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A FURTHER INVESTIGATION OF THE METEOROLOGICAL CONDITIONS CONDUCIVE TO AIRCRAFT ICING

By William Lewis, Dwight B. Kline,
and Charles P. Steinmetz

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Moffett Field, Calif.

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SUMMARY

Meteorological data from flight observations in icing conditions during the winter of 1946-47 are presented. Data on liquid water content, temperature, and mean-effective drop diameter are shown to be consistent with values previously proposed for maximum icing conditions. Data on drop-size distribution as obtained by the rotating-cylinder method, although consistent with measurements previously made, were found to be inconsistent with data on drop-size distribution derived from the ratio of the maximum diameter to the mean-effective diameter when the maximum diameter was calculated from the area of impingement on a stationary cylinder. The relation between temperature and maximum liquid water content in layer clouds is discussed and estimates are given for the highest values of water content to be expected in layer clouds at various temperatures.

INTRODUCTION

Over a period of several years, the NACA has conducted research on the prevention of ice formations on aircraft through the use of heat. The present phase of this research is intended to provide a fundamental understanding of the process of thermal ice prevention and thereby promote improvement in the design of thermal ice-prevention

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[1] Mr. Lewis, U.S. Weather Bureau, has been assigned to work in collaboration with the staff of the Ames Aeronautical Laboratory on the NACA icing research program.

[2] Mr. Kline, U.S. Weather Bureau, has been assigned to the Flight Propulsion Research Laboratory, Cleveland, also in connection with the NACA icing research program.

equipment. The meteorological results of the investigation, up to and including the 1945-46 winter season, have been presented in reference 1. The present report, which may be regarded as a supplement to reference 1, presents the results of additional flight measurements made during the winter of 1946-47. These data include results of flight observations with the XB-24M and XB-25E airplanes operated by the Flight Propulsion Research Laboratory at Cleveland, as well as the C-46 airplane operated by the Ames Aeronautical Laboratory, Moffett Field, Calif.

Appreciation for cooperation in this investigation is extended to United Air Lines, Inc., the U.S. Weather Bureau, and the Air Materiel Command of the Army Air Forces. In particular, Major James Murray, Air Materiel Command, and Mr. Lyle Reynolds, United Air Lines, who were pilot and copilot, respectively, of the C-46 airplane, contributed materially to the research program.

APPARATUS AND METHOD

The equipment and test methods employed in the research of this report were identical to those described in reference 1 with the exception of a few changes discussed in the following paragraphs.

Rotating-Cylinder Measurements

The values of liquid water content and mean-effective drop diameter[3] presented herein were all calculated from the amounts of ice collected on four rotating cylinders, 1/8, 1/2, 1-1/4, and 3 inches in diameter. The assembly used on the C-46 airplane is shown in figure 1. A similar apparatus was used by the Flight Propulsion Research Laboratory.

Previous calculations of liquid water content and mean-effective diameter from rotating-cylinder data obtained in flight have been based upon the true airspeed of the airplane. (See references 1 and 2.) This procedure involves the tacit assumption that the local velocity at the point where the cylinders are exposed is equal to the true airspeed of the airplane. In order to check the validity of this assumption for the installation

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[3] Defined in the appendix of reference 1 as the volume median diameter having the property that there is as much water in the drops larger than the volume median diameter as there is in drops smaller than the volume median diameter.

on the C-46 airplane, the local velocities at the points of exposure of the cylinders were measured for a range of airspeeds. It was found that the local velocity was approximately 12 percent higher than the true airspeed over the entire region in which the cylinders were exposed. The values of mean-effective diameter and liquid water content presented in this report, calculated from observations on the C-46 airplane, are based upon the local velocity. The data presented herein from the Flight Propulsion Research Laboratory are based on true airspeed, since local velocity data were not available for those installations.

Area of Drop-Impingement Measurements

The apparatus for the measurement of the area of drop impingement as used on the C-46 airplane is shown in figure 2. This device consists of a cylinder 5 inches in diameter on which the angle from the stagnation point was marked in intervals of 10°. A means was provided for removing the ice accretion by rotating the cylinder against a scraper which was mounted directly behind the cylinder. The angle between the aft edge of the ice formations and the cylinder stagnation point was read visually to the nearest 5°. The ice formation was not allowed to become large enough to significantly modify the circular cross section of the cylinder.

Icing Rate Meter

An icing rate meter of the rotating disk type was used on the airplanes operated by the Flight Propulsion Research Laboratory. This instrument was similar in principle to the one described in reference 2. Data from this instrument are presented as icing rate in inches per hour collected on the edge of the disk. The data are not presented in terms of liquid water content, since the density of the ice and the collection efficiency of the disk are not known with sufficient accuracy.

RESULTS AND DISCUSSION

The data from the 1946-47 observations have been prepared in a form similar to that used for presentation in reference 1. Tables I and II present a summary of the data for both laboratories for all flights during which icing conditions were measured. Figure 3 presents the relation between liquid water content and mean-effective drop diameter and figure 4 shows liquid water content as a function of free-air temperature. The curves denoting intensity of icing in figure 3 represent the rate of ice accretion on a 3-inch diameter cylinder at 200 miles per hour as specified by the U.S. Weather Bureau for reporting icing intensity from mountain-top observation stations.

All of the values of liquid water content and mean-effective drop diameter listed in tables I and II are within the range of values observed during the previous season except the largest value of drop size from flight 72. In this case the collection efficiency was the same, within the limits of errors of measurement, for each of the four cylinders. This corresponds to a value of mean-effective diameter of at least 150 microns. The liquid water content was 0.04 gram per cubic meter in this case.

Icing Conditions in Altostratus Clouds

In contrast to the experience of the 1945-46 season in which nearly all of the altostratus clouds observed were composed of ice crystals, a large altostratus cloud system composed mostly of water drops was encountered on flight 102 in the zone of convergence ahead of a low-pressure area. This cloud was formed in tropical marine air over Louisiana at a temperature only slightly below freezing. Altostratus clouds containing water drops were also encountered during four flights by the Flight Propulsion Research Laboratory. Three of those were just outside cyclonic precipitation areas and the fourth was ahead of a cold front. A more thorough investigation of the structure of clouds associated with fronts and low-pressure systems will be required to determine the most probable location and extent of icing conditions in such cloud systems.

The following summary of the icing characteristics of altostratus clouds as compared with stratocumulus clouds in the same general area has been prepared from data obtained by the Flight Propulsion Research Laboratory.

Cloud type		Altostratus	Stratocumulus
Number of runs		9	42
Liquid water content	average median range	0.19 .18 .12 to .30	0.21 .18 .06 to .50
Mean-effective drop diameter	average median range	18 microns 18 microns 12 to 24 microns	13 microns 12 microns 7 to 36 microns
Temperature	average median range	18° F 19° F 10 to 23° F	12° F 15° F -11 to 28° F

Although insufficient data are presented here to permit definite conclusions to be drawn, it is noted that there is a tendency for altostratus clouds to have larger drops and more uniform conditions than stratocumulus clouds.

Re-examination of Previously Proposed Design Conditions

Tentative estimates of the most severe icing conditions likely to be encountered in the course of all-weather transport operations in the United States were presented in reference 1 to serve as a guide in the design of ice-prevention equipment These estimates, which were based on data obtained during the 1945-46 season and before are given below:

Cloud type	Duration (at 160 mph)	Liquid water content	Mean-effective drop diameter	Temperature
Cumulus	1 minute	2.0 gm/m^3	20 microns	0° F
Stratus or stratocumulus	20 minutes or longer	0.8 gm/m^3	15 microns	20° F
Stratus or stratocumulus	20 minutes or longer	.5 gm/m^3	25 microns	20° F

It is seen from an examination of the data in figure 3 that these maximum icing conditions were not equaled or exceeded during the 1946-47 observations. The general range and frequency of values of liquid water content and mean-effective diameter in layer clouds are very similar to the results from the previous season. Only a small amount of data were taken in cumulus clouds in 1946-47. These observations all fall within the range established by the 1945-46 observations for cumulus clouds.

The Relation Between Maximum Liquid Water Content and Temperature in Layer Clouds

It was pointed out in reference 1 that insufficient data were available from layer clouds at low temperatures to provide the basis for an estimate of the relation between temperature and maximum liquid water content in layer-type clouds. The data presented herein, while still rather scanty, include observations from 12 flights in layer clouds at temperatures of 10° F or lower and two flights below -10° F. These are believed to provide a sufficient basis for a tentative estimate of maximum liquid water content as a function of temperature in layer clouds.

It was suggested in reference 3 that the maximum liquid water content likely to occur in stratus clouds is the amount that would be produced by adiabatic lifting through an interval of 3000 feet above the condensation level. Subsequent experience, and improved methods of measuring liquid water content indicate that the actual water content is generally substantially less than the theoretical value. The estimate of 3000 feet as the maximum thickness of a continuous stratocumulus or stratus layer appears to be approximately correct. In figure 4, curve A represents one-half of the liquid water content which would be obtained by adiabatic lifting through a pressure altitude interval of 3000 feet from the condensation level. This curve falls very close to the points representing the highest observed values of liquid water content in layer-type clouds. Since it is reasonable to expect that a larger sample of data would include higher values of water content, the curve B (fig. 4), which represents two-thirds of the liquid water content produced by adiabatic lifting through 3000 feet, is proposed as an estimate of the highest values of liquid water content to be expected in layer clouds. This curve indicates a maximum liquid water content of 0.8 gram per cubic meter at 20° F which is in agreement with the estimate given in reference 1. The maximum liquid water content for lower temperatures is 0.5 gram per cubic meter at 0° F and 0.25 gram per cubic meter at -20° F.

Typical Icing Conditions

Estimates of the most severe icing conditions likely to be encountered in the course of all-weather transport operations in the United States have been presented in the foregoing section. Data on typical or average icing conditions and on the relative frequency of various values of liquid water content and drop size are also of interest.

The highest values of liquid water content measured during each of 21 flights in cumulus clouds and 51 flights in layer-type clouds are presented in figure 5 in the form of ogives (cumulative frequency curves, reference 4). These curves include data from the Ames Aeronautical Laboratory for 1945-46 and 1946-47 and from the Flight Propulsion Research Laboratory for 1946-47. The median value of maximum liquid water content per flight is 0.76 gram per cubic meter for cumulus clouds and 0.28 gram per cubic meter for layer clouds. These values approximate those given in reference 1 for typical icing conditions. It is also noted from figure 5 that 90 percent of the flights in cumulus clouds encountered less than 1.2 grams per cubic meter and 90 percent of the flights in layer clouds encountered less than 0.5 gram per cubic meter.

Ogives plotted from observations of mean-effective diameter and maximum diameter made during the 1946-47 season are presented in figure 6. It is noted that 50 percent of the observations of mean-effective diameter fall in the relatively narrow range from 11.2 to 16.2 microns, and 90 percent are less than 22 microns. Fifty percent of the observations of maximum diameter are between 12.6 and 20 microns and 90 percent are below 28 microns.

These distribution curves indicate that the icing conditions most commonly encountered are much less severe than the estimated maximum conditions. Thus, if it were assumed that most cumulus clouds and the most severe 10 percent of icing conditions in layer clouds could be avoided by proper meteorological navigation, it would only be necessary to protect against 0.5 gram per cubic meter at 13 microns or 0.3 gram per cubic meter at 20 microns. The extent to which meteorological navigation can be relied upon, however, can only be determined by an extensive study of the distribution of icing conditions in various weather situations and an analysis of air traffic control procedures.

Maximum Drop Size and Drop-Size Distribution

In the analysis of the test data the fact was noted that, in many cases, the maximum drop diameter as calculated from the area of impingement on the fixed cylinder was equal to or only slightly exceeded the corresponding mean-effective diameter calculated from the rotating-cylinder data. In a few cases the indicated maximum diameter was less than the indicated mean-effective diameter. This would indicate that in a majority of cases the size distribution was fairly uniform. The size distribution obtained by the rotating-cylinder method, on the other hand, frequently indicated broad distributions in cases where the comparison of the mean and the maximum diameters indicated uniform drop size. In order to check the consistency of these two methods of measuring drop-size distribution, they were expressed in terms of a common scale. To do this the assumption was made that the value of drop diameter contributing 10 percent of the water content in the assumed size distributions B, C, D, and E (reference 2) corresponds to the value of maximum drop diameter derived from the area of impingement on the stationary cylinder. On the basis of this assumption, the ratio of the maximum diameter as measured by the area of impingement method to the mean-effective diameter as measured by the rotating-cylinder method was used to define a scale of size distributions as follows:

Size distribution designation (defined in reference 2)	Maximum diameter / mean-effective diameter
A	below 1.16
B	1.17 to 1.41
C	1.42 to 1.62
D	1.63 to 1.87
E	1.88 and over

A comparison of the drop-size distribution obtained by the two methods is shown in the following frequency table:

		Number of observations					
		Size distribution determined by the ratio of maximum diameter to mean-effective diameter					
Size distribution by the rotating-cylinder method		A	B	C	D	E	Total
	A	21	10	1	1	1	34
	B	3	6	3	1	1	14
	C	8	4	0	1	2	15
	D	4	4	0	0	0	8
	E	8	4	2	5	2	21
	Total	44	28	6	8	6	92

It is seen from the foregoing frequency table that the data on drop-size distribution determined by the ratio of maximum diameter to mean-effective diameter indicate a preponderance of fairly uniform drop-size distributions; whereas the data on drop-size distribution obtained from the rotating-cylinder method indicate a larger number of very nonuniform distributions.

The correlation coefficient showing the degree of agreement between the results of the two methods of measuring size distribution was computed from the foregoing table by Pearson's product moment formula (reference 4) and found to be 0.19. This low correlation between the results by the two methods indicates that one or both methods must be regarded as unreliable and that therefore the information presented herein on drop-size distribution must, at present, be regarded with some skepticism. The values of mean-effective diameter presented are nevertheless regarded as being fairly accurate.

An inspection of the data in the frequency table shows that the agreement in drop-size distribution would not be materially improved by a modification of the assumption used to reduce the data to a common scale. For example, if the scale had been chosen to give "E" distribution for a larger fraction of the maximum drop-size data, the improved agreement in the lower portion of the table would be offset by corresponding changes in the upper portion.

One possible explanation for this discrepency in the determination of drop-size distribution lies in the effect of the acceleration in the flow of air around the fuselage in locally modifying the water content, drop-size distribution, and velocity at the points where the rotating cylinders are exposed. Since the 1/8-inch cylinder is exposed nearly twice as far from the side of the fuselage as the 3-inch cylinder, it would appear that the local effects might apply variously to the different cylinders, thus giving rise to a false relationship between cylinder diameter and relative collection efficiency. Only a small change in the curvature of the line defining this relationship is sufficient to produce a significant change in the indicated drop-size distribution. This effect could be measured by the exposure of four rotating cylinders of equal diameters at positions normally occupied by the rotating cylinders. Any differences in the amounts of ice collected would be due to the local acceleration effects just mentioned.

Another possible explanation of the discrepancy is the possibility that flow around the ends of the stationary cylinder caused the observed width of the area of impingement to be less than would occur on a cylinder of infinite length. This effect is believed to be unimportant, however, since the edges of the ice formations were observed to be straight and parallel to the axis of the cylinder.

The frequency of various values of maximum drop diameter are presented in figure 6. It is seen from this curve that the maximum diameter was less than 20 microns in 75 percent of observations and less than 30 microns in 93 percent. In a comparison of the two curves of figure 6, it should be remembered that the curve for maximum diameter is based upon a much smaller sample of data than the curve for mean-effective diameter.

A Further Check of the Icing Intensity Scale Proposed in Reference 1 for Forecasting Purposes

It was pointed out in reference 1 that, while fairly reliable estimates of the liquid-water content in clouds can be made, the size of the drops remains unpredictable. For this reason, a scale of icing intensity based upon liquid water content alone was proposed as an aid in the preparation of icing forecasts. This scale was found to agree with the icing intensity scale used by the Weather Bureau in 78 percent of the 1945-46 observations. The 1946-47 observations have been used to check the general validity of the proposed scale, since these data are independent of those used to define the scale. The following table presents the 1946-47 data in the same form used in reference 1 for the 1945-46 data.

Cloud type	Range of water content	Number of observed cases of icing of various intensities				
		Alternate scale of icing intensity	Weather Bureau scale of icing intensity			
			Trace	Light	Moderate	Heavy
Layer clouds	0–0.11	Trace	23	7	0	0
	0.12–0.68	Light	24	79	2	0
	0.69–1.33	Moderate	0	0	0	0
	over 1.33	Heavy	0	0	0	0
Cumulus clouds	0–0.07	Trace	0	0	0	0
	0.08–0.49	Light	3	13	0	0
	0.50–1.00	Moderate	0	2	3	0
	over 1.00	Heavy	0	0	0	0

This table shows agreement in 76 percent of the observations. The alternate scale indicates icing intensity one degree higher in 18 percent of the cases and one degree lower in 6 percent. The corresponding figures for the 1945–46 data were 78 percent, 17 percent and 5 percent, respectively. Thus, the agreement is nearly as good for the independent data, which indicate, in general, that approximately this degree of agreement can be expected.

CONCLUDING REMARKS

In addition to verifying the specifications of maximum icing conditions proposed previously, the data presented herein have been used to define the relation between temperature and maximum liquid water content in layer-type clouds as follows:

Temperature	Maximum liquid water content in layer clouds
20° F	0.8 gm/m^3
0° F	.5 gm/m^3
–20° F	.25 gm/m^3

Data on drop-size distribution as obtained by the rotating-cylinder method, although consistent with measurements previously made, were found to be inconsistent with data on drop-size distribution derived from the ratio of the maximum diameter to the mean-effective diameter when the maximum diameter was calculated from the area of impingement on a stationary cylinder. In spite of the inconsistency it is believed that the data on mean-effective diameters are fairly reliable.

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3. Lewis, William: Icing Properties of Noncyclonic Winter Stratus Clouds. NACA TN No. 1391, 1947.

4. Worthing, Archie G. and Geffner, Joseph: Treatment of Experimental Data. John Wiley and Sons, Inc., 1943.

TABLE I.– METEOROLOGICAL DATA OBTAINED IN ICING CONDITIONS DURING THE 1946-47 WINTER OPERATIONS OF THE AMES AERONAUTICAL LABORATORY C-46 AIRPLANE

Icing condition number	Flight number	Date	Time (PST)	True air-speed (mph)	Pressure altitude (ft)	Tempera-ture (°F)	[1]Liquid water content (g/m^3)	[1]Mean-effective drop diameter (microns)	[2]Drop-size distribution (rotating cylinder)	[3]Maximum diameter	Drop-size distribution (from max. diameter)	[4]Cloud type	Location and remarks
1	72	1/18/47	1405	179	7000	26	0.04	150+	E			Ns	Between Seattle and Bellingham, Wash. Pre-frontal cloud directly over surface cold front.
			1415	169	7100	26	.20	28	D				
			1420	174	7100	26	.12	22	E				
2	78	2/2/47	1053	164	6800	11	.34	13	A			Cu	Vicinity of Seattle. Unstable polar marine air following low pressure area
			1057	159	7000	10	.17	13	D				
			1101	161	7100	9	.25	15	A				
			1107	165	6600	12	.44	13	C				
			1112	161	6500	12	.17	13	A				
3	79	2/2/47	1536	164	7400	10	.21	17	B			Sc	Northeast of Portland, Oregon in upper part of stratocumulus layer
			1543	176	7400	10	.18	23	B				
			1553	170	7500	10	.21	35	D				
4	83	2/5/47	1230	163	19,300	-11	.09	16	C			As	Vicinity of Yakima, Wash. Flat high pressure ridge. Clear below 18,000 feet.
			1241	149	19,700	-12	.22	23	C				
			1247	160	19,400	-11	.01	13	E				
5	95	3/10/47	1622	169	11,300	23	.57	16	E			Cu and Cb	Near Marysville, Calif. Heavy cumulus in unstable polar marine air following cold front.
			1630	167	11,500	22	.64	17	A				
			1640	165	11,000	24	.44	15	A				
6	99	3/15/47	1459	182	12,300	18	.10	12	C	13	A	Ac	Near Pocatello, Idaho. Thin broken cloud layer in polar continental air mass.
			1508	177	12,100	19	.02	10	A	14	B		
			1515	180	11,700	20	.04	12	B	12	A		
			1520	174	11,700	20	.06	13	A	14	A		
7	99	3/15/47	1712	175	10,700	16	.08	21	A	18	A	St	Near Rawlins, Wyoming. Stationary front east of divide.
8	100	3/16/47	1109	179	11,100	21	.11	12	D	15	B	St	SW of Cheyenne, Wyoming. Low over northern Neb. Clouds formed by northerly upslope flow and convergence ahead of cold front.
			1115	169	10,900	22	.37	13	C	12	A		
			1121	186	10,700	20	.20	12	C	14	B		
			1128	177	10,800	20	.19	11	D	12	A		
			1140	156	10,700	21	.24	12	D	12	A		
			1155	170	10,800	20	.13	10	C	12	B		
9	100	3/16/47	1510	176	10,800	20	.20	12	D	16	B	St	NE of Cheyenne, Wyoming. Clouds associated with passage of cold front.
			1516	171	10,600	19	.23	12	D	13	A		
			1521	153	10,800	19	.41	13	C	15	A		
			1528	170	10,750	19	.20	13	A	16	B		
			1537	168	10,600	19	.39	13	D	16	B		
10	100	3/16/47	1807	163	6000	18	.24	13	E	13	A	Sc	Between North Platte and Omaha, Neb. Strato-cumulus behind cold front.
			1810	163	5100	18	.11	12	E	---	---		

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TABLE I.- CONTINUED.

Icing Condition number	Flight number	Date	Time (PST)	True air-speed (mph)	Pressure altitude (ft)	Temperature (°F)	[1]Liquid water content (g/m³)	[1]Mean-effective drop diameter (microns)	[2]Drop-size distribution (rotating cylinder)	[3]Maximum diameter	Drop-size distribution (from max. diameter)	[4]Cloud type	Location and remarks
11	101	3/17/47	1113	170	5200	14	.10	8	A	8	A	Sc	Eastern Missouri. Thin broken cloud layer.
12	101	3/17/47	1133 1222 1301 1308 1330	170 157 173 160 154	3600 3300 3900 3800 3500	22 25 22 23 24	.12 .15 .37 .36 .22	7 7 9 10 8	A C D B A	7 8 32 13 12	A A E B C	Sc	Memphis to Nashville, Tenn. Unstable polar continental air following cold front.
13	102	3/18/47	1237 1242 1248 1305 1312 1321 1330	170 161 170 177 171 170 167	11,800 11,700 11,500 11,400 11,400 11,500 11,300	24 24 25 25 25 25 25	.34 .13 .16 .16 .08 .33 .29	17 14 15 14 11 17 17	E C E C D E E	30 30 29 16 12 29 20	D E E A A D B	As	Jackson, Miss. to Shreveport La. Condensation in tropical marine air aloft in area of convergence northeast of low centered near San Antonio, Texas.
14	102	3/18/47	1456 1510	166 161	11,400 11,300	26 29	.01 .16	20 20	E E	21 29	A C	As	Shreveport, La. to Jackson, Miss. Same as above.
15	103	3/19/47	1100 1134 1149	172 170 174	10,000 8900 10,000	25 26 25	.14 .10 .17	25 16 18	E E E	44 17 29	D A C	Sc	Eastern Tenn. Just outside of precipitation area associated with low over Georgia.
16	103	3/19/47	1253	163	11,000	17	.10	19	A	17	A	As	North Carolina. Patches of liquid cloud near edge of precipitation area.
17	104	3/20/47	1436	179	8100	16	.06	34	C	26	A	As	Southern Ohio. Near boundary of precipitation area of weak low over eastern Tenn.
18	104	3/20/47	1503 1507 1520	179 166 170	6100 6100 4400	20 20 24	.22 .02 - - -	10 12 13	C A C	22 26 22	E E D	Sc	Southern Ohio. Stratocumulus in polar continental air behind weak low over eastern Tenn.
19	105	3/21/47	1102 1115 - - - 1118 1138 1143	161 148 148 147 158 140	5100 4900 4900 4900 5300 5100	19 19 19 19 18 19	.39 .34 - - - .24 .48 .53	12 14 13 13 13 12	B B A B B A	18 16 18 16 16 12	C A B B B A	Sc	Indianapolis to Terre Haute, Indiana. Polar continental air following occlusion associated with low center just north of Lake Erie.
20	105	3/21/47	1413 1429 1434 1507 1512 1520 1529	155 157 152 166 151 164 158	5100 5100 5000 5100 5100 5300 4500	20 20 21 21 19 20 22	.47 .57 .37 .40 .30 .13 .26	15 16 17 19 21 12 11	C E D E C E E	18 18 20 22 18 15 18	B A B A A B D	Sc	Terre Haute, Indiana to Cleveland, Ohio. Polar continental air following occlusion associated with low central just north of Lake Erie.

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TABLE I.– CONTINUED.

Icing condition number	Flight number	Date	Time (EST)	True air-speed (mph)	Pressure altitude (ft)	Temperature (°F)	[1]Liquid water content (g/m^3)	[1]Mean-effective drop diameter (microns)	[2]Drop-size distribution (rotating cylinder)	[3]Maximum diameter	Drop-size distribution (from max. diameter)	[4]Cloud type	Location and remarks
21	106	3/23/47	2247 2253	181 186	8100 8000	15 15	.14 .04	41 30	E C	31 30	A A	—	60 miles east of Cheyenne, Wyoming. Unstable polar marine air following cold front.
22	111	4/15/47	1225 1234 1310 1316	181 180 180 160	12,400 12,400 9600 9000	17 16 14 14	.03 .08 .25 .37	6 15 29 29	--- A A A	11 12 29 29	D A A A	Sc	Albuquerque, New Mexico to Denver, Colo. Cloud system associated with cold front along eastern slope of mountains.
23	112	4/16/47	1106 1154 1159 1214	180 180 187 196	11,500 10,800 10,300 10,600	5 6 8 5	.10 .20 .10 .14	13 16 13 12	B A E A	16 16 14 15	B A A B	Cu	Denver, Colorado to Kansas City, Missouri. Fair weather cumulus in polar continental air mass. Weak northerly flow.
24	113	4/17/47	1027 1049 1059 1105 1112 1121 1129	195 185 180 185 188 179 195	11,500 11,600 11,600 11,300 11,000 11,100 10,600	13 12 12 13 14 14 16	.12 .25 .12 .33 .21 .11 .10	10 9 8 11 7 7 9	C A B A B B A	12 10 9 11 10 9 8	B A A A C B A	Ac	Kansas City to Omaha. Altocumulus cloud deck ahead of cold front across northern Iowa.
25	116	4/20/47	1140 1146 1159	185 181 167	11,500 11,100 11,000	24 26 26	.12 .12 .11	17 16 15	E E E	19- 19 19	A B B	—	Pittsburg to washington. Warm front extending eastward from low near Evansville, Indiana.
26	117	4/21/47	1232 1314	180 166	11,100 10,500	24 26	.35 .17	13 12	E E	22 30	D E	—	Washington to Dayton. Near edge of precipitation area associated with low over North Carolina.
27	119	4/23/47	1145 1150 1153 1157 1202 1210 1216	168 160 155 162 167 169 162	5400 5400 5600 5900 5500 5400 5300	25 25 24 24 25 25 23	.27 -- .25 .23 .26 .23 .21	11 10 10 14 11 10 12	A B A A A A A	13 13 11 13 13 10 10	B B A A B A A	Sc	Western Nebraska, northerly flow in polar continental air following cold front. Low center over Wisconsin.
28	120	4/25/47	1231 1234 1240 1244 1249 1321	192 --- 151 --- 174 ---	9800 11,600 11,200 11,200 11,000 12,400	16 11 12 12 11 8	.26 .23 .46 .40 .25 .94	13 13 13 14 13 15	A A A A A A	16 14 12 12 16 14	B A A A B A	Cu	Nebraska. Cumulus congestus in unstable polar continental air. Weak northwesterly flow.
29	121	4/26/47	1710	188	17,700	-3	.17	10	A	14	B	Cu	East of Salt Lake. Weak circulation in polar marine air.

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TABLE I.– CONCLUDED.

Icing condition number	Flight number	Date	Time (PST)	True air-speed (mph)	Pressure altitude (ft)	Tempera-ture (°F)	[1]Liquid water content (g/m^3)	[1]Mean-effec-tive drop diameter (microns)	[2]Drop-size distribution (rotating cylinder)	[3]Maximum diameter	Drop-size distribution (from max. diameter)	[4]Cloud type	Location and remarks
30	122	4/27/47	1138	190	14,800	9	.52	13	A	16	B	Cu	Northern Utah. Heavy cumulus in unstable polar marine air. Cyclonic circulation at upper levels.
			1148	190	14,700	10	.41	11	C	16	C		
			1151	187	15,200	9	.53	14	A	24	D		

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[1] Liquid water content and mean-effective drop diameter are from four-cylinder data.

[2] Size distributions are defined in reference 2.

[3] From area of impingement on 3-inch-diameter cylinder.

[4] Ac – altocumulus
As – altostratus
Cb – cumulonimbus
Cu – cumulus
Ns – nimbostratus
Sc – stratocumulus
St – stratus

TABLE II.- METEOROLOGICAL DATA OBTAINED IN ICING CONDITIONS DURING THE 1946-47 WINTER OPERATIONS OF THE FLIGHT PROPULSION RESEARCH LABORATORY

Flight number	Date	Time (EST)	Plane	True air-speed (mph)	Pressure altitude (ft)	Tempera-ture (°F)	[1]Liquid water content (g/m³)	[3]Mean-effective drop diameter (microns)	[2]Drop-size distribution	Icing rate (in./hr)		[4]Cloud type	Location and remarks
										Maximum	Average		
10	12/26/46	1300-1500	B-24M	179	5070	-7	0.09	10	A	---	---	Sc	Northern Ohio and New York. Weak northerly cyclonic flow.
11	12/30/46	0930-1130	B-24M	181	4870	5	.13	14	A	---	---	Sc	Lake Erie. Instability type clouds associated with northerly flow.
				159	3160	9	.06	12	A	---	---	Sc	
				209	3880	7	.06	11	A	---	---	Sc	
13	1/6/47	1430-1520	B-24M	177	3310	13	.37	9	A	---	2.7	St & Sc	Fifty miles south of Cleveland. Post warm front situation. Cloud deck covered most of Ohio and eastern half of Indiana with scattered conditions in surrounding areas.
				177	3210	15	.24	9	A	---	2.7	St & Sc	
				180	3310	15	.26	8	A	---	1.7	St & Sc	
				177	3310	14	.18	9	A	---	2.8	St & Sc	
				177	3310	15	.30	9	A	---	2.2	St & Sc	
				157	3210	16	.28	8	A	---	2.8	St & Sc	
30A	1/6/47	1600-1700	XB-25E	215	3700	-4	.16	9	A	2.1	1.5	St & Sc	Vicinity of Muskegon, Mich. Warm front vicinity of Traverse City, Michigan.
14	1/7/47	1430-1540	B-24M	152	2820	26	.20	17	E	---	1.2	St & Sc	Northern Ohio. Flight path intersected upper cold front, tropical marine overrunning at 6000 ft. Toledo sounding at 1000 EST.
				152	2820	27	.18	17	E	---	1.5	St & Sc	
				155	3985	24	.45	17	E	---	1.6	St & Sc	
				162	3405	25	.31	14	E	---	2.5	St & Sc	
30B	1/7/47	0930-1300	XB-25E	198	4675	-11	.10	11	A	1.5	1.0	St & Sc	60-80 miles east Minneapolis. General area post cold frontal cloud.
				210	4500	-8	.12	12	B	1.7	0.9	St & Sc	
				214	4500	-8	.08	10	B	1.1	0.6	St & Sc	
30C	1/8/47	1100-1500	XB-25E	210	3900	-1	.16	12	E	2.2	1.2	St & Sc	100 miles north of Minneapolis. Weak warm frontal zone.
				208	4100	2	.09	12	E	1.9	0.9	St & Sc	
16	1/16/47	1620-1630	B-24M	155	4085	21	.11	7	B	---	0.6	St & Sc	Northerly cyclonic flow. Lake Erie.
				155	4085	21	.13	8	B	---	0.8	St & Sc	
20	1/29/47	0930-1130	B-24M	168	8270	23	.20	12	A	---	0.7	As	Area of Traverse City north of periphery of precipitation area associated with slow-moving warm front, southern Ohio.
34	1/29/47	1130-1230	XB-25E	215	7400	10	.18	12	A	1.9	0.6	As	Lake Huron. North of periphery of precipitation area.
				208	6200	18	.18	18	A	3.0	1.6	As	
				214	9000	15	.17	20	A	4.5	2.8	As	
35	1/31/47	1030-1330	XB-25E	205	3700	-4	.16	9	A	0.4	0.4	St & Sc	Lake Erie. Northerly cyclonic flow.

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TABLE II.– CONCLUDED.

Flight number	Date	Time (EST)	Plane	True air-speed (mph)	Pressure altitude (ft)	Tempera-ture (°F)	[1]Liquid water content (g/m³)	[1]Mean-effec-tive drop diameter (microns)	[2]Drop-size distribution	Icing rate (in./hr)		[4]Cloud type	Location and remarks
										Maximum	Average		
21	2/17/47	1440-1600	B-24M	153 158	2920 2920	28 26	0.50 .30	9 9	E E	--- ---	2.1 1.6	St & Sc St & Sc	Area of Muskegon and Traverse City. Pre-cold frontal clouds. Front across Lake Michigan.
22	2/18/47	1330-1430	B-24M	181	3670	25	.30	13	E	---	2.2	Sc	Lake Erie. Cold frontal zone. Clouds appeared dark and dense.
37	2/25/47	1330-1600	XB-25E	205 205	7900 7900	4 4	.15 .13	16 16	C E	--- ---	1.7 1.7	St & Sc St & Sc	Local Cleveland area. Northerly cyclonic flow.
38	2/26/47	1200-1400	XB-25E	210 210 210	6500 6500 6500	5 5 5	.12 .11 .40	15 36 12	A A A	2.8 2.8 2.8	1.3 1.3 1.3	Sc Sc Sc	Local Cleveland area. Northerly cyclonic flow.
40	3/3/47	1200-1500	XB-25E	193	5750	2	.06	12	A	---	---	St & Sc	Local Cleveland area. Northerly cyclonic flow.
41	3/5/47	1420-1500	XB-25E	191	3370	14	.22	8	E	---	0.5	St & Sc	Lake Erie. Weak northerly cyclonic flow.
24	3/6/47	1220-1330	B-24M	220 225 214 191	9910 9710 9910 9910	19 19 20 20	.30 .24 .17 .12	18 18 18 18	E E E E	--- --- --- ---	2.7 --- --- ---	As	Vicinity of Elkins, Roanoke and Harrisonburg, Va. Flight north of precipitation area associated with warm front.
44	3/13/47	1500-1730	XB-25E	197	11,040	21	.18	24	E	---	2.3	As	Local Cleveland area. Pre-cold frontal deck of middle clouds.
27	3/14/47	1300-1430	B-24M	178 181 183	5600 5375 5480	20 21 21	.34 .15 .19	15 13 14	A A A	--- --- ---	2.2 2.9 1.7	Sc Sc Sc	Lake Erie. Post cold frontal clouds. Front passed Cleveland 0730 EST.
32	4/7/47	1330-1540	B-24M	179 176	4280 3775	22 21	.42 .09	15 13	A A	--- ---	3.3 0.7	Sc Sc	Local Cleveland area. Cylinder data doubtful. Northerly cyclonic flow over area.
49	4/7/47	1030-1230	XB-25E	180 188 180 185	4300 4300 4300 4300	19 19 19 19	.30 .42 .13 .21	25 15 11 16	A A A A	7.2 6.2 0.4 ---	4.0 3.6 0.4 ---	Sc Sc Sc Sc	Lake Erie. Northerly cyclonic flow.

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See table I for footnotes.

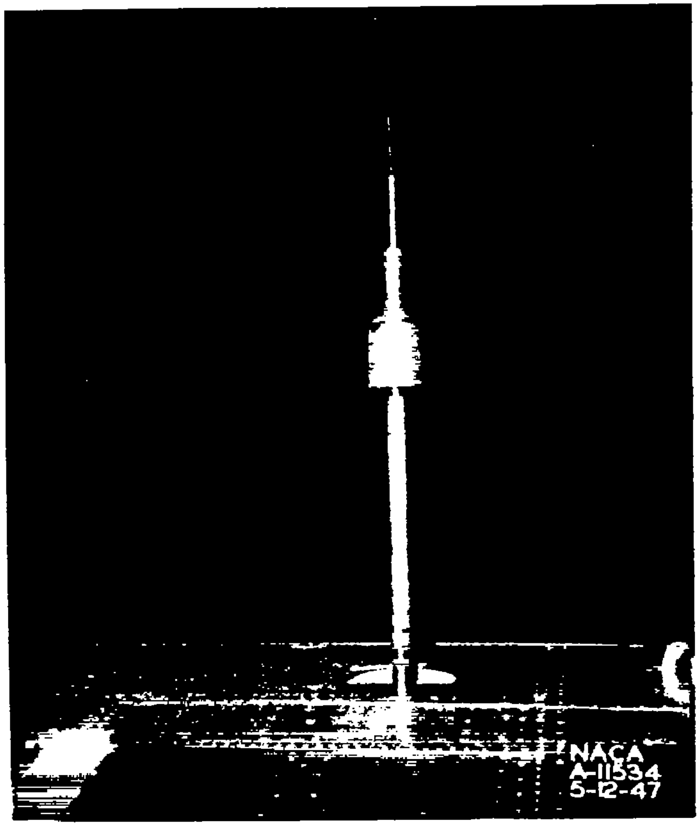

Figure 1.- Rotating cylinder apparatus used on the C-46 airplane during icing research in the 1946-47 winter.

Figure 2.- Apparatus used to measure the area of drop impingement installed on the C-46 airplane.

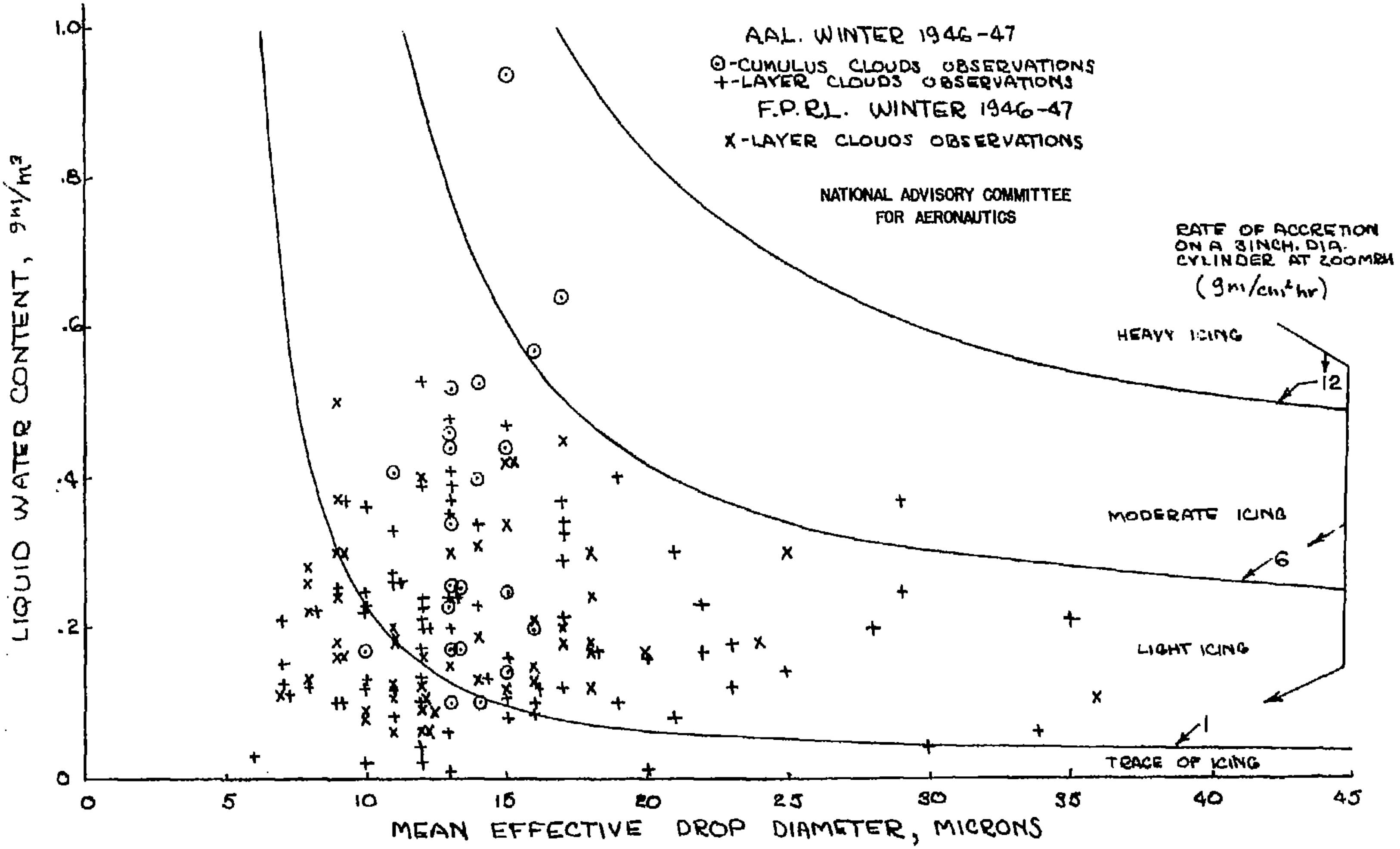

FIGURE 3.- LIQUID WATER CONTENT AS RELATED TO AVERAGE DROP DIAMETER IN ICING CLOUDS.

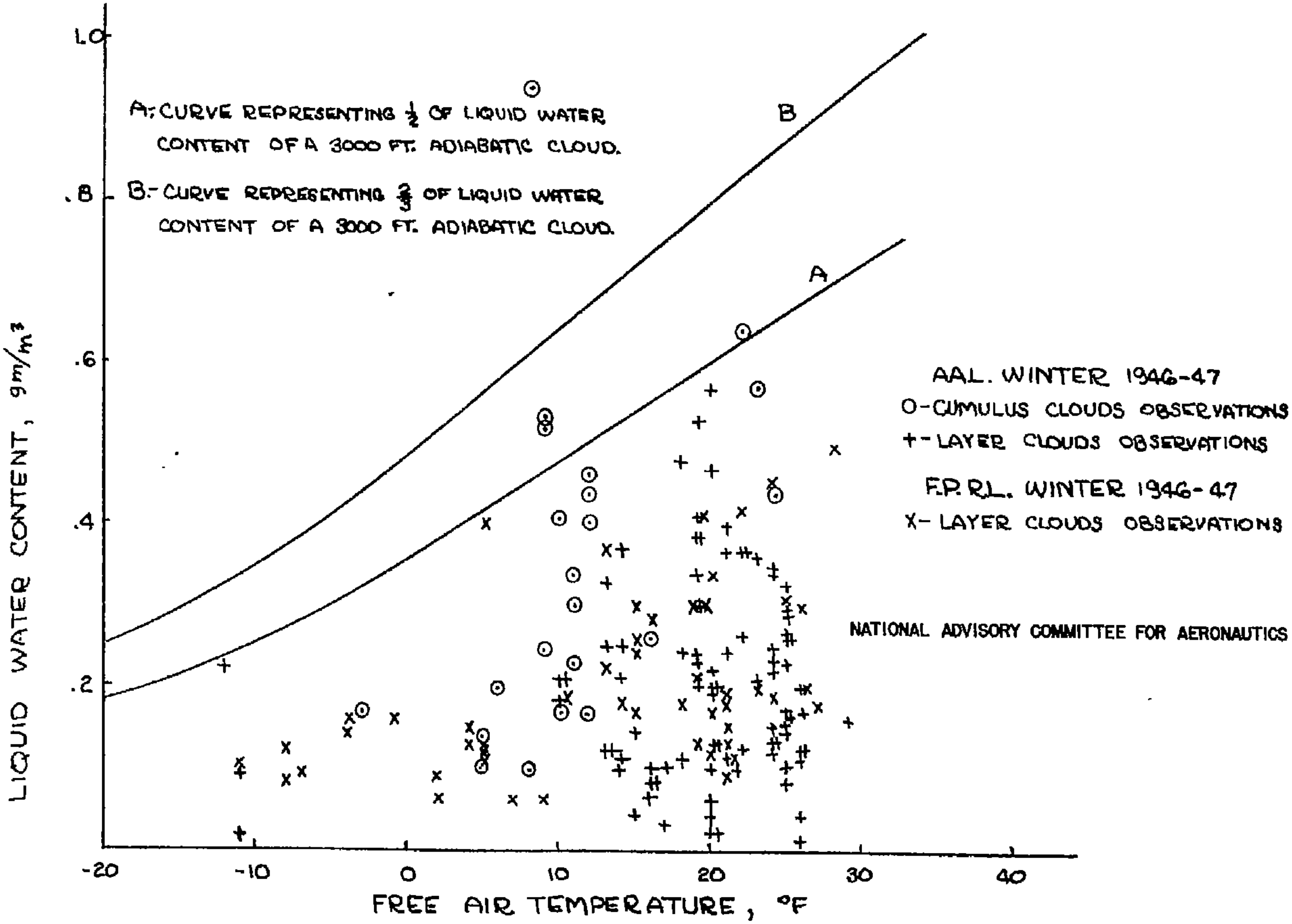

FIGURE 4. - LIQUID WATER CONTENT AS RELATED TO TEMPERATURE IN ICING CLOUDS.

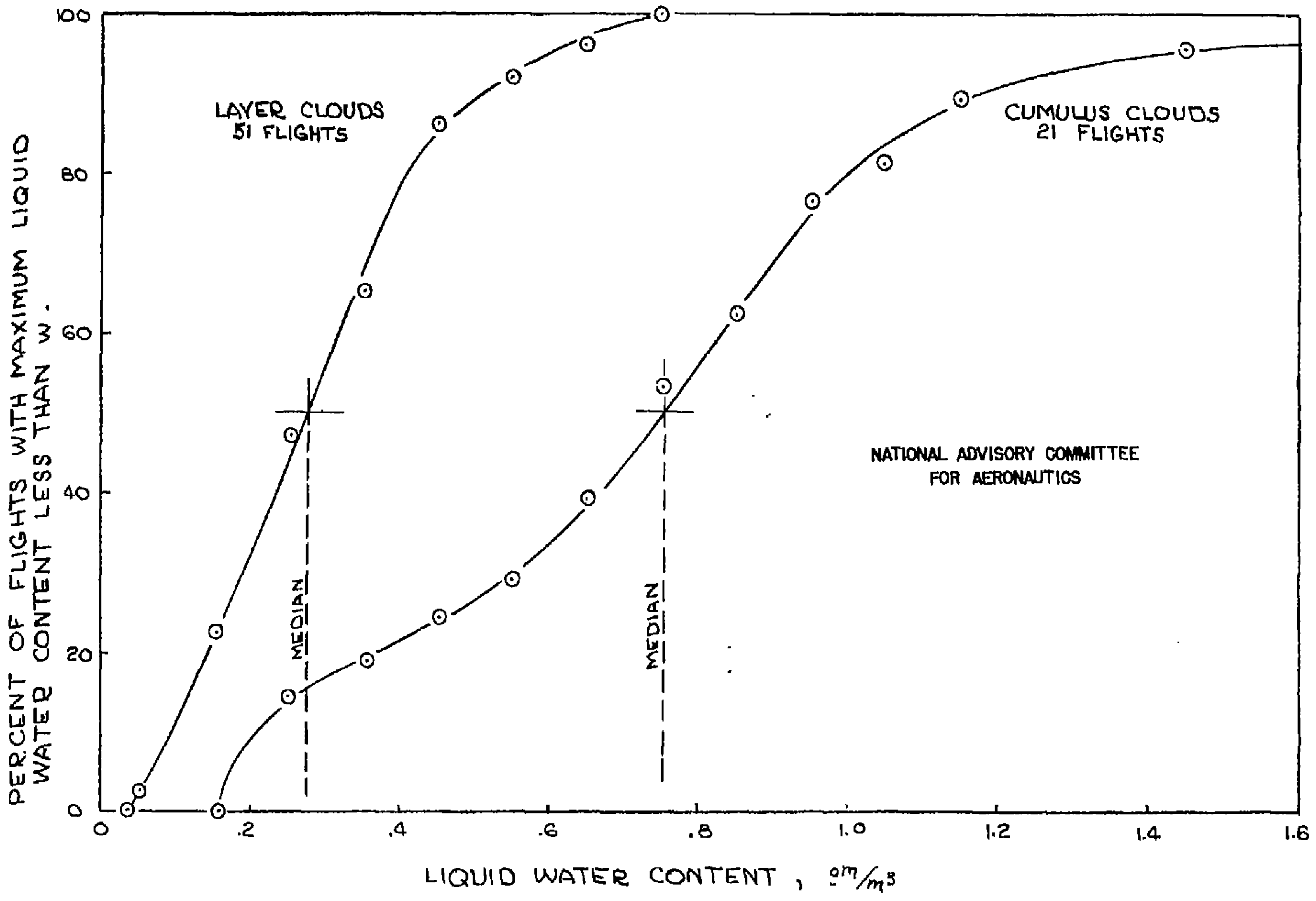

FIGURE 5.- OGIVES OF MAXIMUM LIQUID WATER CONTENT PER FLIGHT

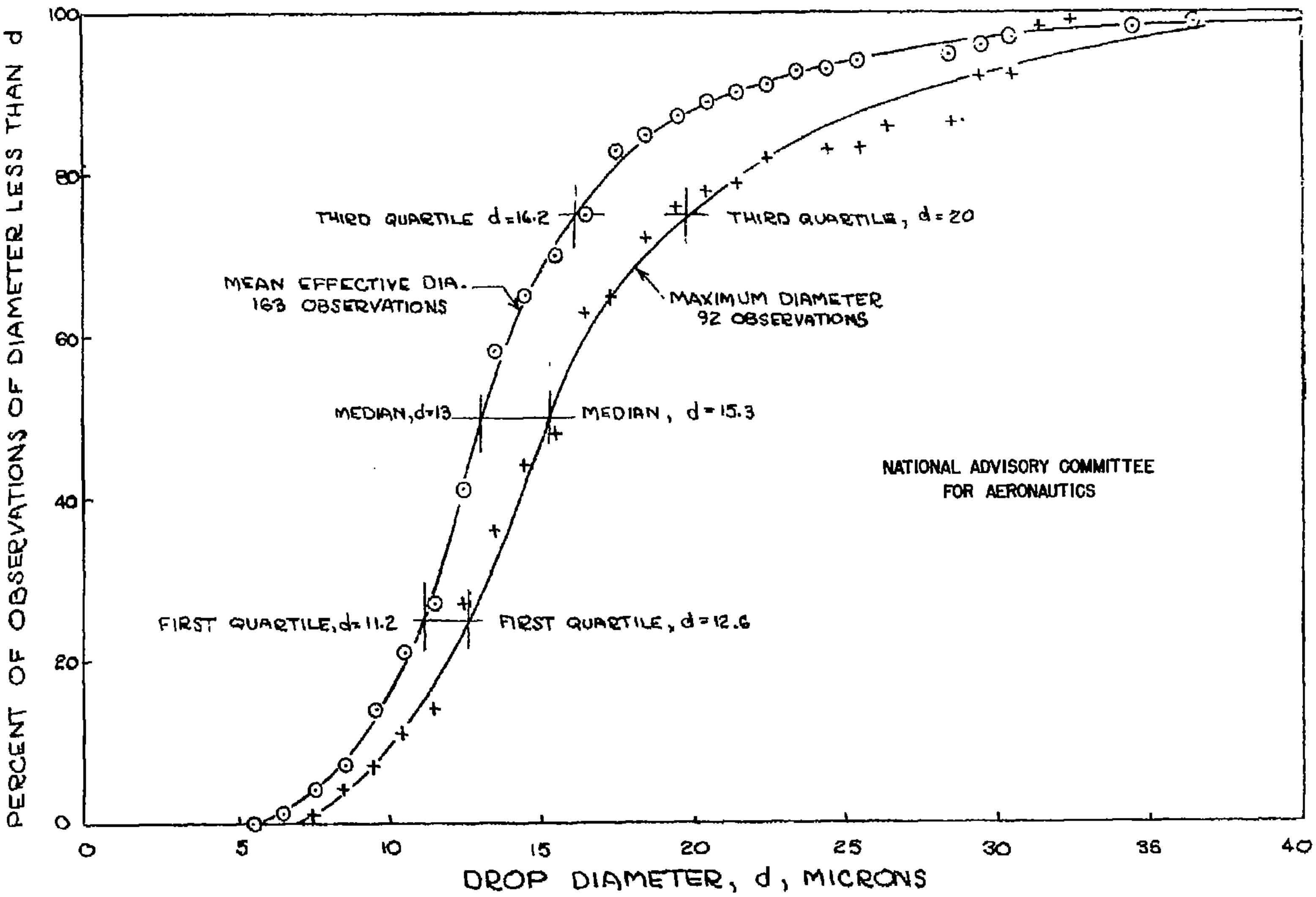

FIGURE 6.– OGIVES OF MEAN EFFECTIVE DIAMETER AND MAXIMUM DIAMETER OF DROPS IN ICING CLOUDS.