data. Eng. Rep. No. AIRL 48-3-2P, Aero. Ice Res. Lab. (Minneapolis), Sept. 1947.

12. Langmuir, Irving, and Blodgett, Katherine B.: A Mathematical Investigation of Water Droplet Trajectories. Tech. Rep. No. 5418, Air Materiel Command, Army Air Forces, Feb. 19, 1946.

13. Houghton, H. G., and Radford, W. H.: On the Measurement of Drop Size and Liquid Water Content in Fogs and Clouds. Papers in Phys. Oceanography and Meteorol., M.I.T. and Woods Hole Oceanographic Inst., vol. VI, no. 4, Nov. 1938.

14. Vonnegut, B., Cunningham, R. M., and Katz, R. E.: Instruments for Measuring Atmospheric Factors Related to Ice Formation on Airplanes. De-Icing Res. Lab., Dept. Meteorol., M.I.T., April 1946.

15. Lewis, William, and Hoecker, Walter H., Jr.: Observations of Icing Conditions Encountered in Flight During 1948. NACA TN 1904, 1949.

16. Conrad, Victor: Preliminary Report on Statistical Investigation of the Mount Washington Series of Icing Observations. Tech. Rep. No. 5676, Air Materiel Command, U. S. Air Force, June 22, 1948, pp. 114-133.

17. Loughborough, Dwight L., Greene, Howard E., and Roush, Paul A.: A Study of Wing De-Icer Performance on Mount Washington. Preprint No. 122, Inst. Aero. Sci., Jan. 1948.

TABLE I

COMPARATIVE OBSERVATIONS MADE WITH OBSERVATORY AND NACA MULTICYLINDERS

| Date (1949) | Time (e.s.t.) | Temperature (°C) | Pressure (mb) | Wind direction | Wind speed (m/sec) | Current weather code | $L_w$ (grams/in.$^3$) | | $d_d$ (microns) | | $s_d$ | | Reliability | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | OA | A | OA | A | OA | A | OA | A | |
| 2/22 | 1000 | -11 | 807.7 | WSW | 17.4 | 49 | 0.13 | 0.12 | 8.6 | 10.1 | A | A | 61 | 52 | Run probably all right |
| 2/22 | 2200 | -5 | 802.5 | WSW | 17.0 | 77 | .42 | .43 | 12.2 | 13.4 | C | C | 83 | 100 | Angle of inclination too low |
| 2/25 | 1300 | -7 | 796.4 | SSW | 25.5 | 78 | .28 | .26 | 14.0 | 16.1 | B | A | 100 | 80 | Some shielding by baffles |
| 2/25 | 1600 | -7 | 796.3 | SSW | 17.0 | 77 | .22 | .20 | 14.7 | 17.0 | A | A | 67 | 67 | Some shielding by baffles |
| 2/25 | 1900 | -8 | 796.2 | SW | 10.7 | 78 | .26 | .24 | 14.3 | 16.5 | C | C | 73 | 89 | Data might fit D curve |
| 2/25 | 2200 | -6 | 795.9 | W | 5.4 | 78 | .33 | .37 | 17.4 | 16.7 | A | C | 61 | 77 | |
| 2/26 | 0700 | -11 | 794.4 | NW | 14.7 | 49 | .60 | .64 | 16.9 | 18.5 | B | B | 73 | 80 | |
| 3/1 | 1000 | -13 | 779.8 | ENE | 17.4 | 78 | .10 | .08 | 8.4 | 12.1 | C | A | 82 | 77 | Possible slight shielding |
| 3/1 | 1600 | -14 | 783.8 | NW | 14.7 | 78 | .20 | .18 | 9.6 | 12.4 | D | C | 61 | 67 | |
| 3/1 | 2200 | -17 | 786.0 | NW | 17.9 | 78 | .20 | .16 | 8.8 | 11.7 | A | A | 82 | 52 | Possible shielding; run believed all right |
| 3/2 | 0100 | -17 | 787.0 | NW | 18.8 | 78 | .34 | .31 | 8.4 | 11.5 | D | A | 82 | 67 | Gusty wind |
| 3/22 | 1900 | -1 | 807.0 | SW | 25.9 | 49 | .49 | .49 | 9.9 | 10.7 | A | A | 61 | 77 | |
| 3/23 | 1900 | -1 | 800.6 | W | 23.7 | 49 | .54 | .49 | 6.9 | 9.1 | H | H | 61 | 67 | Much run-off; run rejected |
| 4/19 | 0700 | -9 | 801.8 | SSE | 32.6 | 77 | .33 | .35 | 20.1 | 21.2 | A | A | 100 | 80 | Gusty wind; weight of cylinder 1 light |
| 4/19 | 1000 | -8 | 801.6 | ESE | 25.5 | 77 | .13 | .15 | 14.6 | 15.4 | B | A | 73 | 67 | |
| 4/19 | 1300 | -2 | 801.4 | S | 14.7 | 49 | .50 | .57 | 20.5 | 23.3 | C | D | 91 | 89 | Ice on cylinder 5 melted before weighing |
| 4/19 | 1600 | -1 | 800.6 | WSW | 12.1 | 41 | .57 | .52 | 18.7 | 18.8 | F | C | 83 | 100 | Possible run-off; weight of cylinder 1 high |
| 4/19 | 1900 | -6 | 800.8 | WNW | 13.8 | 49 | .43 | .43 | 15.5 | 16.6 | A | A | 73 | 89 | |
| 4/20 | 0700 | -8 | 799.5 | WNW | 24.1 | 49 | .66 | .61 | 15.7 | 17.4 | B | A | 100 | 80 | |
| 4/20 | 1000 | -7 | 800.0 | WNW | 24.1 | 77 | .46 | .46 | 17.4 | 18.8 | A | A | 100 | 100 | |
| 4/21 | 0700 | -3 | 801.7 | W | 30.4 | 49 | .41 | .44 | 6.9 | 7.0 | A | C | 82 | 77 | |
| 4/21 | 1000 | -2 | 803.0 | NW | 25.9 | 49 | .79 | .90 | 6.4 | 5.0 | D | G | 67 | 60 | Freezing rain during run; run rejected |
| 5/26 | 1000 | -4 | 799.3 | WSW | 13.4 | 77 | .21 | .20 | 6.0 | 7.7 | D | A | 71 | 63 | |
| 5/26 | 1300 | -3 | 799.3 | WSW | 18.3 | 77 | .25 | .23 | 9.0 | 10.0 | A | A | 61 | 77 | |
| 5/26 | 2200 | -2 | 800.8 | WSW | 13.4 | 77 | .54 | .47 | 14.1 | 15.7 | A | A | 73 | 77 | Tilt too great; embedded snow, all cylinders |
| 5/27 | 0100 | -2 | 800.4 | WSW | 15.6 | 77 | .64 | .65 | 13.5 | 13.8 | A | C | 91 | 77 | Tilt too great; less than last observation |
| 5/28 | 0400 | -5 | 797.2 | NNW | 15.6 | 49 | .24 | .22 | 9.8 | 12.5 | C | C | 82 | 67 | Data might fit A curve |
| 5/28 | 0700 | -4 | 797.5 | NW | 17.9 | 49 | .53 | .62 | 12.0 | 11.9 | C | B | 73 | 89 | Density of cylinder 1 high |
| 5/28 | 2200 | -3 | 799.0 | WNW | 17.0 | 77 | .44 | .45 | 12.3 | 13.4 | A | A | 73 | 89 | |
| 5/29 | 0100 | -4 | 799.3 | WNW | 12.1 | 49 | .40 | .38 | 11.9 | 13.8 | A | B | 82 | 67 | Corona, glory, fog bow |
| 5/29 | 2200 | -3 | 800.9 | NW | 17.2 | 49 | .40 | .41 | 14.2 | 16.3 | A | A | 91 | 100 | Inclination too great |
| 5/30 | 0100 | -3 | 800.4 | WNW | 17.0 | 49 | .64 | .63 | 17.3 | 20.2 | A | A | 100 | 80 | Inclination too low |
| 5/30 | 1600 | -2 | 799.8 | WNW | 25.5 | 77 | .37 | .37 | 12.8 | 15.5 | A | A | 83 | 60 | Inclination too great |
| 5/30 | 2200 | -3 | 801.5 | WNW | 19.2 | 77 | .61 | .58 | 15.9 | 19.6 | C | A | 83 | 100 | Tilt too great; density of cylinder 1 high |
| Mean | | -6.2 | 798.0 | | 18.2 | | .385 | .382 | 13.2 | 14.9 | [a]0.367 | [a]0.266 | 80 | 79 | |

[a]Average $s_d$ given in units of m.

TABLE I

COMPARATIVE OBSERVATIONS MADE WITH OBSERVATORY AND NACA MULTICYLINDERS - Concluded

| Date (1949) | Time (e.s.t.) | Temperature (°C) | Pressure (mb) | Wind direction | Wind speed (m/sec) | Current weather code | $L_w$ (grams/in.3) | | $d_d$ (microns) | | $s_d$ | | Reliability | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | OB | B | OB | B | OB | B | OB | B | |
| 2/25 | 1100 | -7 | 799.9 | SSW | 23.2 | 77 | 0.17 | 0.23 | 10.5 | 7.6 | A | E | 73 | 77 | Cylinder 1 bent |
| 3/23 | 0100 | 0 | 804.4 | SW | 28.1 | 66 | .15 | .10 | 7.8 | 17.9 | J | J | 73 | 67 | Much run-off; run rejected |
| 3/23 | 2200 | -6 | 801.6 | WNW | 21.0 | 49 | .65 | .78 | 12.1 | 12.2 | A | B | 83 | 67 | $s_d$ may be wrong |
| 3/24 | 0100 | -8 | 802.4 | WNW | 19.6 | 49 | .76 | .91 | 14.8 | 14.8 | B | C | 100 | 89 | |
| 3/28 | 1000 | -3 | 789.8 | WNW | 29.5 | 49 | .32 | .34 | 7.8 | 8.3 | B | B | 61 | 67 | Varying sky brightness |
| 3/28 | 1300 | -4 | 790.8 | WNW | 27.3 | 49 | .48 | .48 | 10.5 | 10.6 | A | C | 100 | 60 | |
| 3/28 | 1600 | -6 | 792.8 | NW | 21.0 | 49 | .36 | .54 | 7.7 | 4.7 | C | G | 82 | 77 | Values doubtful; run rejected |
| 3/28 | 1900 | -7 | 793.6 | WNW | 20.5 | 49 | .56 | .58 | 9.8 | 10.3 | C | C | 73 | 89 | Gusty wind |
| 3/28 | 2200 | -8 | 794.5 | NW | 28.1 | 49 | .45 | .39 | 8.8 | 10.3 | C | B | 73 | 77 | Gusty; cylinder 1 lost; density from 2 |
| 3/29 | 0100 | -9 | 794.4 | NW | 32.6 | 49 | .45 | .40 | 11.5 | 12.5 | A | B | 83 | 60 | Very gusty; density on cylinder 1 too high |
| 3/29 | 1900 | -7 | 801.7 | WNW | 18.3 | 78 | .42 | .42 | 8.5 | 10.5 | A | A | 47 | 52 | One data point way off; run rejected |
| 3/29 | 2200 | -6 | 801.0 | WNW | 21.4 | 78 | .60 | .57 | 15.4 | 16.9 | B | A | 83 | 80 | |
| 3/30 | 0100 | -7 | 799.7 | NW | 17.0 | 78 | .43 | .47 | 19.3 | 19.5 | A | C | 100 | 100 | |
| 3/30 | 0400 | -8 | 799.1 | NW | 16.5 | 78 | .42 | .44 | 21.9 | 24.1 | B | B | 100 | 67 | Cylinder 1 lost; density from 2 |
| 3/30 | 1900 | -11 | 799.0 | NW | 18.3 | 49 | .10 | .18 | 7.2 | 5.9 | A | A | 71 | 63 | Sky visible; $s_d$ indeterminate; run rejected |
| 3/30 | 2200 | -12 | 799.0 | NW | 19.6 | 48 | .10 | .11 | 6.6 | 7.1 | A | A | 71 | 63 | Second order corona, glory; stars sometimes seen |
| 4/3 | 1900 | -4 | 801.1 | SW | 9.8 | 78 | .41 | .31 | 8.9 | 10.8 | D | B | 71 | 52 | |
| 4/3 | 2200 | -4 | 801.2 | WSW | 9.8 | 77 | .56 | .32 | 8.7 | 12.5 | C | A | 61 | 77 | $s_d$ of OB run might be B, C, or E; run rejected |
| 4/4 | 2200 | -7 | 800.9 | NW | 17.0 | 77 | ----- | .18 | ---- | 7.5 | - | E | --- | 77 | Very gusty; B set turned on mount; run rejected |
| 4/6 | 1600 | -7 | 777.3 | ESE | 27.3 | 77 | .14 | .09 | 15.4 | 16.6 | A | A | 83 | 67 | |
| 4/6 | 2200 | -8 | 774.7 | WNW | 28.1 | 77 | .28 | .31 | 26.4 | 26.8 | D | E | 100 | 100 | Very smooth ice on all cylinders |
| 4/7 | 0700 | -8 | 780.1 | WSW | 33.1 | 77 | .58 | .56 | 16.9 | 18.8 | A | A | 100 | 100 | Wind WNW after run |
| 4/7 | 1300 | -7 | 790.7 | WNW | 30.8 | 49 | .85 | .70 | 15.3 | 17.6 | A | A | 91 | 80 | Newly shortened mount used |
| 4/7 | 1600 | -6 | 786.0 | WNW | 29.5 | 49 | .68 | .63 | 11.7 | 12.3 | A | A | 83 | 67 | |
| 4/7 | 1900 | -6 | 786.9 | WNW | 28.1 | 77 | .62 | .56 | 10.5 | 11.3 | A | A | 73 | 67 | |
| 4/7 | 2200 | -6 | 788.6 | WNW | 18.3 | 49 | .78 | .78 | 11.3 | 11.6 | A | B | 91 | 89 | |
| 4/8 | 1600 | -7 | 785.4 | WNW | 19.2 | 49 | .38 | .36 | 12.4 | 10.7 | A | A | 82 | 71 | B set shielded by A set; run rejected |
| 4/8 | 1900 | -8 | 785.6 | WNW | 21.0 | 49 | .49 | .50 | 11.4 | 11.4 | B | C | 82 | 77 | $s_d$ doubtful |
| 4/9 | 1000 | -10 | 786.0 | WNW | 25.0 | 49 | .35 | .27 | 21.5 | 29.8 | C | A | 83 | 80 | Instrument turned on mount; run rejected |
| 4/9 | 1300 | -9 | 787.3 | NW | 21.9 | 49 | .52 | .32 | 9.4 | 21.0 | J | C | 83 | 80 | $s_d$ of B run might be A to E; run rejected |
| 4/9 | 1600 | -10 | 784.7 | NW | 21.4 | 77 | .37 | .46 | 22.3 | 20.4 | C | C | 100 | 80 | Gusty wind |
| 4/9 | 1900 | -11 | 791.3 | NW | 21.0 | 49 | .59 | .56 | 17.9 | 18.5 | A | B | 100 | 80 | |
| 4/16 | 0700 | -4 | 787.4 | W | 17.0 | 49 | .41 | .51 | 9.3 | 9.0 | A | C | 61 | 77 | Cylinders not rotated; run rejected |
| 4/16 | 1600 | -5 | 786.0 | W | 8.0 | 77 | .64 | .58 | 16.7 | 17.2 | A | A | 82 | 77 | |
| 4/16 | 1900 | -7 | 786.2 | W | 13.8 | 49 | .67 | .61 | 16.2 | 17.2 | A | A | 91 | 67 | |
| 4/17 | 0700 | -11 | 789.0 | NW | 13.0 | 49 | .56 | .46 | 30.5 | 30.2 | A | A | 100 | 80 | |
| 4/17 | 1000 | -10 | 790.1 | NW | 5.4 | 49 | .40 | .40 | 27.2 | 25.5 | A | A | 82 | 52 | Fog thin; snow embedded in ice; run rejected |
| 4/17 | 1300 | -8 | 792.3 | NNW | 3.6 | 77 | .38 | .37 | 19.1 | 24.2 | B | A | 61 | 77 | Sun visible, out of clouds part of time |
| 4/17 | 1600 | -8 | 794.5 | NNW | 13.0 | 77 | .20 | .35 | 15.7 | 11.4 | B | F | 82 | 52 | Sun sometimes seen; $s_d$ doubtful; run rejected |
| 4/17 | 1900 | -9 | 791.4 | NNW | 6.3 | 49 | .29 | .73 | 22.5 | 9.1 | D | J | 73 | 77 | $s_d$ doubtful; run rejected |
| 4/17 | 2200 | -10 | 799.5 | ENE | 8.0 | 49 | .21 | .24 | 16.0 | 17.2 | B | B | 61 | 67 | Too little tilt; corona, near cloud tops |
| Mean | | -7.0 | 792.9 | | 20.1 | | .470 | .475 | 15.3 | 14.4 | [a]0.425 | [a]0.317 | 76 | 83 | |

[a]Average $s_d$ given in units of m.

TABLE II

COMPARISON OF COLLECTION EFFICIENCY OF 3-INCH O CYLINDER

WITH 3-INCH A CYLINDER FOR 12 OBSERVATIONS

| Data (1949) | Time (e.s.t.) | $E_M$ | |
|---|---|---|---|
| | | OA | A |
| 2/22 | 2200 | 0.033 | 0.048 |
| 2/25 | 1300 | .079 | .103 |
| 2/25 | 1600 | .024 | .037 |
| 2/26 | 0700 | .043 | .081 |
| 4/19 | 0700 | .222 | .252 |
| 4/19 | 1600 | .050 | .080 |
| 4/20 | 0700 | .101 | .133 |
| 4/20 | 1000 | .130 | .153 |
| 5/29 | 2200 | .031 | .055 |
| 5/30 | 0100 | .063 | .113 |
| 5/30 | 1600 | .042 | .077 |
| 5/30 | 2200 | .062 | .123 |
| Mean | | .073 | .104 |

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TABLE III

RATIOS OF K BETWEEN VALUES OF KΦ FOR WHICH

THERE ARE COLLECTION-EFFICIENCY GRAPHS

| Source of data | Ratios of K for values of KΦ of - | | | | |
|---|---|---|---|---|---|
| | 0-20 | 20-200 | 200-1000 | 1000-3000 | 3000-10000 |
| Langmuir and Blodgett (reference 12, p. 33) | 1.21 | 1.20 | 1.16 | 1.16 | 1.17 |
| Clark's graph (reference 4) | 1.18 | 1.17 | 1.16 | 1.16 | 1.15 |
| Langmuir and Blodgett (reference 12, fig. 1) | 1.17 | 1.18 | 1.21 | 1.18 | 1.20 |

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TABLE IV

RATIOS OF DROP RADIUS TO VOLUME MEDIAN RADIUS CORRESPONDING TO

PERCENTILE DIVISIONS OF TOTAL LIQUID VOLUME IN CLOUDS

| Percentile divisions of total liquid volume in clouds | Ratios of drop radius to volume median radius | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $r/\bar{r}$ (1) | $r/\bar{r}$ (2) | $(r/\bar{r})^{1.5}$ | $(r/\bar{r})^{2.0}$ | $(r/\bar{r})^{2.5}$ | $(r/\bar{r})^{3.0}$ | $(r/\bar{r})^{3.5}$ | $(r/\bar{r})^{4.0}$ | $(r/\bar{r})^{5.0}$ |
| 0-5 | 0.56 | 0.53 | 0.386 | 0.281 | 0.205 | 0.149 | 0.109 | 0.079 | 0.042 |
| 5-15 | .72 | .69 | .573 | .476 | .395 | .329 | .273 | .227 | .156 |
| 15-35 | .84 | .91 | .868 | .828 | .790 | .753 | .718 | .685 | .623 |
| 35-65 | 1.00 | 1.00 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 65-85 | 1.17 | 1.09 | 1.138 | 1.188 | 1.240 | 1.295 | 1.352 | 1.411 | 1.540 |
| 85-95 | 1.32 | 1.31 | 1.500 | 1.716 | 1.964 | 2.250 | 2.575 | 2.95 | 3.86 |
| 95-100 | 1.49 | 1.47 | 1.782 | 2.160 | 2.62 | 3.18 | 3.85 | 4.67 | 6.88 |

[1]Data obtained by Langmuir (reference 7).
[2]Data obtained by Clark (reference 4).

TABLE V

CORRECTED VALUES OF COLLECTION EFFICIENCY ON A CYLINDER

AT $K\phi = 1000$ FOR VARIOUS DROP-SIZE DISTRIBUTIONS

| 1/K | Corrected values of collection efficiency for values of $s_d$ of - | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | J |
| 10 | 0 | 0 | 0.001 | 0.004 | 0.008 | 0.013 | 0.020 | 0.028 | 0.048 |
| 5 | .006 | .010 | .016 | .022 | .031 | .041 | .053 | .064 | .087 |
| 2 | .080 | .087 | .096 | .108 | .120 | .135 | .147 | .158 | .179 |
| 1 | .226 | .228 | .229 | .239 | .249 | .260 | .269 | .275 | .291 |
| .5 | .415 | .408 | .407 | .402 | .403 | .408 | .412 | .416 | .421 |
| .2 | .658 | .644 | .628 | .618 | .609 | .606 | .599 | .594 | .589 |
| .1 | .795 | .782 | .768 | .754 | .740 | .727 | .718 | .704 | .692 |
| .05 | .885 | .872 | .862 | .849 | .834 | .818 | .803 | .791 | .761 |
| .02 | .950 | .945 | .939 | .928 | .917 | .903 | .886 | .868 | .847 |
| .01 | .974 | .971 | .969 | .962 | .951 | .941 | .925 | .913 | .886 |

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## TABLE VI

## DEPENDENCE OF MODULUS OF DROP-SIZE DISTRIBUTION ON SEVERAL VARIABLES

### (a) Diurnal variations.

| Season | Values of m at hr of - | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0100 | 0400 | 0700 | 1000 | 1300 | 1600 | 1900 | 2200 |
| 1945-46 | 0.51 | 0.54 | 0.49 | 0.43 | 0.43 | 0.51 | 0.46 | 0.51 |
| 1946-47 | .34 | .24 | .32 | .39 | .42 | .40 | .37 | .46 |
| [a]1948-49 | .42 | .33 | .32 | .25 | .37 | .31 | .33 | .42 |

Correlations: r(45/46)(46/47) = -0.48 r/f = 2.6
r(45/46)(48/49) = 0.25 r/f = 1.1
r(46/47)(48/49) = 0.32 r/f = 1.0

### (b) Variations with temperature.

| Season | Values of m at temperatures ranges (deg below 0° C) of - | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0-3 | 4-6 | 7-9 | 10-12 | 13-15 | 16-18 | 19-21 |
| 1946-47 | 0.56 | 0.50 | 0.34 | 0.36 | 0.35 | 0.29 | 0.23 |
| [a]1948-49 | .41 | .31 | .34 | .28 | .26 | .17 | .18 |

Correlation: r(46/47)(48/49) = 0.85 r/f = 8.8

### (c) Variation with wind direction.

| Season | Values of m at wind directions of - | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | W-WNW | NW-NNW | N-NNE | NE-ENE | E-ESE | SE-SSE | S-SSW | SW-WSW |
| 1946-47 | 0.32 | 0.30 | 0.38 | 0.33 | 0.75 | 0.60 | 0.97 | 0.41 |
| | 0.32 | | | | 0.58 | | | |
| [a]1948-49 | 0.24 | 0.29 | 0.0 | 0.38 | 0.60 | 0.50 | 0.43 | 0.34 |
| | 0.26 | | | | 0.38 | | | |

Correlation: r(46/47)(48/49) = 0.61 r/f = 3.8

[a]Dec. 1948 through March 1949.

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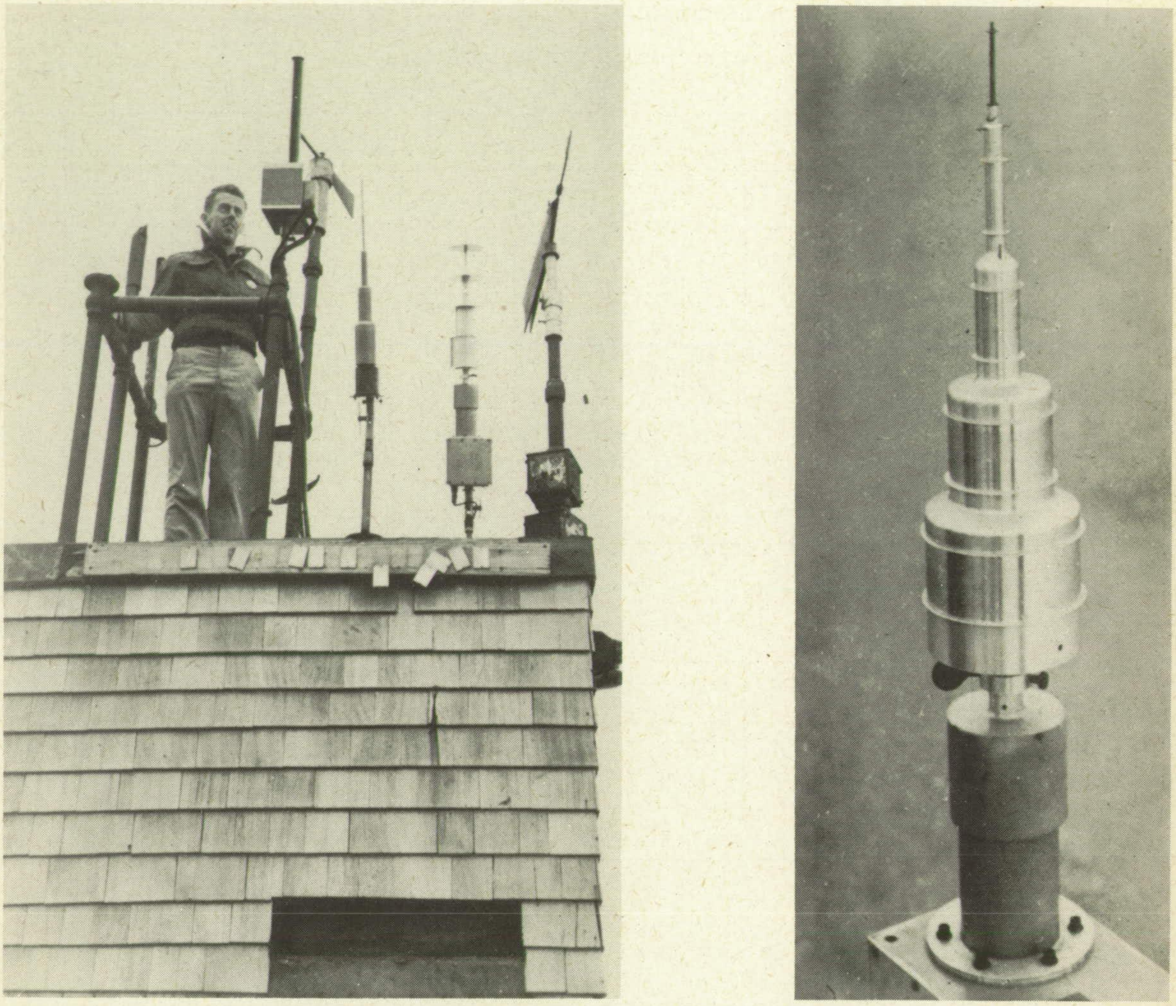

(a) O and A sets on southwest side of Observatory tower.

(b) B set after shaft was shortened.

Figure 1.- Multicylinder cloud meters used in comparative study at Mount Washington Observatory.

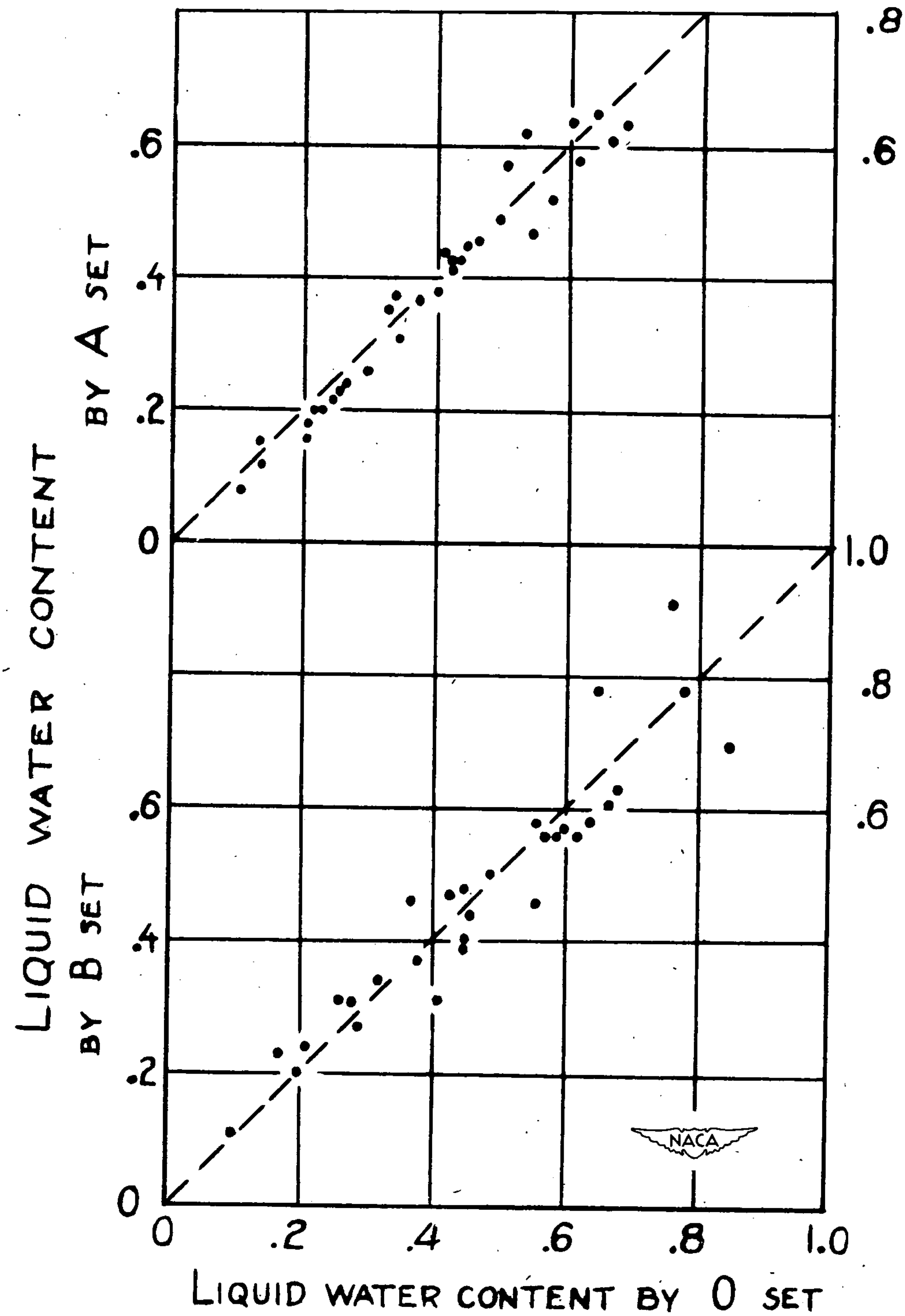


Figure 2.- Liquid water content determined by A and B sets correlated with simultaneous determinations by O set.

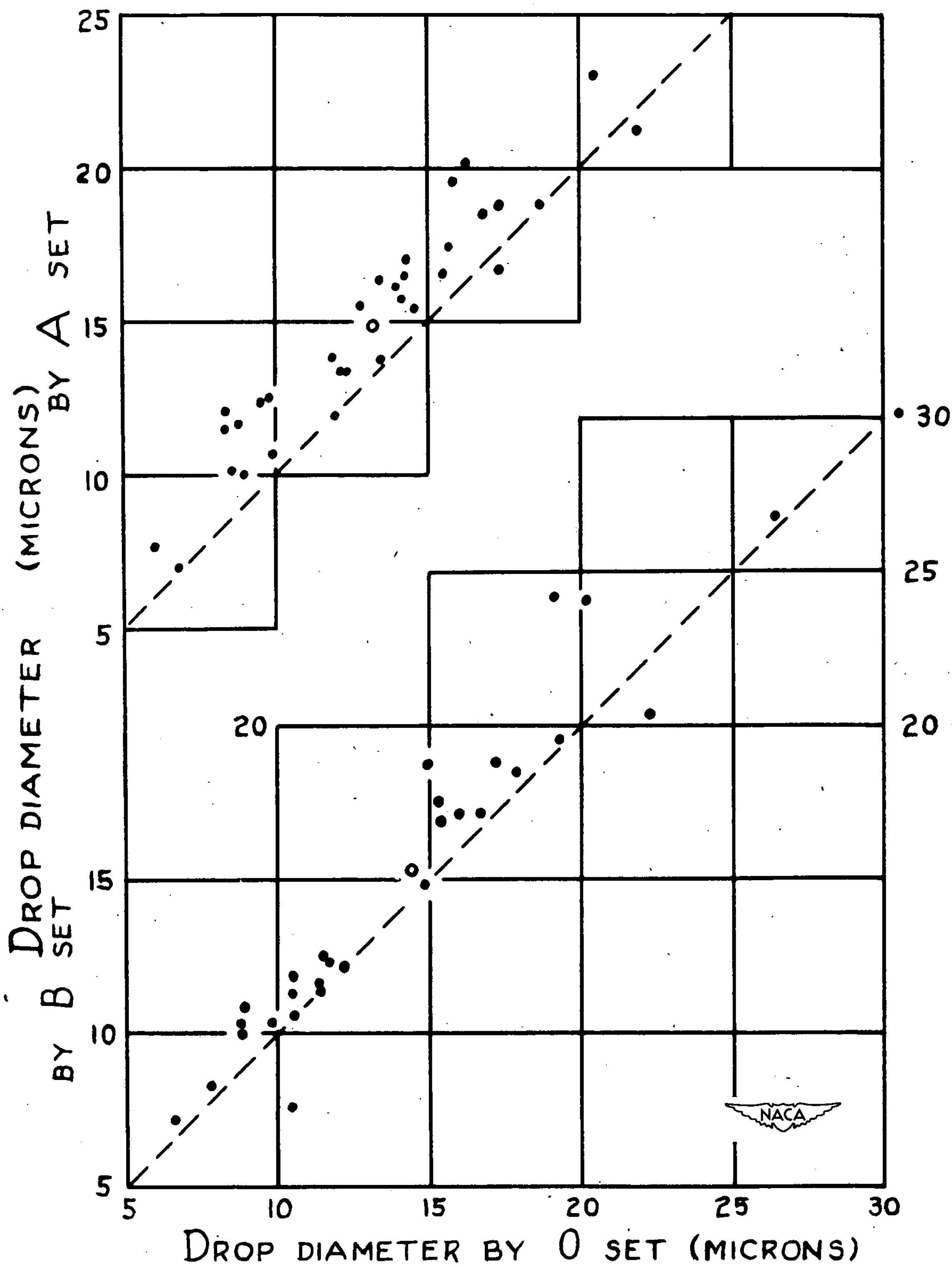


Figure 3.- Drop diameters determined by A and B sets correlated with simultaneous determinations by O set. Open circles are group averages.

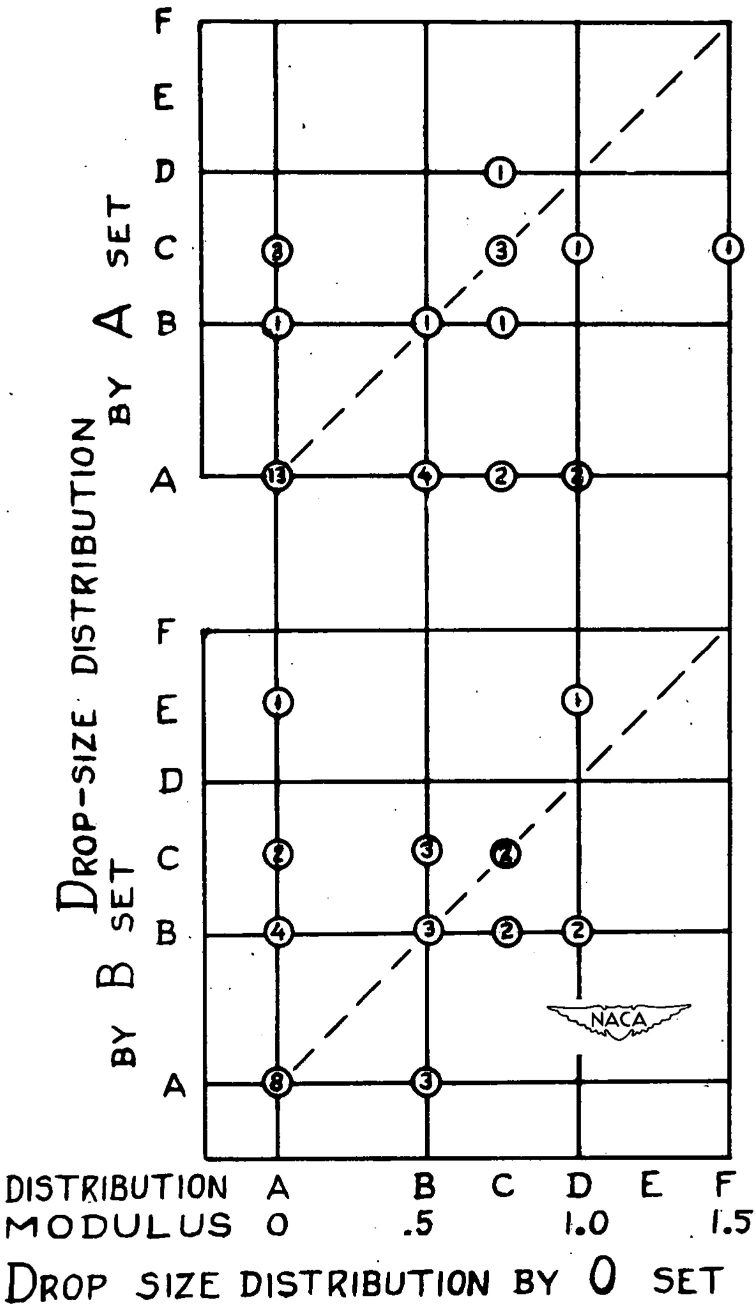


Figure 4.- Drop-size distributions determined by A and B sets correlated with simultaneous determinations by O set.

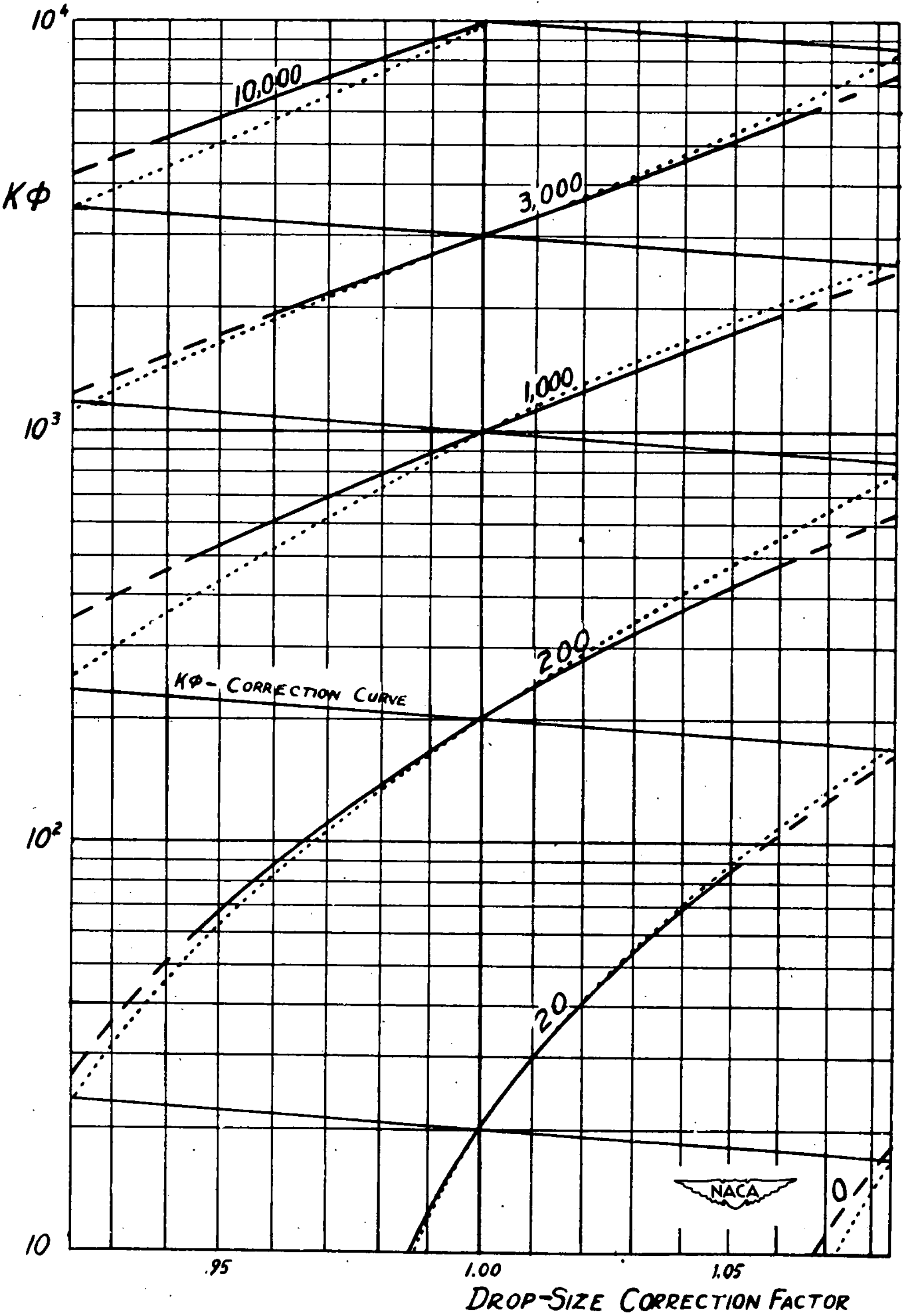


Figure 5.- Drop-size correction factor and K$\phi$-correction chart for use with multicylinder method when approximate K$\phi$ is known. Dotted lines are recommended for use with Clark's collection-efficiency graphs; solid lines are for an ideal set of graphs.

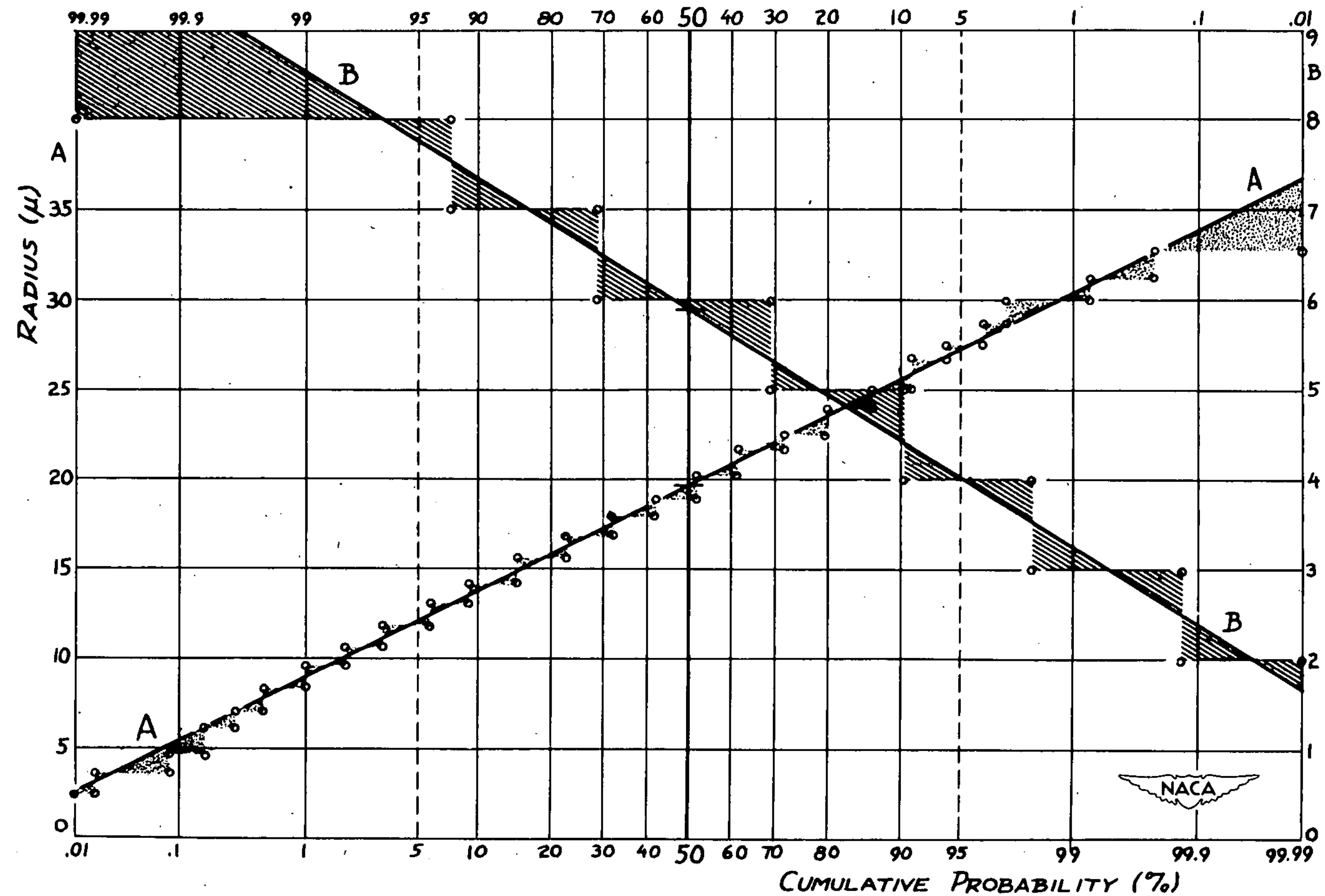


Figure 6.- Volume distribution of water in fog (A-A) according to Houghton and Radford (reference 13) and in cloud (B-B) according to Vonnegut, Cunningham, and Katz (reference 14). Horizontal line segments are interpreted according to the following example (curve B-B): Drops measuring 6 microns in radius, to the nearest micron, correspond to the range between 31 and 72 percent cumulative liquid water content. Sloping lines are the best-fitted normal distributions and shading is for emphasis only.

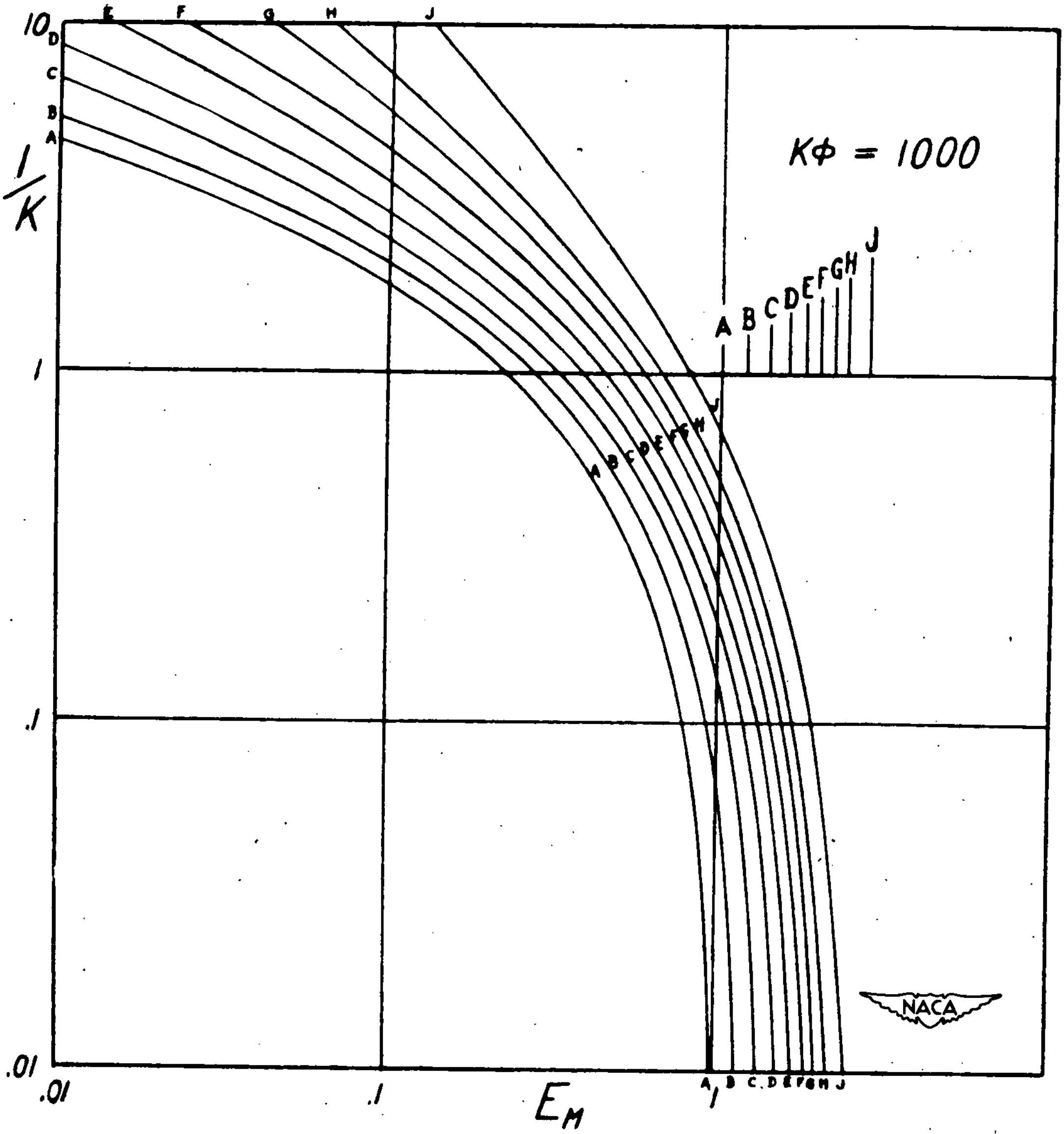


Figure 7.- Revised graph of collection efficiency as a function of K at $K\phi$ = 1000. Successive curves are displaced laterally by amounts indicated on scale along the line K = 1.

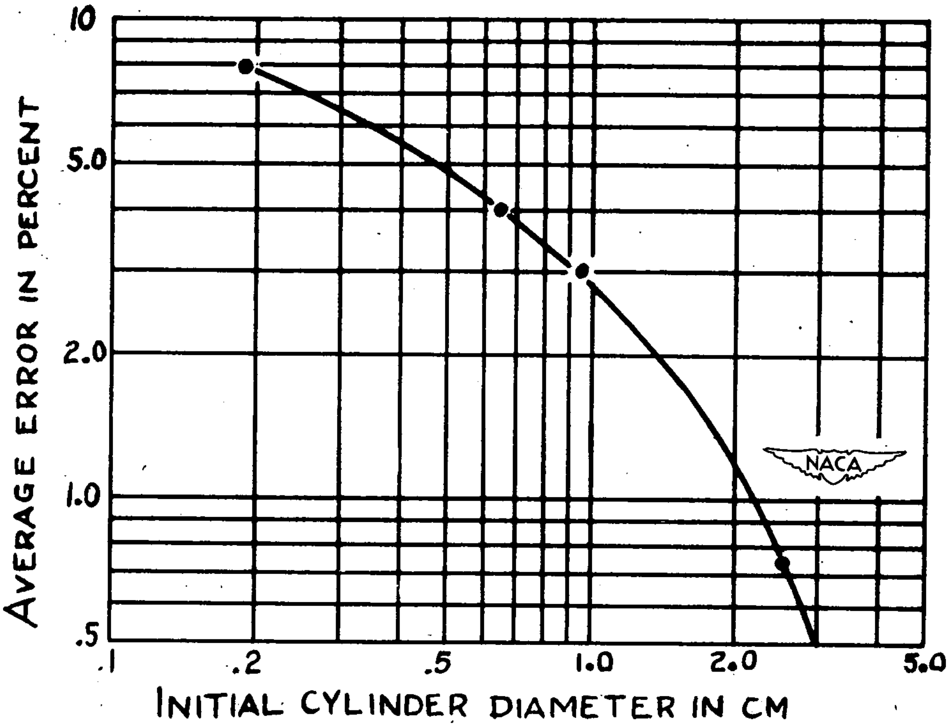


Figure 8.- Average error incurred by assuming density of ice on each cylinder to be equal to the long-period mean density on smallest cylinder.

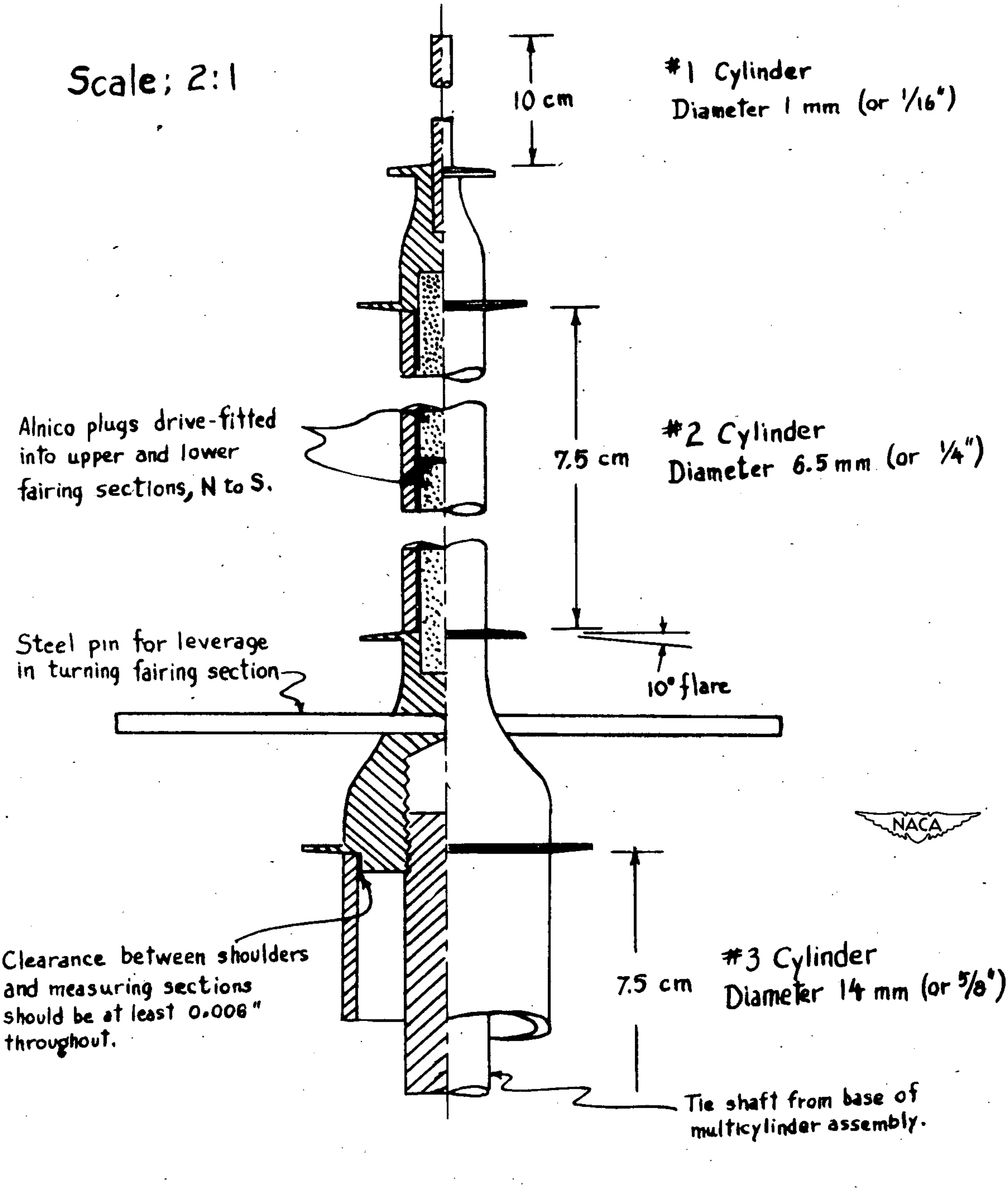


Figure 9.- Details recommended for three smallest cylinders of NACA multicylinders. The same details are recommended for three larger cylinders, with diameters of 3.0, 6.4, and 15 centimeters.