NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2142

PHOTOMICROGRAPHIC INVESTIGATION OF SPONTANEOUS FREEZING TEMPERATURES OF SUPERCOOLED WATER DROPLETS

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SUMMARY

A photomicrographic technique for investigating supercooled water droplets has been devised and used to determine the spontaneous freezing temperatures of supercooled water droplets of the size ordinarily found in the atmosphere. The freezing temperatures of 4527 droplets ranging from 8.75 to 1000 microns in diameter supported on a platinum surface and 571 droplets supported on copper were obtained.

The average spontaneous freezing temperature decreased with decrease in the size of the droplets. The effect of size on the spontaneous freezing temperature was particularly marked below 60 microns. Frequency-distribution curves of the spontaneous freezing temperatures observed for droplets of a given size were obtained. Although no droplet froze at a temperature above 20° F, all droplets melted at 32° F. Results obtained with a copper support did not differ essentially from those obtained with a platinum surface.

INTRODUCTION

Although many important advances have been made in the control of ice formation on aircraft in flight, little progress has been made toward an understanding of the fundamental processes involved in the formation of ice or the prediction of such formation.

Because the presence of supercooled water in the atmosphere is primarily responsible for aircraft icing, it is necessary to know the properties of supercooled water for a complete understanding of the icing process. Although supercooled water has been observed and reported for over two centuries, considerable disagreement exists as to the degree of supercooling possible and the factors that influence supercooling.

During the last 20 years, a few systematic laboratory investigations of supercooled water have been conducted. The studies of Meyer and Pfaff (reference 1), Tammann and Bückner (reference 2), and Rau (presented in reference 3) in Germany, Doucet (reference 4) in France, Cwilong (reference 5) in England, and Dorsey (references 6 and 7) and Heverly (reference 8) in the United States are of particular interest.

Three of the many factors investigated that are thought to influence the degree of supercooling may be particularly important in the prediction of aircraft icing in a supercooled cloud:

1. Effect of contaminating agents, such as undissolved substances in the water

2. Quantity of water comprising the sample, for example, the diameter of a supercooled droplet

3. Length of time the droplet has been at or below 32° F

The results reported in references 1 and 2 on bulk water indicate that impurities in the water are an important factor in its supercoolability.

In references 6 and 7, 3- to 4-milliliter samples of water were used in sealed or stoppered glass tubes and it was found that the temperature of spontaneous freezing of supercooled water was characteristic of the sample of water. (The term spontaneous freezing herein refers to crystallization occurring without external stimuli, such as seeding by an ice crystal.) It was concluded from the observations that the presence of "motes" (undissolved substances in the water or matter bounding the sample) accounted for the spontaneous freezing temperature of a particular sample at a particular time.

The presence of fine particles in the water was found to be an important factor in terminating supercooling (reference 4). The investigation indicated, however, that the presence of these particles is not always necessary in the formation of the microcrystal. It was also found that the degree of supercooling increased with decreasing volume of water.

In reference 3, it was reported that freezing of supercooled water on a polished metal surface started on special "freezing nuclei," which determined the freezing temperature. It was stated that these freezing nuclei can gradually be made inactive by successive freezings. By rendering all freezing nuclei inactive, it was found that water could be supercooled to -72° C. A marked decrease in surface tension below about -55° C was also reported.

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An unsuccessful attempt to duplicate the results of reference 3 was reported in reference 5. So long as only air or pure water vapor was present in the surrounding chamber, none of the unusual phenomena reported were found. It was noted only that "supercooled droplets froze on the test plate at various temperatures, which were constant for each droplet. Successive melting and freezing did not lower the freezing points."

An investigation (reference 8) has recently been conducted on spontaneous freezing temperatures of supercooled droplets suspended by a thermocouple and on wax paper for purposes of comparison. It was found that below 400 microns the rate of decrease of the spontaneous freezing temperature varied inversely with droplet diameter. However, it was also found that the spontaneous freezing temperature was independent of the source of the water used to obtain the droplets.

The previously mentioned investigators seem to agree in general as to the importance of the effect of time on the spontaneous freezing temperature. It may be concluded from their work that, with the exception of sudden chilling where a large temperature gradient is present, the time a sample has remained in the supercooled state is not an important factor. Rather, the temperature reached by any part of the water sample is important.

The purpose of an investigation conducted at the NACA Lewis laboratory, and described herein was to study the spontaneous freezing temperatures of droplets within the size range encountered in a supercooled icing cloud in order to determine size dependency. Because the spontaneous freezing temperatures of various samples of water investigated by Dorsey (reference 7) differed by as much as 29° F, although all samples were approximately the same volume, a statistical study of water droplets was made to determine if similar variations in freezing temperature exist for droplets of a fixed size. No attempt was made to find any absolute minimum temperature limit for the existence of supercooled water or to determine the effect of time on the spontaneous freezing temperature. Although further research under conditions closely duplicating the supercooled cloud in the atmosphere is necessary, it is believed that the effect of size and presence of impurities on the state of the water droplets in a natural cloud may be similar to that found in this investigation.

In the investigation reported herein, the freezing temperatures of 4527 droplets condensed on a platinum surface and 571 droplets on a copper surface were obtained. Photographs were taken through a microscope at 1-second intervals and a corresponding record of the temperature was made. The method used has several desirable features: (1) The temperature of the supporting surface can rapidly be brought to a desired temperature as well as be changed at controlled time rates; (2) a permanent history of a group of droplets is obtained for each data run; (3) data on a large number of droplets can be taken rapidly without sacrificing accuracy of observation; and (4) a study of the photographic history of a given supercooled droplet allows an accurate determination of its state at a given temperature. Because conventional precision cryostats are not adaptable to rapid cycling of temperature, the temperature of the supporting surface was controlled by radio-frequency induction heating. 1327

APPARATUS AND PROCEDURE

The apparatus employed for this investigation is schematically shown in figure 1. The droplet-supporting surface (fig. 1(b)) consisted of very thin (0.003-in.) platinum foil 0.180 inch in diameter. Sandwiched between the foil and a temperature equalizing plate of 1/32-inch sheet copper was an iron-constantan thermocouple (No. 28 wire) in excellent thermal contact with the platinum. The copper was soldered to the top of a small cylindrical piece of steel that was heated by induction from a surrounding copper coil. The steel was attached on its lower side to a copper rod that was immersed in a cold bath consisting of dry ice and the solvent Varsol. Radio-frequency heating was used to compensate for the heat sink. The temperature could be rapidly changed or kept nearly constant by varying the power supplied to the radio-frequency oscillator. The platinum support surface was surrounded by a small brass chamber with plastic observation ports. This chamber provided a local atmosphere that was isolated from the exterior atmosphere. A thermocouple was also placed in this enclosed air space to record the temperature of the air 1 centimeter from the surface. The surface temperature was recorded by a recording potentiometer that printed the temperature on a strip chart at 1-second intervals. A microswitch was utilized to actuate a relay on a 16-millimeter movie camera, which viewed the surface through a microscope and exposed a single frame at the instant the temperature was printed. A second microscope viewed the surface at an angle for visual observation during each run. A microscope lamp at a 20° angle with the surface was used for illumination. The windows were kept free of condensation by a very light jet of air directed against their external side. A general view of the apparatus with the low-magnification chamber in place is shown in figure 2.

For droplets smaller than 23 microns, it was necessary to modify the original chamber surrounding the surface in order to allow the objective of the microscope to be closer to the surface for higher magnification. This chamber was also of brass and had one large window close to the platinum surface. The surface was in no manner changed from that described in the preceding paragraph. The window was made from a microscope coverglass. Because of the much smaller chamber volume, additional air was supplied from without the chamber to obtain moisture when needed. In order to supply the additional air, two long copper tubes (1/16-in inner diameter), which were cold because of thermal contact with the cooling rod, were inserted into the chamber from opposite sides. A rubber bulb attached to one tube forced additional air to circulate through the chamber when additional moisture was desired. The platinum surface was protected by an inner shield that allowed the new air to enter the inner region of the chamber only through small holes immediately beneath the glass window. The air forced in could not impinge directly on the platinum surface and the inner chamber was thus isolated from the open ends of the small tubes entering the chamber. Because the window was close to the supporting surface, the entire apparatus was placed in a large refrigerated chamber. This chamber air could be readily dried and chilled to a suitable low temperature to reduce the temperature gradient between the surface and the window of the small chamber and to eliminate the necessity of using an air jet to keep condensation off the window. In order to be certain that changing the chamber surrounding the surface did not influence the accuracy of the data obtained, the size of the largest droplets studied with the second chamber was allowed to overlap those of the lower range investigated with the low-magnification chamber.

Water droplets were obtained on the surface and then supercooled by the following procedure: Frost was deposited on the surface by lowering the temperature to approximately -30° F; the frost was then melted. Because of surface tension, the water gathered into small approximately hemispherical droplets. The average size of the group of droplets obtained depended on the amount of frost gathered. Next, the temperature was lowered to 32° F and then decreased at a rate of 0.2° to 0.5° F per second.

Size calibration of each run was made by using a stage micrometer. The total magnifications used (including magnification by viewer) were 20 to 30 times for the larger droplets and up to 200 times for the smallest droplets measured. Although higher magnification by the microscope would be desirable, a limit is imposed by the decrease in depth of the field at high magnifications. Visual observations indicated that the droplets were approximately hemispherical in shape; the diameter measured was therefore the diameter of the circle of contact of the hemisphere with the supporting surface. Because of the possibility that evaporation or condensation may change the size of a droplet as the temperature is lowered, the diameter was measured just after freezing took place and before any frost growth was detected on the frozen droplet. 1327

The spontaneous freezing of the droplets was determined by a change in appearance on freezing. In studying each droplet in the photomicrograph frame-by-frame throughout its cooling history, a frame was reached in which a sudden change in opacity occurred. The corresponding temperature was taken as the freezing temperature. As a check on the reliability of this method, a comparison was made between the freezing temperature of large droplets (over 500 microns) obtained by observing the abrupt temperature rise associated with the release of latent heat, and the visual method. In all cases investigated, the temperature at which the abrupt temperature rise occurred corresponded to the freezing temperature as determined from the frame number of the photograph showing a change in opacity. For droplets smaller than 500 microns, the latent heat released could not be detected by the thermocouple in most cases. A very large drop (1600 microns) is shown before and after freezing in figures 3(a) and 3(b), respectively. In the 1-second interval between the two pictures (frames 110 and 111), the large drop in the lower right quadrant of the supporting surface turned opaque or milky. Figure 4 is a copy of the strip chart from the recording potentiometer. A temperature rise of approximately 2.5° F occurred between frames 110 and 111 due to the release of latent heat as this large droplet froze.

Selected photographs from one data run (fig. 5) are typical of those obtained in the investigation. Inasmuch as the droplets were photographed each second, the frame numbers correspond to the elapsed time in seconds from the start of the data run. Because of the low angle of illumination from one side, each liquid droplet has two distinct high lights that can be used as a guide to its location.

The accuracy of the temperature measurement provided by the thermocouple located beneath the platinum foil was periodically checked by noting the temperature at which melting occurred. Within the accuracy of the recording potentiometer, which was read to the nearest 0.5° F, the melting always occurred at 32° F for all chamber conditions used. A critical survey of the photographic records of droplet freezing showed no areas on the supporting platinum in which freezing proceeded more readily than in other areas. Suitable temperature uniformity on the support surface was thus indicated. Although only the temperature of the platinum surface was accurately controlled, the small droplet size relative to the supporting surface and the presence of an isolated air space between it and the surrounding chamber permitted only a small temperature gradient within the droplet. As an experimental check on the effect of the temperature difference in the droplet on the spontaneous freezing temperature of the droplet, runs were made with various fixed chamber temperatures. The chamber temperature recorded was measured by the thermocouple placed 1 centimeter above the platinum surface in the low-magnification runs and at the chamber wall for the high-magnification runs.

Freezing runs made with the radio-frequency oscillator turned off were compared with runs in which compensating heat was used to decrease the cooling rate in order to determine the effect of the radio-frequency field on the droplet freezing temperature. No difference was noted. Because the induction coil of the radio-frequency heater encircled the iron cylinder below the platinum surface, the flux density through the water droplets was assumed negligible.

Various methods of cleaning the inside of the chambers and the support surface were used. The surface was rinsed with water of varying degree of purity. The droplets condensed on the surface thus had a possibility of being contaminated to a variable degree. The data were examined to determine the influence of the surface finish of the platinum support, modified by gently scrubbing the surface, on the freezing temperatures measured. As a further check on the effect of the support surface on the spontaneous-freezing-temperature measurements, the platinum foil was replaced by copper foil and additional data were taken for comparison.

RESULTS AND DISCUSSION

The spontaneous freezing of 5098 droplets was observed. The size, the length of time below the melting point, and the spontaneous freezing temperature of each droplet were recorded. The distribution of droplet sizes for which the spontaneous freezing temperatures were determined is shown in figure 6. For comparison, a distribution of the mean effective droplet diameters found in icing clouds (references 9 to 11) is shown in figure 7. The region investigated in this report corresponds fairly well to the droplet sizes ordinarily found in natural clouds when it is considered that spherical droplets of the same volume as hemispheres would have smaller diameters than that given for the near-hemispherical droplets studied in this report and that the mean effective droplet diameter is a volume-median droplet size.

The spontaneous freezing temperatures obtained for droplets ranging in size from 8.75 ±2.5 to 230.0 ±11.5 microns are plotted in figure 8 for a constant value of droplet size indicated in each figure. In each case shown, the frequency of occurrence of a particular freezing temperature as a function of the freezing temperature of droplets of a given size provides a distribution curve with a well-defined peak frequency. The ordinate was adjusted to make the peak frequency unity, with other frequencies proportional to the peak frequency. As the number of droplets observed for a particular size increased, the more nearly a smooth single-peaked curve could be drawn through the plotted data, as indicated by the frequency-distribution curves for 46- and 69-micron droplets (figs. 8(f) and 8(g), respectively), where over 600 droplets were observed in each group. The standard deviation computed for each size group is given with each figure. With the exception of the 230-micron data (fig. 8(l), where the standard deviation was 7.63° F, all size groups had standard deviations within the range 4.31° to 5.75° F. The greatest difference between the maximum and the minimum freezing temperatures observed for droplets of the same size was 41.5° F for 115-micron droplets (fig. 8(i)). For comparison, data taken on the copper surface is plotted with that taken on platinum in figures 8(f) and 8(h) for droplet diameters of 46 and 92 microns, respectively. As indicated by these figures, the distribution curves obtained are similar.

The distribution of spontaneous freezing temperatures of 3- to 4-milliliter samples of water investigated by Dorsey (reference 7) is shown in figure 9. The data have been plotted on the same coordinates as figure 8. Comparison of this curve with the frequency-distribution curves for droplets indicates that the same type of variation in the spontaneous freezing temperature found for bulk water exists for droplets of a given size. This comparison suggests that the variations in the freezing temperature of droplets of a fixed size may be due to the presence of "motes", as postulated by Dorsey for bulk water.

The variation of average, maximum, and minimum freezing temperatures with droplet size taken from the data used for figure 8, with additional data on droplets up to 1000 microns, are shown in figure 10. The average spontaneous freezing temperature for each size decreased as the droplet size decreased for the entire size range. Below 60 microns, the spontaneous freezing temperature decreased rapidly with size. This curve shows the same trend as that published by Heverly (reference 8). The pronounced change in slope in Heverly's curve at 400 microns appears at 60 microns in the data of this report. The wide variation in spontaneous freezing temperature for droplets of a given size is indicated by the large separation of the curves for the maximum and minimum temperatures observed for each size. None of the 4527 droplets supported by the platinum surface was observed to freeze spontaneously at a temperature above 20° or below -38° F, but all droplets melted at 32° F.

The average spontaneous freezing temperatures for droplets of given sizes supported by a copper surface are plotted in figure 11. For comparison, the data of the average spontaneous freezing temperatures for droplets of given sizes on platinum are also shown. Good agreement exists between the data taken on the copper and those on the platinum support, which shows that the nature of the supporting metal surface does not materially influence the freezing temperature.

Selected photographs of droplets from two data runs are shown in figures 5 and 12. The first series (fig. 5) illustrates the general dependency of the spontaneous freezing temperature on the size of the droplet, as indicated in figure 10. At temperatures as low as 0.5° F, none of the droplets were frozen in spite of being as much as 31.5° F below the melting point (fig. 5(c)). In figure 5(d), with the surface at -5° F, three droplets were frozen. Figure 5(e) shows the droplets at -9.5° F; here the larger droplets were frozen but the small droplets were still liquid. As the temperature decreased to -30° F (fig. 5(j)), the small droplets gradually froze. Frost growth on the frozen droplets can be seen as the temperature decreases.

Photographs from another run are presented in figure 12. The first frozen droplets appear in figure 12(e), which is at -3.5° F. In this photograph, several small droplets were frozen but the majority of the large droplets, including the largest drop present, was still liquid. Figure 12(h), the last photograph shown of this series, at -14° F, has most of the droplets frozen. Close examination of this photograph shows a few small droplets that were not frozen.

Also in figure 12 is shown two droplets uniting to form a single larger droplet, although both are in the supercooled state. In the center of figure 12(b) a droplet can be seen just below the largest drop, at a temperature of 28.5° F. At 20° F (fig. 12(c)), the droplet can be seen uniting with the large droplet, and in the next photograph, 10 seconds later, they are one droplet at a temperature of 18° F.

Repeated observations of the freezing temperature of a given droplet frequently indicated that the spontaneous freezing temperature may remain constant during successive freezings. The results of successive observations (3 or 4 runs) of the freezing temperatures of 27 different droplets are presented in table I. The successive freezing temperatures of 11 of the 27 droplets were within 0.5° F of their average temperature for the runs. The other 16 droplets show typical variations observed in the freezing temperature of droplets. Droplets 10 and 22 are interesting inasmuch as for both droplets the second run has a marked change in spontaneous freezing temperature from that of the first and third runs. The changes are in opposite directions for each of these droplets.

The fluctuations in the freezing temperatures might be explained on the basis of chance seeding, because ice crystals have always been found to initiate crystallization if dropped into a test tube of supercooled water. It would be difficult, however, to explain the change in the freezing temperature of droplets 10 and 22 for the second freezing in this way, because the first and third freezings of each droplet were nearly at the average temperature for all droplets of the respective size.

Because cold surfaces support and surround the droplets, frost will be present to some extent and a possibility always exists in an experiment of this type of frost particles seeding the supercooled water. As a check on this possibility, water droplets were suspended at the boundary of two oils insoluble in water, one having a density slightly less and the other having a density slightly greater than water. A thermocouple was placed adjacent to the droplet. The same randomness in the freezing temperature was observed; that is, although the general tendency was for the larger droplets to freeze first, there was considerable variation in the spontaneous freezing temperature for droplets of a given size. Inasmuch as there was no air-water boundary and the droplets did not rest on a metallic surface, it should have been more difficult in this case for frost to come in contact with the water droplets.

The temperature of the chamber surrounding the droplet supporting surface determined the amount of frost forming on the surface itself (for a given amount of moisture in the chamber) as well as any temperature gradient within the droplet. In the many runs analyzed with various fixed chamber temperatures, no consistent shift in the spontaneous freezing temperatures measured was observed. For example, with the surrounding chamber warmer than the surface, some runs indicated that the droplets were freezing at surface temperatures above average, whereas others indicated freezing at surface

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temperatures below average. Because the droplets were not the same particles of water, the variations observed were likely due to differences in impurities in the water. In order to illustrate the type of variation observed, the average spontaneous freezing temperatures for 69-micron droplets, measured with the surrounding c' iber temperatures as indicated, are shown in table II. The mean deviation in the average spontaneous freezing temperatures for various fixed chamber temperatures from the average for all 69-micron droplets observed is 1.3° F. The droplets in this example froze, on the average, at higher temperatures when the walls were warmer than the droplet (even though freezing might be expected to be retarded if the top of the droplet is somewhat warmer than the surface) than when the walls were colder than the droplet. Even if an average error of 2° F (or approximately 1° C) is assumed to be introduced by the lack of homogeneity of the droplets surroundings, in view of the large magnitude of the effects measured, it is felt that the conclusions drawn from the data are not invalidated.

The surface finish of the platinum support did not appreciably influence the spontaneous freezing temperatures of the droplets. For example, droplets did not freeze sooner when in contact with a fine scratch in the surface than when on a relatively smooth area of the surface. Nothing could be done about the adsorbed layer of water present on the droplet support. This layer may influence the spontaneous freezing temperatures of the droplets in contact with it. Because the chamber surrounding the platinum support was changed for droplets below 23 microns in diameter, data between 18 and 100 microns taken with both high- and low-magnification chambers were compared. No significant shift occurred in the average spontaneous freezing temperatures for various sizes determined with the high-magnification chamber from those found with the low-magnification chamber. Light mechanical vibrations were present in the laboratory during many of the data runs due to the presence of heavy machinery operating on a lower floor of the building. During one data run, the vibration was heavy enough to affect the clarity of the photographs. No significant shift in data were observed with and without the presence of these vibrations.

An interesting effect was frequently observed when frozen droplets were rapidly warmed. A bright white flash appeared just at or before melting (30° to 32° F). This effect may have resulted from an increase in scattered light from the low-angle illumination due to the breaking up of the ice structure into small randomly oriented pieces in melting. It may also in some way be connected with the gas bubbles that are often seen in the droplets just after melting, and that gradually disappear as the droplet is supercooled again.

SUMMARY OF RESULTS

The spontaneous freezing temperatures of 4527 droplets on a platinum surface and 571 droplets on a copper surface in the range 8.75 to 1000 microns were observed and the following results were obtained: 1327

1. The average spontaneous freezing temperature for each size decreased as the droplet size decreased for the entire range investigated. Below 60 microns, the decrease in the spontaneous freezing temperature with decrease in droplet size was particularly marked.

2. The frequency of occurrence as a function of the freezing temperature of droplets of a given size provided a distribution curve with a well-defined peak frequency.

3. The spontaneous freezing temperature of a given droplet tended to be the same on successive freezings.

4. No droplet froze spontaneously at a temperature above 20° F, but all droplets melted at 32° F.

5. Spontaneous freezing data taken with a copper supporting surface were not significantly different from that taken with a platinum support.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronatuics,
Cleveland, Ohio, February 24, 1950.

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TABLE I

SUCCESSIVE FREEZING TEMPERATURES OF GIVEN DROPLETS

Drop number	Drop diameter (microns)	Spontaneous freezing temperature, °F					
		Successive runs on same droplet				Average	Average from figure 10
		1	2	3	4		
1	23	-22	-22	-22	----	-22	-16.8
2	35	-20.5	-19	-17.5	----	-19	-15.1
3	46	-16	-16	-16.5	----	-16.2	-13.5
4	46	-20.5	-21	-19	----	-20.2	-13.5
5	69	-14	-15.5	-14	----	-14.5	-13.3
6	92	-12	-13	-12.5	----	-12.5	-12.1
7	138	-14	-10	-10	----	-11.3	-11.1
8	161	-12	-13.5	-12	----	-12.5	-11.5
9	253	- 9.5	-10	-10	----	- 9.8	- 7.6
10	253	- 8.5	.5	- 7	----	- 5	- 7.6
11	299	- 7.5	- 7	- 8	-7	- 7.4	- 6.5
12	322	- 7	- 7.5	- 7	-7	- 7.1	- 6.3
13	322	- 4	- 4	- 4.5	-4	- 4.1	- 6.3
14	322	- 9	- 8	- 7.5	-8.5	- 8.3	- 6.3
15	322	- 5.5	- 7.5	- 7.5	----	- 6.8	- 6.3
16	368	- 6.5	- 4	- 4.5	-3.5	- 4.6	- 5.5
17	376	- 7.5	- 7	- 8	-7.5	- 7.5	- 5.2
18	391	- 7	- 9.5	- 8	-4.5	- 7.2	- 5.0
19	414	- 7.5	- 8.5	- 9	-9	- 8.5	- 4.6
20	437	- 4.5	- 3.5	- 3.5	-5.5	- 4.2	- 4.1
21	460	- 3.5	- 3	- 2	----	- 2.8	- 3.6
22	460	- 2.5	-12.5	- 2	----	- 5.7	- 3.6
23	529	- 7	- 7	- 7	----	- 7	- 2.8
24	575	6	6	6	----	6	- 2.0
25	575	1	3.5	3.5	----	2.7	- 2.0
26	667	- 3	- 3	- 3	----	- 3	.8
27	713	1	0	1	----	.7	0

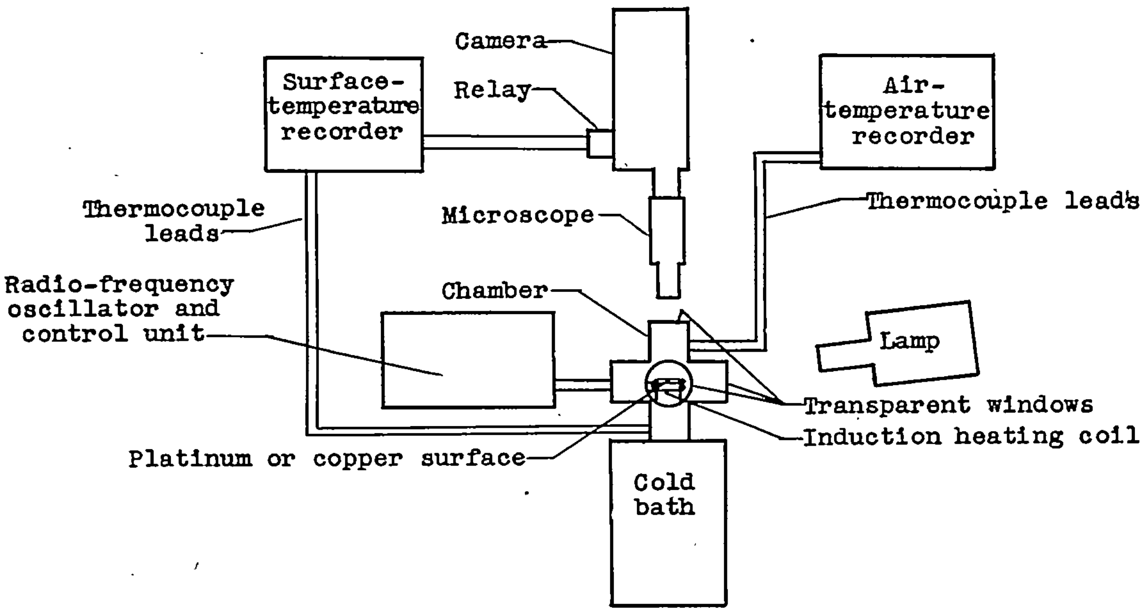
TABLE II

SPONTANEOUS FREEZING TEMPERATURE OF 69-MICRON DROPLETS

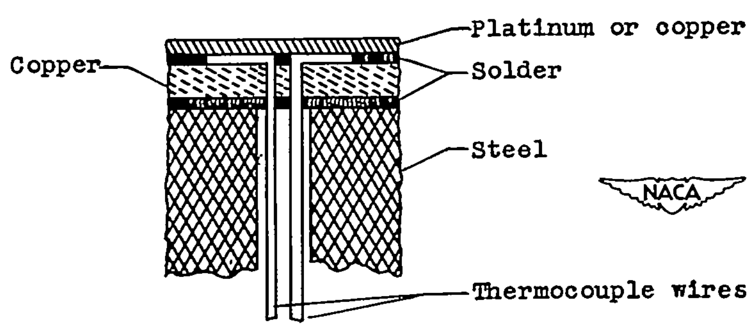
FOR VARIOUS FIXED CHAMBER TEMPERATURES

Chamber temperature range (°F)	Number of droplets observed	Average freezing temperature[a] (°F)
41 - 23	97	-11.9
22 - 14	202	-11.6
13 - 5	203	-14.7
4 - -4	123	-14.9
-5 - -22	50	-13.6

[a]Average spontaneous freezing temperature for all 69-micron droplets, -13.3° F; mean deviation of average freezing temperatures from average for all 69-micron droplets, 1.3° F.



(a) General schematic diagram of apparatus.



(b) Enlarged cross section of droplet-support assembly.

Figure 1. - Schematic diagrams of apparatus.

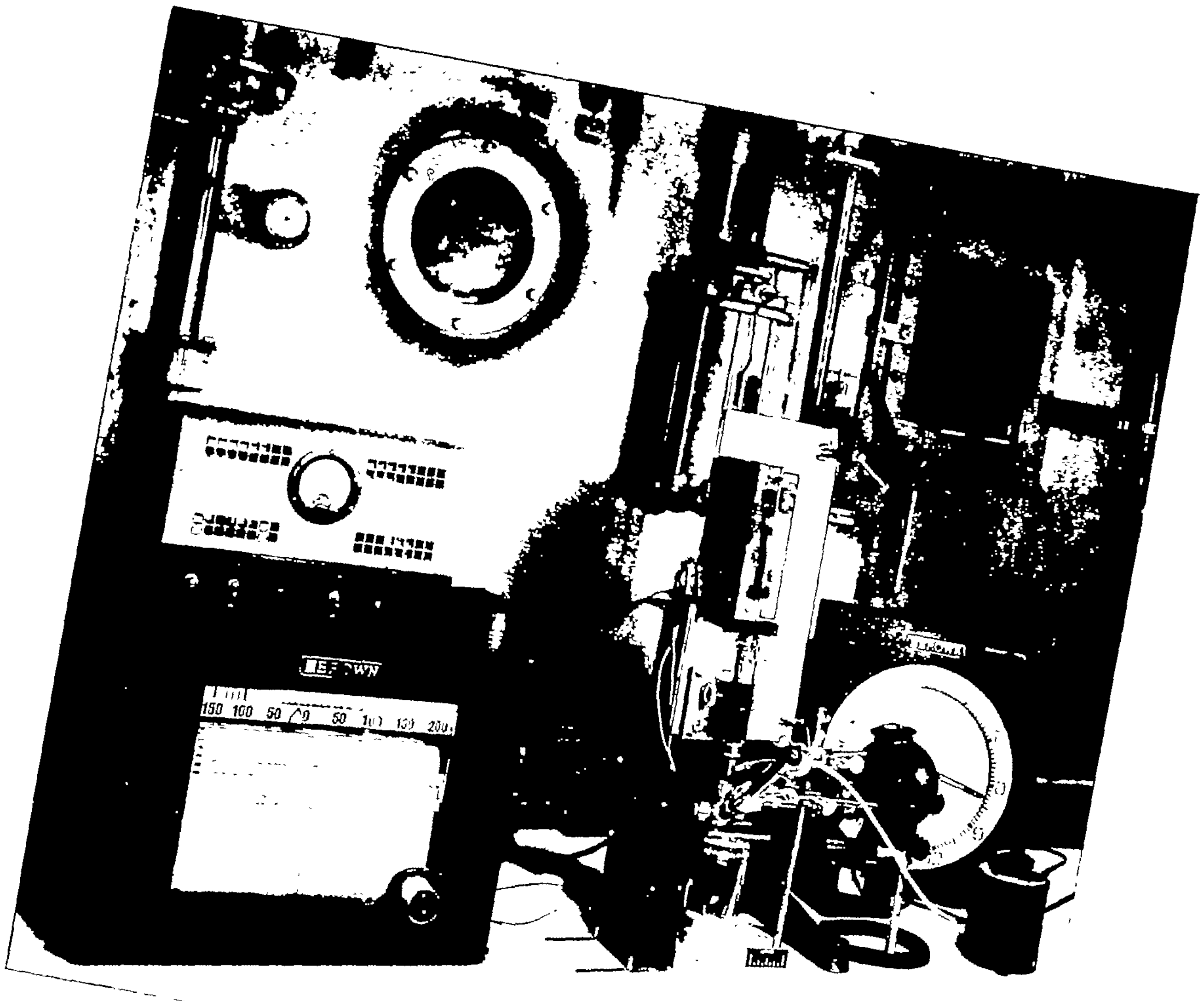


Figure 2. - Apparatus with low-magnification chamber in place.

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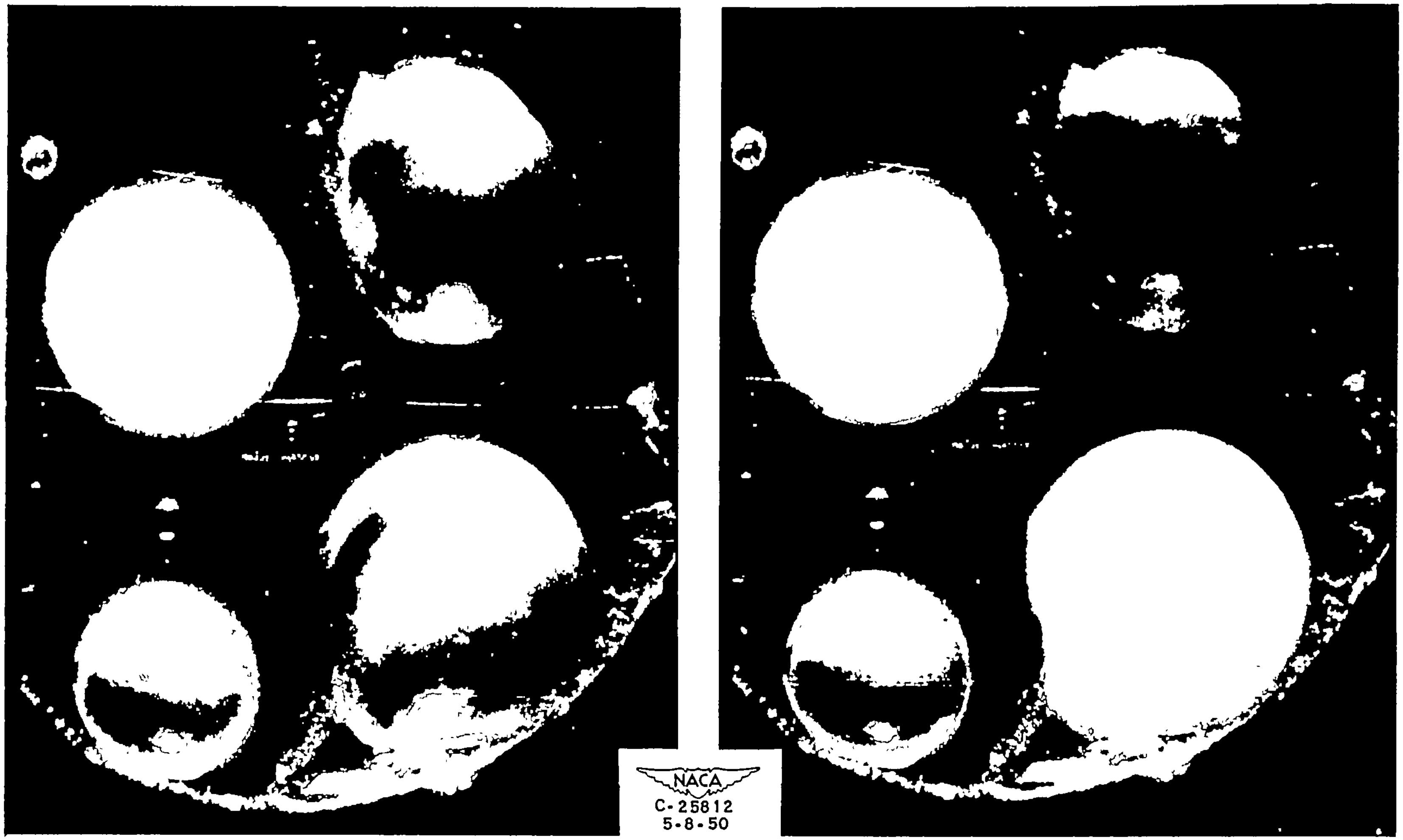


(a) Frame 110; before freezing; temperature, 3.5° F.

(b) Frame 111; after freezing; temperature, 6° F.

Figure 3. - Appearance of droplets before and after freezing. (1 in. = 1000 microns.)

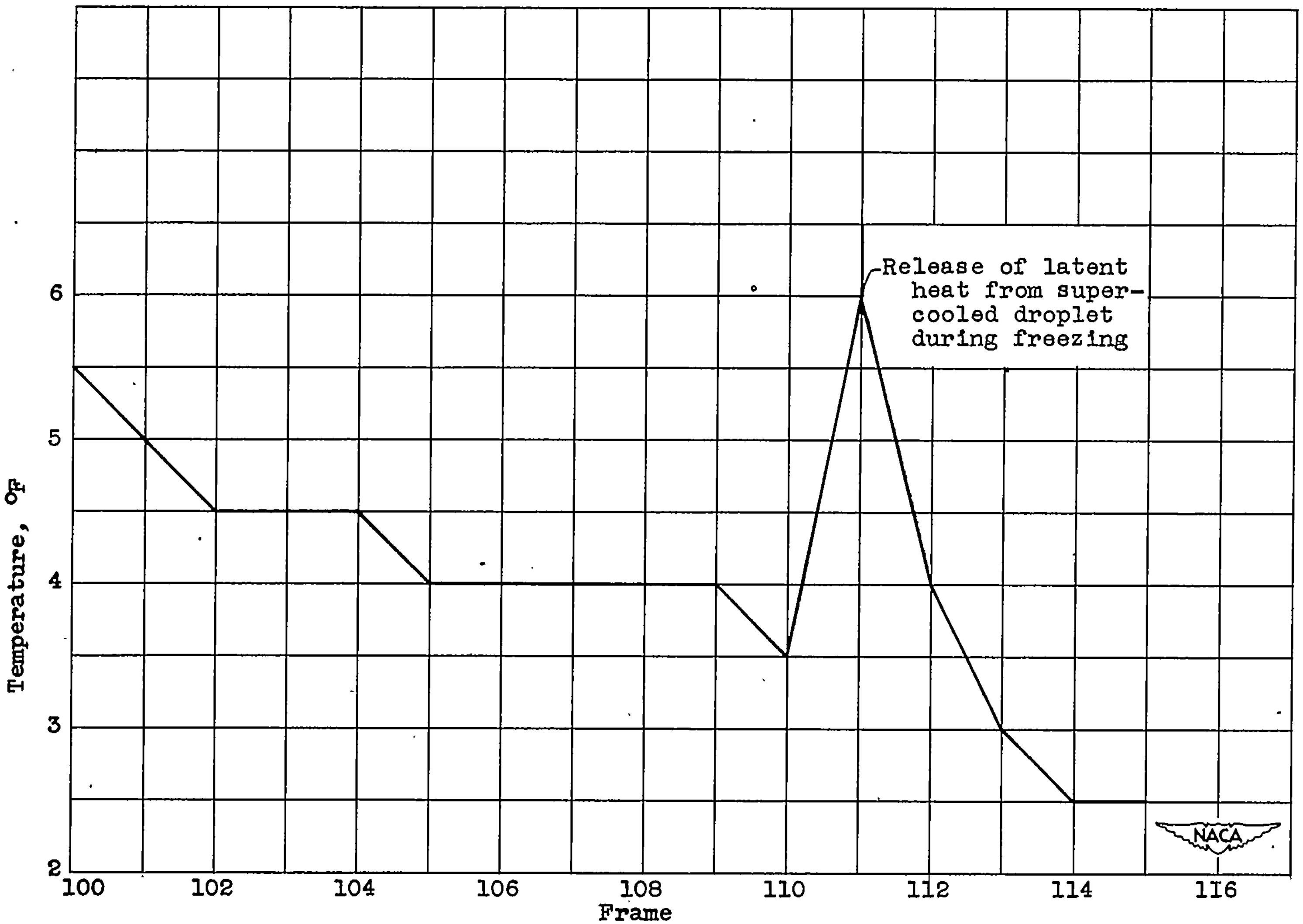
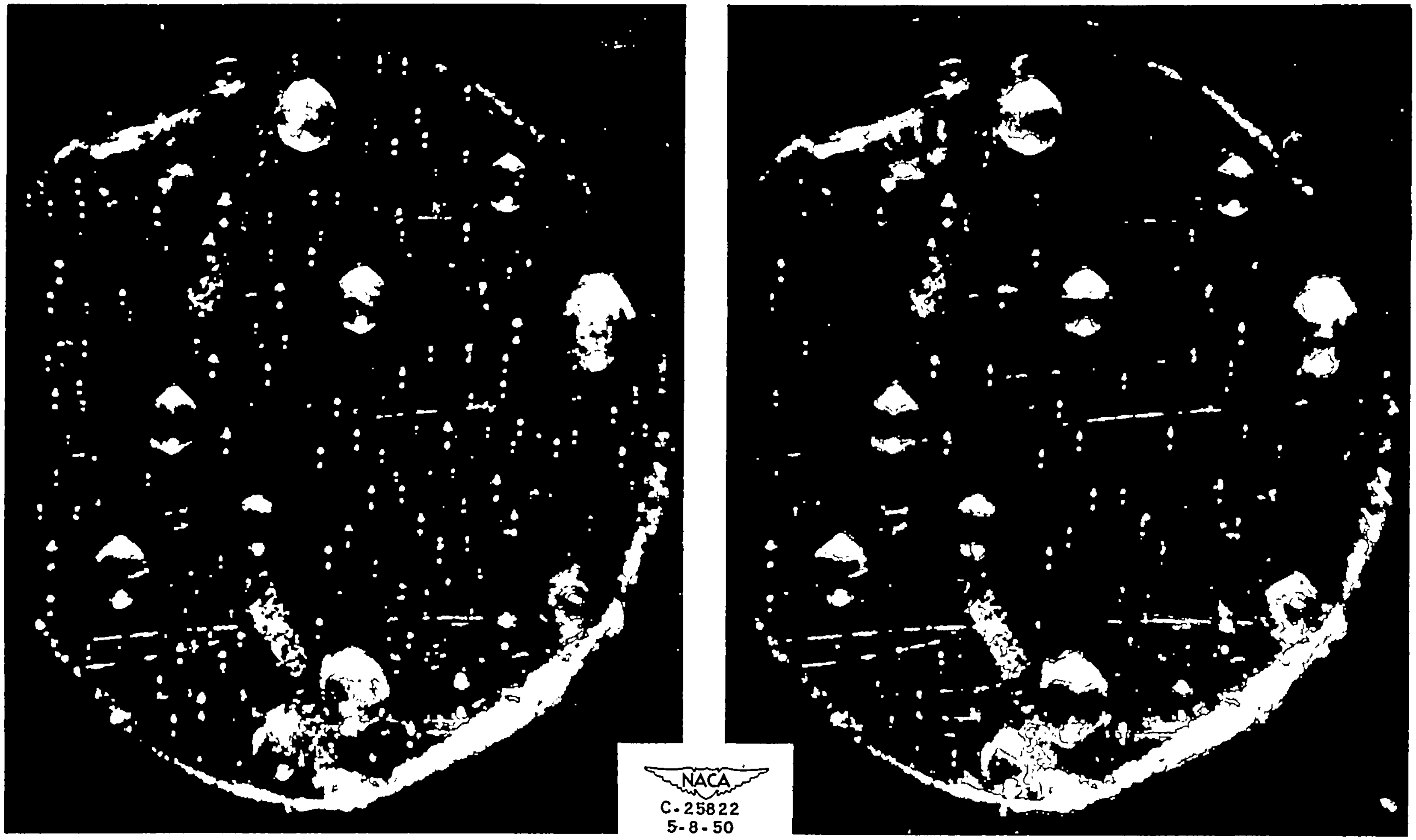


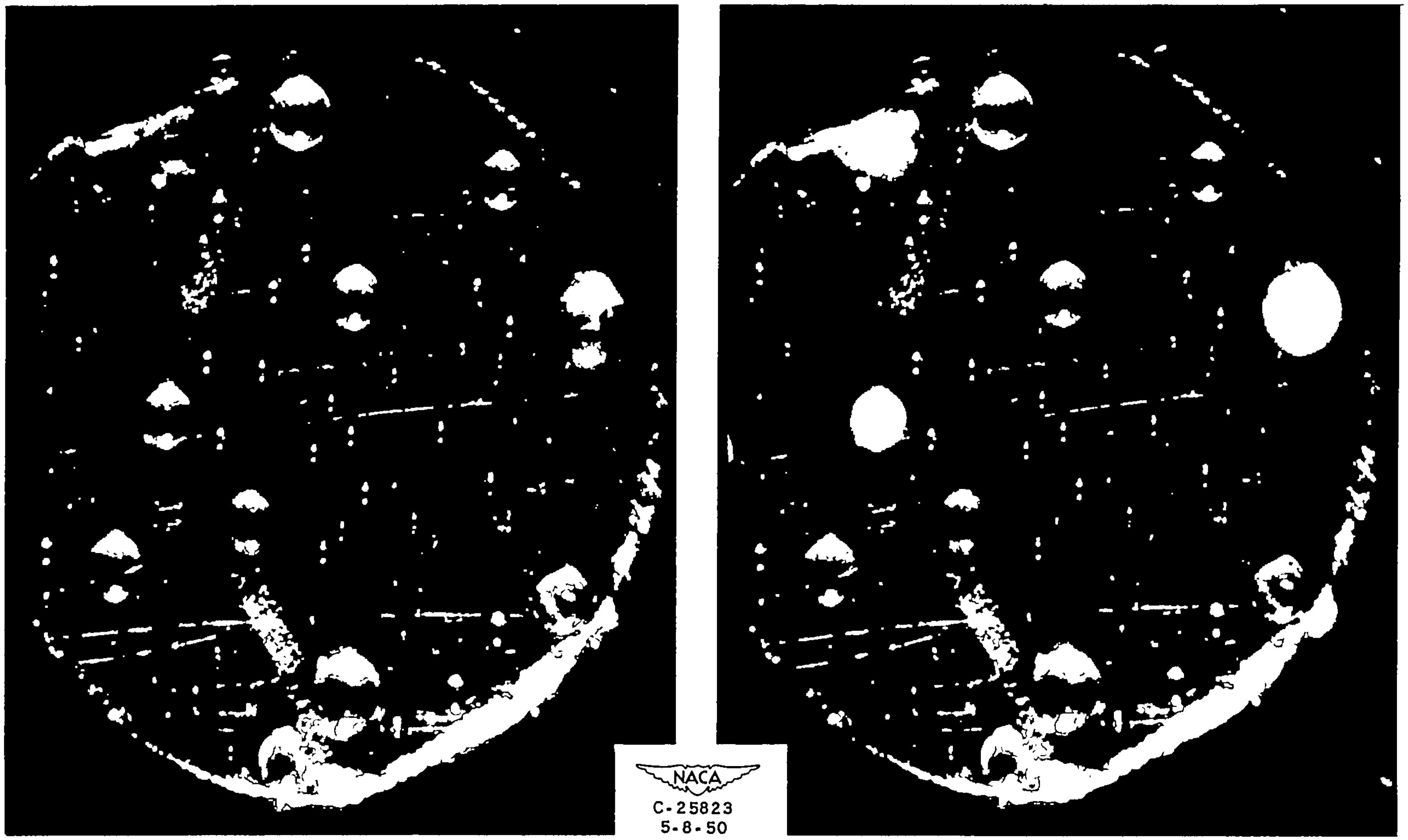
Figure 4. - Copy of chart from surface-thermocouple temperature recorder illustrating rise in temperature due to release of latent heat of fusion.



(a) Frame 10; temperature, 32° F.

(b) Frame 70; temperature, 10° F.

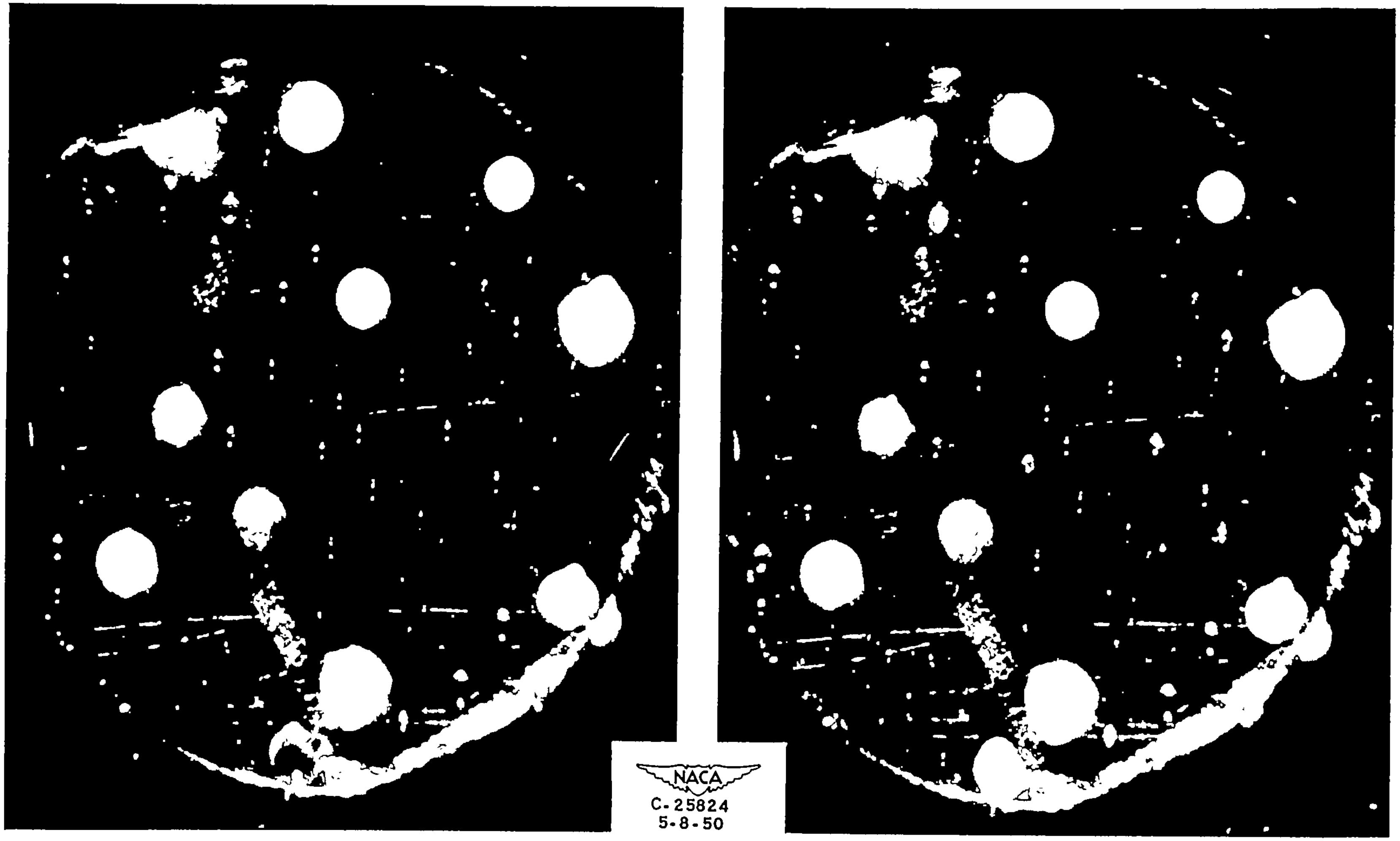
Figure 5. - Selected photographs from data film illustrating method of determining spontaneous freezing temperatures of supercooled droplets. (1 in. = 1000 microns.)



(c) Frame 100; temperature, 0.5° F.

(d) Frame 120; temperature, -5° F.

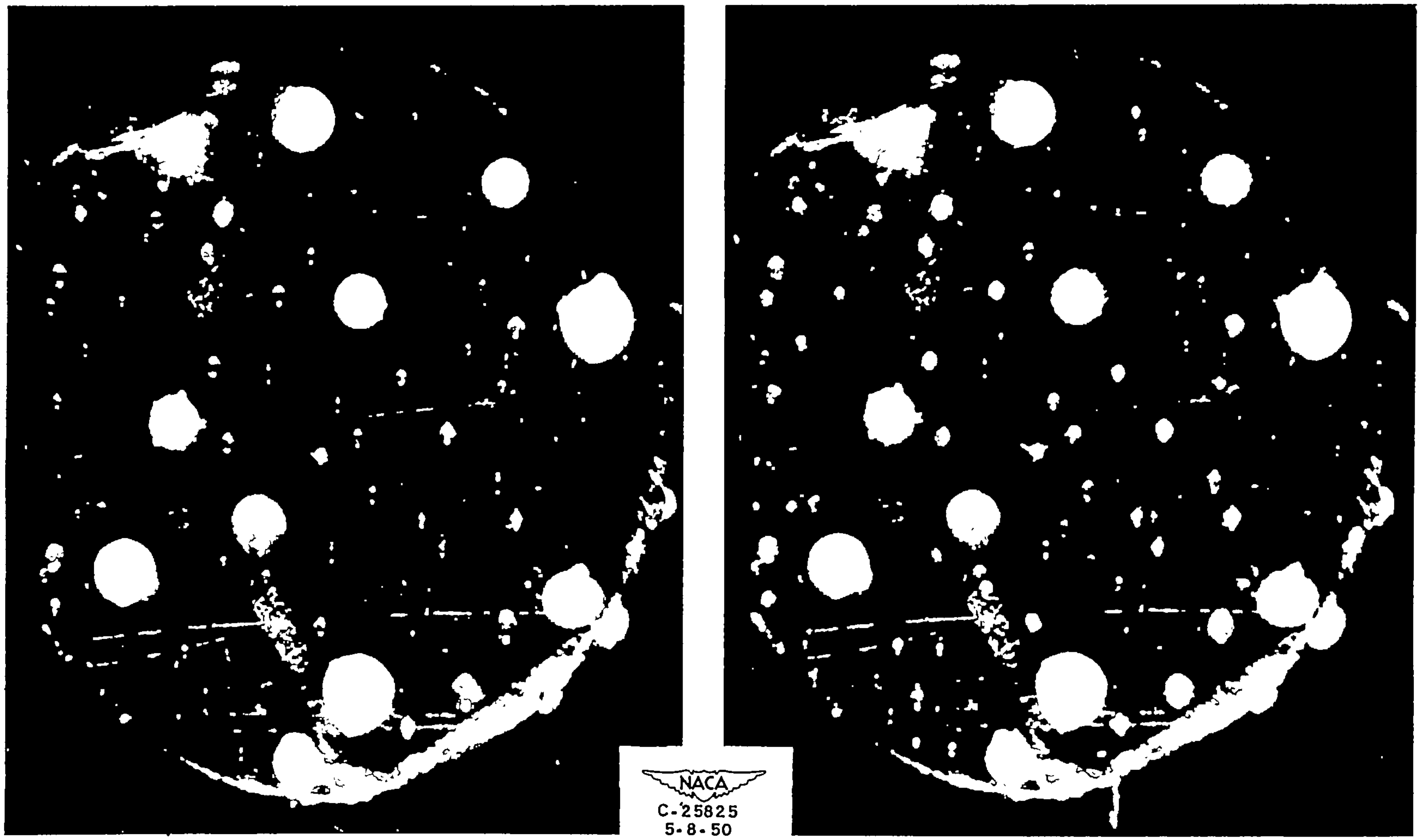
Figure 5.- Continued. Selected photographs from data film illustrating method of determining spontaneous freezing temperatures of supercooled droplets. (1 in.= 1000 microns.)



(e) Frame 140; temperature, -9.5° F.

(f) Frame 150; temperature, -12.5° F.

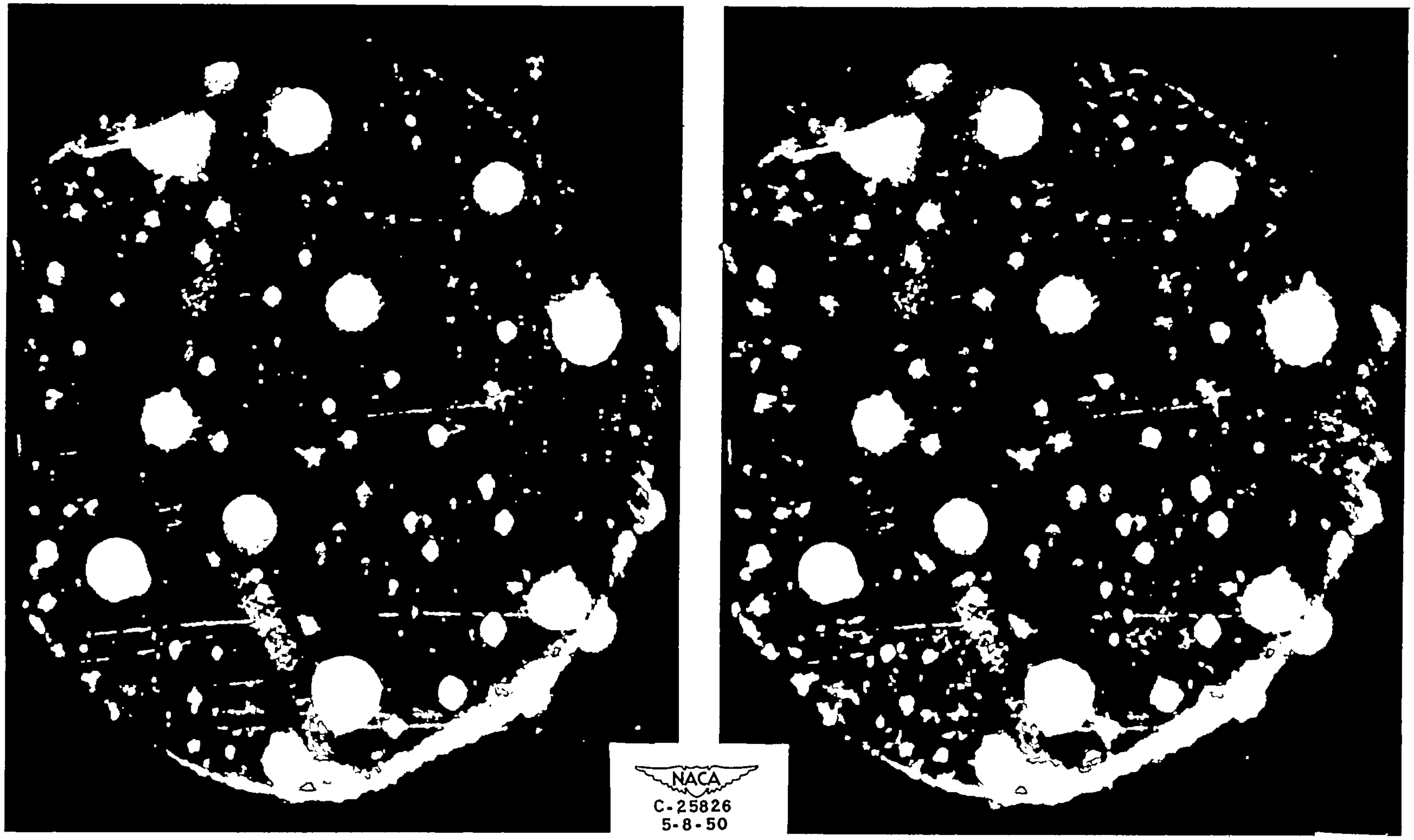
Figure 5.- Continued. Selected photographs from data film illustrating method of determining spontaneous freezing temperatures of supercooled droplets. (1 in. = 1000 microns.)



(g) Frame 160; temperature, -15.5° F.

(h) Frame 180; temperature, -19.5° F.

Figure 5.- Continued. Selected photographs from data film illustrating method of determining spontaneous freezing temperatures of supercooled droplets. (1 in. = 1000 microns.)



(i) Frame 190; temperature, -22° F.

(j) Frame 210; temperature, -30° F.

Figure 5.- Concluded. Selected photographs from data film illustrating method of determining spontaneous freezing temperatures of supercooled droplets. (1 in. = 1000 microns.)

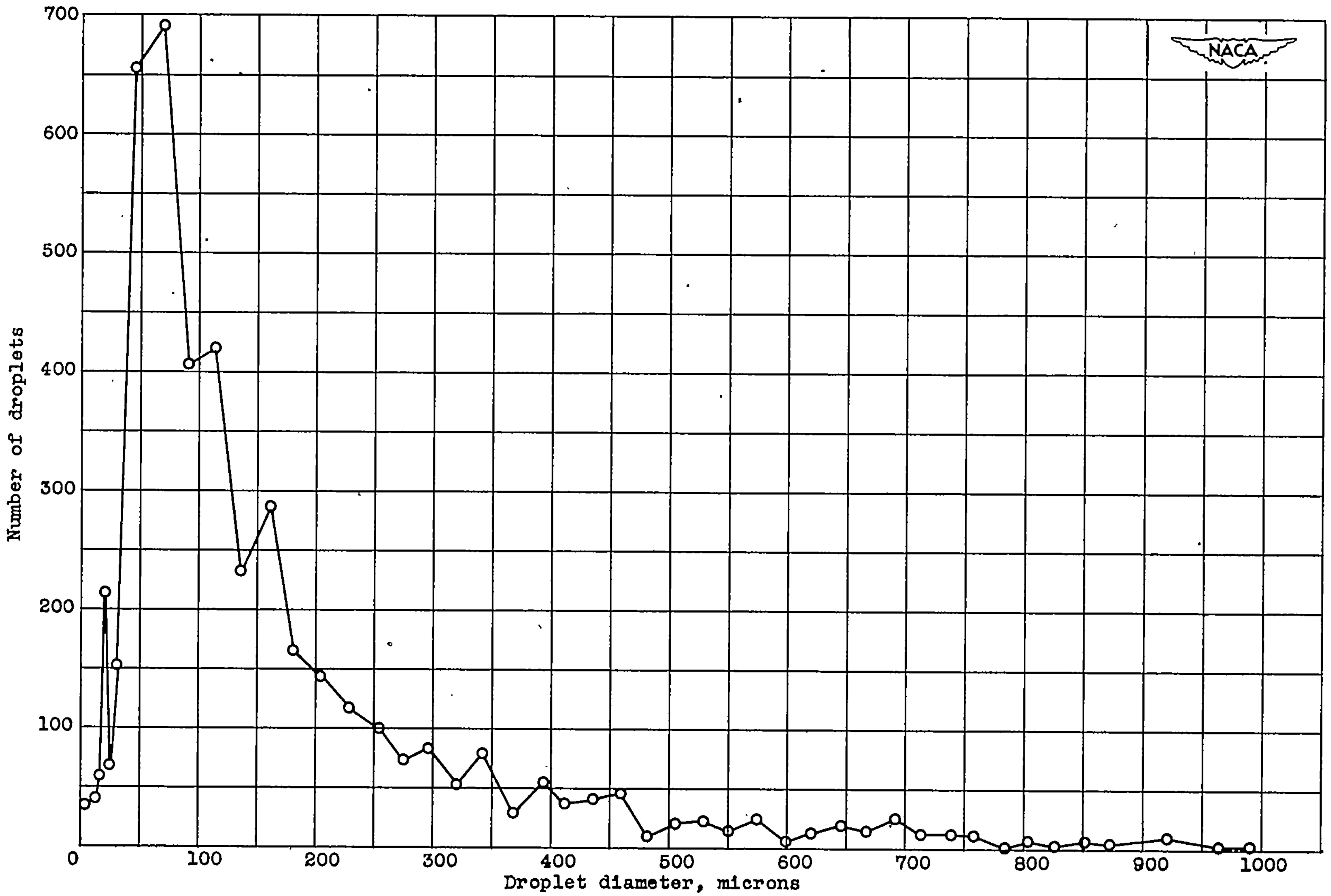


Figure 6. - Distribution of droplet sizes obtained in range of 8.75 to 1000 microns.

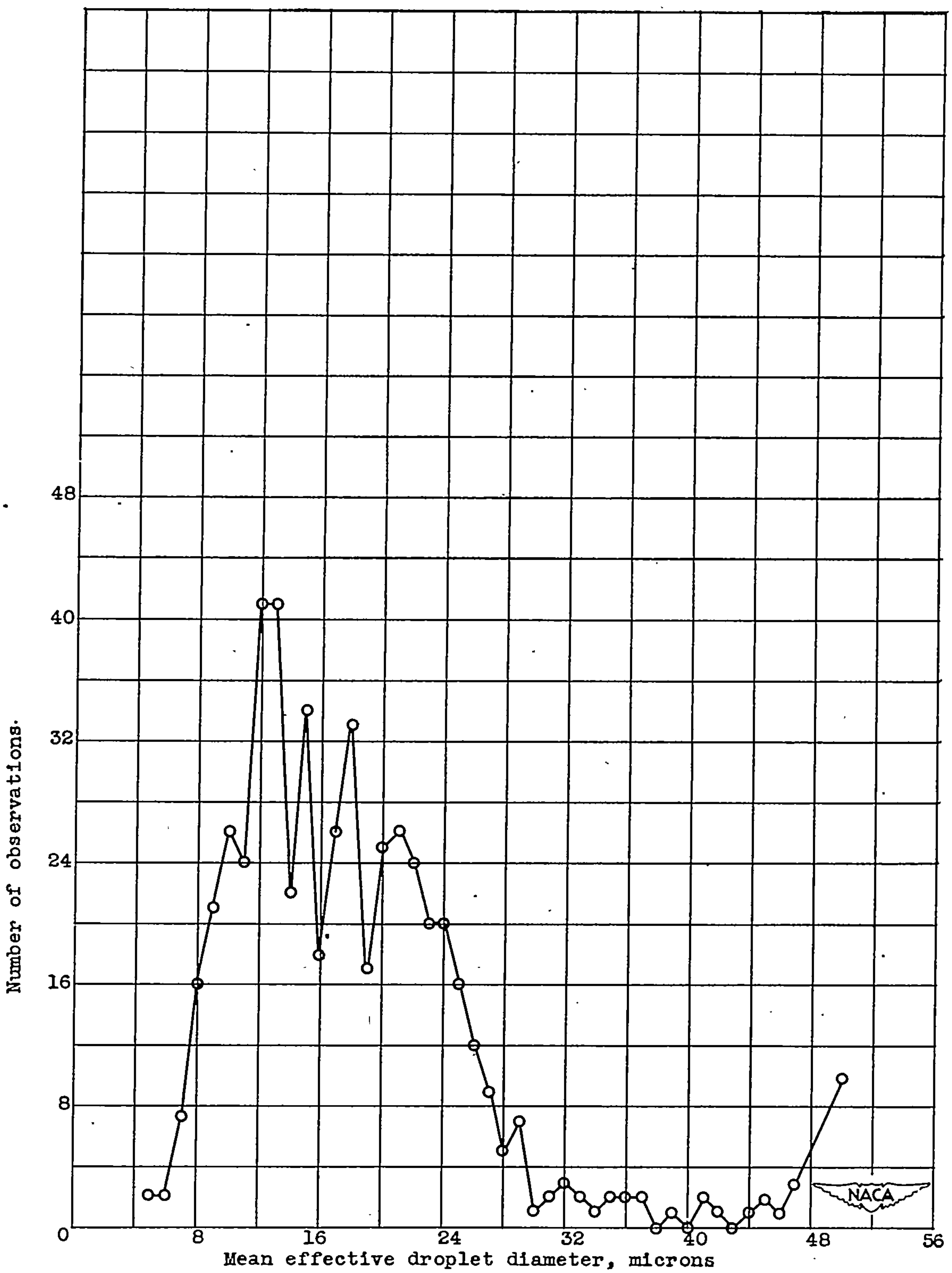
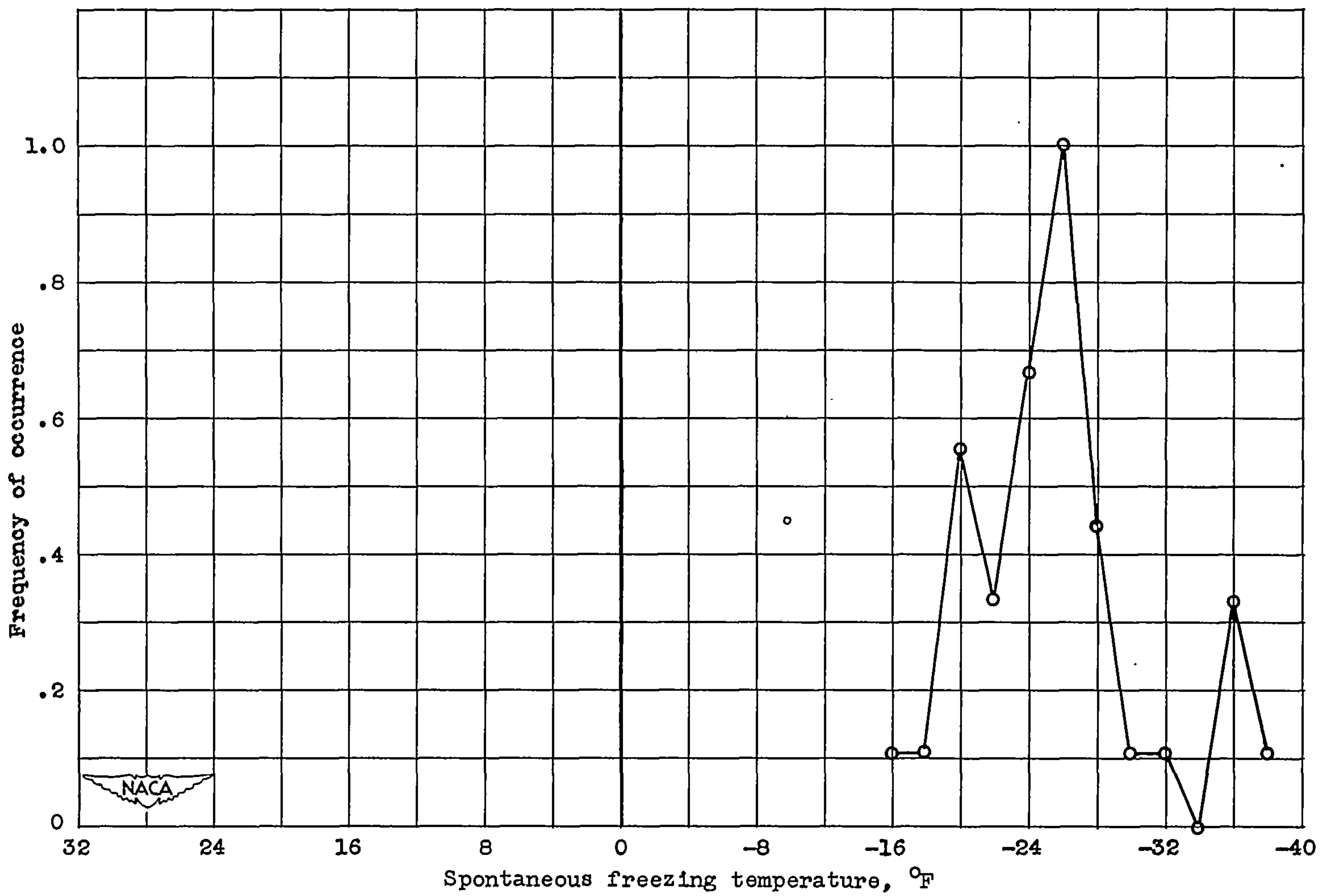
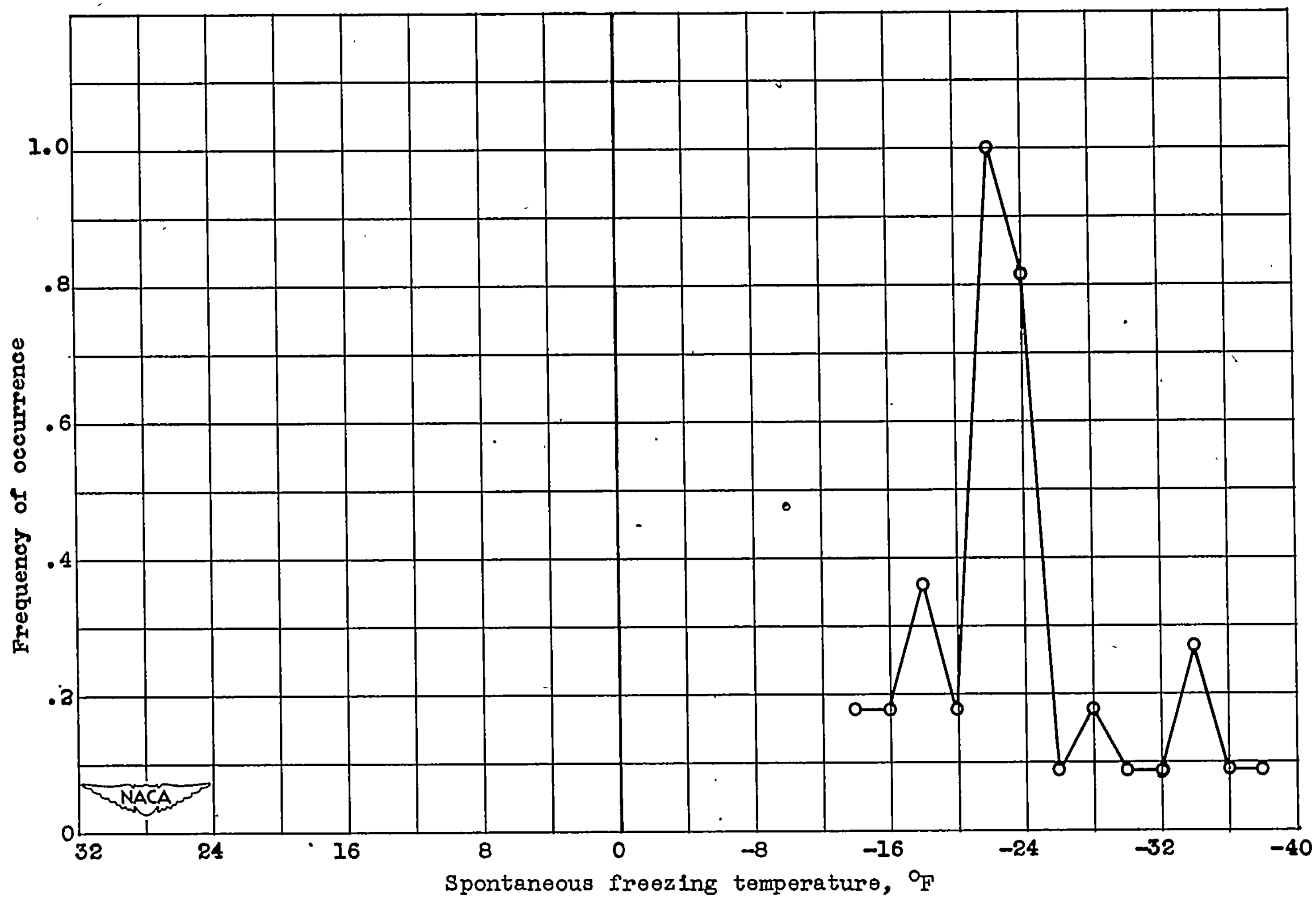


Figure 7. - Distribution of mean effective droplet sizes in icing clouds. (Data obtained from references 9 to 11.)



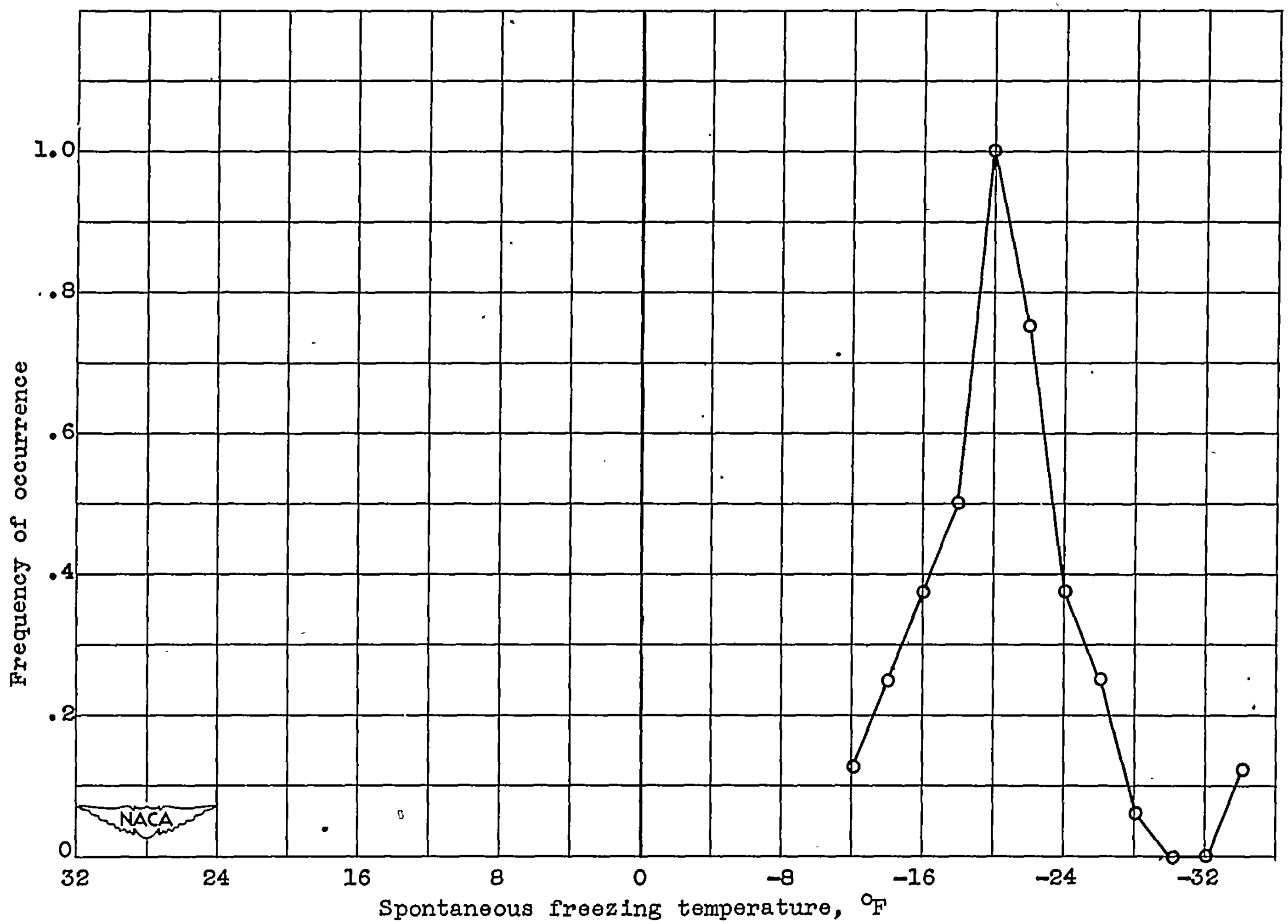
(a) Droplet diameter, 8.75 ± 2.5 microns; droplets observed, 35; average spontaneous freezing temperature, -25.7° F; standard deviation, 5.13° F.

Figure 8. - Distribution of spontaneous freezing temperatures.



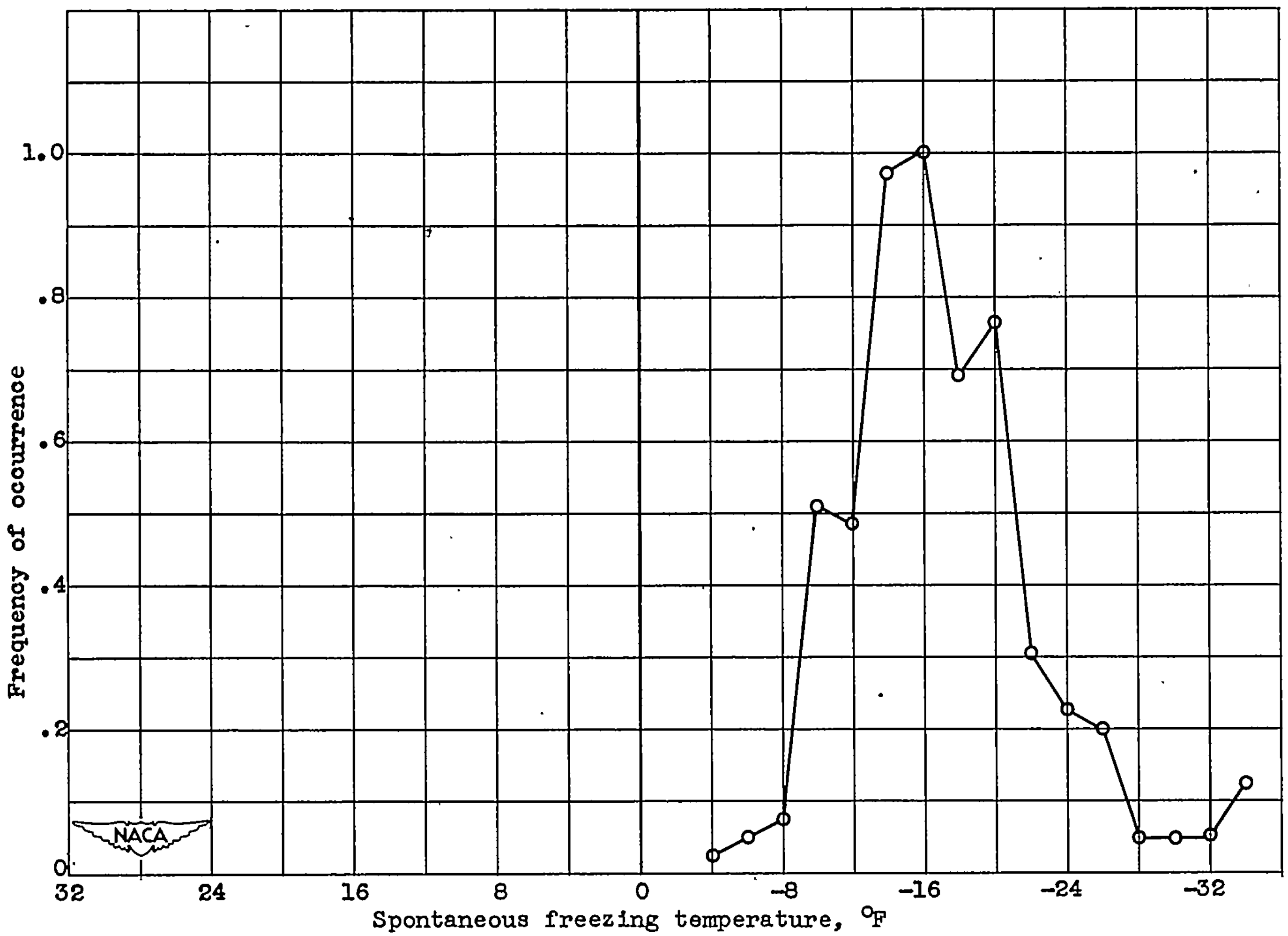
(b) Droplet diameter, 13.75 ± 2.5 microns; droplets observed, 40; average spontaneous freezing temperature, -23.8° F; standard deviation, 5.75° F.

Figure 8. - Continued. Distribution of spontaneous freezing temperatures.



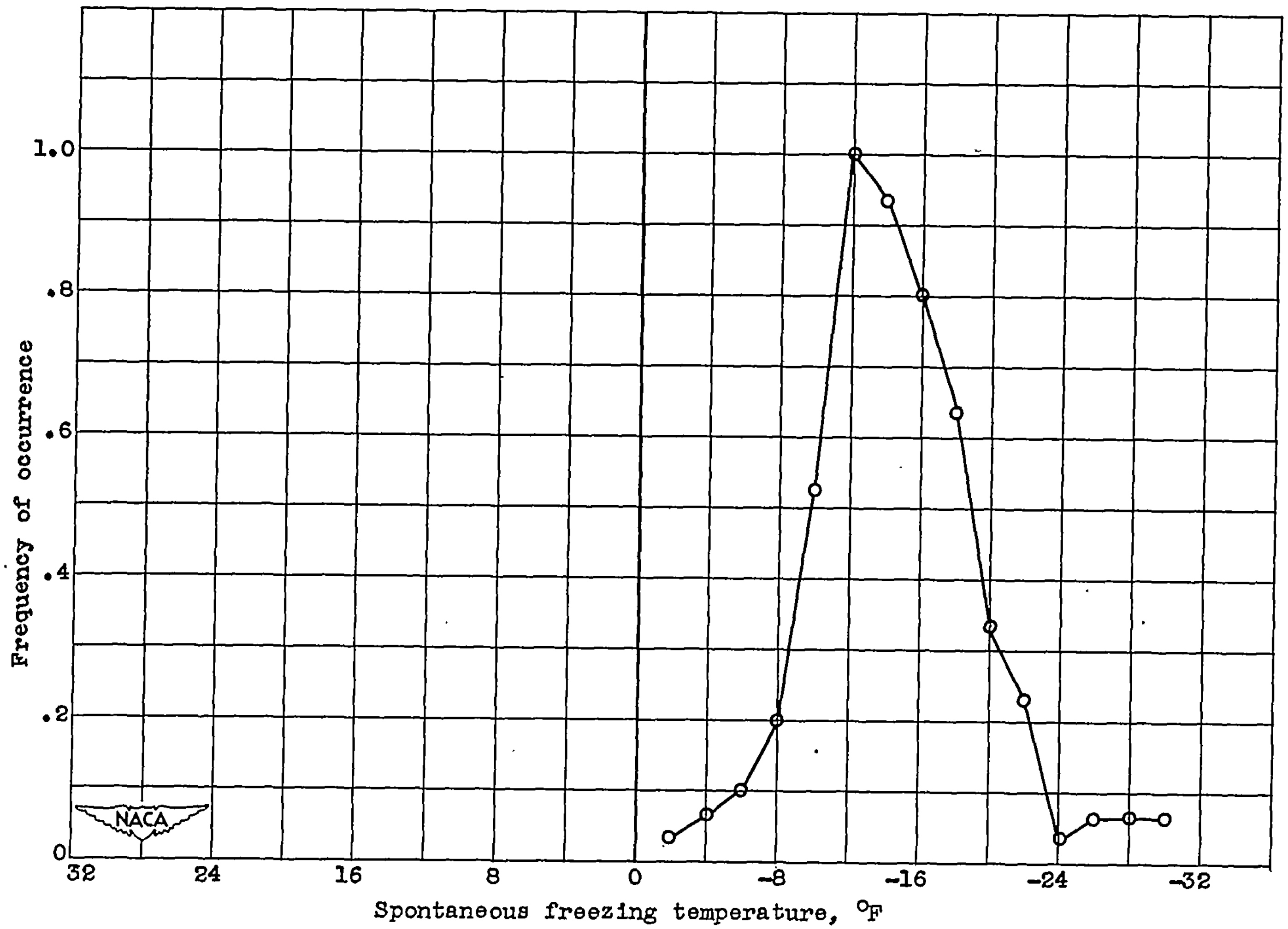
(c) Droplet diameter, 18.75 ± 2.5 microns; droplets observed, 61; average spontaneous freezing temperature, -20.5° F; standard deviation, 4.31° F.

Figure 8. - Continued. Distribution of spontaneous freezing temperatures.



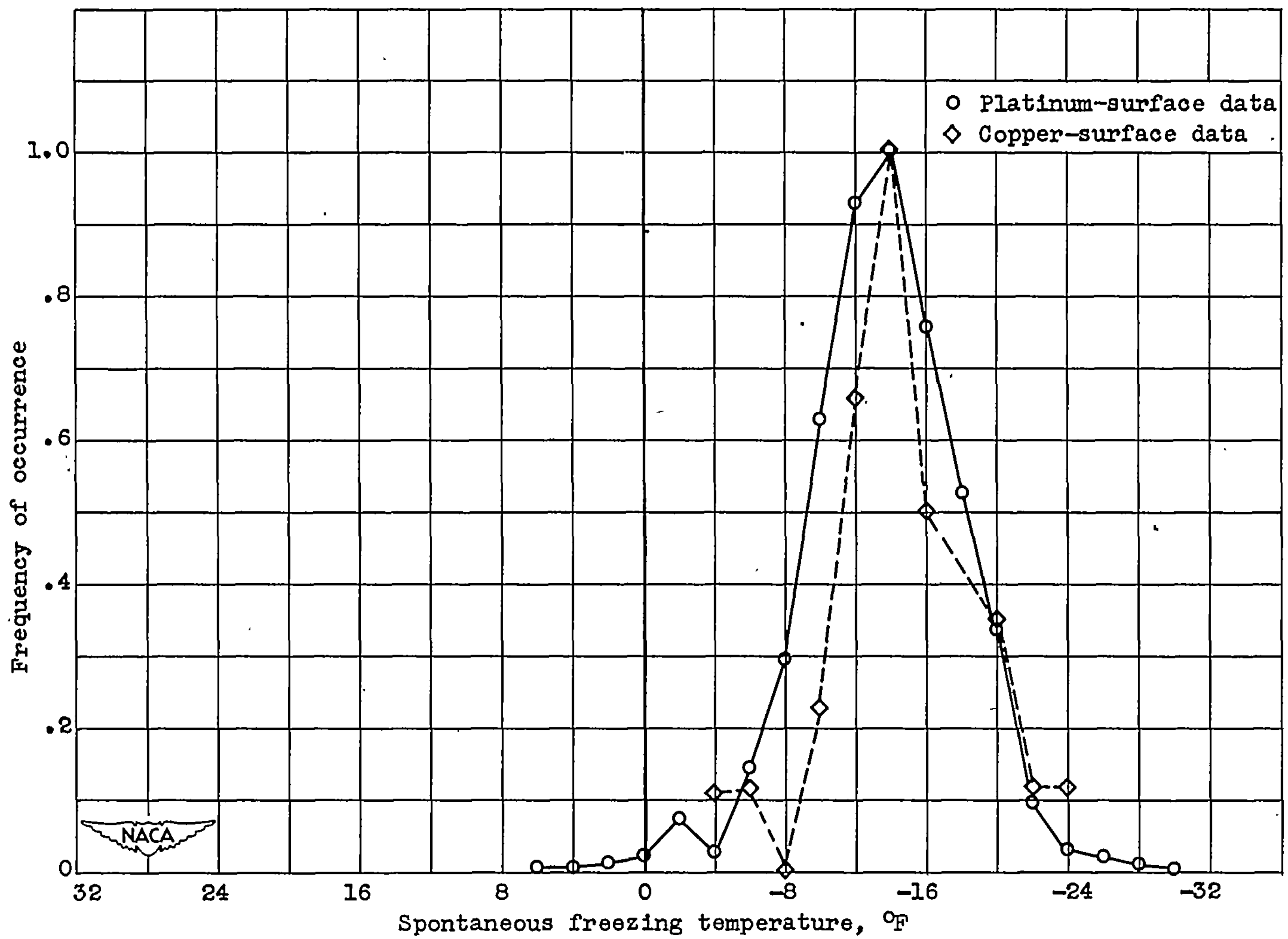
(d) Droplet diameter, 23.0 ± 3.0 microns; droplets observed, 215; average spontaneous freezing temperature, -16.8° F; standard deviation, 4.38° F.

Figure 8. - Continued. Distribution of spontaneous freezing temperatures.



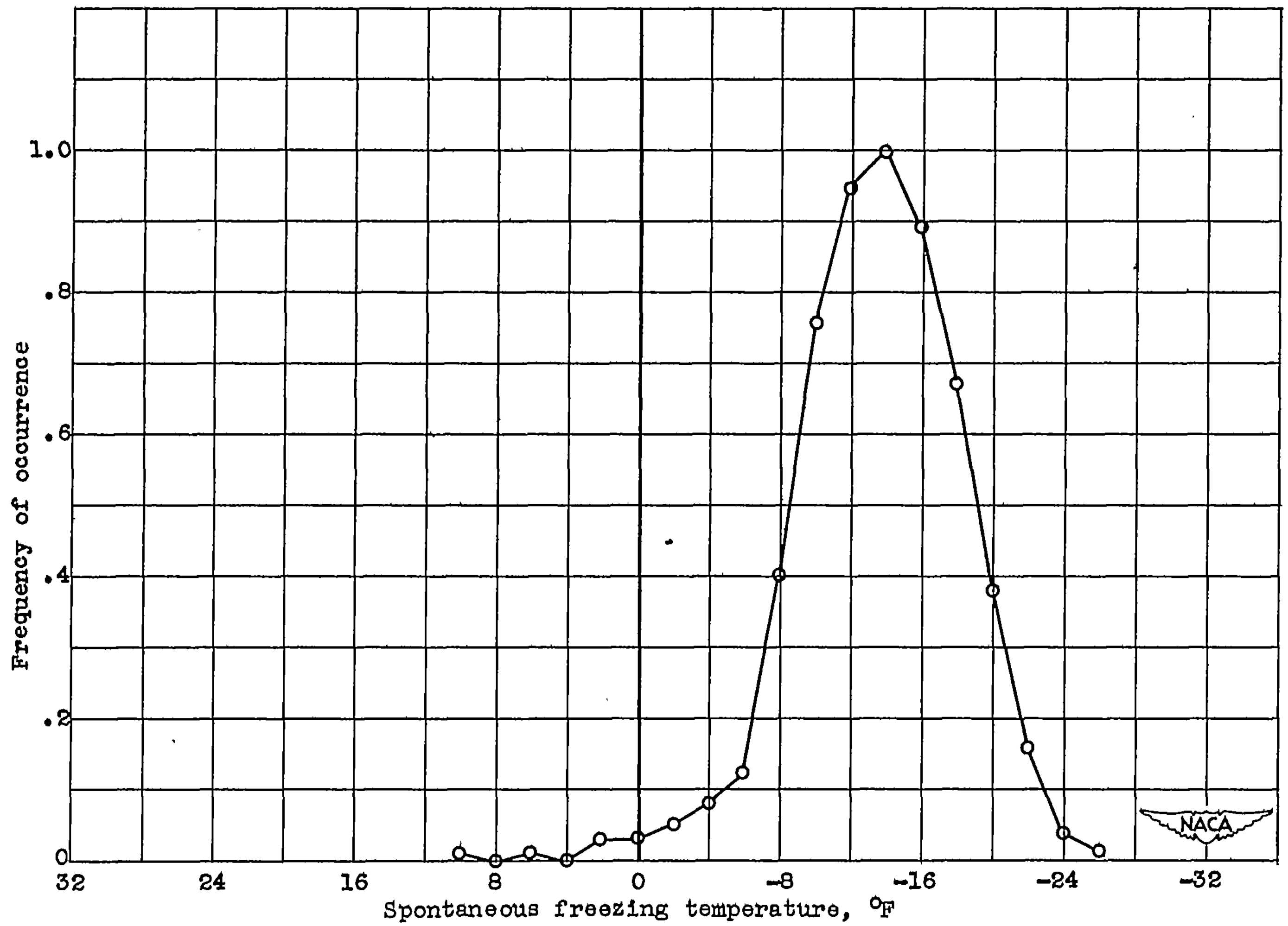
(e) Droplet diameter, 34.5 ± 3.0 microns; droplets observed, 153; average spontaneous freezing temperature, -15.1° F; standard deviation, 4.82° F.

Figure 8. - Continued. Distribution of spontaneous freezing temperatures.



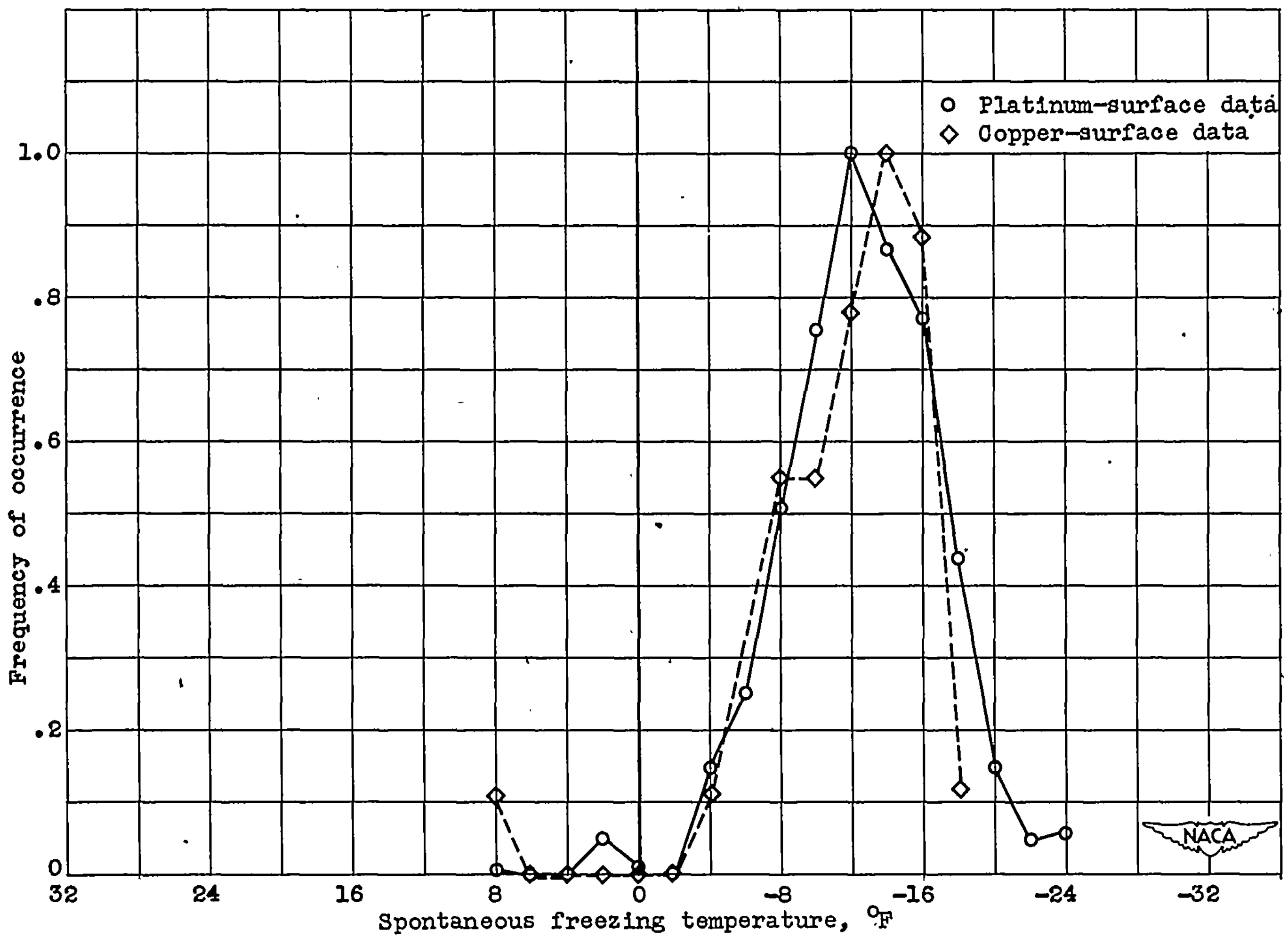
(f) Droplet diameter, 46.0 ± 11.5 microns; droplets observed, on platinum 656, on copper 36; average spontaneous freezing temperature, platinum -13.5° F, copper -15.0° F; standard deviation for platinum data, 4.48° F.

Figure 8. - Continued. Distribution of spontaneous freezing temperatures.



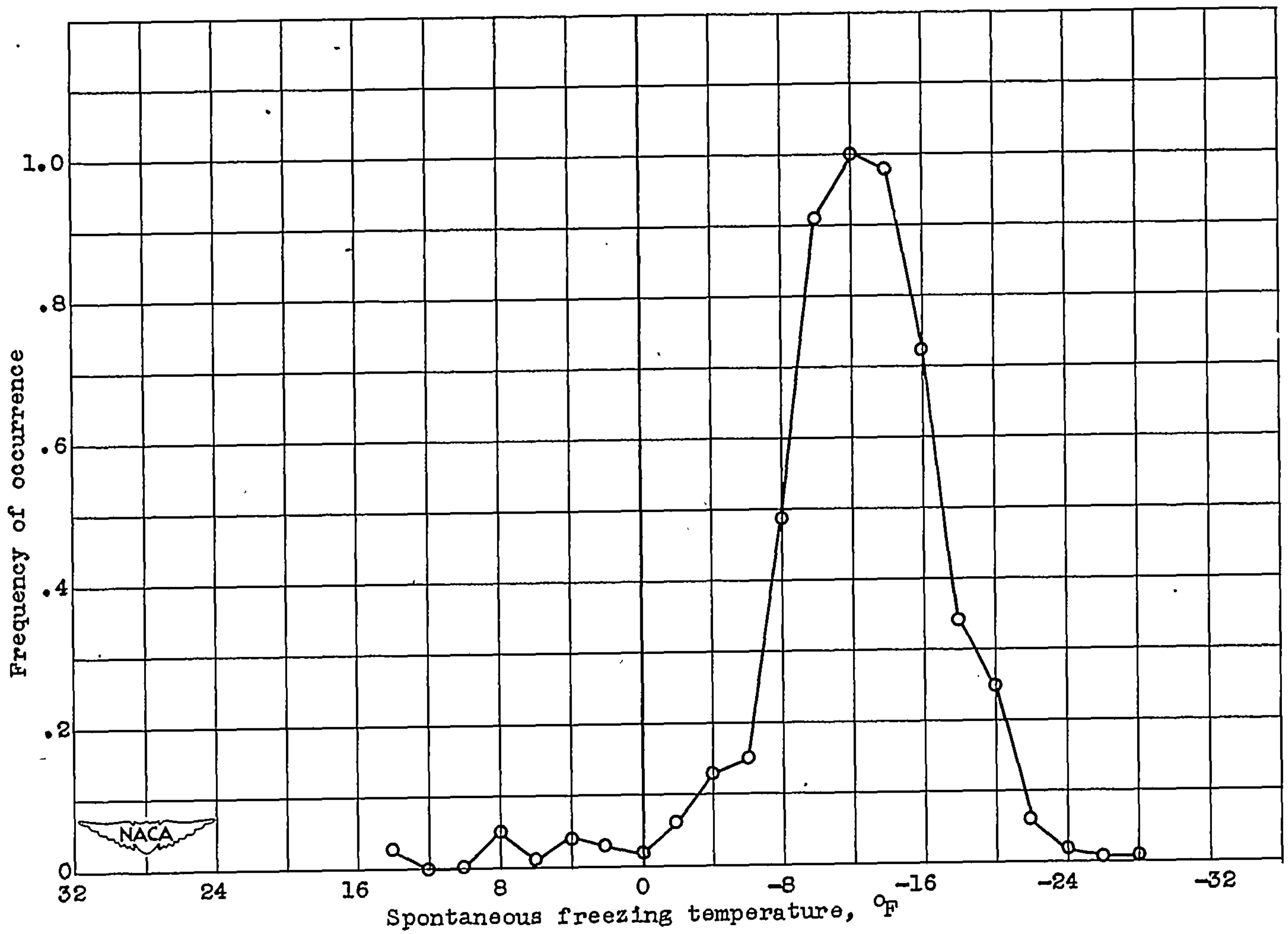
(g) Droplet diameter, 69.0 ± 11.5 microns; droplets observed, 692; average spontaneous freezing temperature, -13.3° F; standard deviation, 4.66° F.

Figure 8. - Continued. Distribution of spontaneous freezing temperatures.



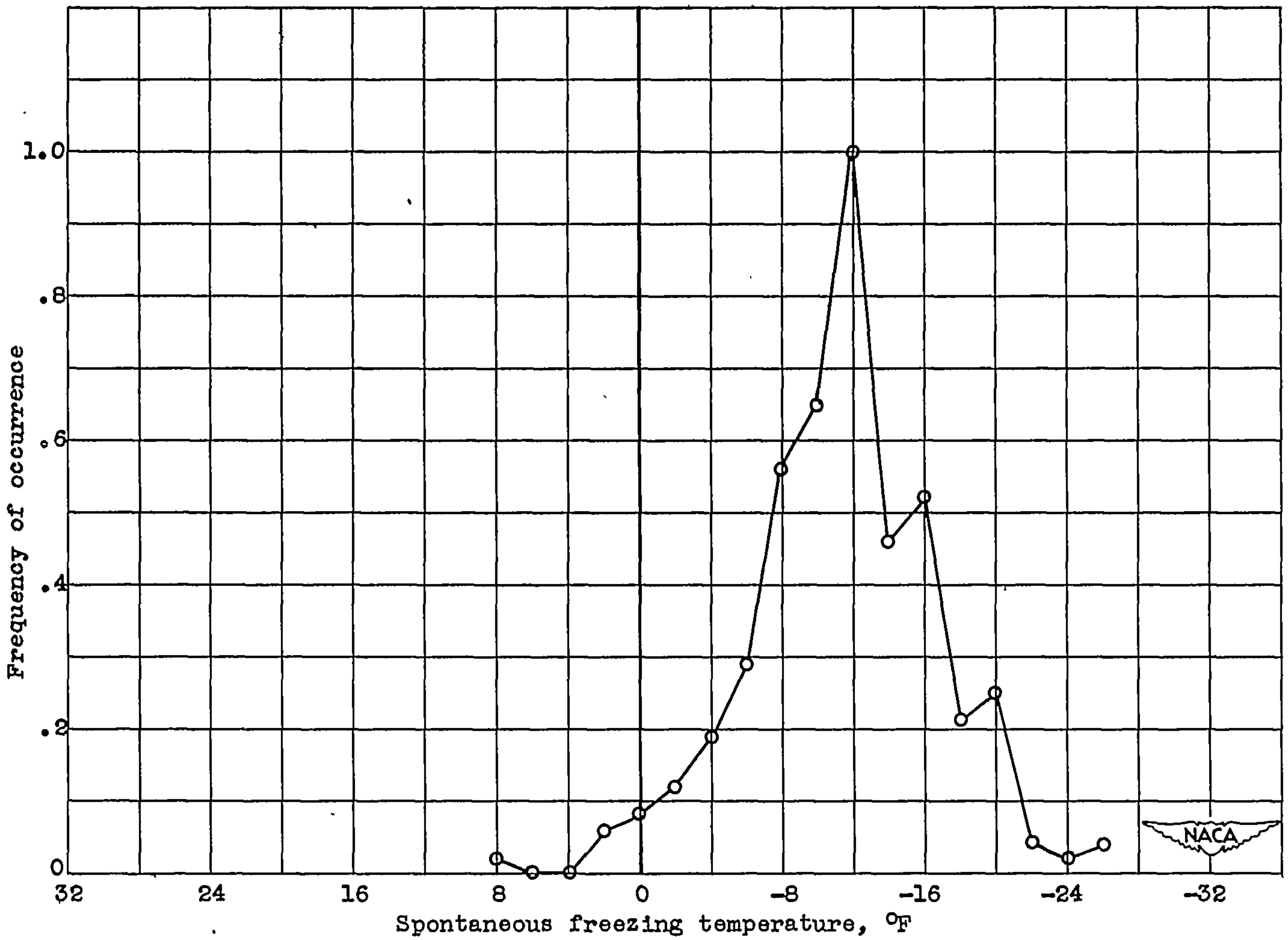
(h) Droplet diameter, 92.0 ± 11.5 microns; droplets observed, on platinum 405, on copper 39; average spontaneous freezing temperature, platinum -12.1° F, copper -11.6° F; standard deviation for platinum data, 4.48° F.

Figure 8. - Continued. Distribution of spontaneous freezing temperatures.



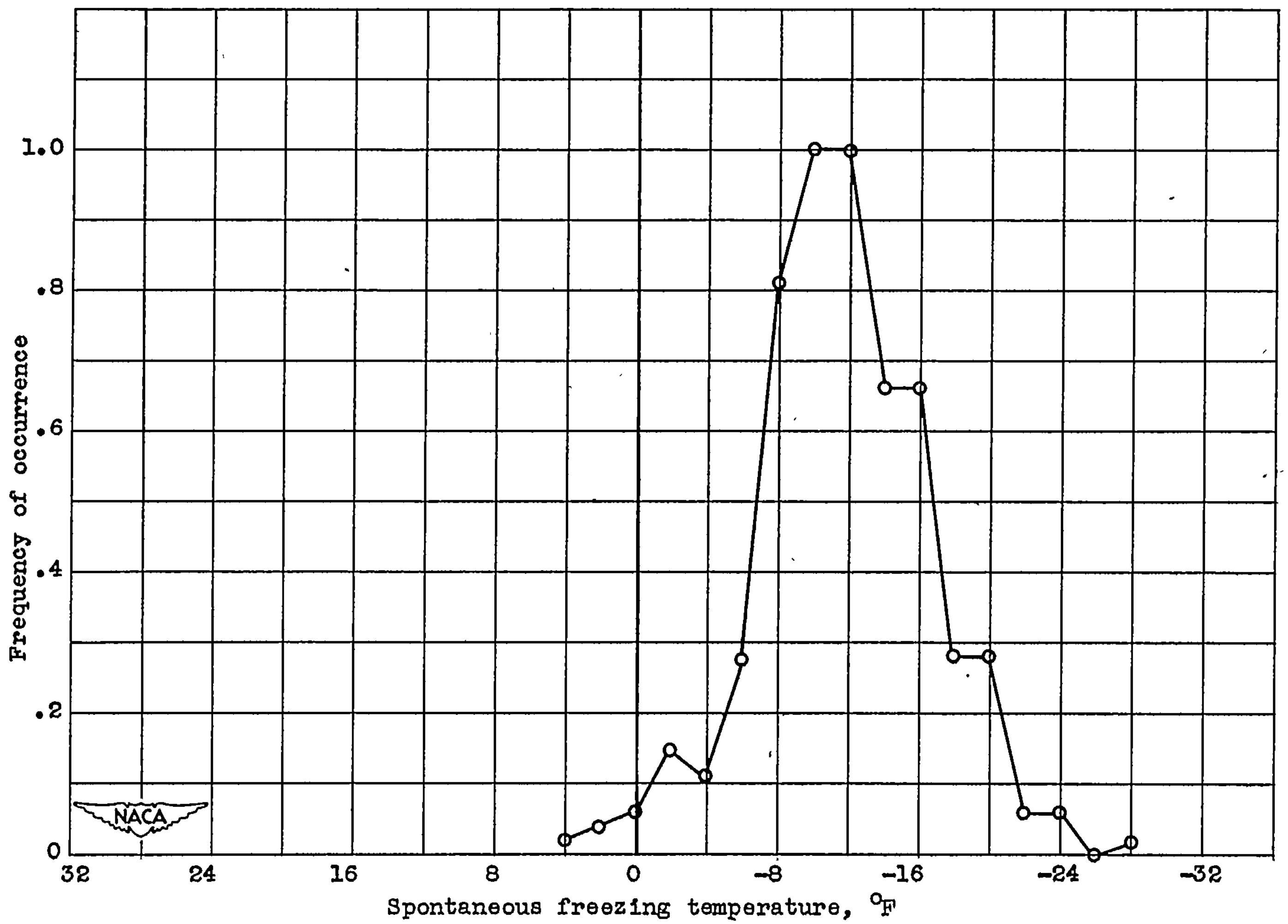
(i) Droplet diameter, 115.0 ± 11.5 microns; droplets observed, 424; average spontaneous freezing temperature, -11.8° F; standard deviation, 5.31° F.

Figure 8. - Continued. Distribution of spontaneous freezing temperatures.



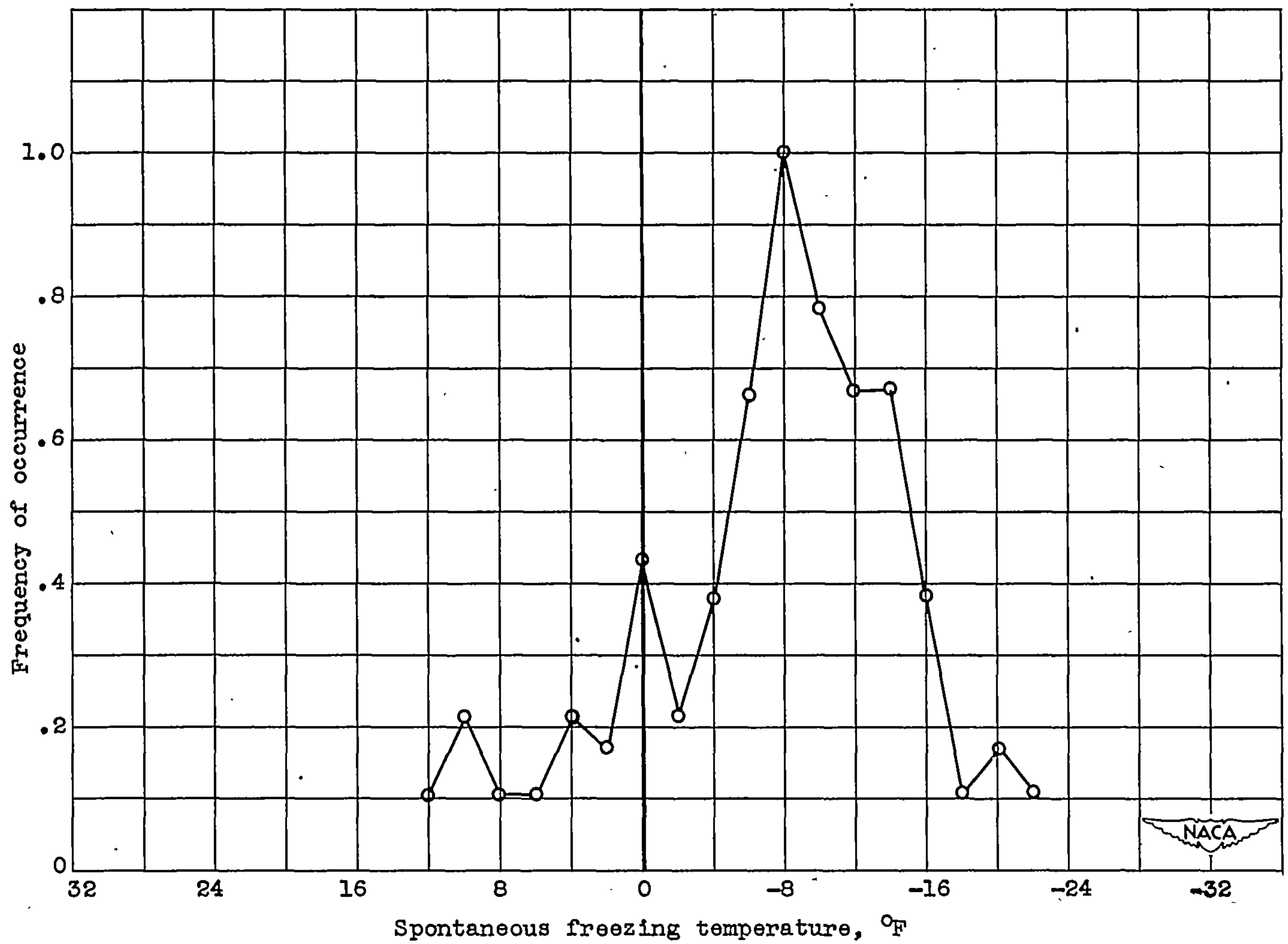
(j) Droplet diameter, 138.0 ± 11.5 microns; droplets observed, 234; average spontaneous freezing temperature, -11.1° F; standard deviation, 5.22° F.

Figure 8. - Continued. Distribution of spontaneous freezing temperatures.



(k) Droplet diameter, 161.0 ± 11.5 microns; droplets observed, 290; average spontaneous freezing temperature, -11.5° F; standard deviation, 4.87° F.

Figure 8. - Continued. Distribution of spontaneous freezing temperatures.



(l) Droplet diameter, 230.0 ± 11.5 microns; droplets observed, 116; average spontaneous freezing temperature, -6.9° F; standard deviation, 7.63° F.

Figure 8. - Concluded. Distribution of spontaneous freezing temperatures.

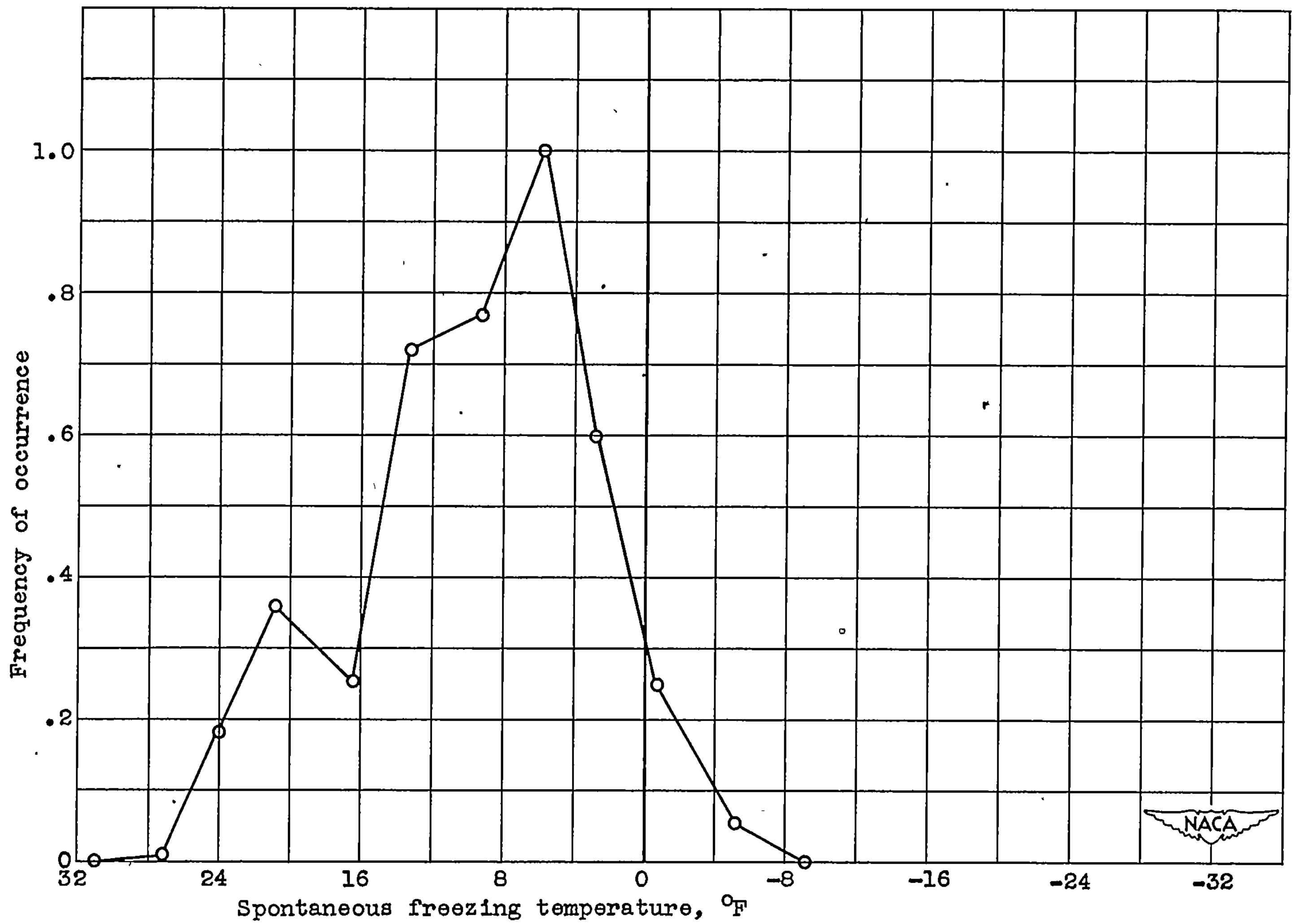


Figure 9. - Distribution of spontaneous freezing temperatures for 3- to 4-millilitre samples of water. (Data from reference 7.)

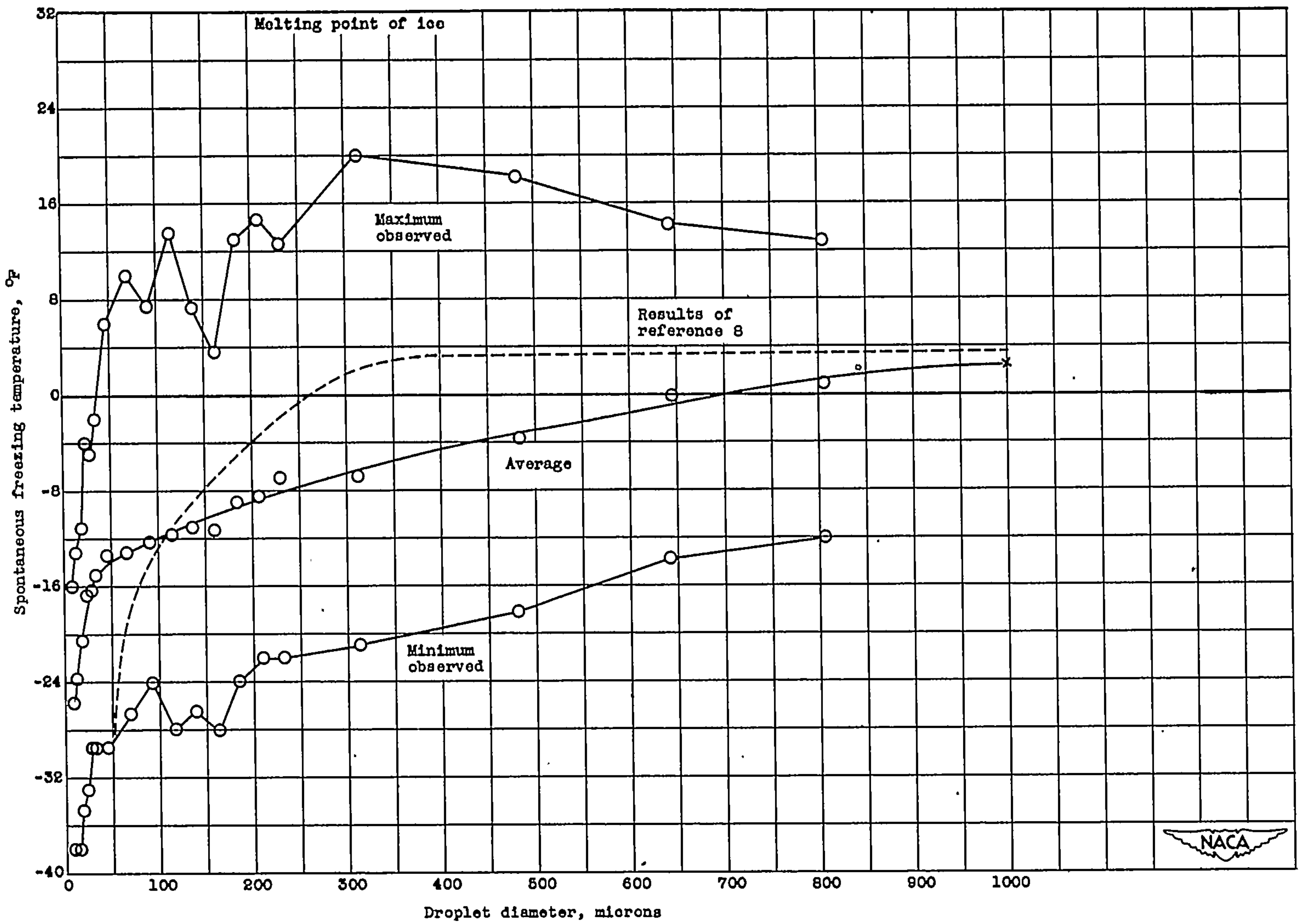


Figure 10. - Variation of spontaneous freezing temperature with droplet size for droplets supported by platinum surface.

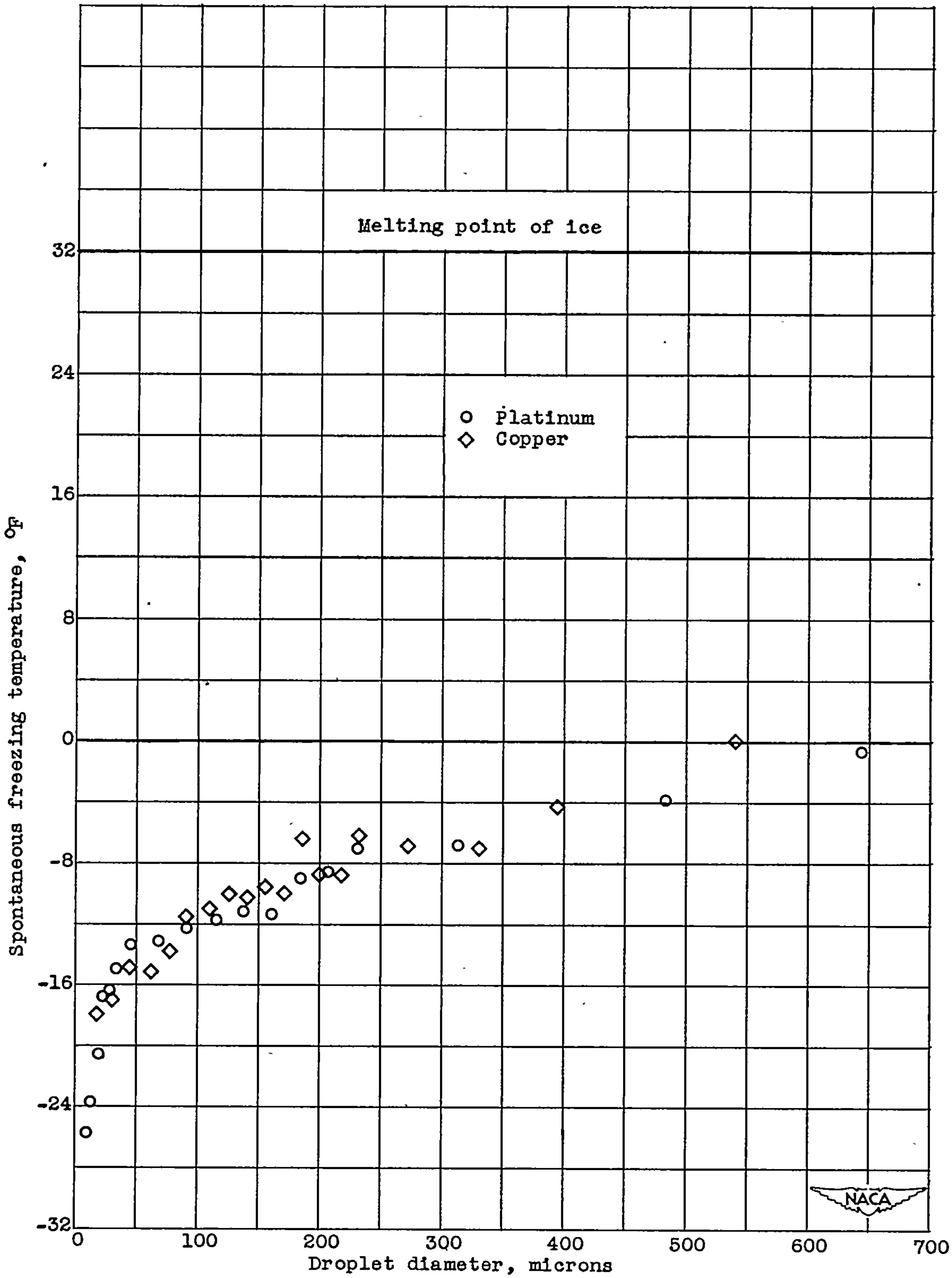


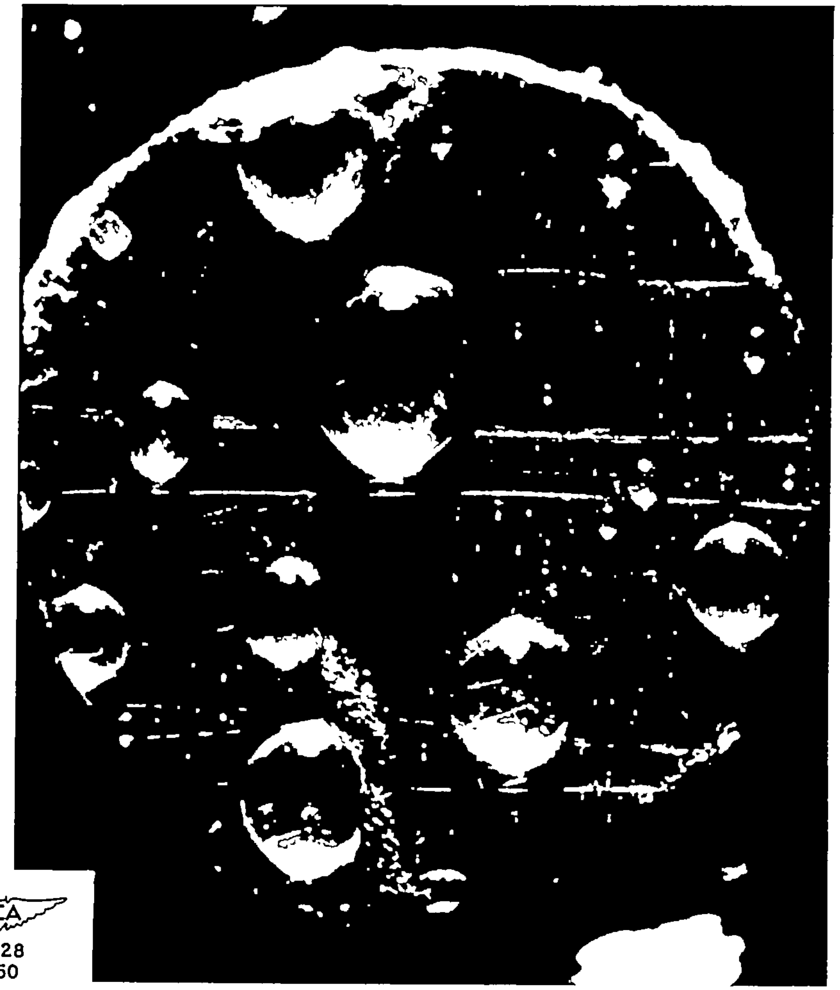
Figure 11. - Comparison of variation of average freezing temperature with droplet diameter for droplets supported on platinum and copper surfaces.

(a) Frame 25; temperature, 47° F.

(b) Frame 45; temperature, 28.5° F.

Figure 12. - Selected photographs from data film illustrating variation in spontaneous freezing temperatures of supercooled droplets. (1 in. = 1000 microns.)

(c) Frame 85; temperature, 20° F.



(d) Frame 95; temperature, 18° F.

Figure 12. - Continued. Selected photographs from data film illustrating variation in spontaneous freezing temperatures of supercooled droplets. (1 in. = 1000 microns.)

(e) Frame 175; temperature, -3.5° F.

(f) Frame 185; temperature, -6° F.

Figure 12. - Continued. Selected photographs from data film illustrating variation in spontaneous freezing temperatures of supercooled droplets. (1 in. = 1000 microns.)

(g) Frame 195; temperature, -9.5° F.

(h) Frame 225; temperature, -14° F.

Figure 12. - Concluded. Selected photographs from data film illustrating variation in spontaneous freezing temperatures of supercooled droplets. (1 in. = 1000 microns.)

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