Fig. 1. Ice fog at Eielson AFB, Alaska. Jan. 3, 1954.

ICE FOG AS A PROBLEM OF AIR POLLUTION IN THE ARCTIC

Elmer Robinson, William C. Thuman, and Ernest J. Wiggins*

THE term "arctic" frequently evokes an image of vast expanses of ice and snow and rock and tundra, with widely separated and sparsely populated settlements, where many of the normal problems of community life in the temperate regions are unknown. Whereas this picture may be generally true in respect to small, relatively static settlements, the rapid growth and development of larger communities, such as Fairbanks, Alaska, have brought with them many of the problems inherent in typical industrial communities throughout the world. Air pollution is one such problem. Air pollutants may be solid, liquid, or gaseous, and are usually produced by domestic and industrial heating plants. If certain meteorological conditions and topographical features combine, these products of combustion are held in suspension in the air and increase in concentration until troublesome effects occur. In many communities in the Alaskan and Canadian Arctic, air pollution during the winter months manifests itself primarily as ice fog. These fogs are troublesome because they frequently reduce visibility sufficiently to hamper both aircraft and automobile operations.

Winter fogs of natural origin have been reported frequently, and have been called "ice crystal fogs," "frost smoke," "sea smoke," "arctic ice smoke," "arctic sea smoke," and "smoke frost" by various observers. Petterssen (1940) attributed the formation of "ice crystal fogs" to a process of sublimation of atmospheric water vapor on sublimation nuclei beginning at temperatures of about -20°C, and he said that at still lower temperatures (-30 to -50°C), ice crystal fogs are a common occurrence in regions such as Siberia and Northern Canada. He also describes the cloud to be of such density at extremely low temperatures that it appears as a thin mist or haze ("frost haze"). Frost (1934) describes winter fogs as a disagreeable feature associated with extreme cold. He reports that at Fairbanks, temperatures of -45°C or lower are always accompanied by dense fog. For example, during January 1934 there were 348 hours during which the temperature was -45°C or lower. Of the 348 hours, 320 hours were accompanied by dense fog. On one occasion, the fog prevailed for 155 consecutive hours. This was undoubtedly the same type of ice fog as that studied in the present program.

The earliest report of ice fog, which the authors found in the literature, is in Nansen's narrative of the 1893-6 voyage of the *Fram* (Nansen, 1897).

*Stanford Research Institute, Menlo Park, California. The research reported in this paper was sponsored by the Geophysical Research Directorate, Air Force Cambridge Research Center, under Contract No. AF 19(122)-634.

He observed that at very low temperatures (evidently below -40°C) the *Fram* always gave off a mist, which was carried downwind.

General Aspects

Water vapor is not thought of as an air pollutant in the usual sense, that is, a product of human activity that produces loss of visibility or other deleterious effects when released into the atmosphere. Whereas water fogs are a serious handicap to air operations, ocean shipping, and land traffic in many localities, they are primarily of natural origin and aggravation of the situation through human activities is usually caused by providing additional condensation nuclei rather than water.

At temperatures below 0°C conditions change considerably. For example, at -40°C the amount of water vapor in the air at saturation is only 0.12 gm./m.^{3}, as compared with 4.8 gm./m.^{3} at 0°C, a ratio of 40 to 1. Once saturation is reached the additional amount of particulate water required to reduce the visibility to a restrictive value such as 400 meters is very small, of the order of 0.05 gm./m.^{3}. Furthermore, the turbulence of the lower atmosphere usually decreases with falling temperatures so that the volume of air that must be saturated to produce fog becomes smaller at lower temperatures. In addition, wind speeds are mostly quite low at inland localities in very cold weather, and the distribution of surface temperatures tends to confine any material that is emitted near ground level to a layer not more than 10 to 20 m. thick. Added to the factors that reduce the quantity of water vapor required to form a fog is the increase in the rate of production of water vapor that usually occurs when air temperatures fall. The then necessarily more intensive heating causes a higher consumption of fuels and, because of the hydrogen in the fuel, large quantities of water are produced when they are burned. For example, the combustion of one gallon of gasoline results in the production of approximately one gallon of water. Obviously, at most localities, when the temperature falls, there is a rapid increase in the probability that the air exceeds the saturation point in respect to water vapor in the vicinity of human activities.

The ice fog problem encountered at most centers of population, including military installations, at inland localities in the arctic is a good example of the situation just described. Particular difficulties with ice fog have been encountered at the United States military installations of Ladd and Eielson Air Force Bases in the Fairbanks, Alaska area. Stanford Research Institute was engaged by the Air Force Cambridge Research Center to investigate the problem. The study included an initial, short-term field program in the winter of 1952, and extensive field programs in the same area during the winters of 1952-53 and 1953-54. Field investigations were conducted primarily at Eielson Air Force Base, where a laboratory was established near the main runway. Additional observations were made at Ladd Air Force Base, and in the city of Fairbanks. Studies to augment the field investigations were conducted at the laboratories of Stanford Research Institute in Menlo Park, California.

The ice fog situation observed in this program is probably typical for most centers of activity in the Alaskan and Canadian interior, while at coastal locations a different situation is to be expected. At these latter places wind speeds and temperatures are generally higher, the influence of artificial water vapor sources is reduced, and ordinary sea fog is often observed. The present investigation is limited to the inland type of low-temperature fog, which is characteristically "ice fog."

In general, the ice fogs observed during the field investigations were shallow with well-defined upper limits. Fig. 1 shows a clearly defined ice fog from a distance. This fog covered the air field at Eielson AFB. On some occasions stratified fog layers were observed. The horizontal extent of the fogs typically coincided with the areas of human activity, including the well-travelled road outside the built-up areas, although during prolonged periods of cold weather the area covered by fog gradually increased. On at least one occasion a 20- to 30-mile section of the Tanana Valley became filled with fog after a week of temperatures in the vicinity of -40°C.

The study of the ice fog problem proceeded along two general lines: (1) the physical-chemical characteristics of the fogs, and (2) the meteorological conditions accompanying their formation and disappearance. The constituent particles of the fogs were studied first by conventional collection methods such as settling and filtration. It was demonstrated at an early stage that the principal reduction of visibility at Eielson AFB resulted from water or ice aerosols, with little contribution from soot, fly-ash, or other non-aqueous materials. This may not always be true in a city such as Fairbanks, where a considerable amount of low-grade bituminous coal is used for domestic heating. The presence of numerous sources of ice fog in the city of Fairbanks is evident in Figure 2. Most of the sources are heating plants in residential and business buildings.

The Fog Aerosol

The ice fog has most of the visual characteristics of water fog, and seldom shows optical evidence of the presence of crystals. It has been stated by George (1951) that ice fog is composed of ice crystals, but we know of no previous studies describing the crystal forms of the particles of the fog aerosol.

During the studies in the Eielson area the method used most frequently for examination of the fog particles was simple settling on microscope slides. The collected particles were either viewed and photographed directly by using a microscope and camera located outdoors, or plastic replicas were prepared for permanent records by the Schaefer technique (Schaefer, 1941).

These studies showed that the ice aerosol had the following general characteristics. At temperatures above -30°C, the aerosol particles consisted principally of well-developed hexagonal plates and prisms such as those shown

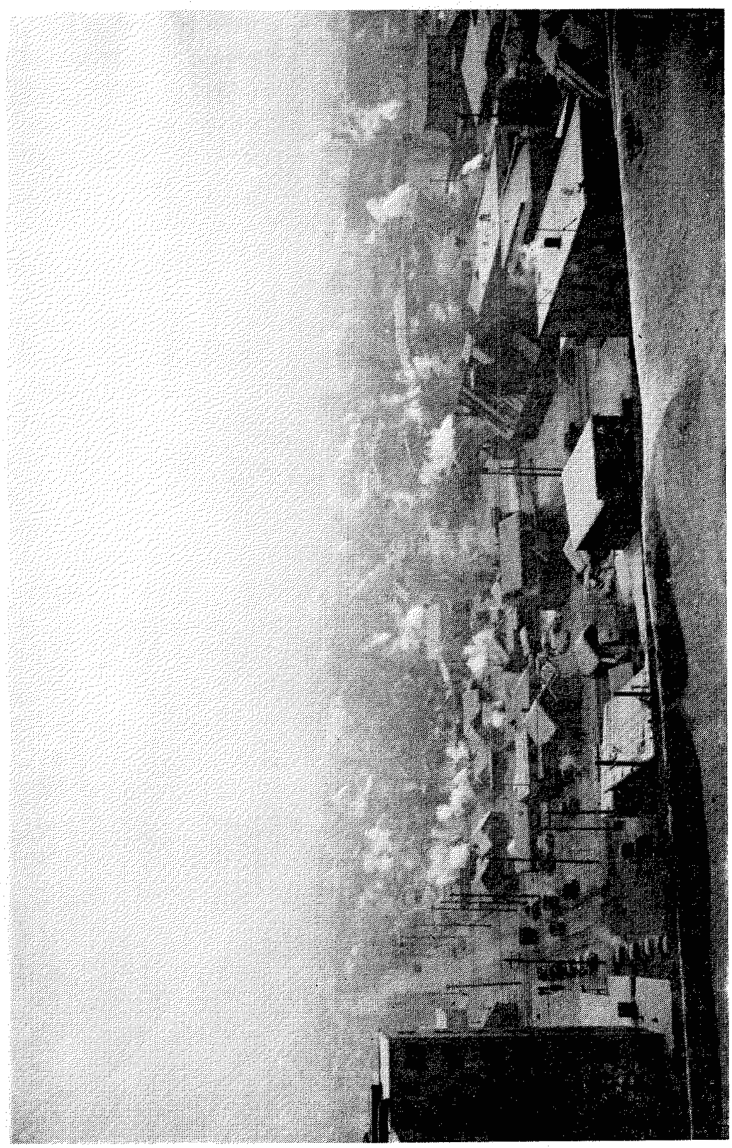

Fig. 2. Ice fog over Fairbanks, showing domestic heating sources.

in Fig. 3. The ice crystal aerosol observed in the absence of fog at various temperatures consisted also largely of hexagonal crystals of this nature. At temperatures below -30°C, when ice fog began to appear, an increasing proportion of small, nearly spherical particles was observed (Thuman and Robinson, 1954a). Fig. 4 is a typical example of this ice fog aerosol. At temperatures of -40°C and below, the fog normally consisted almost exclusively of such particles. For convenience the authors labeled these particles "droxtals." The name seemed descriptive since they appear to be frozen water droplets with only rudimentary crystal faces, as seen at higher magnification

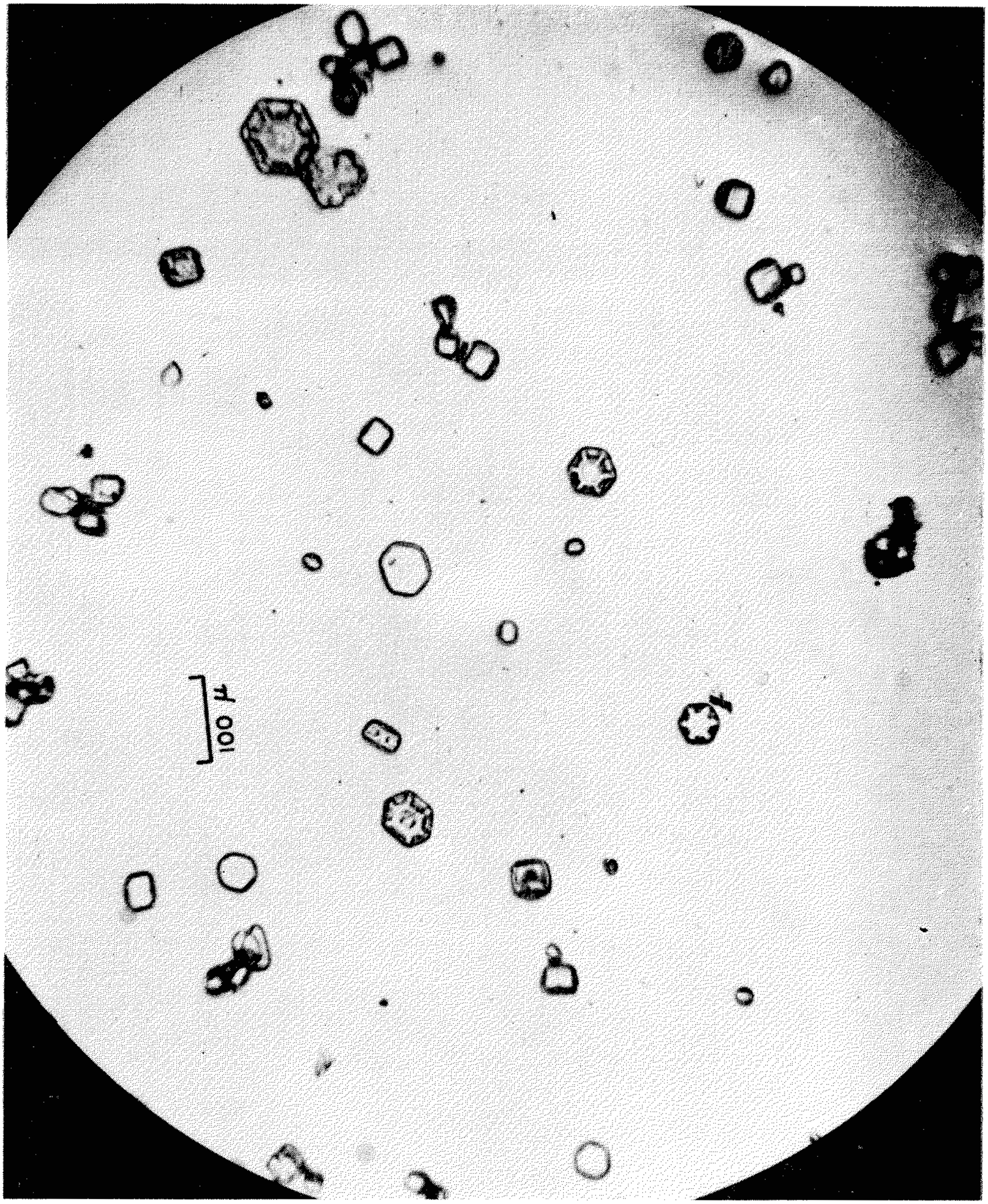

Fig. 3. Ice crystals collected at -27°C, visibility 20 miles.

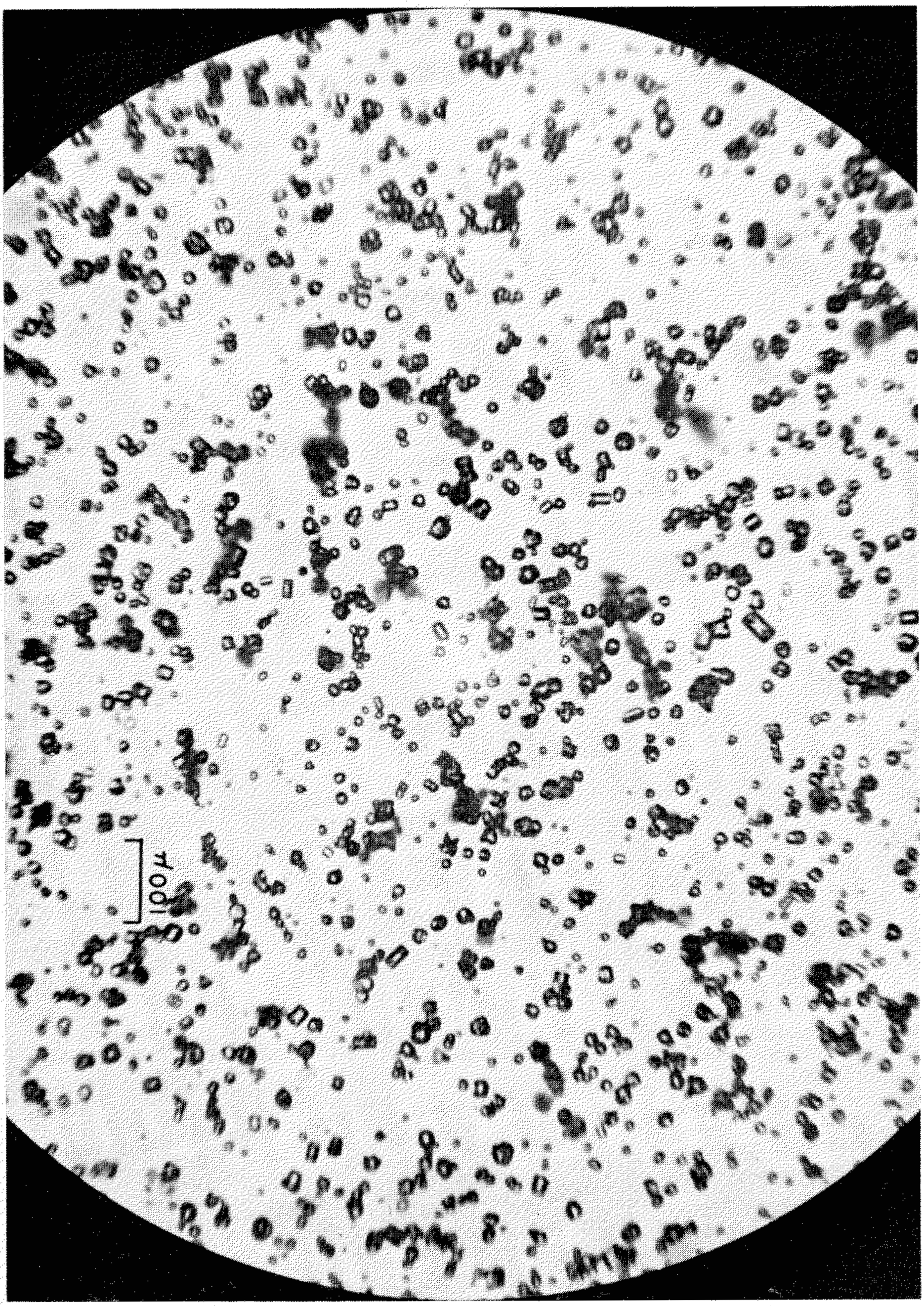

Fig. 4. Particles collected in ice fog at -41°C, visibility ⅜ mile.

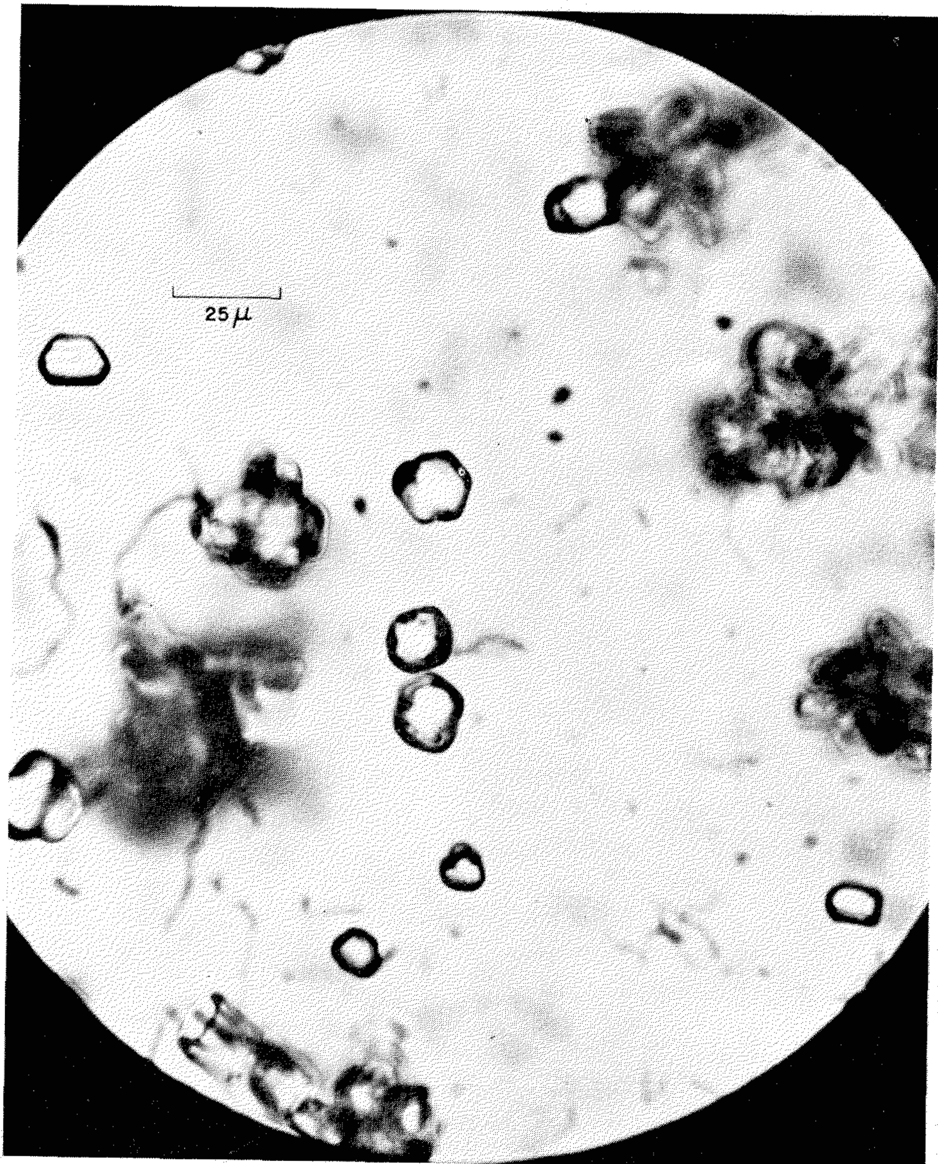

Fig. 5. Ice fog particles, -39°C, visibility ¼ mile. Febr. 25, 1954.

in Fig. 5. Since no more apt terminology was found in the literature the name droxtal has been retained for these particles. The droxtals appear to be the constituent which gives a low-temperature ice fog the typical dull gray appearance and causes the reduction in visibility. The larger, well-developed crystals that are found at higher temperatures in the ice crystal aerosols produce the characteristic pillars and other optical effects but cause little reduction in visibility. Fig. 6 shows the percentage distribution of ice particle types as a function of temperature. Note the rapid increase in droxtals at the lower

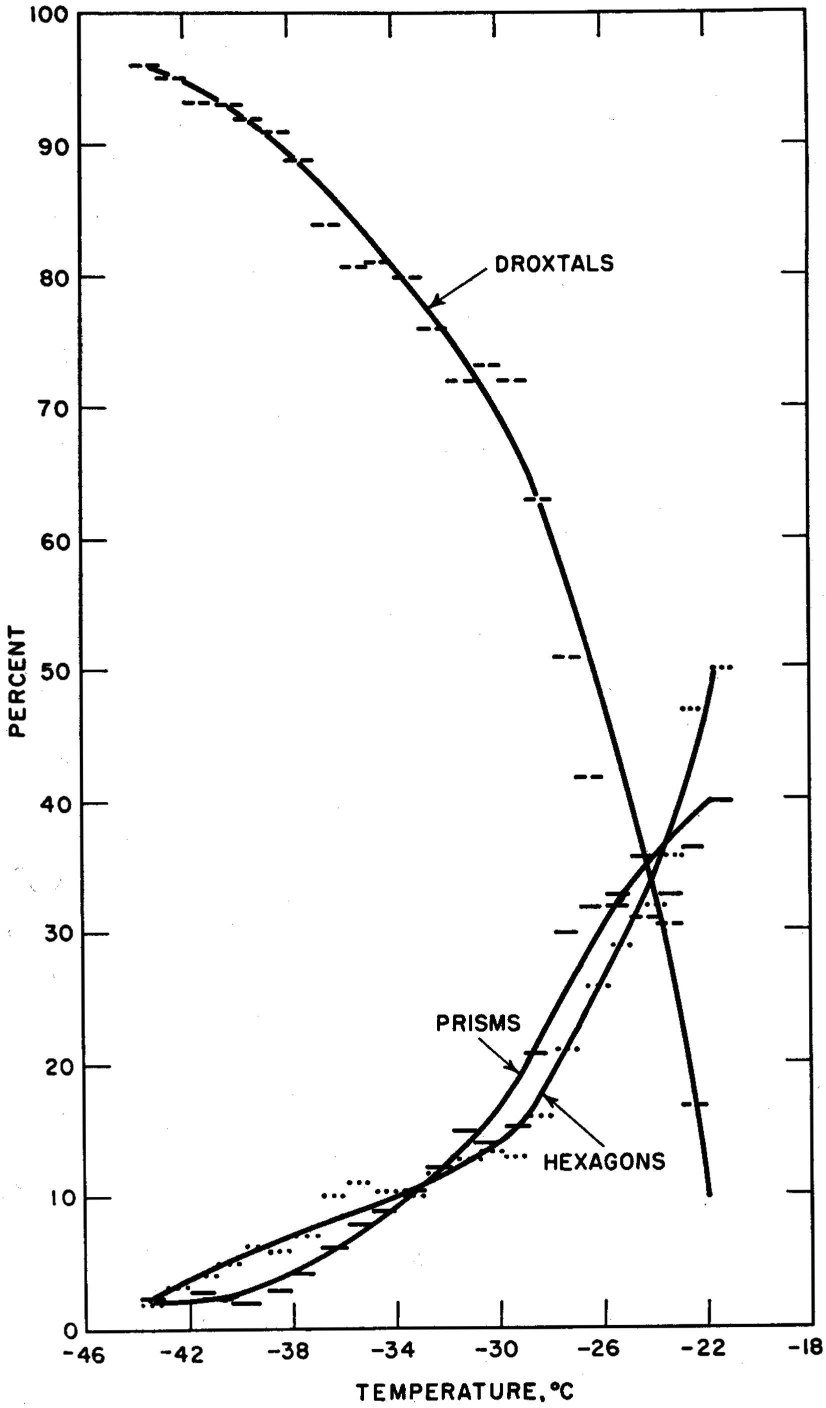

Fig. 6. Percentage distributions of ice particle types, Eielson AFB, Dec. 1953 to March 1954.

temperatures until at temperatures below -38°C droxtals account for over 90% of the particles.

After the droxtals were definitely identified as the major constituent of ice fog, the question arose whether the droxtals observed on the collection slides actually existed in the air as ice particles or were supercooled water droplets that froze on contact with the slide. This question was of some practical importance, since if the fog were supercooled water it might be possible to modify its properties by artificial addition of freezing nuclei. However, experimental seeding of ice fogs with dry ice and with silver iodide produced no observable changes, and suggested that the fog contained little, if any, supercooled water. Tests with a whirling wire showed no icing at the leading edge such as would be expected to occur if appreciable quantities of

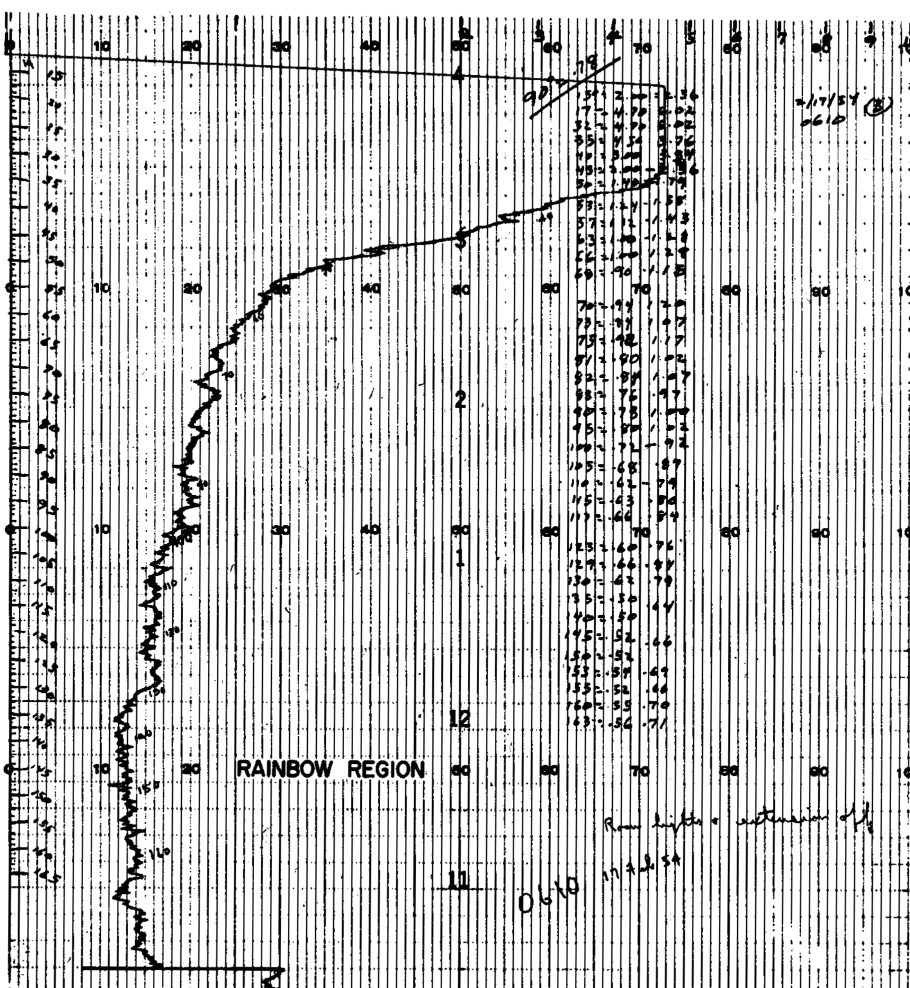

Fig. 7a. Typical scanning record of light scattering taken during an Alaskan ice fog.

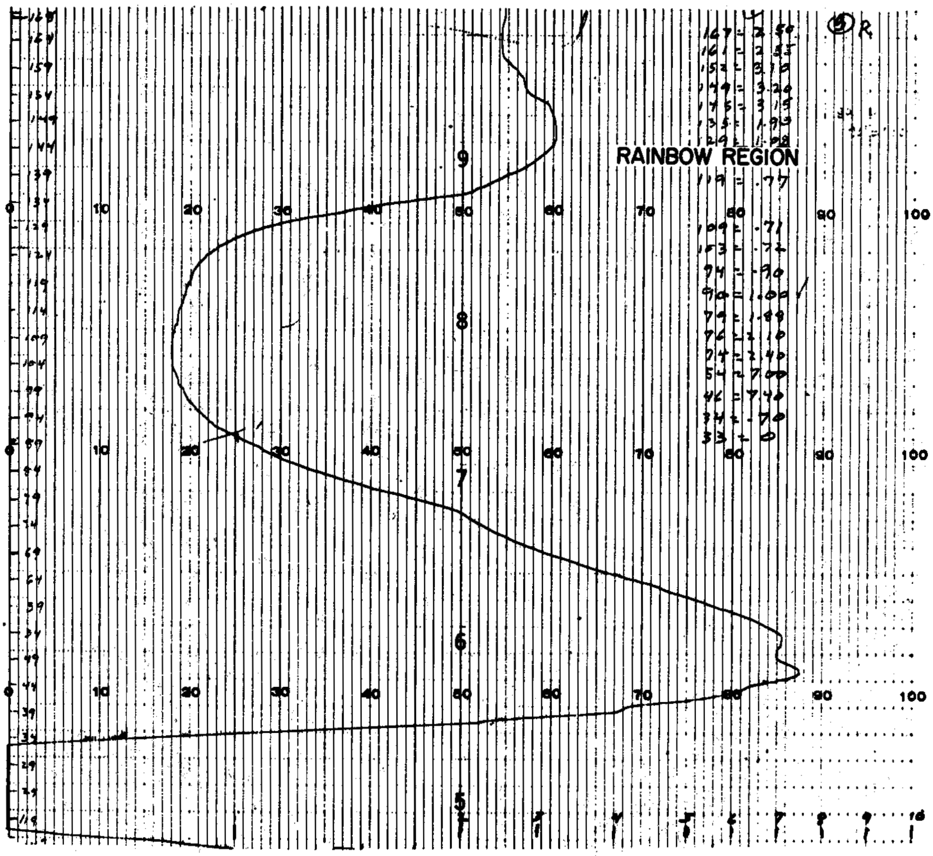

Fig. 7b. Typical scanning record of light scattering by water fog in cold chamber.

supercooled water were present. The most convincing proof was obtained by the use of an apparatus measuring the angular distribution of the intensity of light scattered by the fog, since the presence of liquid water droplets, even in small amounts, may be distinguished by the characteristic "rainbow" at an angle of 144° from the direction of the transmitted light beam (Thuman and Brown, 1954). Characteristic curves were obtained for ice fogs and water fogs produced in a cold chamber. Fig. 7a shows the typical intensity distribution curve for an ice fog in the field and Fig. 7b that for a supercooled water fog in the laboratory. No indication of the presence of water droplets is seen in the ice fog record, but the 144-degree rainbow is clearly indicated in the water fog curve.

Sources of Ice Fog

As a part of the research program attempts were made to identify the sources of water vapor responsible for ice fog formation, by making observations and taking photographs at ground level, by taking time lapse motion pictures from vantage points above or outside the fog area, and by correlating wind direction and fog density at the field station. Low-level steam sources such as temporary heating plants, defective steam traps, kitchens, and so forth appeared to be major contributors to ice fog. The main power plant at Eielson AFB usually did not appear to contribute to the ground level fog, since the high exit temperature and velocity of the stack gases carried them to an altitude from which the water vapor did not return to ground level within the limits of the air base. This power plant plume is visible at the right in Fig. 1.

Vehicles appeared to make a substantial contribution to the fog at Eielson and Fairbanks, particularly since it was usual to let many engines run continuously during cold weather, even while the vehicles were parked. Many vehicles also carried auxiliary gasoline-burning heaters. The fog resulting from vehicle operation constitutes a special hindrance since it is concentrated on the roads and streets, which other vehicles must use. Aircraft engines also contribute large amounts of water vapor to the ice fog at an air base. This is not too serious during actual take-off, since the quantity of water vapor emitted per foot of runway is not great. However, when a number of aircraft engines are being warmed up prior to take-off large areas can become heavily obscured.

In cities such as Fairbanks a major source of water vapor appears to be domestic heating systems, as pictured in Fig. 2. Passenger cars and trucks produce local concentrations of fog on streets, particularly in downtown areas. No "natural" sources of ice fog were observed at any time in the Fairbanks area, although the writers were told that natural ice fog could be observed in places such as Circle Hot Springs where open water persists through the winter season. From the data gathered at Fairbanks and Eielson it appears that the prime contribution of the combustion processes is water vapor that is first condensed into droplets, then supercooled, and finally frozen into droxtals. In this process special nuclei are not necessary since the only nuclei required in the mechanism are the very common condensation nuclei.

Godson (1952) came to a similar conclusion about the influence of various settlements after a study of low temperature fogs in Canada. His data clearly showed that at Yellowknife, N.W.T., low-temperature fog at the observing station 5 miles from the town was closely associated with wind from the town toward the station. He concluded that the smoke from the town contributed water vapor and also nuclei active at the low temperatures. Godson mentions that low-temperature fog at Watson Lake is also closely associated with combustion processes in the settlement.

In addition to reports of ice fog associated with combustion in urban areas, there are frequent reports of ice fog over or near herds of caribou during very low temperatures. While no actual measurements have been made on caribou, it has been estimated that the breathing rate of a resting animal is 50-100 liters/minute and that of a trotting animal is twice that amount (Karstens, 1951). The deep-body temperature of the caribou is about 37°C, and the temperature of exhaled air about 32 to 36°C. The exhaled air is probably saturated. On the basis of these estimates the breath of the animal contains about 3 grams of water vapor per 100 liters of air. A resting animal would thus exhale about 3 grams of moisture per minute and a trotting animal 6 grams per minute. Saturated air at a temperature of -40°C contains only 0.12gm./m.^{3}. Thus almost all of the 3 to 6 grams given off by the animal at air temperatures of -40°C will be precipitated in the form of ice particles. It seems therefore quite logical that a herd of caribou, whether resting or on the move, can create an ice fog when weather conditions are favorable.

Ice Fog Formation Mechanism

The process by which ice fog particles are produced from combustion gases and steam sources is apparently quite simple. The water vapor first condenses into small water droplets when the warm, moist gases are discharged into the cold atmosphere. An adequate supply of condensation nuclei is available at all times from the combustion of the fuel. At temperatures down to -30°C the supercooled water droplets are relatively stable and only a small number of crystals are formed. These crystals grow by transfer of water from the remaining droplets, forming comparatively large and well-developed crystals.

At temperatures below -30°C the effectiveness of most solid particles as freezing nuclei rapidly increases, until at approximately -40°C spontaneous freezing of water droplets occurs without the aid of nuclei. Below -30°C it may therefore be expected that increasing numbers of water droplets will freeze rapidly with little opportunity for growth in size or into crystalline structures and thus produce numerous small, nearly spherical particles. At intermediate temperatures a combination of these processes will occur.

Meteorological Conditions

As mentioned earlier, a program of meteorological measurements was carried out concurrently with the physical studies of ice fog. An instrument tower, 29 m high, was used for continuous recording of air temperature, vertical temperature profile, wind speed and direction, and net radiation exchange. The tower and its instrumentation are shown in Fig. 8. The instrument readings were recorded on a Brown 16-channel recorder coupled to a tape punch and programming unit. The perforated tape record consisted of readings of each channel at 4-minute intervals, together with time and scale range information. This record was subsequently transferred to IBM punch cards for machine processing of the data.

Vertical temperature profiles were measured by wiresonde soundings to heights up to 275 meters. Humidity profiles were measured by drawing air through polyethylene tubing carried aloft by the wiresonde balloon. Humidities were also measured at fixed heights by means of permanent tubing installations on the 28-meter instrument tower. The water content of the air was

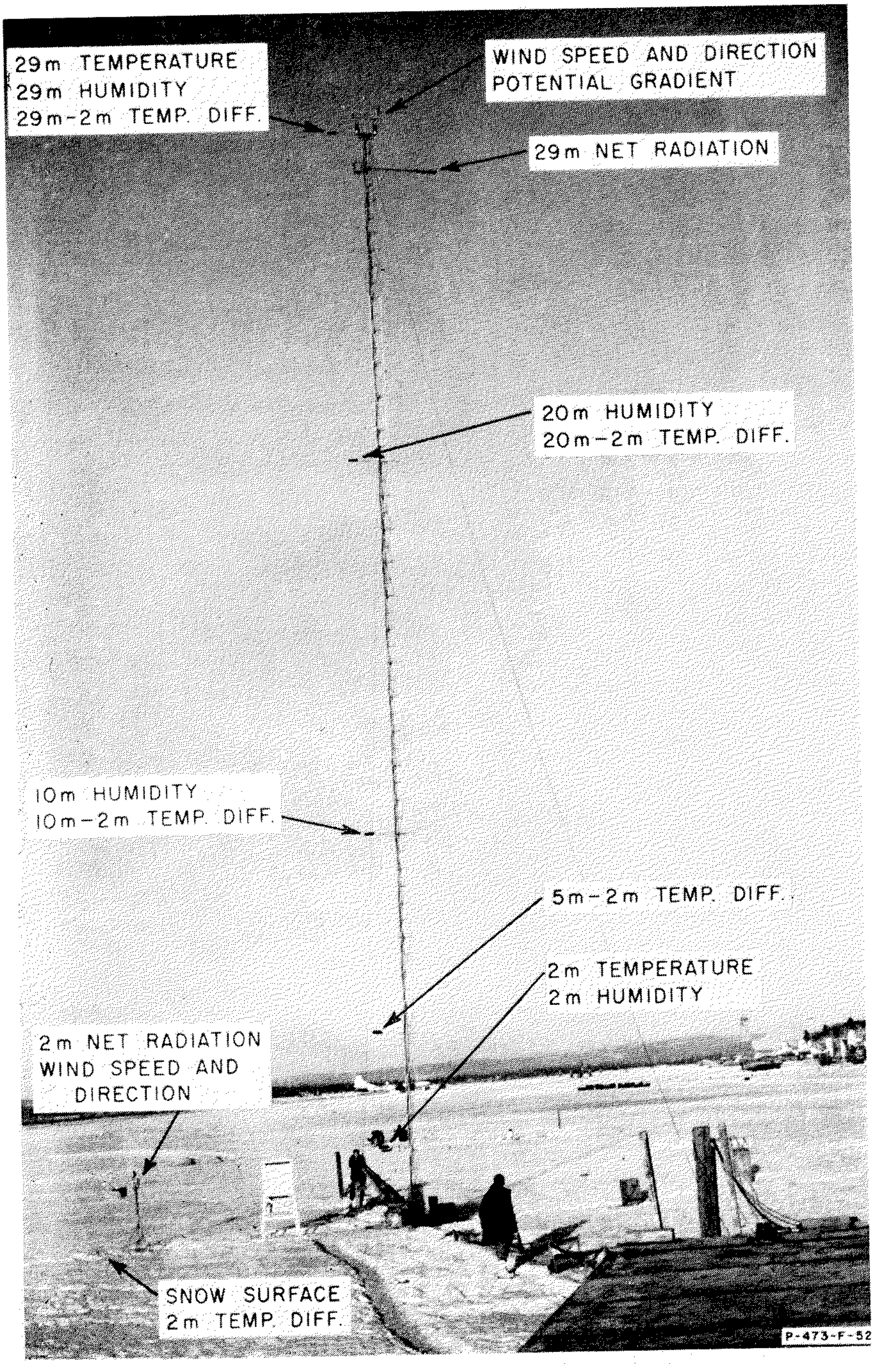

Fig. 8. Tower instrumentation.

determined chemically by drawing a measured volume of air through a methanol solution and then determining the amount of water removed from the air by a titration procedure using Karl Fischer reagent (Thuman and Robinson, 1954b).

The measurements of the temperature profile showed in general that steep, shallow surface inversions were present during clear, cold weather. These were modified, when ice fog began to form, so that the steepest portion of the inversion was just above the fog layer. The ice fog therefore occupied a generally stable surface layer, which was capped by an even more stable layer (Robinson and Bell, 1956). Surface winds were characterized by low speeds and highly variable directions.

The air at Eielson AFB was usually found to be unsaturated with respect to ice during the winter. Subsaturation of the air during the arctic winter is, of course, no rarity and has long been recognized. A very early attempt to quantify this situation was made by Hayes during the early explorations of north Greenland in the winter of 1860-61 when he conducted some crude experiments with strips of ice-coated flannel and small plates of ice. While his numerical data are missing, his observations were (Hayes, 1885): "The flannel becomes perfectly dry in a few days, and the ice-plates disappear slowly—while the thermometer is down in the zeros." Using the Karl Fischer technique it has been possible to improve on Hayes' observations.

The results of the 1952-53 winter season's humidity measurements during the present Alaskan ice fog studies are summarized in Fig. 9, covering temperature ranges of -4°C to -31°C in clear weather and -30°C to -43°C during ice fog. Of the clear weather runs, 95 per cent show unsaturation with respect to ice, with an average relative humidity of 83.6 per cent, and a standard deviation, s, of 12. Of the runs during ice fog, 79 per cent show unsaturation with respect to ice, with an average relative humidity of 91.1 per cent and a standard deviation of 11.8. As previously mentioned the ice particles are formed in supersaturated zones produced by the emission of steam or combustion products, and are capable of surviving for a considerable length of time in air that is somewhat below ice saturation. An ice fog period is terminated by the onset of conditions that favor the sublimation of the ice particles, such as higher temperatures or increased wind movement, which brings in drier air.

Summary

The ice fog aerosol results from the freezing of supercooled droplets, and as a result it is composed of irregular spheroidal particles. An ice fog appears to the observer to be very similar to a water fog. There is no rime ice accumulation. The ice fog particles are small enough so that their settling speed cannot be discerned in the open air. Accumulations of ice fog particles on exposed level surfaces resemble an "ice dust" rather than an accumulation of readily discernable particles as in the case of crystals. The ice fog is usually restricted in area and is associated with relatively large local sources of water vapor, almost exclusively man-made. Ice fog begins to form at temperatures

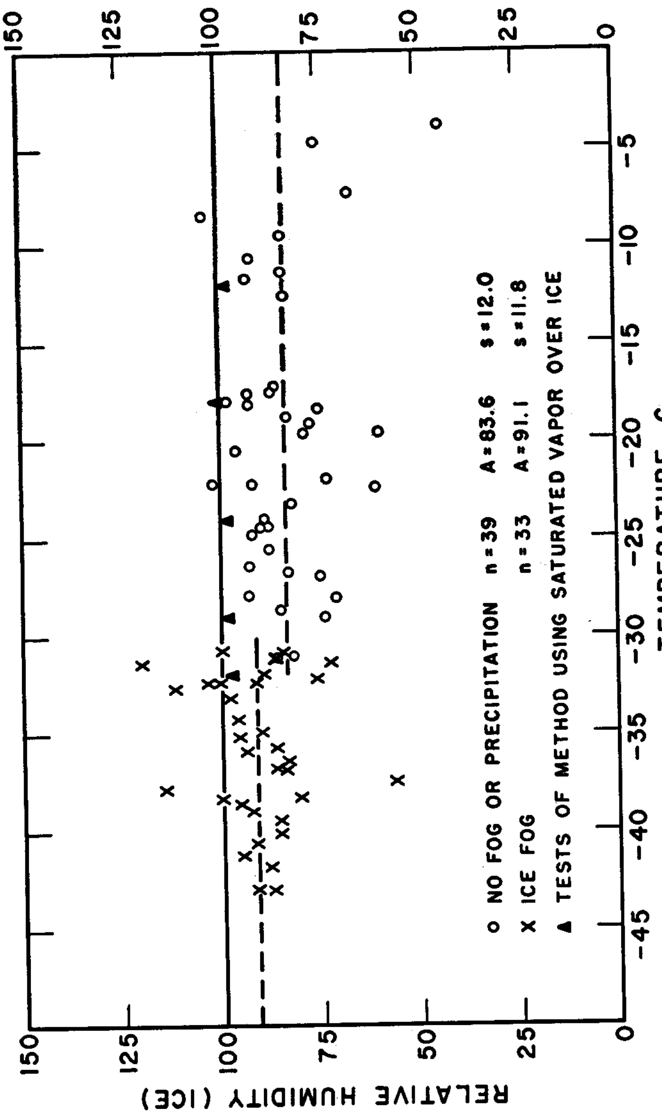

Fig. 9. Low temperature humidity determinations with use of Karl Fischer technique.

around -30°C and becomes increasingly probable when temperatures drop still lower. Because its source is the local discharge of water vapor, each area will exhibit its own pattern of formation. Spectacular optical phenomena such as halos and pillars are not characteristic of ice fog.

Ice fog is an example of an air pollution situation in which water vapor is the principal culprit. It appears to be an inevitable result of the emission of more than minor amounts of water vapor at low temperatures. Under these conditions only small amounts are required for saturation and the conditions in the surface layers of the atmosphere are such that only a relatively small volume of air needs to be saturated to produce fog. These conditions are common in many areas in the Arctic. The only hope for alleviating the situation in communities where such conditions prevail in winter is to curtail vapor emission or to confine it to tall stacks in selected locations. While ice fog, as such, causes inconvenience to the general public only by reducing visibility, and is not a health hazard, its presence is an indication of local conditions which could equally well lead to the accumulation of other pollutants. If industrial expansion of Fairbanks or any similar area should occur in accordance with current hopes and desires of the local citizens, prospective industries as well as the communities should plan carefully to avoid future air pollution problems more serious than those at present resulting from ice fog.

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