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INVESTIGATION OF METEOROLOGICAL CONDITIONS ASSOCIATED WITH AIRCRAFT ICING IN LAYER-TYPE CLOUDS FOR 1947-48 WINTER

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By Dwight B. Kline[1]

SUMMARY

Rotating-cylinder measurements of the icing conditions encountered in flight during the winter of 1947-48 are presented. Liquid-water content, drop size, and temperature data are shown to be consistent with previously measured conditions and with proposed maximum icing conditions in supercooled layer-type clouds. Cumulative-frequency graphs of meteorological parameters indicate the frequency with which various icing conditions have been encountered in the Great Lakes area and surrounding states.

INTRODUCTION

One of the problems closely associated with the development of adequate and practicable thermal ice-prevention equipment for airplanes is the determination of the range of the pertinent meteorological variables that occur in icing conditions likely to be encountered during flight. One phase of the basic research on aircraft icing problems conducted by the NACA has therefore been an attempt to find and to fly through natural icing conditions for the purpose of measuring the meteorological factors associated with supercooled clouds.

Incomplete information concerning the fundamental physical processes that determine the structure of clouds and cloud systems has necessitated a statistical approach to the problem. The accumulation of considerable meteorological data over differing geographical and climatological regions in various weather conditions is therefore required before the design limits for ice-prevention systems can be stated with reasonable certainty.

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

Throughout recent investigations of the physical properties of icing clouds, the following quantities have been measured: (1) liquid-water content, (2) mean-effective drop diameter, (3) distribution of drop sizes, and (4) free-air temperature. No completely reliable method of measuring these quantities in flight has yet been developed. Data have been obtained, however, that are of considerable value in the meteorological analysis of icing conditions.

Results of the meteorological phases of previous NACA icing-research programs are presented in references 1 to 5. Reference 1 describes the methods first used by the NACA to measure liquid-water content of icing clouds. Meteorological aspects of icing conditions in stratus clouds and warm-front precipitation areas are discussed in references 2 and 3. Reference 4 presents the results of numerous measurements of liquid-water content and drop size and discusses tentative estimates of the most severe icing conditions likely to be encountered in all-weather transport operations. Data from further and more extensive icing flights, including the 1946-47 winter data collected by the Lewis laboratory, are presented in reference 5.

In an effort to assist in achieving a satisfactory solution of the design problem, the B-24M and XB-25E airplanes were equipped with special meteorological instruments similar to those used during previous NACA flights and were flown in natural icing conditions during the winter of 1947-48. Most of the flights were conducted over the Great Lakes area or surrounding states. The need for reasonably homogeneous and continuous icing conditions for engineering test purposes required flights in overcast layer-type clouds such as stratus, stratocummulus, or alto-stratus.

Potential icing conditions not included in this investigation are those associated with freezing rain and the heavier, but intermittent, conditions to be found in cumulus-type clouds. Measurements were made only in those conditions requiring continuous operation of ice-prevention equipment.

The flight measurements made by the Lewis laboratory in 1947-48 and a comparison of them with data available from previous flights (references 4 and 5) are presented herein. The need for flight measurements for statistical purposes makes desirable the presentation of the data, despite the somewhat limited scope of the additional information.

APPARATUS AND METHOD

Rotating-Cylinder Measurements

Measurements of liquid-water content, mean-effective drop diameter, and drop-size distribution were calculated from the weight of ice collected on each of four rotating aluminum cylinders of $\frac{1}{8}$-, $\frac{1}{2}$-, $1\frac{1}{4}$-, and 3-inch diameters. The procedure used to calculate the desired quantities was similar to that outlined in reference 6, except that a density of 0.8 was assumed for all ice deposits in calculating the average cylinder diameter during the exposure period. Because of flight conditions, this procedure was used in place of the more tedious, but slightly more accurate, method of measurement of the thickness of the ice deposited on each cylinder. For all computations the velocity in the vicinity of the cylinders was assumed equal to the true airspeed of the airplane. Once a desired icing condition was encountered, as many runs as possible were made in order to approximate a continuous record of the cloud characteristics.

Free-Air Temperature

Flight temperature measurements were made by means of a resistance-bulb thermometer shielded to eliminate radiation effects and direct impact of water. The thermometer was subject to kinetic heating because of the speed of the airplane. Corrections for the kinetic heating were obtained by the procedure outlined in reference 4.

RESULTS AND DISCUSSION

The 1947-48 data have been prepared in a form similar to those presented in references 4 and 5. Table I is a summary of all 1947-48 flights in which rotating-cylinder measurements of drop size and liquid-water content were possible. Nine icing conditions were encountered, during which a total of 42 observations of liquid-water content and mean-effective drop diameter were made by the rotating-cylinder method. All icing conditions encountered were in stratus or stratocumulus clouds, which were associated with either cold or occluded fronts or, more generally, were in the colder air mass behind the surface density discontinuity.

Icing condition 2 is of interest in that the value of 0.57 gram per cubic meter is the highest concentration of liquid water measured in icing clouds during two seasons of flights from the Lewis laboratory.

Icing condition 9 was the most extensive and prolonged flight possible in conditions with a relatively high concentration of liquid water. Because the heaviest icing condition was along the shore line of Lake Michigan, there is reason to believe that the air trajectory over the lake was a factor affecting the intensity of the condition. Less ice was encountered 30 to 40 miles inland (first and fourth cylinder runs) where a light-drizzle condition was reported at a few of the weather-observation stations indicating a significant depletion of supercooled water in the clouds once precipitation began to occur.

Comparison of 1947-48 Data with Icing Conditions Encountered during Winter of 1946-47

The relation between liquid-water content and drop size is shown in figure 1. The three curves indicating intensity of icing conditions were computed on the basis of U.S. Weather Bureau specifications for icing intensity in reports from mountain observation stations. The intensity is based on the rate of ice accretion on a 3-inch-diameter cylinder moving at 200 miles per hour. A uniform drop size, a temperature of 15° F, and a pressure altitude of 10,000 feet were assumed in computing the intensity curves. Also shown in figure 1 is the range of conditions encountered during the previous season.

The average of the values of drop size and liquid-water content in stratus and stratocumulus clouds from 42 runs compares closely with the conditions measured during the previous season, as indicated in the following table:

		1946-47	1947-48
Liquid-water content, gm/cu m	Average	0.21	0.23
	Median	.18	.19
	Range	0.06 to .50	0.05 to .57
Mean-effective drop diameter, microns	Average	13	13
	Median	12	12
	Range	7 to 36	5 to 22
Temperature, °F	Average	12	19
	Median	15	21
	Range	-11 to 28	9 to 26

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Of interest is the similarity of the average of the drop-diameter measurements to the value of 12.96 microns based on an analysis of Mount Washington icing observations (reference 7). The average concentration of liquid water measured in flight, however, was approximately half the value of 0.472 gram per cubic meter calculated from the Mount Washington data.

Comparison of Data with Proposed Design Conditions

Tentative estimates of the most severe icing conditions likely to be encountered in flight are contained in reference 4. The values for stratus and stratocumulus clouds are:

Liquid-water content (gm/cu m)	Mean-effective drop diameter (microns)	Temperature (°F)
0.8	15	20
.5	25	20

Examination of table I and figure 1 indicates that these proposed maximum conditions were neither equalled nor exceeded during the 1947-48 season. Whereas the first cylinder run of icing condition 2 approximates the estimated maximum conditions with respect to liquid-water content and temperature, the decreased collection efficiency of exposed airfoil surfaces due to the small drops considerably lessened the rate of ice formation.

Frequency-Distribution of Meteorological Parameters

During the two seasons of icing flights from the Lewis laboratory, 31 flights were made in icing conditions during which 93 rotating-cylinder observations were collected. Nearly all the data were gathered in layer-type clouds, including nine observations in alto-stratus. Owing to the procedure of attempting to find, and to fly as long as possible, in the heavier-icing conditions, the data are believed to be weighted in favor of the more severe conditions that existed in the Great Lakes area and surrounding states.

An ogive (cumulative-frequency curve) based on observations of liquid-water content during the 1946-47 and 1947-48 seasons is shown in figure 2. A liquid-water content of less than 0.40 gram per cubic meter was measured in nearly 90 percent of the cases and 50 percent of all observations were made in conditions with less than 0.18 gram per cubic meter.

The ogive of drop-size measurements in figure 3 indicates that about 90 percent of the measurements of mean-effective diameter of the drops in icing clouds were less than 20 microns and 50 percent were less than 13 microns.

Because the actual icing intensity observed in flight is related to both the concentration of supercooled water and the drop sizes, computations have been made of the theoretical rate of ice accretion on a 3-inch-diameter cylinder, which roughly approximates the leading edge of at least part of an airplane wing. Although no simple measure of icing intensity is adequate for engineering purposes, the use of a 3-inch cylinder as a reference for icing-intensity measurements relates the observations to conditions that would normally be observed by a pilot. Values for the collection efficiency for a 3-inch cylinder for various drop sizes were taken from reference 6. Figure 4 indicates that 90 percent of all measured icing conditions caused an icing rate of less than 3 grams per square centimeter per hour (1.5 in./hr, with an ice density of 0.8). One-half of the observations were in icing conditions of less than 1.3 grams per square centimeter per hour (0.6 in./hr). The maximum condition observed so far has been 5.3 grams per square centimeter per hour, which is equivalent to about 2.6 inches per hour. The maximum design conditions for layer-type clouds specified in reference 4 give a computed icing rate of approximately 4 inches per hour when related to a 3-inch-diameter cylinder.

CONCLUSIONS

The following general conclusions are based on the observations gathered during two winters of icing flights from the Lewis laboratory:

1. In supercooled layer clouds that exist over the Great Lakes area, icing intensities are usually light (based upon the U. S. Weather Bureau scale of icing intensity in reporting icing conditions at mountain stations) but may occasionally approach an icing rate of moderate intensity.

2. Data collected during the two seasons indicate that the specifications of maximum icing conditions in terms of liquid-water

content, mean-effective drop diameter, and temperature previously proposed for supercooled layer-type clouds appear to be adequate for the Great Lakes area and surrounding regions.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, November 4, 1948.

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7. Conrad, V.: Statistical Investigation of the Mount Washington Series of Icing Observations. The Mount Washington Observatory Monthly Res. Bull., vol. II, no. 10, Oct. 1946.

TABLE I - METEOROLOGICAL DATA OBTAINED IN ICING CONDITIONS DURING 1947-48 WINTER OPERATIONS

Icing condition	Date	Time (EST)	Air-plane	True airspeed (mph)	Pressure altitude (ft)	Temp-erature (°F)	Liquid-water content (gm/cu m)	Mean-effective drop diameter (microns)	Drop-size distribution (a)	Cloud type	Location and remarks
1	12/11/47	1230	B-24M	172	5560	11	0.29	13	A	Stratocumulus	Over Lake Erie. All data taken near tops of clouds 30-50 miles east of a cold front. Occasional breaks in clouds during last two runs.
		1240		202	6170	9	.10	9	C		
		1251		189	5640	11	.08	10	A		
2	1/2/48	1530	B-24M	168	3600	21	0.57	8	A	Stratus and stratocumulus	Local Cleveland area. Cloud layer associated with weakening occluded front.
		1540		169	3600	25	.32	8	A		
3	3/3/48	1214	XB-25E	199	3650	11	0.24	11	A	Stratocumulus	Area 20 miles south of Dunkirk, N. Y. to 50 miles southeast of Buffalo, N. Y. Post cold frontal clouds.
		1221		189	3650	11	.40	9	C		
		1233		182	3090	14	.15	11	A		
		1240		202	3150	13	.08	10	A		
		1309		200	3620	15	.15	12	A		
		1316		199	3620	13	.21	10	A		
		1328		197	3150	11	.08	9	A		
4	3/3/48	1036	B-24M	181	3740	19	0.31	14	E	Stratocumulus	Central and northern Ohio. Instability clouds 150-200 miles north of a cold front.
		1045		172	3890	22	.38	13	E		
		1053		174	3540	21	.19	18	E		
		1104		181	3680	23	.14	21	E		
		1114		191	3890	22	.16	20	A		
		1125		175	3800	24	.18	22	A		
5	3/4/48	1205	B-24M	188	2920	22	0.10	15	A	Stratocumulus	Southern Pennsylvania
6	3/16/48	1508	B-24M	195	6080	26	0.18	20	A	Stratocumulus	Vicinity of Detroit, Mich., 350 miles west of cold front.
		1520		199	6130	25	.21	15	E		
		1532		200	7300	23	.23	17	A		
7	3/23/48	1820	B-24M	196	8900	21	0.15	15	A	Stratus and stratocumulus	Eastern Montana. Orographic and instability clouds north of a nearly stationary cold front.
		1832		201	8100	20	.17	20	A		
		1844		196	8710	18	.13	22	E		
		1853		200	9250	17	.10	21	A		
		1900		203	9110	16	.22	11	E		
		1913		192	9210	15	.12	15	A		
		1916		200	9850	16	.05	7	A		
8	3/30/48	1001	B-24M	194	6990	14	0.19	10	A	Cumulus and stratocumulus	Vicinity of Megantic, Quebec. Mixture of ice crystals and water.
9	4/1/48	0841	B-24M	182	7190	22	0.13	6	A	Stratocumulus	Between Muskegon and Traverse City, Mich. Heaviest icing along shore line of Lake Michigan.
		0904		188	5880	26	.47	8	E		
		0909		188	5720	24	.20	8	E		
		0916		186	6740	20	.08	10	A		
		0925		195	5070	23	.39	9	E		
		0933		187	5170	26	.48	12	E		
		0940		179	4870	25	.44	12	E		
		0953		189	4830	26	.38	11	E		
		1000		180	5120	26	.32	12	E		
		1007		198	4470	24	.28	12	E		
		1014		170	3890	25	.46	6	E		
		1435		197	7290	16	.16	16	A		

[a]Size distributions are defined in reference 6.

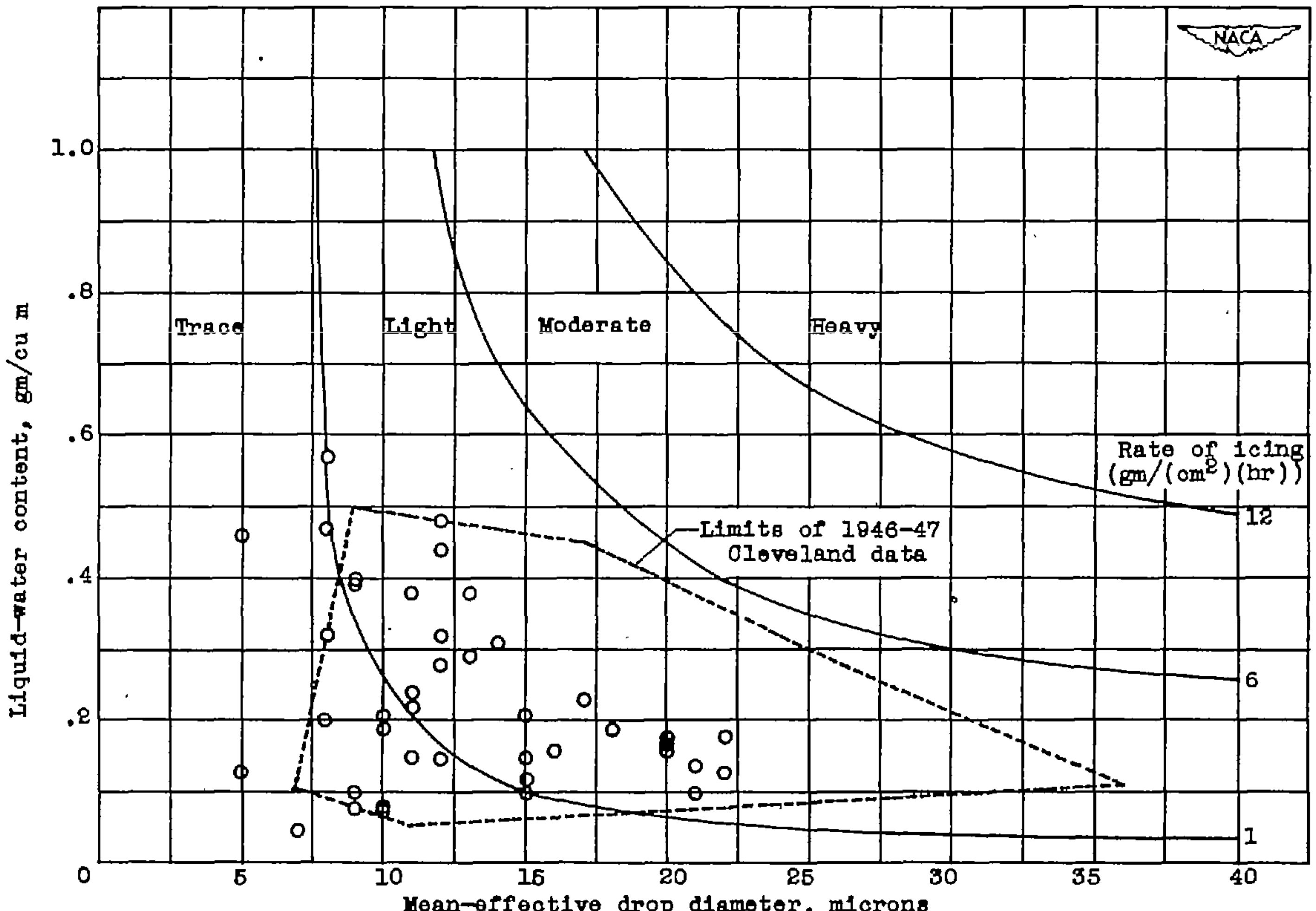

Figure 1. - Relation between liquid-water content and mean-effective diameter of drops in icing clouds from 42 observations in nine flights of 1947-48 winter. Rate-of-icing curves based on U. S. Weather Bureau specifications: uniform drop-size distribution; cylinder, 3-inch diameter; true airspeed, 200 miles per hour; temperature, 15° F; pressure altitude, 10,000 feet. (All data points shown obtained by rotating-cylinder method from layer-type clouds.)

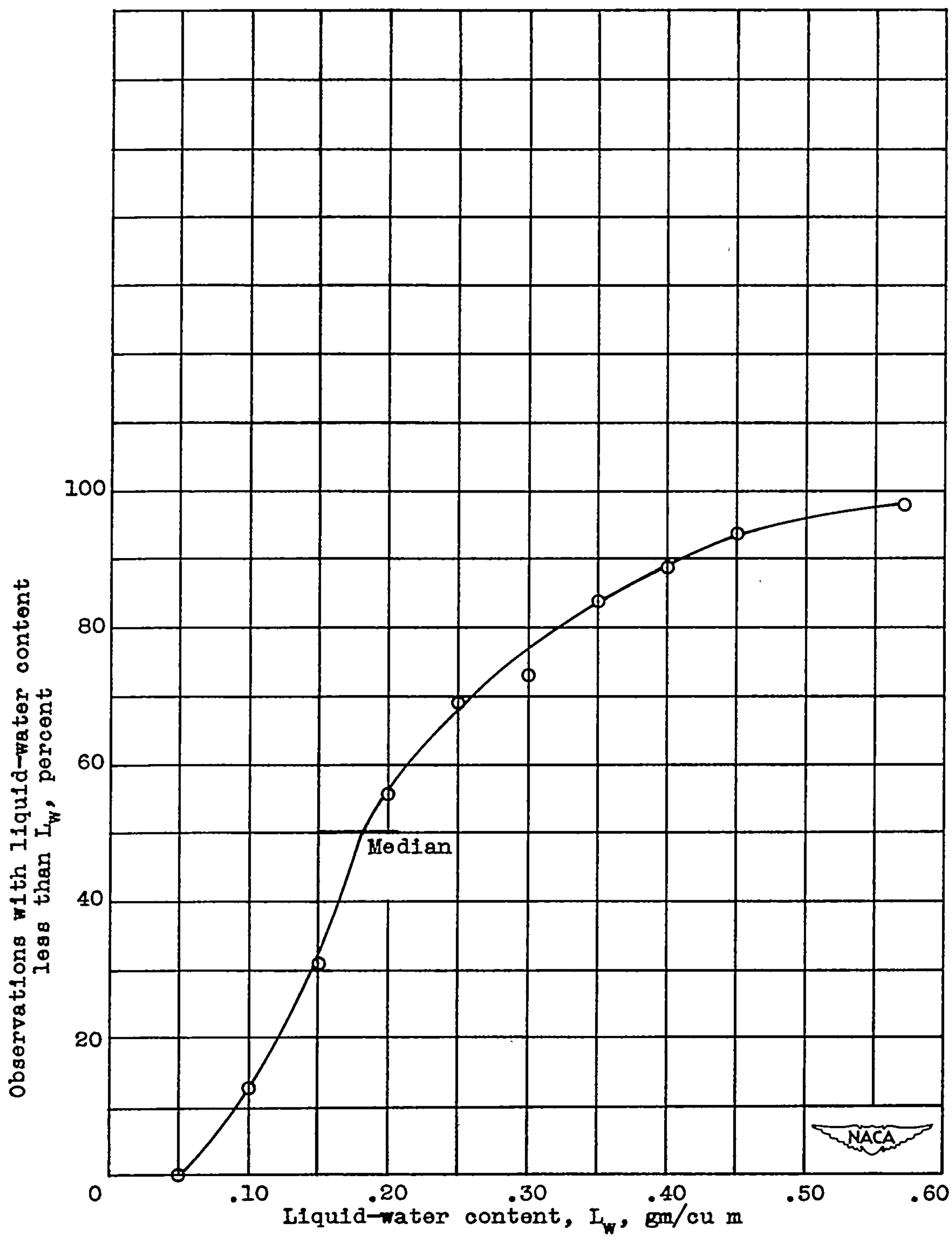

Figure 2. - Ogive of 93 observations of liquid-water content in icing clouds measured during 31 winter flights during 1946-47 and 1947-48.

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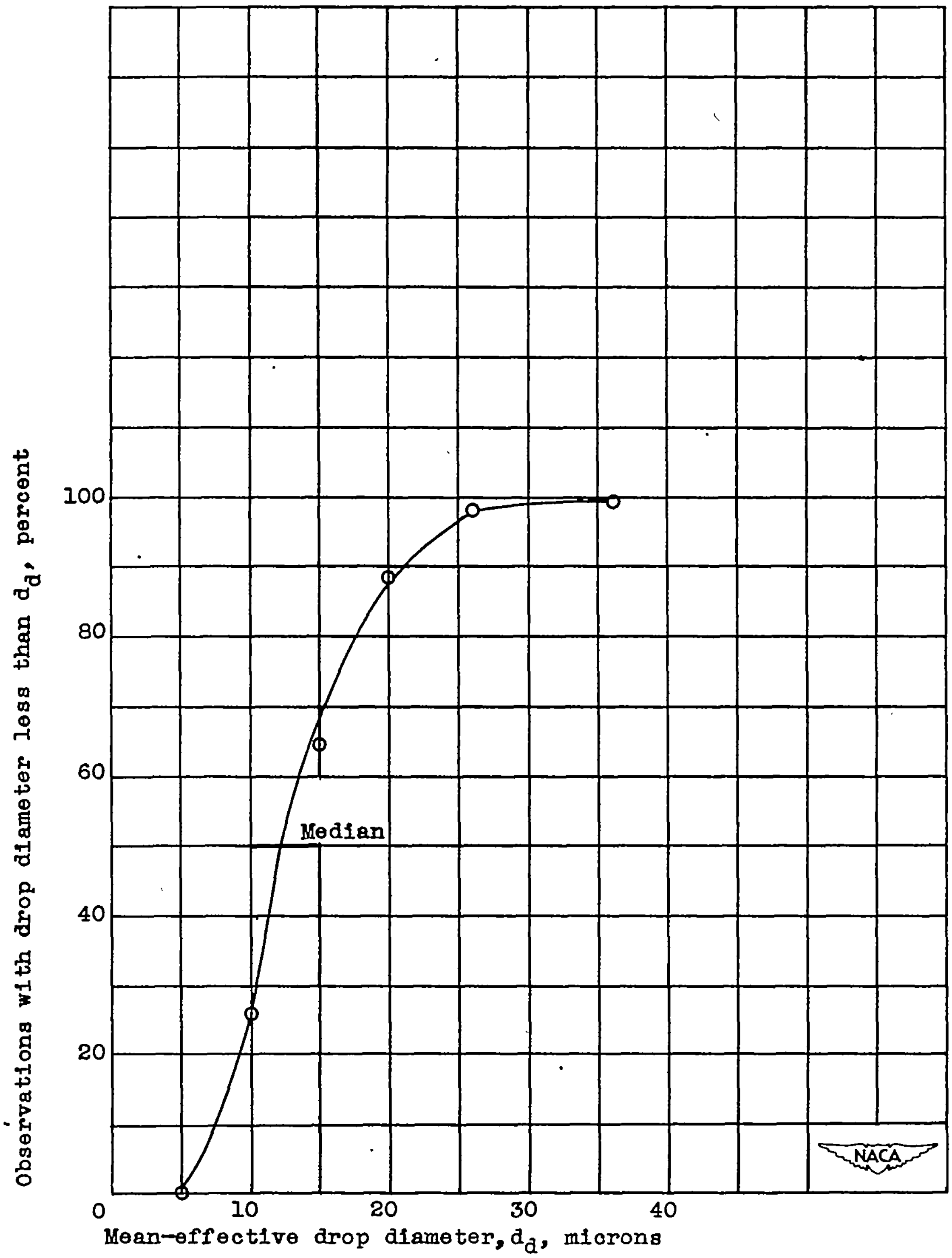

Figure 3. - Ogive of drop diameter measured in icing clouds for 93 observations during 31 flights.

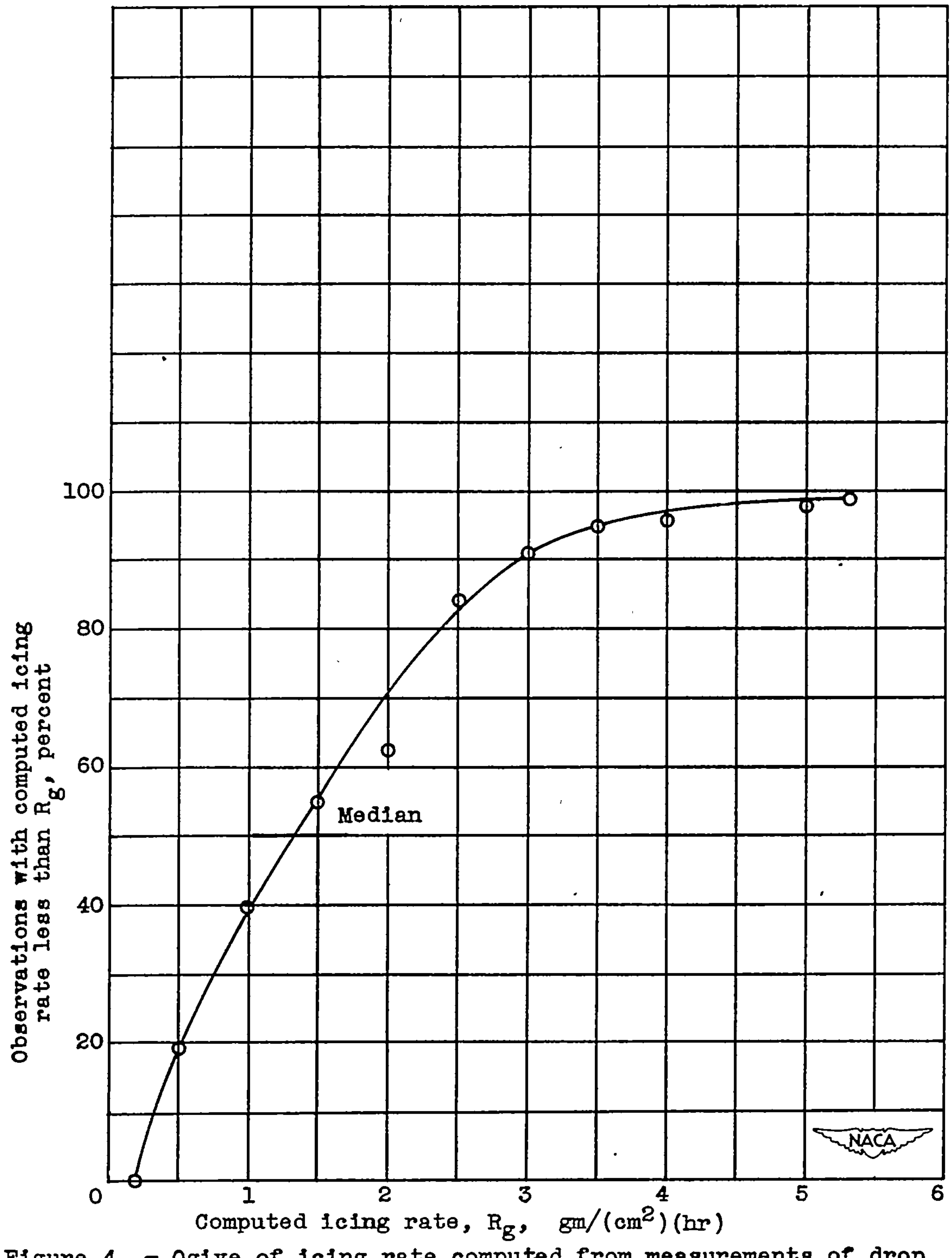

Figure 4. - Ogive of icing rate computed from measurements of drop size and liquid-water content in icing clouds. Icing-rate computations based on collection efficiency of 3-inch-diameter cylinder moving at 200 miles per hour, temperature of 15° F, and pressure altitude of 10,000 feet.

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