Research Report 150

APRIL, 1965

A Study of Ice Fog
and
Ice-Fog Nuclei
at
Fairbanks, Alaska

Part II

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COLD REGIONS RESEARCH & ENGINEERING LABORATORY
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PREFACE

This report was prepared by Dr. Motoi Kumai, Physicist, and Mr. Harold W. O'Brien, Physicist, Environmental Research Branch. This work was under the general direction of Dr. R. W. Gerdel, Chief, Environmental Research Branch as a project of the Research Division, Mr. J. A. Bender, Chief.

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This report has been reviewed and approved by Headquarters, U. S. Army Materiel Command.

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SUMMARY

A study of ice fog and ice crystals was made in Fairbanks, Alaska, during January and February, 1963. This report includes a meteorological study of the occurrence and duration of ice fog, and a description of a new type of cascade impactor used in studying ice-fog nucleation in the exhaust water vapor from the chimney of an electric power plant and from an automobile exhaust, as well as a study of the size relationship between ice-fog crystals and their nuclei.

In studies conducted in the Tanana Valley of central Alaska, ice fog was found to persist only over populated areas and only at temperatures of -40C or lower, although ice nucleation was observed to occur at about -20C. At temperatures near -20C the ice crystals grow rather large (10-150 μ diam) and the concentration is low, permitting good visibility, whereas the ice-fog crystals which form at -40C or below are smaller (2-25 μ diam) and frequently of sufficiently high concentration to drastically reduce visibility.

A STUDY OF ICE FOG AND ICE-FOG NUCLEI
AT FAIRBANKS, ALASKA
PART II

by

Motoi Kumai and Harold W. O'Brien

INTRODUCTION

Studies on ice fog and ice crystals have been conducted at Fairbanks, Alaska, since 1962. USA CRREL Research Report 150, Part I, presented the results of the first study, conducted during January and February 1962, which was concerned with the identification of nuclei of ice crystals, ice-fog crystals, and supercooled droplets; counts of condensation nuclei; and measurement of ice-fog concentrations and liquid water content.

The second study of the series, conducted during January and February 1963, is the subject of this report. This investigation encompassed (1) a meteorological study of conditions favoring the occurrence and persistence of ice fog; (2) observations of ice-crystal formation with water vapor and hydrocarbon ice-forming nuclei provided by combustion products from a power plant chimney and an automobile exhaust; (3) design of a cascade impactor for use with a tethered blimp; (4) studies of the size relationship between ice-fog crystals and their nuclei; and (5) a comparison of size distributions between some seeding agents and natural ice-fog crystals, and their nuclei.

CLIMATE OF THE FAIRBANKS AREA

Fairbanks is located in the Tanana Valley of interior Alaska, near the confluence of the Chena and Tanana Rivers, at latitude 64°54' N — about 193 km south of the Arctic Circle. The Tanana Valley is surrounded by mountains: on the north and east by the Yukon-Tanana Uplands beginning with the White Mountains in the north, on the south by the Alaskan Range, and in the west by the Kuskokwim Mountains. The area is thus sheltered from maritime influences.

The climate of the Fairbanks area was studied by Pickett (1963). The climate is continental, and characterized by wide temperature variations, particularly during the winter season. These rather large fluctuations in temperature occur not only seasonally, but are evident in daily temperature recordings, and are a composite result of the character of the land mass, the prevailing air mass, and the balance between incoming solar radiation and outgoing terrestrial radiation. The solar altitude and the number of daylight hours vary considerably with the seasons in Fairbanks. In May and June, the maximum solar altitude is from 45° to 48°, producing 18 to 21 hours of daylight, while during November and December the maximum solar altitude is only 2° to 6° and there are only 4 to 6 daylight hours. At the winter solstice the maximum solar altitude is less than 2° and the amount of daylight reaches its annual minimum of 3 hours 42 minutes.

A 32-year compilation of record maximum and minimum temperatures, daily average maximum, daily average, and daily average minimum temperatures is shown in Figure 1.

It can be seen from Figure 1 that the daily average temperatures for the 32 years are above 0C from April to October and below 0C from October to April, with October and April being periods of transition. It is interesting to note that the seasonal warm periods and cold periods lag behind the summer and winter solstices, respectively, by approximately one month. During June and July the average daily temperature is 15C with a record maximum of 33C and record minimum of -1.7C, whereas the average daily temperature for December and January is -23C with a record maximum and minimum of 14C and -54C, respectively. During the winter, the daily temperature variation is from 2 to 20C. The total number of hours of temperature below -40C during a given winter is from 0 to 325 hours.

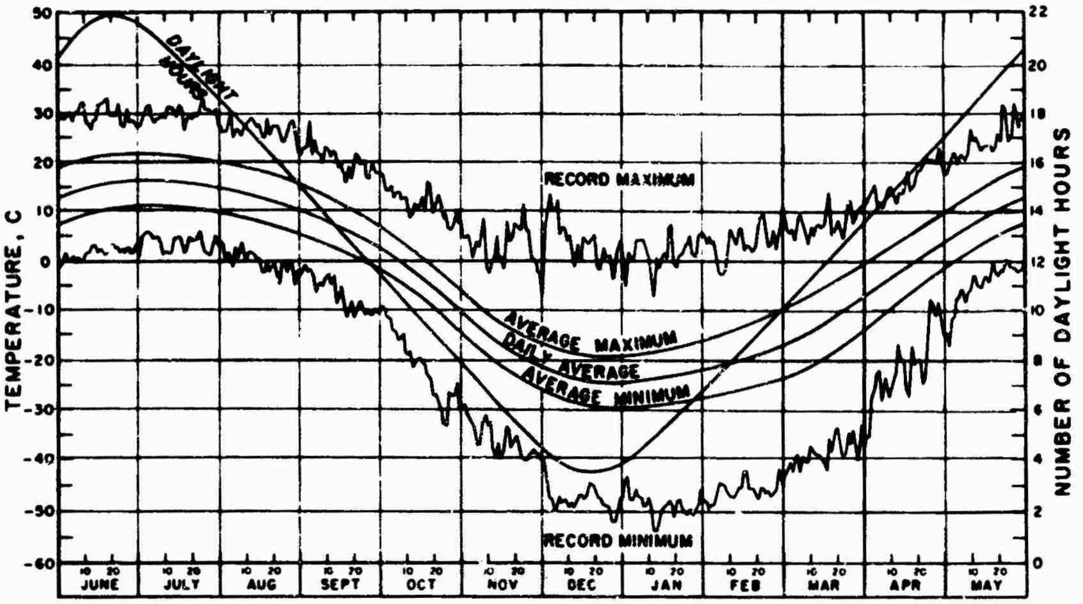


Figure 1. Temperatures and daylight hours at Fairbanks, Alaska.

Winds in the Fairbanks area are generally rather weak (Table I). The average windspeed is 1.8 m/sec, with a prevailing northerly direction. The stronger winds recorded were mainly southerly, with the maximum wind speed observation being 17 m/sec.

Precipitation in the form of snow and ice crystals is very common during the winter season. Although ice-fog crystals also precipitate, their volume is negligible compared to that of snow and ice crystals. Rain, drizzle, and sleet are uncommon during the winter, but have been observed on occasion.

Table I. Wind direction and speed in winter at Fairbanks.

Month	Hourly average wind Prevailing direction	Hourly average speed		Maximum wind Direction	Speed	
		m/sec	mph		m/sec	mph
October	NE	2.3	5.2	S	12.0	26.2
November	N	1.7	3.8	S	12.9	28.8
December	N	1.4	3.1	SW	12.0	26.2
January	N	1.4	3.1	SW	15.0	33.6
February	N	1.7	3.8	SW	13.5	30.2
March	N	2.1	4.7	S	17.0	38.0

Table II. Ice-fog frequency and its total hours in each month at Fairbanks for the period 1 January to 10 February 1963.

Winter	Oct.		Nov.		Dec.		Jan.		Feb.		Mar.		Apr.		Total	
	No.	Hr.	No.	Hr.	No.	Hr.	No.	Hr.	No.	Hr.	No.	Hr.	No.	Hr.	No.	Hr.
1956-1957	-	-	-	-	-	-	1	42	4	59	0	0	0	0	5	101
1957-1958	0	0	0	0	7	186	1	1	0	0	0	0	0	0	8	187
1958-1959	0	0	3	20	1	41	9	153	0	0	4	29	0	0	17	243
1959-1960	0	0	0	0	7	59	2	95	0	0	0	0	0	0	9	154
1960-1961	0	0	4	26	0	0	3	10	1	2	3	12	0	0	11	50
1961-1962	0	0	6	28	6	323	5	98	1	6	2	9	0	0	20	464
1962-1963	0	0	5	48	8	136	4	74	2	89	-	-	-	-	19	347
Total	0	0	18	122	29	745	25	473	8	156	9	50	0	0	89	1546

No. - Number of occurrences during month.
Hr. - Total number of hours during month.

METEOROLOGICAL CONDITIONS OF ICE FOG

Frequency of ice fog

The frequency of ice fog and the total ice-fog hours for the winter months from January 1957 to February 1963 are shown in Table II. During the period of these observations no ice fog was observed during the transitional months of October or April, although ice fog was observed as early as November and/or as late as March during several years. As seen from Table II, the frequency of ice-fog occurrence varies somewhat from winter to winter, with ice fog occurring during as few as 2 months to as many as 5 months of a winter. The maximum frequency during one winter is seen to be 20 times, with a total of 464 hours of ice fog in the winter of 1961-62. The minimum frequency of ice fog was 8 times, with a total of 187 hours of ice fog in the winter of 1957-58.

Persistence of ice fog

The occurrence and duration of ice fog depend upon the meteorological conditions, especially air temperature. Ice fog generally continues while the air temperature is about -40C, provided there is little or no wind. The persistence of ice fog in Fairbanks during the winter months from January, 1957 to February, 1963 is shown in Table III. These data indicate that about 60% of all ice-fog occurrences were of less than 6 hours duration and that about 80% were of less than 24 hours duration. The longest continuous ice fog since 1957 was a period of 186 hours in December 1961.

Table III. Persistence of ice fog at Fairbanks for the period 1 Jan 1957 to 10 Feb 1963.

Duration of ice-fog period	Number of periods of stated duration	Relative frequency of periods of specified duration	
1-6 hours	53 times	58.0%	81.1%
7-12	15	16.5	
13-24	6	6.6	
25-48	7	7.7	18.9
49-72	3	3.5	
73-96	5	5.5	
97-120	1	1.1	
121-144	0	0	
145-168	0	0	
169-192	1	1.1	
Total	91	100.0	100.0

Hourly temperature measurements at the Fairbanks International Airport (133 m above sea level) and at the top of Birch Hill West (338 m above sea level) are compared to visibility readings at the airport in Figure 2a and b. The distance between the two stations is 12 km. The radiosonde temperature data over the airport, at a height equivalent to the top of Birch Hill, almost coincide with actual temperature data at the top of Birch Hill (Fig. 2b). A temperature inversion existed throughout nearly the entire period. While the ground temperature ranged between -30C and -40C, thin ice fog was observed at the airport, but persisted only a few hours at these temperatures. Visibility was generally in excess of 1 km. At ground temperatures of -40C or lower, dense ice fog persisted at the airport, and the visibility was about 100 m. The temperature inversion was generally more intense during ice fog, and was between 2C and 8C per 100 m altitude above ground level.

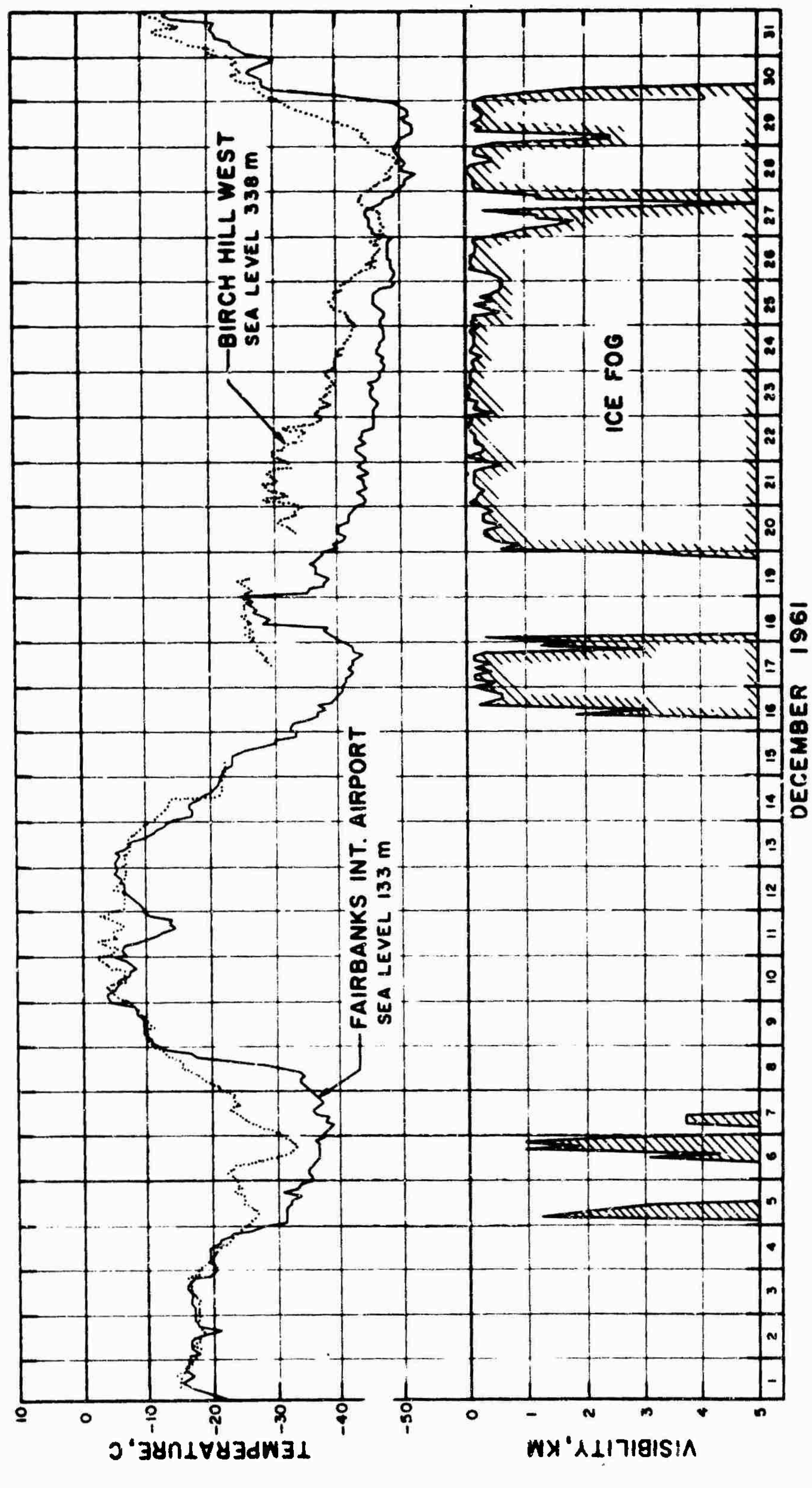


Figure 2a. Correlation of visibility at Fairbanks International Airport with temperatures at the airport and at Birch Hill West

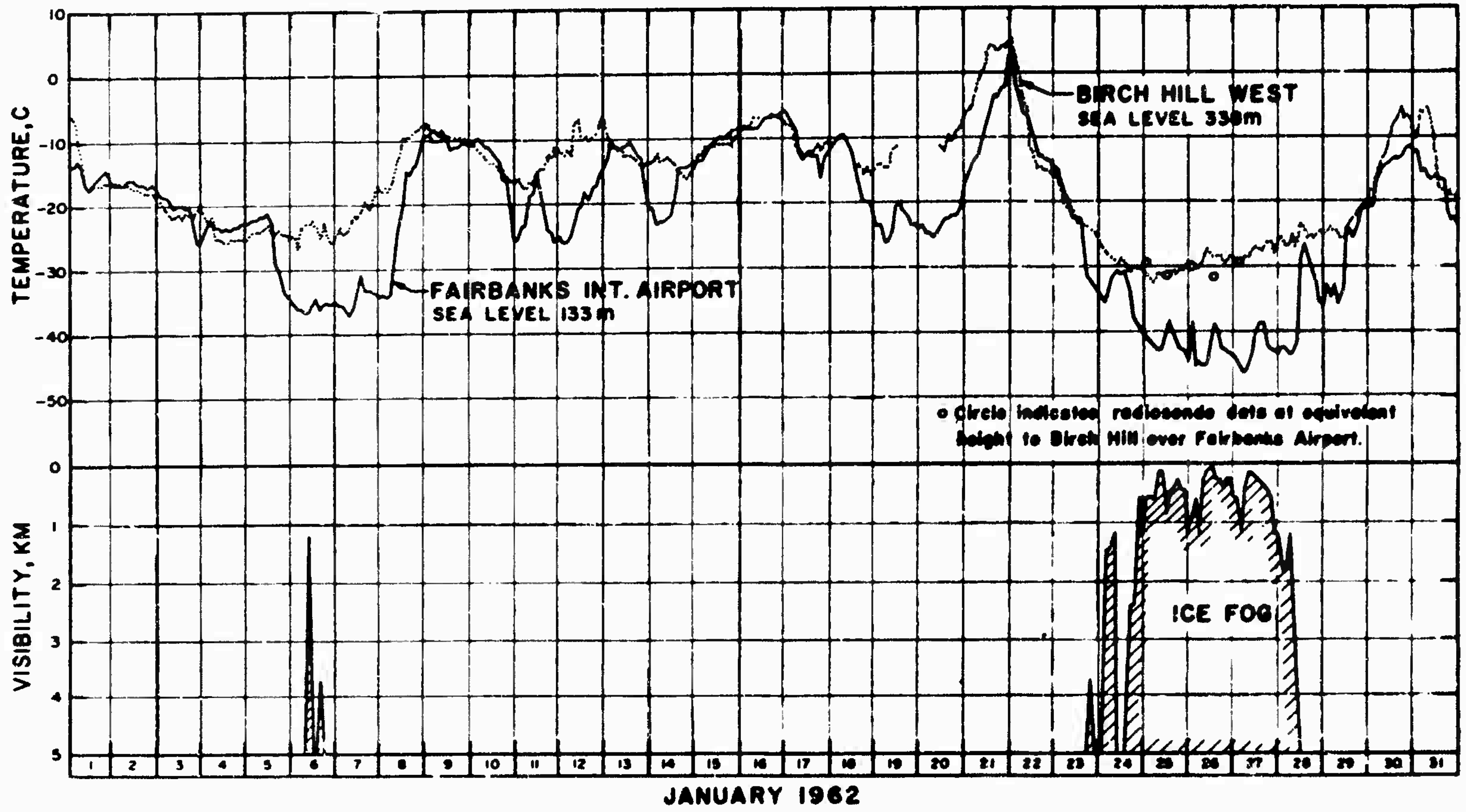


Figure 2b. Correlation of visibility at Fairbanks International Airport with temperatures at the airport and at Birch Hill West.

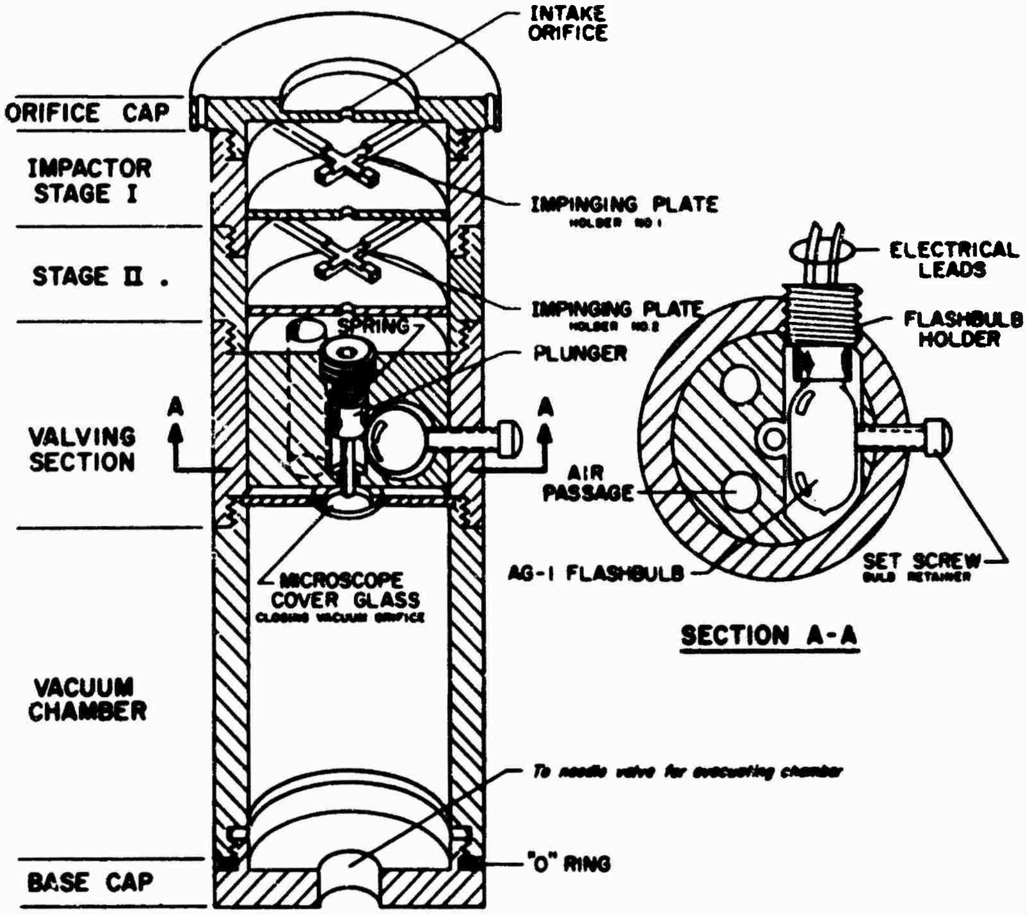


Figure 3. Cascade impactor

ICE-FOG FORMATION

Design of a cascade impactor

A cascade impactor (Fig. 3) has been designed by the authors for quantitative sampling of fog droplets and ice-fog crystals in the size range 1 to 100 μ diam. A primary consideration in the design of the impactor was the desirability of making sample collections at various heights, from a tethered blimp.

The impactor is essentially a cylindrical set of four machined-aluminum chambers, connected in tandem by threaded joints. The first two chambers are cascaded impactor stages, the third chamber contains a valving mechanism, and the fourth is a vacuum chamber having at its free end a needle valve through which the chamber may be evacuated.

In operation, the valving mechanism opens the vacuum chamber and atmospheric pressure forces air through the cascaded impactor stages, where fog droplets and/or ice-fog crystals impinge upon collector disks. The collector disks are 10 mm diam circular microscope cover glasses coated with a silicone oil of suitable viscosity for the collecting temperature so that impinging droplets and/or crystals will be suspended in the oil.

The valving chamber is sealed off from the vacuum chamber by a brass diaphragm with a 7-mm hole in its center. Closure is completed by placing a microscope cover glass over this hole and sealing with vacuum grease.

The valving mechanism is rather unconventional. An electrical system seemed most feasible. Because of the requirements of remote operation, minimum weight, and preferably operation in the field with hand-carried batteries, it was necessary to devise a system using a minimum amount of current, thereby allowing use of lighter wires and smaller batteries. The valving device constructed consists of a spring-loaded plunger which will break the cover glass sealing the vacuum chamber. The cocked plunger is held in check by an AG-1 flashbulb (with plastic coating removed). Delivery of less than $\frac{1}{8}$ amp to the bulb causes it to shatter, releasing the plunger. Although the impactors have been used only singly so far, it is calculated that four impactors, connected in parallel, could be fired simultaneously at different heights (e.g. 40, 60, 80, and 100 m) with a current draw of only about $\frac{1}{2}$ amp. This would actually result in a sequential firing, but with such rapidity that it could be considered simultaneous.

Although the flashbulb is semi-isolated from the path of air intake, some particles of burned magnesium ribbon are occasionally found on the second collector disk. Solenoid valves are being tested for use in the impactors. This type of valve would eliminate the particles of burned magnesium ribbon, but would have the disadvantage of requiring currents of approximately $\frac{1}{2}$ amp for each valve, whereas, as previously mentioned, four bulb-actuated valves can be fired using the same current draw.

Volume calibration of the impactors is necessary to calculate the concentration of hydrometeors.

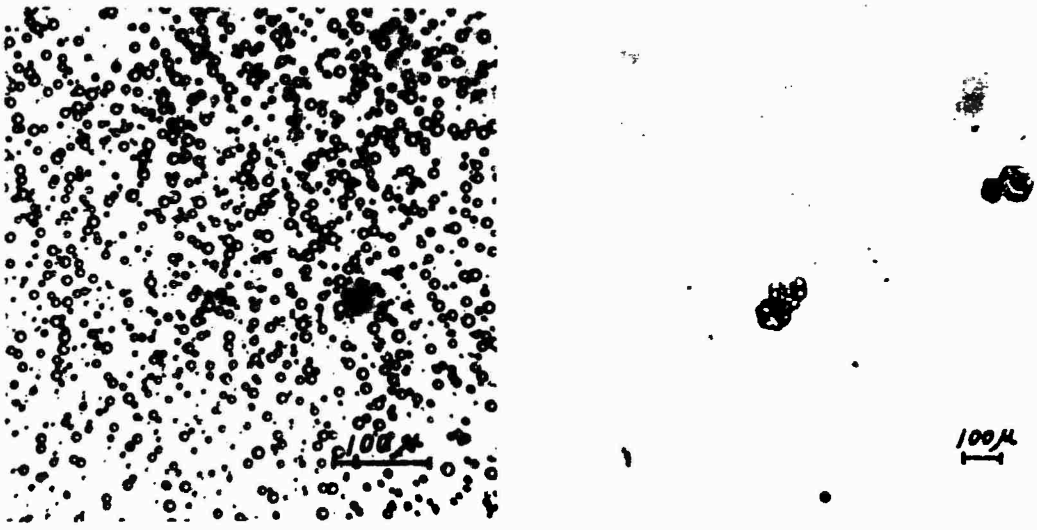
Observation of ice-fog nucleation

In these observations, dense ice fogs persisted in populated areas, at temperatures of about -40C and lower. The populated areas provide sufficient water vapor and nucleating material for ice fog by the combustion of hydrocarbons such as gasoline, fuel oil, and coal.

Observations were made of the ice-fog formation process in the water vapor discharged from an automobile exhaust pipe and from the chimney of a steam heat and electric power plant. Samples were collected by use of an impactor at various distances from the sources. Samples collected at the exhaust tailpipe showed only water droplets, although the ambient air temperature was about -40C. Further from the tailpipe, the droplets were cooled down to near the ambient temperature, and ice nucleation occurred at the threshold temperature of the freezing nuclei present in the exhaust products.

To observe ice formation from the exhaust gases of the power plant, a blimp was used to locate the impactors in the drifting vapors from the stack. Samples were collected in silicone oil at a height of approximately 50 m and at horizontal distances of 20 m, 50 m, and 100 m downwind from the stack. There was no natural ice fog present during the sampling period. The samples collected 20 m downwind from the chimney showed only supercooled water droplets (Fig. 4a). The 50-m samples contained mixtures of supercooled droplets and ice crystals, while the 100-m samples displayed only ice crystals (Fig. 4b). These observations tend to lead to the same conclusion as that derived from the study of automobile exhaust gases; nucleation occurred only at the threshold temperature of the available freezing nuclei.

A gross observation of the phenomenon of ice-fog nucleation may be made from Figure 5, a view of the Fairbanks, Alaska, area from College Road (looking nearly south). At the time of the photograph, the wind was very weak from the northwest. The pillar of steam fog seen near the left center of the photograph issued from the chimney of a coal-burning electric power plant. The warm steam fog, after rising



a. Supercooled water droplets at -22C, 20 m from the power plant stack.

b. Ice crystals nucleated at -22C from the supercooled droplets, 100 m from the power plant stack.

Figure 4. Supercooled droplets and ice crystals produced by exhaust water vapor from an electric power plant stack at Fairbanks, Alaska.

Figure 5. Fairbanks ice fog produced by exhaust water vapor from electric power plants, heating furnaces and automobiles.

to a considerable height, cooled to ambient temperature (approximately -40C), whereupon ice nucleation occurred. After nucleation, crystal growth occurred by the Bergeron-Findeisen process and the crystals precipitated slowly into the lower ice-fog layer near the ground. The water droplets in the steam fog from the chimney are relatively dense and produce an opaque appearance while the ice fog produced after ice nucleation is much less dense and appears thin. As Figure 5 illustrates, the ice fog tends to form around the populated area, and the outlying, sparsely populated or unsettled area remains clear.

ICE-FOG NUCLEI

Size relationship between ice-fog crystals and their nuclei

Condensation nuclei larger than 0.001 μ radius were counted with a small particle counter on a fogless day at -12C. The concentrations ranged between 22,500 and 36,000 particles/cm³. The nucleus concentration in an unpopulated area outside of Fairbanks was only 450 particles/cm³, but the number in the exhaust from an automobile tailpipe was over 1,000,000 particles/cm³. It is apparent that the primary source of condensation nuclei in downtown Fairbanks is the exhaust of automobiles and probably fuel furnaces. Ice-fog crystal concentration during a typical ice fog in downtown Fairbanks was found to be 100-200 crystals/cm³. It appears that only a small fraction of the available condensation nuclei act as ice-fog-forming nuclei, while a large number of potential condensation nuclei remain inactive.

A solid particle of from 0.1 to 1.2 μ diam was observed in the center of the residue of each ice-fog crystal. These particles were found to be combustion products by electron-diffraction analysis (Kumai, 1964). Around the large central particle of each specimen, many small particles of the order of 0.01 μ diam were found, presumably collected as a result of the Brownian motion characteristic of such small solid aerosols, and by migration of aerosol particles to the surface of ice-fog crystals when the water vapor flux moves in that direction (Facy, 1955).

Aerosols are removed from the atmosphere through ice-fog precipitation. Physical and chemical processes of wash-out of aerosols in the atmosphere have been described by Junge (1958). The following processes contribute to the accumulation of aerosols in ice-fog crystals.

1) The consumption of condensation, freezing, and sublimation nuclei during the formation of ice-fog crystals.

2) The subsequent attachment of inactive solid particles to the ice-fog crystals as a result of Brownian motion.

3) The subsequent attachment of aerosol particles to ice-fog crystals through the process of the migration in the direction of water vapor flux as water vapor sublimes onto the ice crystal surface.

4) The absorption and fixation of trace gases on ice-fog crystals.

In every sample studied, a nucleus was found in the center of the ice-fog crystal residue. In the residues of sintered ice-fog crystals, several solid particles of 0.1 to 1.0 μ diam were observed. Occasionally only one center nucleus was found in the residue of sintered ice-fog crystals, indicating the possibility that during the sublimation process the collective nuclei of the sintered ice-fog crystals must have become coagulated into one nucleus.

The nucleus of an ice-fog crystal is shown in Figure 6. The shape of the ice-fog crystal, formed at -37C, was that of a hexagonal plate. The nucleus was 0.4 μ in largest extension. The nucleus is a combustion by-product of more than one component. Under the strong electron beam, part of the nucleus evaporated, and an unevaporated particle remained as seen in Figure 6. The nucleus was shadowed by chromium vapor at an angle of 19°25'. The nucleus height is about one third of the length of shadow. Around the big center nucleus, many particles of the order of 0.01 μ diam are also found. These small nuclei may have been collected by Brownian motion. Nucleating substances in ice-fog crystals collected at Fairbanks, Alaska, in 1962 and 1963 are shown in Table IV. About 80% of the ice-fog nuclei were combustion by-products, 10% hygroscopic substances with combustion by-products, and 10% clay minerals.

Figure 6. Ice-fog nucleus with condensation nuclei possibly collected by Brownian motion.

Table IV. Nuclei substances in ice-fog crystals collected at Fairbanks, Alaska, in 1962 and 1963.

Substances	1962	1963	Total	%
Combustion by-products	170	157	327	80.0
Hygroscopic substance with combustion by-products	2	38	40	9.8
Clay minerals	32	3	35	8.5
Unidentified	3	4	7	1.7
No nuclei	0	0	0	0
Total	207	202	409	100.0

A study was made of 125 samples of ice fog from the Fairbanks area in an attempt to establish a size relationship between ice-fog crystals and their nuclei (Fig. 7). The size of each nucleus was measured by its mean diameter. There was no apparent relationship. The nuclei ranged from 0.1 to 1.2 μ diam for ice-fog crystals of 5 to 22 μ diam. These results are quite similar to those observed for fog droplets and their nuclei (Kuroiwa, 1957).

Figure 8 shows a typical ice-fog nucleus derived from the combustion products of hydrocarbon fuels. The size range of these nuclei is from 0.1 to 1 μ diam with a maximum frequency of 0.3 μ. The ice-fog crystals (Fig. 8) which form on the combustion product nuclei in the Fairbanks area are 2 to 20 μ diam — 10 to 100 times the diameter of the nuclei.

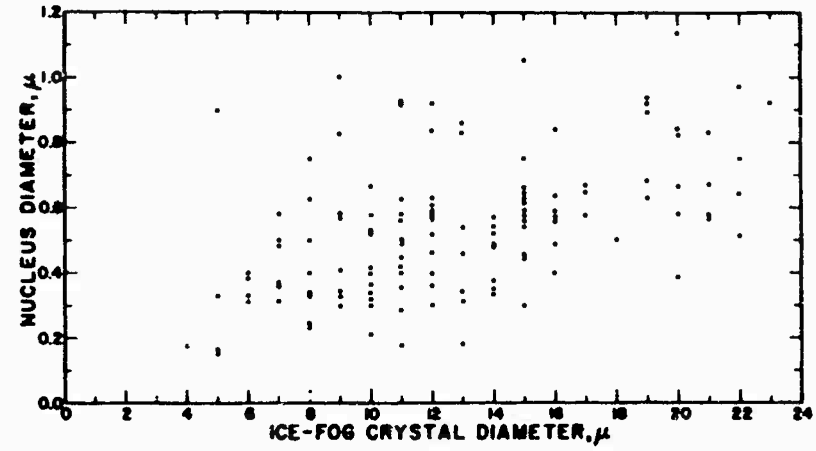


Figure 7. Size relationship between ice-fog crystals and their nuclei.

Seeding agents, and their size distributions

Both organic and inorganic substances are used as seeding agents for ice-crystal formation. Silver iodide (AgI) is an inorganic seeding agent which has been shown to be effective at temperatures as high as -4C. Phloroglucinol, an organic seeding agent, is effective at -2C and below. Electron photomicrographs of silver iodide, phloroglucinol, and the nucleus of an ice-fog crystal, as well as an optical photomicrograph of an ice-fog crystal are shown in Figure 8, together with a graph of the size distributions of the respective particle types. The silver iodide samples were prepared by heating silver iodide crystals in a nichrome wire basket and collecting the smoke on electron microscope grids. The size range of the prepared silver iodide was found to be 0.01 to 0.1 μ diam with a frequency maximum of approximately 0.035 μ. The phloroglucinol samples were prepared by grinding commercially available phloroglucinol in a ball mill. Numerous small phloroglucinol particles and part of a large one are shown in Figure 8. The particle size range of this phloroglucinol seeding agent is 0.08 to 3 μ diam with two frequency maxima: 0.1 and 1 μ diam. In field experiments of phloroglucinol seedings of winter stratus, Braham (1963) has found that phloroglucinol does induce the transformation of undercooled stratus into a mixed-phase cloud. However, his experiments do not indicate that phloroglucinol will replace silver iodide for cloud seeding purposes.

CONCLUSION

1. A study of the 32-year record of average daily temperatures at Fairbanks, Alaska, shows the seasonal periods of maximum summer warmth and winter cold lag behind their respective solstices by approximately one month.

2. The prevailing winter winds in Fairbanks are generally northerly and weak (1.8 m/sec avg). Higher winds (17 m/sec recorded maximum), when they occur, are usually from the south.

3. Meteorological conditions, especially temperature and wind, affect the occurrence and duration of ice fog. In the period from 1957 to 1963, the longest continuous ice fog was a period of 186 hours which occurred in December, 1961, while 60% of all ice fogs were of less than 6 hours duration and 80% were of less than 24 hours duration.

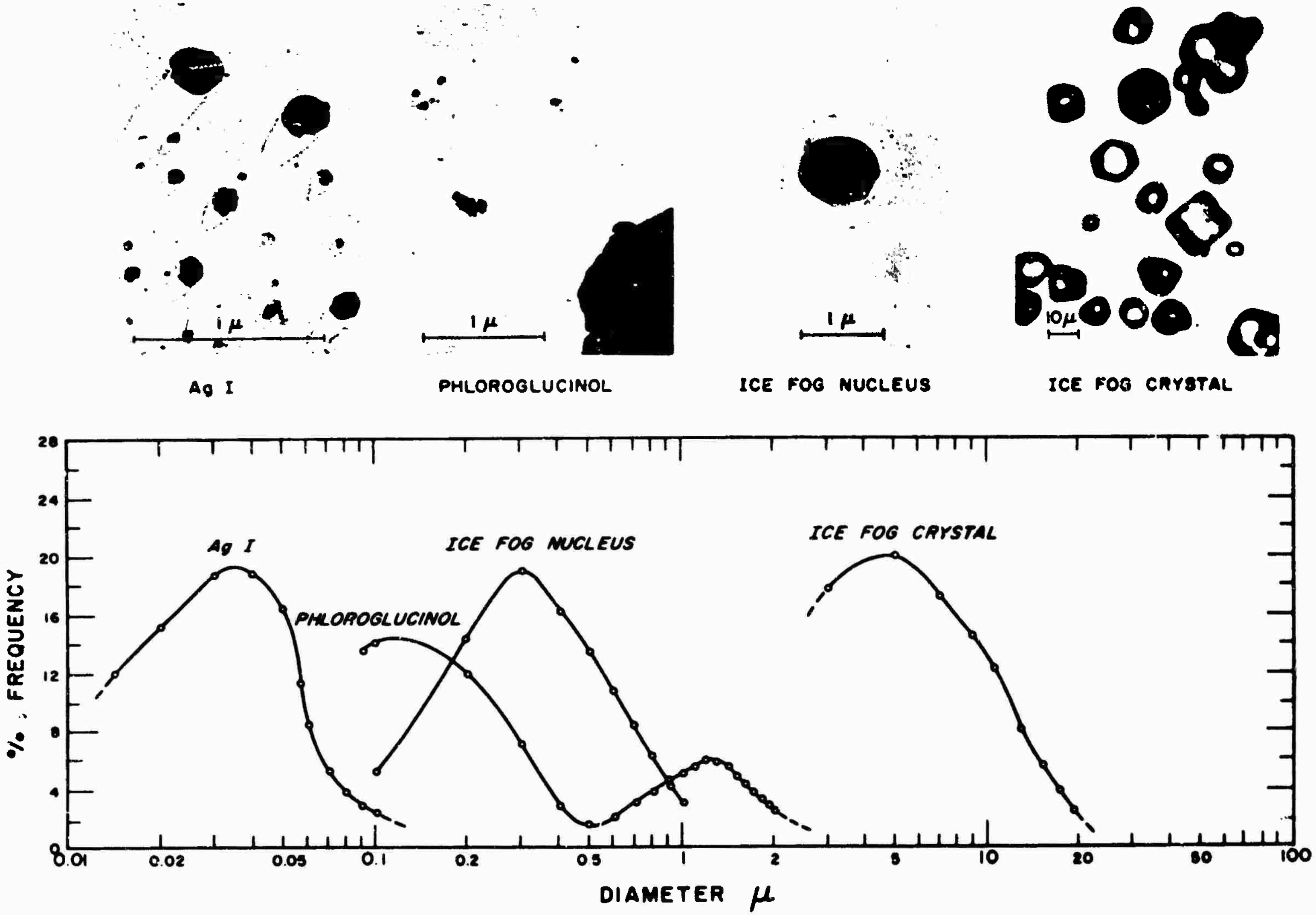


Figure 8. Seeding agent, nuclei, ice-fog crystals and their size distribution.

4. The measured mean diameters of ice-fog nuclei ranged from 0.1 to 1.2 μ for ice crystals of 5 to 22 μ mean diam, with no apparent size relationship between a given crystal and its nucleus.

5. Sampling of exhaust vapors from a power plant chimney on a clear day, ambient temperature -22C, 20 m downwind from the chimney, revealed only supercooled water droplets: samples 50 m downwind contained a mixture of supercooled droplets and ice crystals; while samples taken 100 m downwind displayed only ice crystals. Thus, ice nucleation can be observed at around -20C but, in general, the concentration of crystals formed at these temperatures is low.

6. In these observations, dense ice fog persisted only at about -40C or lower, and only over populated areas, where products of hydrocarbon combustion from industry, homes, and vehicles provide sufficient water vapor and nucleating material.

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