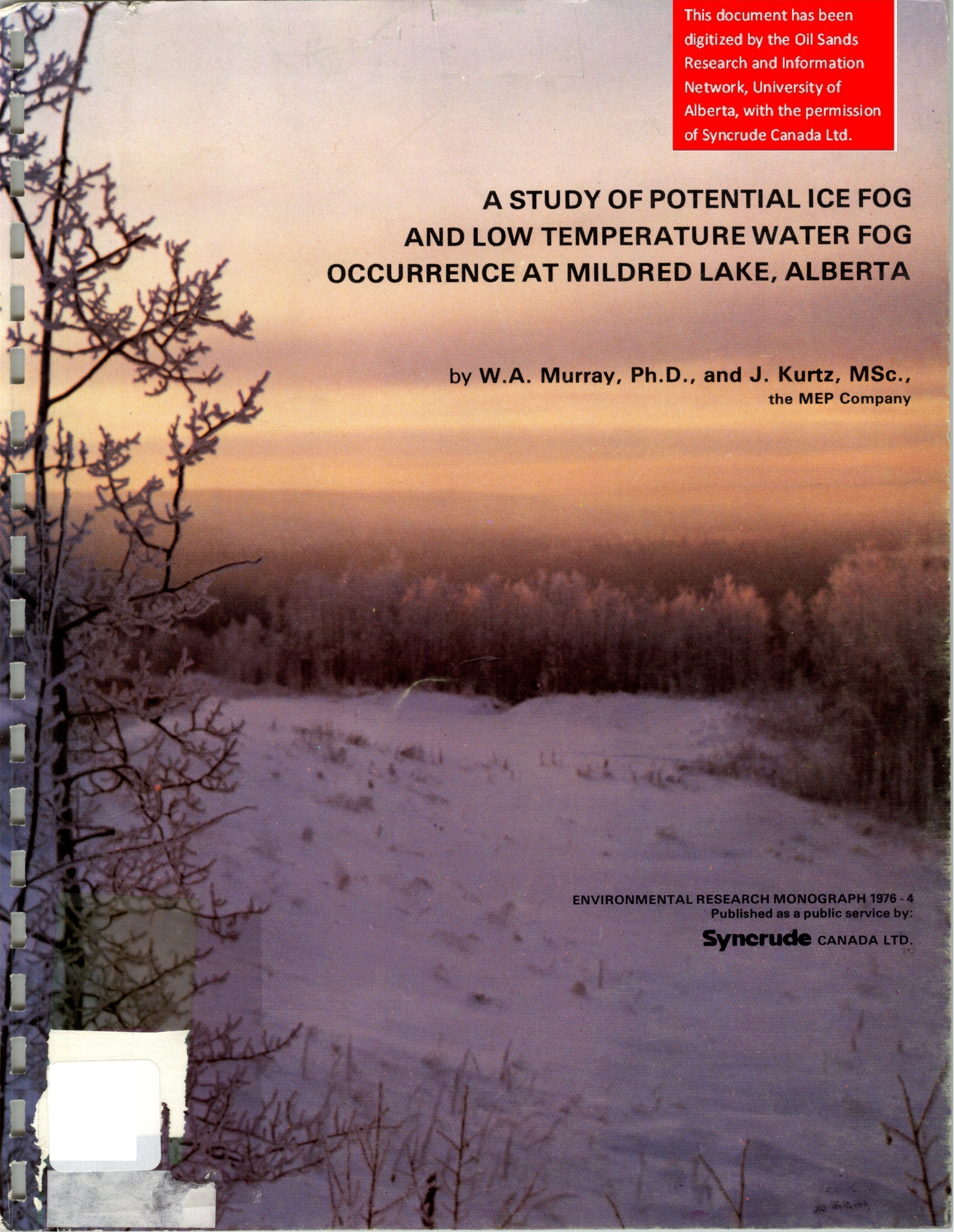

A STUDY OF POTENTIAL ICE FOG AND LOW TEMPERATURE WATER FOG OCCURRENCE AT MILDRED LAKE, ALBERTA

by **W.A. Murray, Ph.D., and J. Kurtz, MSc.,**
the MEP Company

ENVIRONMENTAL RESEARCH MONOGRAPH 1976 - 4
Published as a public service by:
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FOREWORD

Syncrude Canada Ltd. commissioned the MEP Company to investigate the potential occurrence of ice fogs at Crown Lease #17 in the Athabasca Tar Sands. The study is largely a review of the literature pertaining to ice fog and low temperature water fogs. More site-specific research will be undertaken if necessary in the future.

It is Syncrude's policy to publish its consultants' final reports as they are received, withholding only proprietary technical information or that of a financial nature. Because we do not necessarily base our decisions on just one consultant's opinion, recommendations found in the text should not be construed as commitments to action by Syncrude.

Syncrude Canada Ltd. welcomes public and scientific interest in its environmental activities. Please address any questions or comments to Syncrude Environmental Affairs, 9915 - 108 Street, EDMONTON, Alberta, T5K 2G8.

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SUMMARY

In early 1976 a literature review of low temperature fog was carried out so that the potential for this fog type in the vicinity of the Syncrude synthetic crude oil complex could be assessed. Moreover, a site visit under suitable synoptic meteorological conditions was made in early March 1976 to determine the local controls on fog at low temperatures.

The incidence of winter fogs at Mildred Lake is expected to increase due to the water vapour emitted by plant operations. However, evaporation from the large tailings pond is not expected to make a significant contribution, because during winter the pond should be frozen over except where the hot tailings enter.

Additional dust and smoke particles may be associated with industrial operations and human activities. The presence of additional condensation or freezing nuclei will alter the temperatures at which fogs occur. However, the concentration and types of nuclei that may be present in the vicinity of the Syncrude plant have yet to be determined.

Fogs are often accompanied by increased pollution levels in urban or industrialized areas because of the light winds and stable atmospheric conditions which accompany the fog. The depth of the layer through which the pollutants are mixed is shallow, only 10 to 100 metres, when low temperature fog occurs. Mixing of the elevated plant plumes with fog is unlikely to occur, because under the very stable atmospheric conditions associated with fog, the plumes diffuse slowly and remain above the fog layer.

1.0 INTRODUCTION

1.1 General

Fog forms when the surface layers of the atmosphere cannot hold all the water vapour they contain. Two physical processes, namely, cooling of the surface air, and addition of water vapour to the atmosphere can lead to a surplus of water vapour and result in fog formation.

Low temperature fogs, which include ice fogs, generally occur as a result of an increase of moisture due to human activity. The moisture for fog formation is added by the combustion of fuels, the emission of water vapour in industrial processes or by the artificial maintenance of open bodies of water. This type of fog occurs at temperatures below about $-30^{\circ}C$.

Low temperature fog can be exceptionally dense due to the large numbers of small particles. As a result, outdoor industrial and human activities can be severely restricted.

1.2 Objectives

The primary objective of this review is to provide an understanding of the potential of ice fog at Mildred Lake particularly in the vicinity of the Syncrude synthetic crude oil complex.

The literature search was carried out in

February 1976 and a site visit was made in early March 1976 to determine the local controls on ice fog.

The study was commissioned because of concern for possible environmental degradation in the Athabasca Tar Sands area and because of potential increase in ice fog due to increased industrial activity. Because of the serious consequences that ice fog may have on tar sands operations and the environment generally, it was thought that a more thorough understanding of this phenomenon was warranted.

2.0 A REVIEW OF THE LITERATURE ON ICE FOG

2.1 Introduction

Overview

Much of the research in ice fog has been done by members of the Geophysical Institute of the University of Alaska or under the auspices of the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). This work focusses on the city of Fairbanks and on other communities in central Alaska where ice fog in winter is not uncommon. Recent Canadian research is scarce, but includes a study of ice fog occurrence at Arctic and sub-Arctic airports (Lawford et al, 1974), and a design study for the Mackenzie River Valley, to determine whether ice fog formation may interfere with human activities, such as the operation of construction camps (Csanady and Wigley, 1973).

The guide for Canadian Meteorological observers (MANOBS, 1970) defines ice fog as a suspension of numerous minute ice crystals in the air which limits the visibility to ten kilometres or less.

The literature indicates that ice fog occurs in several communities of central Alaska and at a number of airports in the Canadian Arctic and sub-Arctic. On the other hand, unpopulated areas of the continental north, where the air is dry, experience little ice fog (Thompson, 1967). Its occurrence at a maritime location was described by Tarand (1973): "The first winter fog ever seen at Molodezhnaya Station (U.S.S.R. base on Antarctica) was recorded in September 1969 after a night of clear weather with drainage wind and rime formation. An advancing fog bank was seen far out at sea around noon. Ice needles fell at 3:00 p.m., and fog was thick on land by late afternoon . . ."

In the Canadian sub-Arctic, ice fog is normally limited to areas of human habitation. Occurrences at Whitehorse (Ives and Berry, 1974) and Edmonton (Robertson, 1955; Hage, 1971) are not uncommon.

At settlements in the north, ice fog occurs when the water vapour released into the air is almost immediately condensed and frozen into tiny ice particles. In the city of Fairbanks, vapour output is due to vehicle and aircraft exhausts, flue gases from power and heating plants and power plant cooling ponds. At Eielson Air Force Base in Alaska, automobiles left idling overnight in winter make a substantial contribution to ice fog. At temperatures between -50 and -55°C, the probability of ice fog at Eielson (with visibility less than 5 km) is over 50% (Benson, 1970).

2.2 A Brief Description of Ice Fog

Benson (1965A) has termed ice fog "low temperature air pollution", a somewhat unusual classification for atmospheric water. The term is justified, however, when one considers the irritating and sometimes harmful effects; visibility may fall to less than ten metres during severe incidents, and the concentrations of particulate and gaseous pollutants often increase.

The ground-based ice fog layer generally ranges in thickness from 10 to 30 metres, with a sharply defined upper boundary. Its depth increases as the temperature remains below $-40^{\circ}C$ and it may, on occasion, reach 100 metres (Csanady and Wigley, 1973).

Dense, but localized ice fog including liquid droplets forms in the vicinity of open water (that is, artificially maintained open), while thinner widespread fog is associated with low level combustion sources. The ice fog cloud spreads with sustained low temperatures and Weller reports an occasion when a 40 kilometre stretch of the Tanana Valley in Alaska was filled with fog after a week of temperatures near $-40^{\circ}C$. This ice fog cloud may also spread by advection and the effects of gravity drainage. At Fairbanks, the spread by drainage is of the order of one kilometre per day as temperatures remain below $-40^{\circ}C$ (Weller, 1969).

Ice fog incidents may last eight days or longer (Bowling et al, 1968) but Kumai (1969) has noted that in Fairbanks 60% of the cases are of less than six hours duration.

2.3 The Mechanism of Ice Fog Formation

Ice fog is not the result of a high moisture content in the ambient atmosphere; rather, it is associated with local moisture sources such as the combustion of fuels or the open water associated with industry (Ohtake and Suchannek, 1970). At temperatures conducive to ice formation the water content of air at saturation is small, that is, approximately 0.000042 lb H_2O/lb air at $-50^{\circ}F$ versus 0.02 lb H_2O/lb air at $75^{\circ}F$. If an excess of water vapour is introduced, condensation will result in the formation of water droplet clouds. At -40° ($\pm$ $1.5^{\circ}C$), spontaneous freezing follows. When particulate impurities or nuclei are present in the air, the process may occur at a higher temperature (Ohtake, 1970). The formation of ice fog by sublimation (i.e. by a direct phase change from the vapour to the solid state) is a highly improbable event at temperatures above $-70^{\circ}C$ (N.R.C., 1964).

Once freezing has been initiated, the particles begin to grow at the expense of the water droplets. This can be understood as follows. Air that is saturated with respect to water droplets is supersaturated with respect to ice particles (See, for example Berry et al, 1945). Hence, if ice particles and water droplets coexist, there will be a vapour pressure gradient such that water molecules will evaporate from the liquid drop surfaces and condense (and then immediately freeze) on the particle surfaces.

Water droplets in an ice fog cloud are normally found only in the immediate vicinity of the vapour source. At higher levels, the ice particles can no longer grow and they remain suspended by virtue of their low terminal velocities (Ohtake, 1970). Clearing can result from any or a combination of the following: downward precipitation of particles, condensation and evaporation of particles, or advection of the cloud out of the region.

In Fairbanks, ice fog occurs initially in high density over industrial cooling ponds. Later it appears in a thin layer along the roads as a result of automobile exhausts (Ohtake, 1967). Power plant plumes are generally ejected with sufficient buoyancy to penetrate the surface layer of the atmosphere, although condensing plumes have been observed to merge directly into an already established ice fog (Weller, 1969). Stack emissions in general are not a major cause of ice fog, but they may contribute to an existing fog on the ground by precipitating particles into it (Ohtake, 1969).

Roberts and Murray (1968) note that the ice fog cycle is degenerative; cold air which leads to ice fog also causes an increase in combustion rates as more heating systems come into operation. As more vapour and nuclei are introduced into the atmosphere, the situation worsens.

2.4 Sources of Moisture and Nuclei

Moisture

The generation of ice fog requires moisture sources, the most common being cooling ponds, combustion products, human and animal respiration and buildings with moisture leaks. In Fairbanks, five power plant cooling ponds constitute the largest source - approximately 64% of the total, or 2.6 million kilograms of water per day. The five ponds cover a combined area of 60,000 square metres (Benson, 1970).

Ice fog clouds generated by even small combustion sources are large. For example, Csanady and Wigley (1973) state that a single incinerator operating for two hours may generate a disc-like cloud of 500 metres diameter. Development of a surface-based ice fog layer, however, is largely dependent on low level sources. Automobile exhausts, which contribute only 3% to the moisture in Fairbanks, are second in importance only to cooling ponds in their contribution to ice fog formation (Weller, 1969).

The loss to the atmosphere of water vapour from people and animals breathing and perspiring is not insignificant. Although human respiration and perspiration rates vary with level of activity and temperature, Benson (1970) estimates the average loss due to each to be one kilogram of water per person per day. He also cites reports of ice fog clouds emanating from caribou herds at air temperatures below -45°C.

Including the loss of moisture from homes and other buildings, Benson estimates that a total of four million kilograms of water are released to the atmosphere each day in Fairbanks.

Nuclei

The threshold temperature for the occurrence of ice fog increases (and the probability of occurrence increases) when convenient sites for condensation and freezing are available. Nuclei (see Figure 1) provide such sites. Typically, nuclei range in diameter between 0.1 and 1.0 microns (10^{-6} metres). Atmospheric concentrations can be in the order of 100,000 particles per cubic centimetre in urban environments, or less than 300 per cc away from human habitation (Kumai, 1969).

In an urban area, most nuclei are combustion by-products, but hygroscopic substances and clay minerals are also common constituents (Kumai, 1964). Major sources of nuclei at ground level may be aircraft and vehicle exhausts as stack emissions are often too high. Holty (1971) reports that during the late 1960's nuclei concentrations have increased in Fairbanks with an increase in vehicular traffic. Cinders and sand used on the roads in winter can result in increased concentrations of suspended particulates in the atmosphere.

2.5 Ice Fog Particles

Study of the individual particles in an ice fog is important as it provides a better understanding of the origins of the cloud. The ice particles also determine the properties of the cloud and govern its large scale behaviour. Initially one must distinguish between ice crystals in general and ice fog particles.

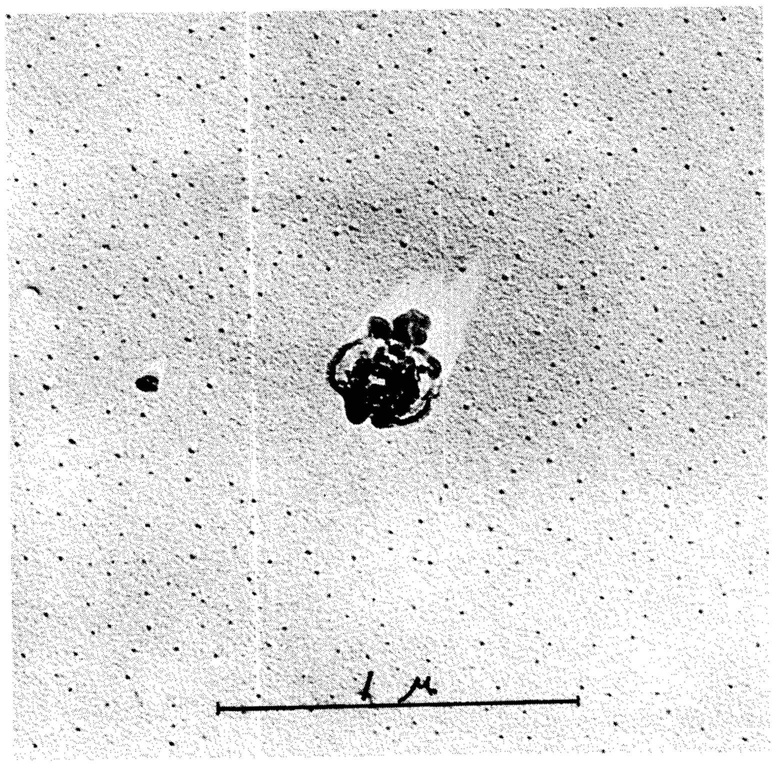


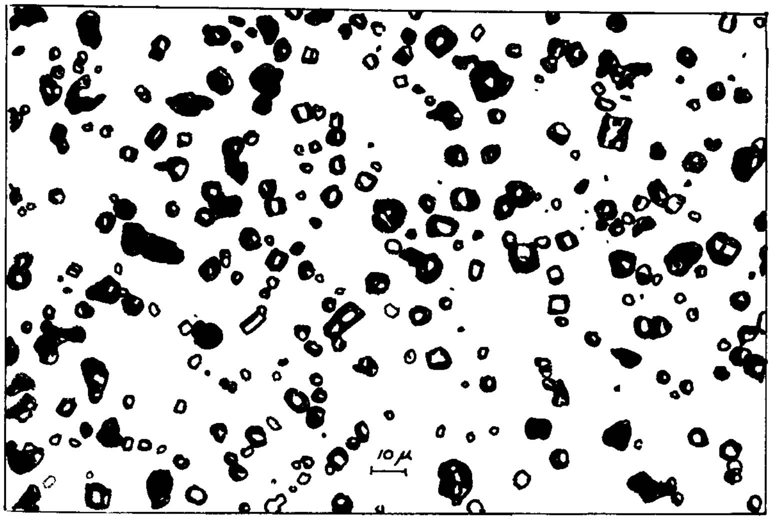
Figure 1 Ice Fog Nucleus (from Kumai, 1964)

Both of the above species represent initial stages of snow crystal formation. Ice crystals are generally well formed hexagonal plates or columns, often called "diamond dust" as they tend to twinkle in moonlight. They generally form at an air temperature near -25°C and arise from slow cooling (a few Celsius degrees per day) of atmospheric vapour. They frequently occur in the upper atmosphere in low concentration and do not appreciably affect visibility. The diameters of ice crystals range from 20 to 300 microns (Kumai and Russel, 1969).

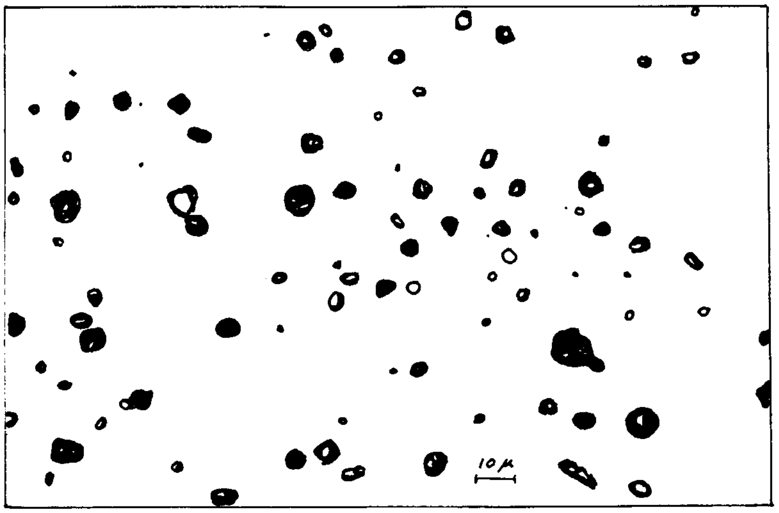
Ice fog, on the other hand, is made up of smaller particles which are spherical or crystalline. With a water vapour source and nuclei present, these may form at -25°C, but are more likely at a temperature lower than -35°C when cooling is very rapid (in the order of 5° C /second) (Kumai and Russel, 1969). The size and shape distributions of the particles in an ice fog cloud are controlled by the air temperature at formation (Huffman and Ohtake, 1971) and the vapour source temperature (Ohtake and Huffman, 1969). The particles are generally smaller than 20 microns in diameter (Weller, 1969) (see Figure 2).

2.5.1. Types of Ice Fog Particles

The type of particle which dominates an ice fog is largely a function of the air temperature (Ohtake, 1970). At temperatures below -40°C, small (2 to 15 microns diameter) spherical and irregular-shaped



a. Ice-fog crystals collected at $-39^{\circ}C$ in the city of Fairbanks



b. Ice fog crystals collected at a temperature of $-41^{\circ}C$ at Fairbanks International Airport during take-off of a jet-powered aircraft.

Figure 2 Ice Fog Particles (from Kumai, 1964)

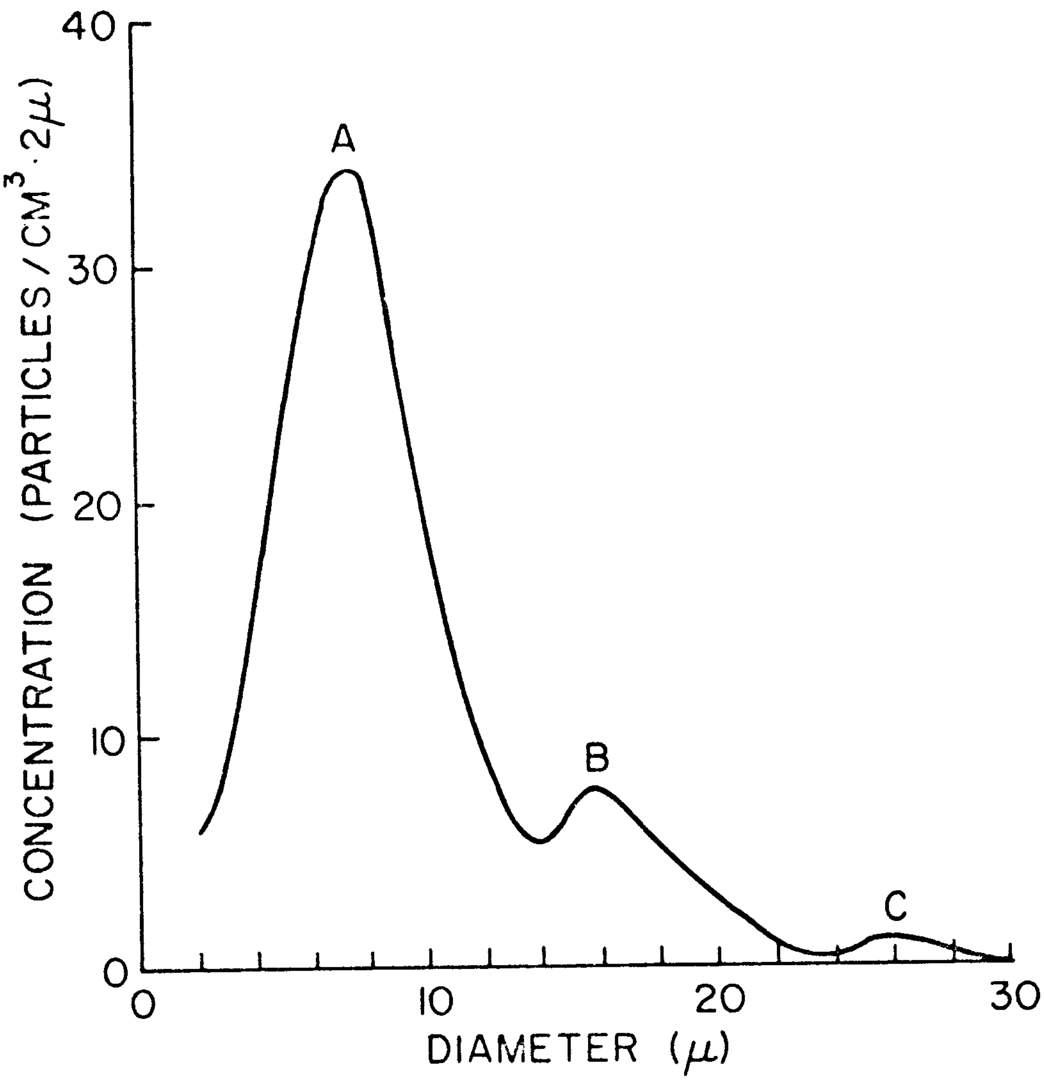


Figure 3 Typical Size Distribution of Ice-Fog Crystals in Downtown Fairbanks, at -36.5°C (from Benson, 1970). Peaks A, B and C represent crystals from car exhausts, open water and heating plants respectively. Heights of the peaks are different from place to place owing to different moisture and temperature conditions.

ice fog particles, which have formed from hot combustion exhausts, dominate. At temperatures near -30°C or warmer, ice fog consists primarily of larger (5 to 20 microns diameter) crystalline particles which arise from open ponds (Ohtake and Huffman, 1969; Porteous and Wallis 1970). The different types of particles are apparent from Figure 3 which shows a typical size distribution in Fairbanks. Weller (1969) has indicated that the large particles more frequently contain nuclei.

Although these results were derived for Fairbanks, the same principles would likely apply wherever a combination of combustion sources and open ponds introduce large amounts of vapour to the atmosphere.

2.5.2. Characteristics of Ice Fog Particles

Both particle size and particle density are functions of the air temperature. Henmi (1969) has found that the mean diameter of the crystalline particles within a cloud is a linearly increasing function of air temperature, one implication being that lower temperatures cause ice fog crystals with a lower settling (or precipitation) rate. There is no relation between particle size and the size of the ice fog nucleus (Kumai, 1969).

Ice fog density, which may range from tens to hundreds of particles per cubic centimetre, increases exponentially with decreasing temperature (Henmi 1969). If other factors (e.g. a wind which may advect the fog) are ignored, lower temperatures will contribute to denser and longer-lasting ice fogs.

The optical properties of an ice fog are controlled by particle size and particle shape. Smaller particles reduce visibility to a greater extent than larger ones (Kumai, 1964); the spherical particles impart to the cloud its typical dull-grey appearance (Weller 1969).

The rate of precipitation of the ice fog particles increases with particle size. In Fairbanks, rates of precipitation during ice fog incidents vary between 700 and 3000 particles per square centimetre per minute (Weller, 1969).

2.6 The Effects of Ice Fog

2.6.1 Visibility Reduction and Radiation Attenuation

In ice fog, local visibilities are often reduced to as low as ten metres; as a result construction and other industrial operations may be brought to a halt. As well, vehicular traffic flow and aircraft operations may be interrupted. An estimate of the visual range in a liquid droplet fog is given by the empirical Trabert formula (Csanady and Wigley, 1973) and there is evidence (Ohtake and Huffman, 1969) that the same formulation can be applied to ice fogs.

According to the Trabert formula, the visual range is;

$$R = 1.3\, K\, \bar{d} / \sigma$$

where K depends on the spread of the particle size distribution (kg/m^3)

$\bar{d}$ is the mean diameter of the particles (m) and

σ is the liquid water content of the cloud (kg/m^3)

Based on eight ice fog occurrences in Fairbanks, Ohtake and Huffman determined that K is nearly constant with a value of 2000 kg/m^3. The visual range is then directly proportional to mean particle size and inversely proportional to the liquid water content of the cloud. As mean particle diameter may be as low as 4 microns, and the liquid water content as high as 2×10^{-4} kg/m^3 (Csanady and Wigley, 1973), this formula will generate visibilities as low as 50 metres.

A particularly upsetting aspect of the visibility effect is described by the term Arctic Whiteout. This is an atmospheric condition in which the combined effect of a highly reflective snow surface and ice fog can destroy all horizontal visibility. The condition is caused by the almost infinite number of light reflections between the snow surface and the suspended particles. Since 85% of each incoming light ray is reflected and scattered, light appears equally intense in all directions; the result may be disorientation and vertigo (Hicks, 1972).

The attenuation and backscattering of infra-red radiation within both ice and water fogs can cause extinction of the infra-red beam in an aircraft or other guidance system (N.R.C., 1964). U.H.F. signal loss due to ice fog has been measured by Perry (1974).

2.6.2. Air Pollution Aspects

Air pollution and ice fog are often interrelated sufficiently that Benson (1970) considers ice fog merely another type of air pollution. During periods of ice fog the ground level concentrations of all gaseous and particulate pollutants are higher than normal. Lead aerosols and carbon monoxide gas show the largest increases in Fairbanks (Holty, 1973; Benson,1970) though concentrations of other combustion products and road dust are higher as well. These increases result from the stagnation (Section 2.7.1) which accompanies ice fog and permits high concentrations of other pollutants (Weller, 1969). Winchester et al (1967) report for example, that after ten days of ice fog in Fairbanks, the CO_2 content of the air may exceed 1% by volume.

Ice fog may also contribute directly to higher pollution levels in two ways: (a) by providing an extensive surface area capable of adsorbing and concentrating pollutants, and (b) by promoting certain harmful chemical reactions (Benson, 1970).

Adsorption

Assuming that an ice fog cloud consists of spherical particles, each of 10 microns diameter, in a concentration of 500 particles per cc, an adsorption surface of about 1500 cm^2 per m^3 of air is available. (The surface provided by non-spherical particles would be greater). Particulate pollutants gather on the ice particles which become local concentration points for particulates. As ice fog particles precipitate out of the air, they take particulates with them, and cleanse the air. However, other particles evaporating near the top of the ice fog layer drop particulate matter back into it and increase particulate concentrations within the layer (Benson,1970).

Reaction with SO_2

The oxidation of sulphur dioxide in air produces sulphur trioxide, albeit at a slow rate. Sulphur trioxide has a strong tendency to combine with atmospheric water and form sulphuric acid (Andrews and Kokes, 1965). The tendency to form acid increases at temperatures below $0^{o}C$. That the reaction occurs on droplets of water fog was shown by Coste and Courtier (1936) in a study of London air. Acid formation on the surface of ice fog particles was discussed by Benson (1970). Sulphuric acid droplets in the air may cause human and animal cardiac and respiratory problems (Sim and Pattle, 1957; Treon et al, 1950) or skin, eye and nasal irritation (U.S. Govt., 1970). They may injure vegetation (Middleton et al, 1958) or cause corrosion of materials (Yocum and McCaldin, 1968). In addition, the reduced vapour pressure over these droplets (relative to water droplets) can lead to a more sustained fog (Benson, 1970).

Ice fog conditions are associated with very strong inversions of temperature. Under these conditions the vertical diffusion is so slow that the plume from the 183 m. Syncrude stack will be embedded in the inversion layer and will not mix to ground level. Because of the temperature increase through the inversion it is not likely that the fog would extend to 100 metres above ground level.

As discussed above, ice fog may cause an increase in the levels of atmospheric pollutants. But the reverse effect is also true, that is, pollutants cause an increase of ice fog. As particulate (nuclei) concentrations increase, ice fog becomes more common. For example, in the early 1950's ice fog in Fairbanks only occurred at temperatures of -40°C or lower, while more recently it has occurred near -30°C. The change is due to an increase in the number of vehicles, industrial plants and other combustion sources (Pearson and Smith, 1975).

2.7 Environmental Controls and Ice Fog Prediction

The occurrence of ice fog depends on urban, meteorological, geographical and diurnal factors. The urban factors were discussed in Section 2.4 in terms of the water vapour and nuclei content of the atmosphere. The remaining controls, as determined from research in Alaska, and in the Canadian Arctic and sub-Arctic, are discussed below.

2.7.1 Ice Fog at Fairbanks

Fairbanks, Alaska experiences ice fog during 15 to 20 days of each winter. Being the only sizeable city in the North American sub-Arctic, and possessing a state university, it is ideal for ice fog research; the environmental controls on ice fog in Fairbanks are thus well known.

The city is situated in a basin surrounded on three sides by hills which rise 500 to 600 metres above the floor. This topography retards ventilation, and creates a pollution potential as significant as that of much larger cities (Holty, 1973).

Atmospheric stratification (or the organization of the atmosphere into discrete horizontal layers, accompanied by little vertical motion of air) is evident during the entire year, but is exaggerated in winter by the stable characteristics of the cold continental air which covers central Alaska. Steep inversions (where air temperature at the ground is lower than at higher elevations) are characteristic of the stratified winter air. It is not unusual, for example, for the surface temperature to drop to $-30^{\circ}C$ while, a hundred metres above the surface, the temperature is $-15^{\circ}C$ (Holty, 1973).

The development of such pronounced stratification is a consequence of (a) the semi-permanent nocturnal condition of winter contributing to a net upward radiation flux (i.e. a net loss of heat from the ground), and (b) the restricted wind flow in the basin, often less than two metres per second (Benson, 1965A). The result of such stratification is that water vapour and nuclei are contained within a shallow layer near the ground. At temperatures near $-40^{\circ}C$, when winds are calm, ice fog is almost unavoidable within this layer (Weller, 1969).

Local radiative cooling of the ground surface contributes to the steep inversions and low temperatures near the ground; it is not, however, the major meteorological control on ice fog occurrence. Ice fog is more closely linked to cold air advection over the region (as may be determined from upper level weather charts) (Bowling et al, 1968). Csanady and Wigley (1973) agree that cold air advection aloft is the single most important meteorological factor in ice fog prediction.

The work of Bowling et al has determined that ice fog in Fairbanks is almost invariably accompanied by a definite sequence of weather events. It is preceded by cloud cover and relatively low pressure. A High (or high pressure area) approaches, skies clear and surface temperatures drop while the strength of the inversion increases. The ice fog phase may last up to two weeks. The approach of a new Low, with cloud cover, and a temperature increase, signals the end of the event (Bowling et al, 1968).

2.7.2. Ice Fog at Canadian Arctic and Sub-Arctic Airports

The ice fog studies by Lawford et al (1974) cover twenty years of weather observations at nine northern airports. It should be kept in mind that in this work, the predicted event was ice fog occurrence at a point (i.e. the airport) which was removed from the water vapour and nuclei sources (in the townsite). To some extent, then, the results reflect on the behaviour of advected ice fog.

The authors recognize that subjectivity exists in the reporting of ice fog and visibilities, particularly in the dark hours. Errors introduced by this type of subjectivity would be most serious at locations where ice fog occurrence is rare. Despite these difficulties, the following results were obtained.

Temperature

The threshold temperature for ice fog formation is unique to each station. It varies with the nearby population, and with wind speed and wind direction. The temperature dependence of ice fog is greatest where the population is large due to the increased amounts of nuclei and water vapour released at lower temperatures. At six stations (out of nine), the relative frequency of ice fog occurrences increased rapidly as temperature decreased from $-37^{\circ}C$ to $-43^{\circ}C$.

Wind Direction

Csanady and Wigley (1973) have noted that ice fog plumes which form over Arctic settlements are elongated in the direction of the wind. Not unexpectedly, then, the highest probability of ice fog normally occurred when the wind blew from the moisture source toward the airport. The fog often drifted along the length of a valley.

Wind Speed

Oliver and Oliver (1949) have associated ice fogs with calm or light winds; such is the case in Fairbanks. The wind speed dependence, however, varies with aspect relative to the vapour and nuclei sources. At four stations, ice fog occurred most frequently with calm or light winds while at three others, it was most often associated with wind speeds greater than 6 m/s. These differences are due in part to varying distances from the sources of vapour. For example, ice fogs at Resolute Bay, associated with winds in excess of 9 m/s, were possibly generated over open leads in the ocean ice cover; thus strong winds were required to advect them to Resolute.

At some stations, the maximum relative frequency of ice fog occurred at a higher temperature when the wind was light rather than when it was calm. Lawford et al suggest that the light wind may generate sufficient mechanical turbulence to allow ice fog particles, which would otherwise have precipitated out, to remain in suspension.

Diurnal Variation

Generally, ice fog was most frequent in the late morning. A rise in surface temperature of $2C^{\circ}$ at noon, or shortly thereafter, produced sufficient thermal turbulence to mix and disperse the fog. At Fort Smith, the peak hours for ice fog were 0700 and 1000 LST; ice fog was least frequent between 1800 and 2200 LST. This cycle may, however, simply reflect aircraft activity in the area.

Annual Variation

At airports south of the Arctic Circle ice fog was most frequent in the month of January. Its frequency was positively correlated to the amount of aircraft activity, and negatively correlated to the value of the mean monthly temperature.

2.8 Artificial Methods of Modification and Dissipation

Sax et al (1974) have stated that, to date, there has not been any real progress at alleviating ice fog once it has formed. Most successful methods of ice fog modification have been aimed at reducing the flux of vapour to the atmosphere and preventing ice fog occurrence, rather than at dissipating the fully formed cloud. Under certain meteorological conditions, however, some success at local dissipation has been achieved.

2.8.1 Prevention of Vapour Escape

Reducing the Area of Open Water Surfaces

The simplest method for reducing the area of open ponds may be to allow them to freeze over. Taylor and Church (1966) describe a partially successful effort at Eielson A.F.B. where hot ($60^{\circ}C$) cooling water from steam turbines was allowed to collect in a deep trench rather than return to the pond. Due to a lack of water to replenish the supply, however, only half the pond was eventually allowed to freeze over.

The Fairbanks Municipal Utilities System was redesigned so that cooling water, previously discharged at the surface, would instead be discharged close to the river bed. The ice cover over the river could thus be maintained (Weller, 1969). Benson (1970) has further proposed that the warm water be passed through pipes, with cooling fins in contact with the air, before it is discharged.

A second method of preventing vapour escape is the use of liquid surface covers. Tests on a small insulated tank using impermeable, polyethylene sheeting (Behlke and McDougall, 1973) included the measurement of evaporation rates and energy losses from both open and covered water surfaces. In the conclusions to the study, the authors wrote: "from a heat transfer viewpoint . . . polyethylene sheeting is an effective water surface cover that can, with little decrease in energy loss, virtually eliminate evaporation from cooling ponds and thus reduce a large portion of ice fog". Experimentation with thin chemical films (Weller, 1969) proved less successful. These films included cetyl alcohol, $CH_3(CH_2)_{14}CHOH$, a suspension of the same in water, and a solution in petroleum ether. The difficulty lay in maintaining a continuous film on the water surface.

Weller indicates that the suppression of evaporation can generally not be used on a large scale, from thermodynamic considerations of the cooling process. He cites an alternate technique viz. the collection of ice particles close to the pond surface by metal nets and fences (Weller, 1969).

Reduction of Vapour Output from Combustion Sources

Various techniques have been advanced for scrubbing the vapour out of combustion emissions (Porteous and Wallis, 1970; Kumai, 1969). Taylor and Church (1966) have described a heat exchange system which is designed to condense water vapour out of flue gas before it is released to the air. However, neither this system nor an ethylene glycol dehumidifier have been successful at the Eielson A.F.B. power plant stack where they have been applied. Vapour removal by use of pre-dried coal is suggested by the authors.

In order to reduce the vapour content in the exhausts of internal combustion engines, the National Research Council has designed and built a suppressor which has proved effective up to normal engine speeds (N.R.C., 1964). The complete elimination of automobile ice fog contrails, however, has not been possible (Murcray, 1969).

2.8.2 Attempts at Ice Fog Dissipation

Once the ice fog has fully formed, removal of the suspended particles is difficult. Soviet scientists have experimented with lasers; however, these are insufficient as broad scale producers of heat energy (Sax et al, 1976). Two other approaches that have shown positive results, though on a small scale, are described below.

Mixing of the Air

If the ice fog layer is mixed with the warmer, drier air above it, ice fog crystals may be evaporated, thus resulting in dissipation of the cloud. Mixing produced by helicopter downwash has been found to produce clearings in ice fog large enough to allow noninstrumented aircraft operations "under certain limited meteorological conditions"

(Hicks and Kumai, 1971). These conditions were: a dissipating ice fog, and a fog in the process of formation. Further research on this technique is required to determine all of the meteorological conditions, and to assess the effect that the addition of water from the helicopter fuel may have. There is some indication that this additional water may also contribute to clearing by causing an increase in particle size and consequent particle precipitation.

Mixing of the ice fog layer may also be induced as a result of thermal turbulence generated by a combination of heat sources at the ground. This approach has been suggested by Csanady and Wigley (1973).

Electrostatic Precipitation

This technique of ice fog dissipation is based on the observation that ice fog particles either possess a dipole moment or it can be induced when they are placed in a non-uniform electric field. Within such a field, ice fog particles will be preferentially deposited on the positive electrode of an electrostatic precipitator. This can be explained by the Weyl model of ice crystals which proposes that the dipole nature of the particle is such that its extreme outer layer carries a negative charge (Ohtake and Suchannek, 1970).

Electrostatic precipitation of ice fog on a small scale has indicated encouraging collection rates (Roberts and Murray, 1968). Weller (1969) has suggested that by optimizing its design and increasing the potential difference between electrodes, the precipitator could be applied successfully at airport runways and over cooling ponds.

2.8.3 The "Best" Approach

The reduction of ice fog frequency can best be achieved by a decrease in low level vapour and nuclei emissions (including the discharge of these pollutants at the highest possible level) combined with an effective removal system. Benson strongly urges the use of metal tubes with fins to reduce the temperature of discharged waters. Ice fog over pond discharge points could be controlled by the use of a local arrangement for electrostatic precipitation (Benson, 1970).

3.0 LOW TEMPERATURE WATER FOG

3.1 Natural Fog

The addition of large amounts of water vapour to the air may, in addition to causing fog, serve to initiate or intensify natural fogs or increase their frequency (Vogel and Huff, 1975). The major type of natural fog that may occur at Mildred Lake in winter is radiation fog.

Radiation fog results from nocturnal cooling of relatively windless air over land (Petterssen, 1956). As the outgoing radiation at the ground exceeds the incoming radiation, temperature at and near the ground begins to fall, causing a temperature inversion (increase of temperature with height). While the air cools, the relative humidity increases; at some value, depending on the number and composition of condensation nuclei, the vapour condenses into water droplets causing fog. After sunrise, the inversion often breaks up and the fog begins to dissolve.

The occurrence of radiation fog depends on the relative humidity of the air, a quantity which is likely to increase as additional vapour sources are created in the vicinity of Mildred Lake. If the moisture-laden air is advected some distance downwind, the possibility may exist for radiation fog at distances far removed from the vapour sources.

3.2 Steam Fog

This is the type of fog which is expected to form over the open portions of the tailings pond in winter. Also termed arctic sea smoke, it forms when cold air flows over a warmer water surface. The fog results from thermal turbulence which causes mixing of the moist air near the surface of the pond with air at higher elevations. Typically, the fog is shallow; it resembles irregular tufts of whirling smoke which disintegrate at some short distance above the surface. If an elevated inversion exists, steam in the turbulent layer below it may become extremely dense.

The controls on the production of steam over a water surface are subject to some controversy. Jacobs (1954) claims that steaming never occurs in the Gulf of St. Lawrence when the air is less than 9 C^{o} colder than the water. However, Saunders (1964) has observed differences near 14C^{o} in the absence of steaming. A major factor in determining this threshold value is the relative humidity which depends in part on the wind force. Gordon (1952) determined that relative humidity tends to be higher with strong winds than with light.

A theoretical determination of whether or not steaming will occur has been accomplished and experimentally verified by Saunders. Fresh water at 0^{o}C requires air-water temperature differences of 7C^{o} and 16C^{o} for the two cases cited above, respectively. The temperature differences required for steaming increase by 15 to 20% if the water temperature is increased to 30^{o}C (Saunders, 1964).

3.3 Fog Over Snow Surfaces

In the temperature range 0^{o}C to -25^{o}C, fog is rarely observed over snow surfaces. This phenomenon has been explained by Petterssen (1956) as the result of the difference in saturation vapour pressure over ice (or snow) and water and the consequent "drying out" of water fogs over a snow surface. (See also Section 2.3). Another dissipating influence on fogs in this temperature range, suggested by Oliver and Oliver (1949), is the fact that the snow surface, trees, buildings, wires, etc. are all better radiators than air, and thus become colder, allowing rapid frost deposits and drying of the air.

At some temperature between -25^{o}C and -40^{o}C, depending on local factors, the frequency of fog again begins to increase, this being largely due to the occurrance of ice fog. Figure 4 shows this effect at Fairbanks between 1942 and 1947 where the critical temperature was about $-35^{\circ}C$. A fog frequency curve similar to Figure 4 has been derived for Edmonton by Hage (1971).

3.4 Effects of Water Fog

The visibility effects of water droplet fog are not dissimilar to those of ice fog. Determination of the visual range utilizes the Trabert formula (Section 2.6.1); mean droplet diameters typically vary between 5 and 30 microns and liquid water content ranges between .02 and 0.2 g/m^3 (Malone, 1951).

The reaction of water droplets in the air with sulphur dioxide to form a sulphuric acid mist has been mentioned (Section 2.6.2.). The combination of fog with several impurities in the air to form "London Smog" has been described by Meetham (1955) for the episode of December, 1952. Excerpts from his account of this extreme case follow.

"The fog over London covered 1200 km^2 and extended to a height of 150m; the temperature at the ground was near $0C^{\circ}$. In four days there was less than one complete air exchange in the region. During this time, the atmosphere contained (from mass balance calculations) 1.8×10^8 kg of liquid water and 6.8×10^8 kg of water vapour; water vapour was supplied almost entirely from the evaporation of water on the ground at the rate of 7.3×10^8 kg per day.

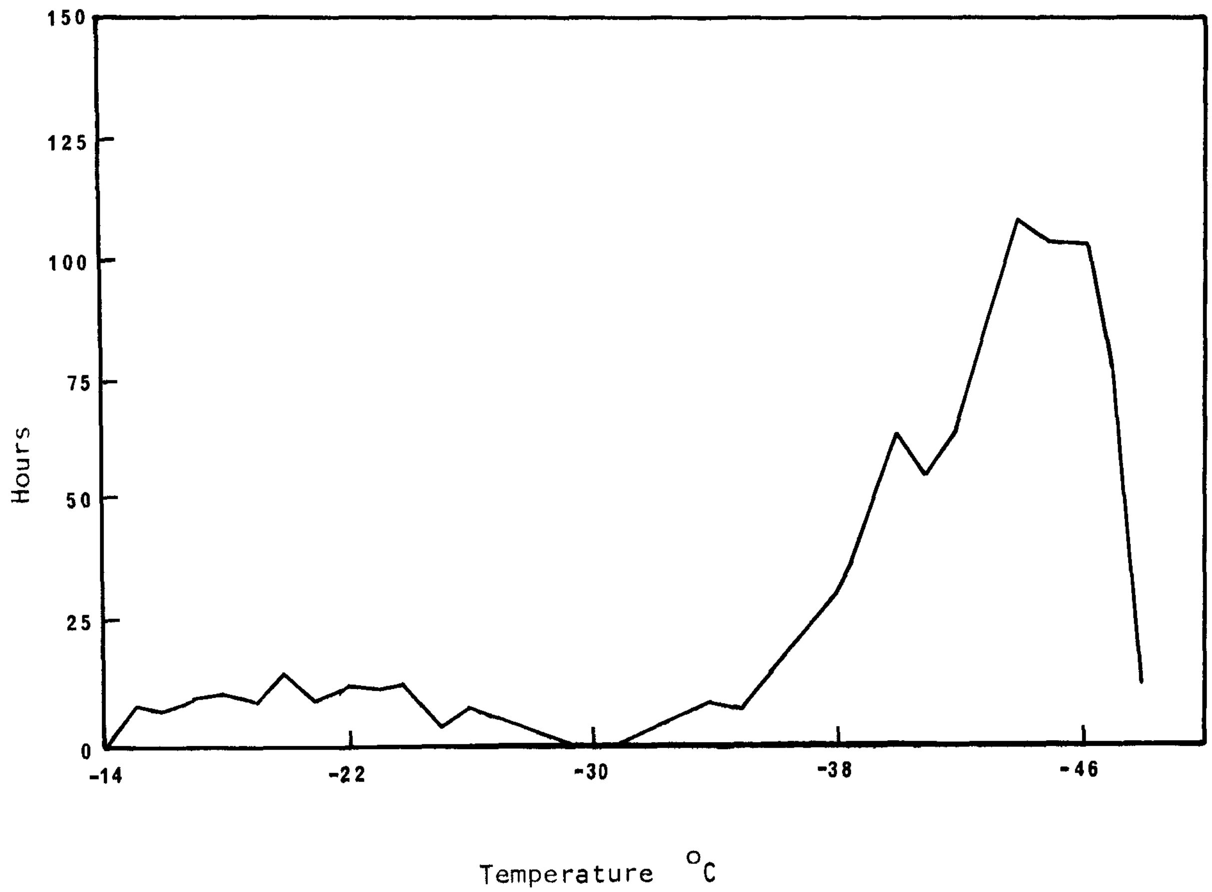


Figure 4 Number of Hours of Fog For Various Temperatures at Fairbanks, Alaska 1942-1947 Inclusive (from Oliver and Oliver, 1949).

Sulphur dioxide entered the air at a rate of 1.8×10^6 kg per day and left it (on water droplets) at the same rate, maintaining a balance of 3.4×10^5 kg. Large amounts of many gaseous and particulate by-products of combustion were present, but medical opinion attributes the high mortality during the period to sulphuric acid above any other cause" (Meetham, 1955).

3.5 Fog Prediction

The formation and dissolution of fog depends on a large number of local factors such as moisture and nuclei sources, heat capacity and conductivity of the soil, snow cover, topography and local breezes (Petterssen, 1956). The physical processes which produce fog are strongly influenced by the turbulent transfers of heat and moisture in the vertical. In fog prediction schemes these processes have been described only by empirical methods. It is evident, then, that a scheme for predicting fogs can be determined only from onsite observations and measurements. Several prediction schemes which have been determined for specific locations are discussed by Petterssen (1956).

3.6 Water Fog Seeding

The introduction of dry ice crystals into a water droplet fog at low temperatures results in the growth of the crystals at the expense of the water droplets (Section 2.3). Ice crystals grow to a size too large to be supported in the cloud and then precipitate as snow. Airborne seeding, which has resulted in clearing after one hour or less, has become a routine operation at Elmendorf A.F.B., Alaska (Wise, 1975).

Another seeding method for clearing of cold fog consists of spraying liquid propane into the fog in order to generate ice crystals. The system has several advantages over the airborne system, including reduced cost and a lower reaction time for initiating clearing actions (Wise, 1975).

4.0 SITE RECONNAISSANCE

4.1 Description of Site Visit

A trip to Mildred Lake was undertaken on March 3, 1976 when meteorological conditions appeared conducive to ice fog formation. The weather charts indicated a ridge (or line) of high pressure across northern Alberta. Winds were very light and daily minimum temperatures were in the mid-thirties below zero (Celsius). With similar temperatures in the winter of 1974/75, a MEP crew engaged in meteorological studies near Mildred Lake, had watched ice fog crystals form in their exhaled breath. Consequently, with the aim of observing and photographing ice or cold water fog, a professional meteorologist arrived at Mildred Lake.

Several instances of water fog were observed enroute. Fog filled the gully near the Calgary Airport, likely a radiation fog. (See Section 3.1). At

Edmonton, steam fog (Section 3.2) covered open portions of the North Saskatchewan River and rose to about ten metres above the surface. From the air, a cloud seemed to cover the entire city. This polluted layer which commonly forms over Edmonton, has been observed to contain ice fog in winter (Hage, 1971).

On arrival at Fort McMurray, the weather was clear and cold (-32°C). About ten kilometres north of Fort McMurray, and extending as far as the G.C.O.S. plant (40 km north of Fort McMurray), the Athabasca River was filled with fog which rose to an average height of 30 metres, and occasionally restricted visibility to 0.5 km. By early afternoon, the fog was dissipated (See Figures 5 and 6). Note that the fog drifted up-river due to north westerly winds associated with the high pressure system. That is, a down-river drainage flow was not present.

On March 4, early morning temperatures were -34°C, skies were clear, and again fog filled the valley (Figure 7). A tour of the G.C.O.S. plant site revealed its cause. Vapour plumes from the various emission sources were drifting along the valley in a northward direction (Figure 8). The sulphur plant plume, at a higher elevation, was observed to move in roughly the opposite direction, but it later combined with the other plumes to sustain the ground-based valley fog for a distance of several kilometres.

Close inspection of the various vapour sources at the G.C.O.S. plant indicated that the tailings and other open ponds did not contribute significantly to the valley fog, though they did cause dense localized fogs (Figure 9). For example, the visibility was less

Figure 5. Fog Along the Athabasca River Valley (North of the G.C.O.S. Plant) at mid-morning.

Figure 6. Elevated Vapour Plumes in the Late Morning.

Figure 7. Black and White and Colour Photographs of Early Morning Fog in the Athabasca River Valley (taken from the same location at the Syncrude Lower Camp).

than five metres on the road separating the outfall and fresh water ponds. The localized fogs were limited to the vicinity of the pond and were less than ten metres deep. Ice fog crystals were not observed in any of the vapour emissions.

The tailings pond, which covers 400 acres, was capped by a crust of ice except at the hot tailings discharge points where vapour clouds rose from the surface and extended 30 to 50 metres downwind. The ice cover develops when air temperatures remain below $-30^{\circ}C$ for a few days or when production stops (Little, 1976).

As the regional weather maps indicated a warming trend, the study was concluded on the afternoon of March 4.

4.2 Summary of Site Visit

A cold water droplet fog which arose as a result of G.C.O.S. emissions and extended some kilometres down valley, was observed on March 3 and 4, 1976. During this period, the winds were light, minimum temperatures dipped into the mid-thirties below zero Celsius, and a temperature inversion (increase of temperature with height) extended from the ground to height of 300 metres. Weather maps showed a ridge (or line of high pressure) stretching across northern Alberta.

The sources of the fog were the various emissions of the G.C.O.S. operation. Local, but dense fogs appeared around the open water ponds. No ice fog crystals were observed visually though they may have

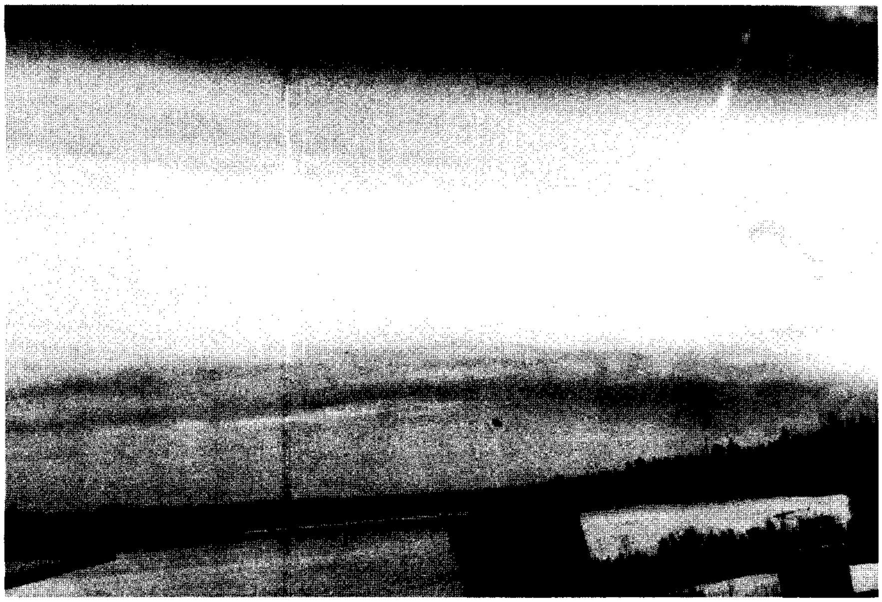


Figure 8. Vapour Plumes Causing Low Level Fog in the Early Morning.

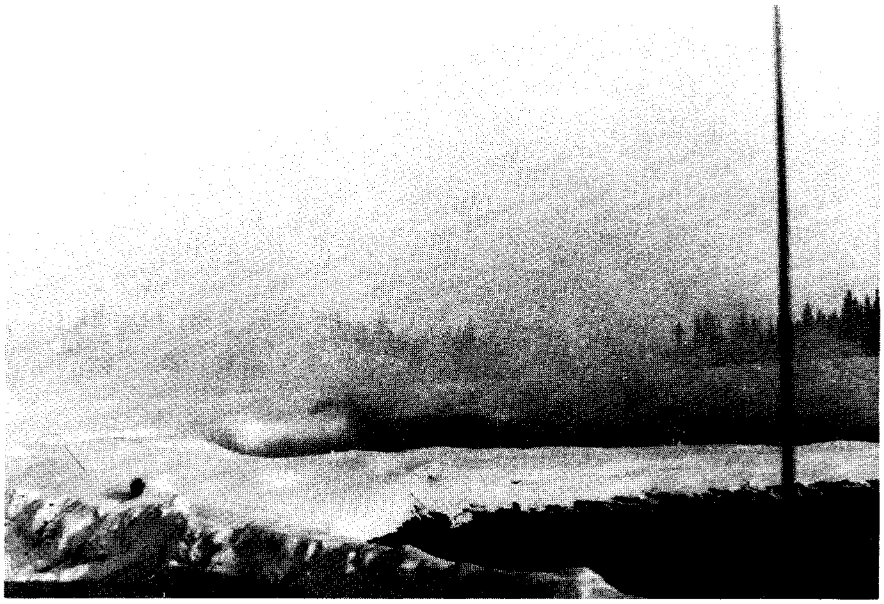


Figure 9. Steaming Over An Open Water Pond.

occurred. The relatively high solar angle of March contributed to a rapid dissipation of the fog and inhibited ice fog formation. The occurrence of fog associated with local emission sources indicates a real possibility of ice fog particularly when vapour and nuclei concentrations increase. The potential will be highest during the mid-winter months.

The occurrence of fog along the Athabasca Valley in the vicinity of Mildred Lake has been reported as a common winter occurrence by several area residents. Ice fog crystals, on the other hand, have rarely been observed except in small patches (e.g. from aircraft exhaust).

5.0 SOME PRELIMINARY CALCULATIONS

5.1 Vapour from Open Water

There is little mention in the literature of open water evaporation rates during the winter months, when natural waters are frozen over; it appears that knowledge in this area is lacking. Presented below, however, are two "ball park" estimates for the amount of vapour that might be released from the Syncrude tailings pond at its maximum extent, during the coldest days of winter. The purpose of this analysis is not to obtain precise evaporation rates but rather to acquire a qualitative feel for the potential water vapour output at Mildred Lake compared to other areas, where the extent of ice fog is known.

Equation (1) is a semi-empirical relation for the flux of water vapour from one horizontal surface to another (Thornthwaite and Holzman, 1942; Gray, 1970).

$$E = \frac{pk^2 (q_1 - q_2)(u_2 - u_1)}{\{\ln (z_2/z_1)\}^2} \qquad \ldots(1)$$

E is the rate of evaporation (kg/m^2s)
p is the air density (kg/m^3)
q_1 is the specific humidity at surface 1
q_2 is the specific humidity at surface 2
u_1 is the horizontal wind speed along surface 1 (ms^{-1})

u_2 is the horizontal wind speed along surface (ms^{-1})

k is Karman's constant and is approximately equal to 0.4

This relation applies under conditions of neutral stability (i.e. when air temperature cools with height at the rate of 0.98°C per 100 m). It can be used under other conditions if errors up to 20% can be tolerated (Thornthwaite and Holzman, 1942).

At an air temperature of -40°C and pressure of 950 millibars:

$p = 1.4\ kg/m^3$ (Berry et al, 1945)

assume: $z_1 = 1m;\ z_2 = 10m$

$q_1 = 13 \times 10^{-5}$ (saturated air);

$q_2 = 0$, (dry air)

$(u_2 - u_1) = 1.4\ m/s$ - (using $u_1 = 2\ m/s$ and a logarithmic velocity profile over the pond (Munn, 1955).

therefore,

$$E = \frac{1.4 \times .16 \times 1.4 \times 13 \times 10^{-5}\ kg/m^2\ s}{2.3 \times 2.3}$$

$$= 0.7\ kg\ H_2O\ per\ m^2\ per\ day$$

This is probably an upper limit as both differences in the numerator of (1) are estimated high.

The Syncrude tailings pond will, at

maximum extent, cover $2.3 \times 10^7\ m^2$ so that the total amount of vapour escaping from the pond, according to the assumptions made above, would be 1.6×10^7 kg H_2O per day.

A second estimate may be based on the annual evaporation rate of .48 m/yr observed at Fort McMurray Airport.

$$E = .48 \text{ m/year} \times 2.3 \times 10^7 \text{ m}^2 \times \frac{10^3 \text{ kg}}{\text{m}^3} \times \frac{1 \text{ year}}{365 \text{ days}}$$

$$= 3.0 \times 10^7 \text{ kg } H_2O \text{ per day.}$$

This analysis neglects the effects of an oily film that may cover the surface and retard evaporation. On the other hand, the evaporation rate in winter should be greater than the annual average rate since the air-water temperature difference is a maximum (Phillips and McCulloch, 1972).

Noting that both estimates are of the same order of magnitude we may tentatively conclude that on the coldest days of winter, a completely open pond of surface area $2.3 \times 10^7\ m^2$, might present up to 3×10^7 kg of water vapour to the atmosphere.

5.2 Vapour from Other Sources

By adding the cooling tower losses (annual average 1.2×10^7 kg/day) and thermal losses from the hot tailings stream (0.8×10^7 kg/day) a total of 5.0×10^7 kg H_2O per day will be the maximum output as an annual average.

This is a factor of ten higher than the water output from the city of Fairbanks as estimated by Benson (1970). (See Section 2.4.1).

5.3 Time (and Height) Dependence of Vapour Temperature Above Open Water

From measurements above open ponds, the temperature profile obeys the following function:

$$T = T_0 + \frac{(T_i - T_0)}{(T_i - T_o)\ ax + 1} \qquad \ldots(2)$$

(Huffman and Ohtake, 1971)

where T is the vapour temperature at height x (^{o}C)
T_i is the initial vapour temperature (^{o}C)
T_o is the ambient temperature (^{o}C)
x is the height above the pond (m)
and a is a constant (m^{-1})

And since the turbulent updraft velocity of the vapour (dx/dt) can be expressed as a function of the height above the pond as follows:

$$\frac{dx}{dt} = v_o e^{-x/b} \qquad \ldots(3)$$

where v_o is the initial velocity of the vapour and b is a constant for a particular source,

we may integrate (3) and substitute in (2) to get:

$$T = \frac{T_i - T_o}{a\,b\,(T_i - T_o)\,\ln(1 + v_o t/b) + 1} + T_o$$

Above open water, the values empirically determined by Huffman and Ohtake (1971) were:

$a = 5 \times 10^{-2}\ m^{-1}$

$b = 66.7\ m$

$v_o = 0.2\ m\ sec^{-1}$ (constant for several metres)

By assuming $T_o = -40^{\circ}C$, one can derive the time dependence of the temperature of an elemental volume of vapour. (See Figure 10). Since the velocity is relatively constant up to several metres, the abscissa can also be interpreted as a height above the pond surface.

Apart from helping to understand the mechanism of fog formation, this curve also predicts the probable upper boundary of ice fog. At 20 metres above the surface, the temperature of the vapour is close to the environmental temperature; thus the dilution of the vapour is high and the air is not likely to be saturated with vapour. Ice fog might not be expected to extend beyond this level.

5.4 Size Distribution of Ice Fog Particles Above Open Water

From theoretical considerations of the diffusion growth rate, the size of the ice fog particles can be derived. The technique of Rooth (1957) was used

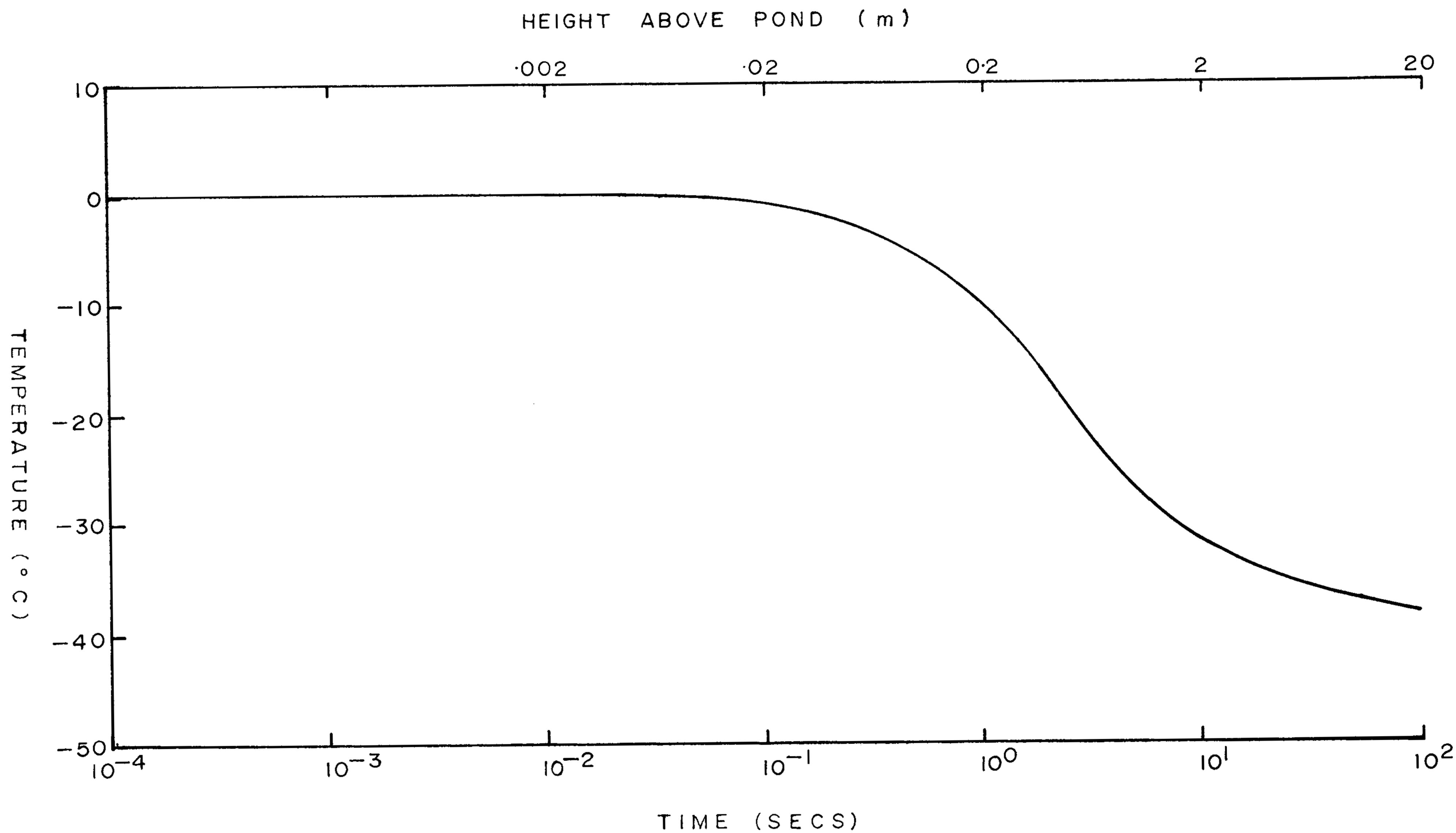


Figure 10 Computed Time (and Height) Dependence of the Temperature of a Vapour Element Over an Open Pond (See Section 5.3)

by Huffman and Ohtake (1971) to solve numerically for the size distribution of the particles in a cloud which has formed due to the cooling rates of Figure 10. This distribution, shown in Figure 11, compares favourably with observed size distribution of ice fog particles in the vicinity of open ponds. The model predicts a shift in size distribution towards smaller diameters as the temperature decreases (approximately 1 micron diameter per 10 C^{o}). The model has also demonstrated that the water vapour, and not the nuclei, are of primary importance in the formation of ice fog.

5.5 Mass Budget of Ice Fog

The mass budget of a system provides a complete description of all of the processes tending to increase or decrease the total mass of the system. The mass budget equation developed by Benson (1970) can predict the growth and dissipation rates of ice fog clouds as well as the area covered by ice fog when equilibrium exists. The equation takes the form:

$$l = pA_B + qA_T + r \frac{dv}{dt}$$

where

l = rate of water vapour input to the atmosphere (kg H_2O/day)

p = precipitation rate of ice fog particles (kg H_2O/m^2 day)

q = evaporation rate at ice fog particles (kg H_2O/m^2 day)

A_B = area of bottom of ice fog cloud (m^2)

A_T = area of top of ice fog cloud (m^2)

r = density of ice fog particles in the air (kg H_2O/m^3)

$\frac{dv}{dt}$ = rate of change of cloud volume with time (m^3/day)

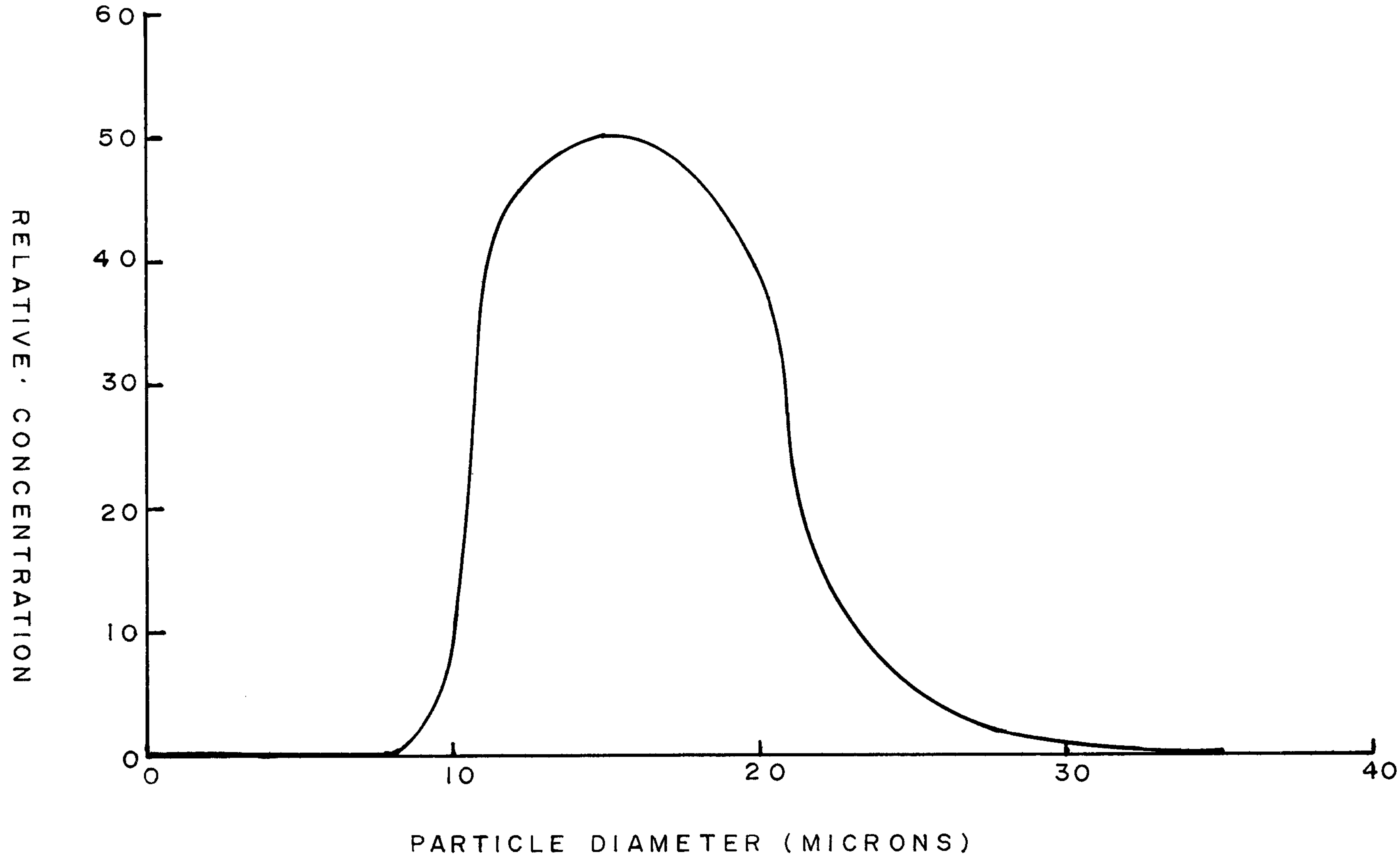


Figure 11 Computed Size Distribution of Ice Fog Particles Over an Open Pond (See Section 5.4)

As an example of the use of this equation, allow the temperature to increase; thus, q increases, and to keep l constant, $\frac{dv}{dt}$ must be less than zero, i.e. the volume decreases and dissipation is predicted. Or, an equilibrium state may exist where l, p and q remain relatively constant and where $\frac{dv}{dt}$ equals zero. The volume will remain constant until a change occurs in one or more of l,p or q.

As another example, the rate of evaporation at the top of the ice fog cloud can be determined from knowledge of the remaining parameters, i.e.

$l = 4100 \times 10^6$ g H_2O/day (estimate by Benson)

$p = 43$ g H_2O/m^2 day (based on the number of crystals landing on microscope slides) (Kumai and Russel, 1969)

$r = .21$ g/m^3 (from measurement)

$A_B = A_T = A = 5 \times 10^7$ m^2 (from observation)

$\frac{dz}{dt}$ = cloud thickening rate = $\frac{1}{A}\frac{dv}{dt}$ = 3m/day (observation)

The evaporation rate, q, can now be computed to be 38 g H_2O/m^2 day.

A comprehensive study of ice fog must entail a determination of the mass budget; at Mildred Lake some of the parameters may be approximated and others determined from observation and measurement.

5.6 Ice Fog Drift

Diffusion rates and the mechanisms involved in the spreading of ice fogs originating over open ponds are not well understood. The observation of Lawford et al (1974), that the cloud is elongated in the direction of the mean wind, suggests treating the pond by the classic diffusion equations as an area emission source. In Figure 12 σ_{yo} (=½ pond radius) is taken as the initial crosswind standard deviation of cloud density; it is in effect ± one standard deviation of a normal density distribution centred on point C (Figure 13). A virtual emission source is placed at a distance X_y corresponding to the value of σ_{yo} in empirically established diffusion curves (Turner, 1969). X_y will vary with atmospheric stability; under stable conditions, it is approximately 100 km. Cloud density at any downwind point may then be estimated as a function of the density at point C by means of the diffusion equations for point sources (Turner, 1969).

The basic shortcoming of the foregoing technique is that the complex processes of cloud growth and dissipation as described by the mass budget equation (Section 5.5) are not taken into account.

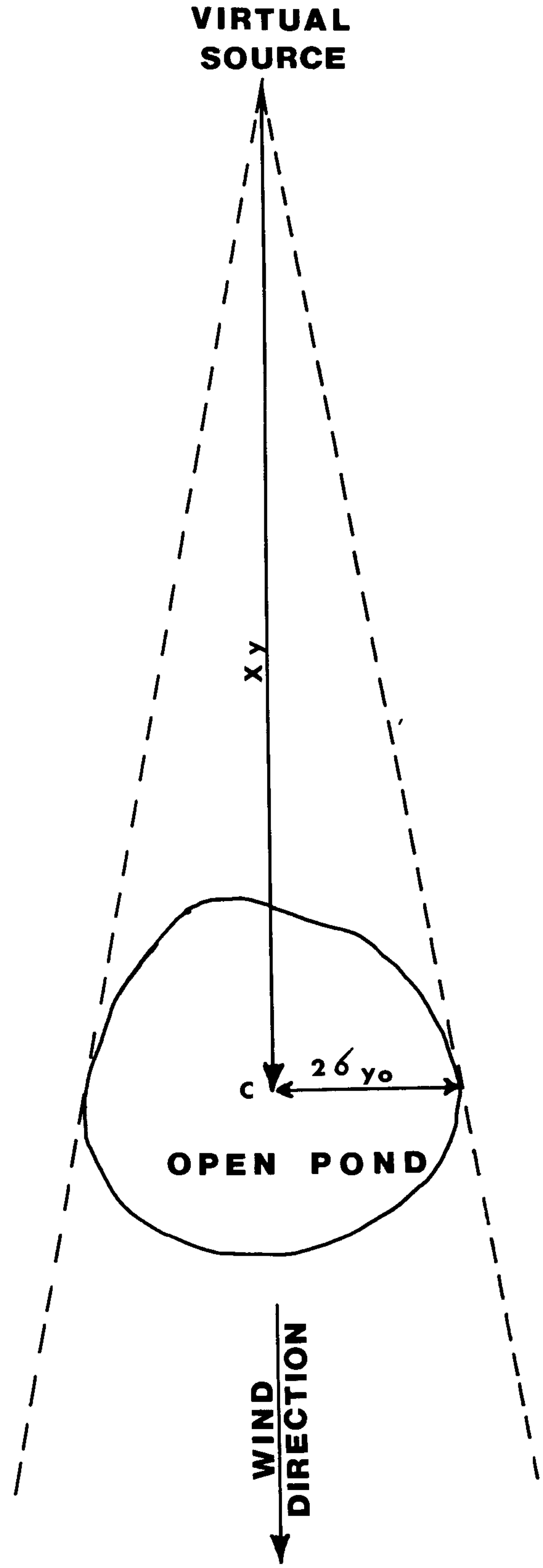


Figure 12 Diffusion of Ice Fog Cloud as an Area Source (see Section 5.6)

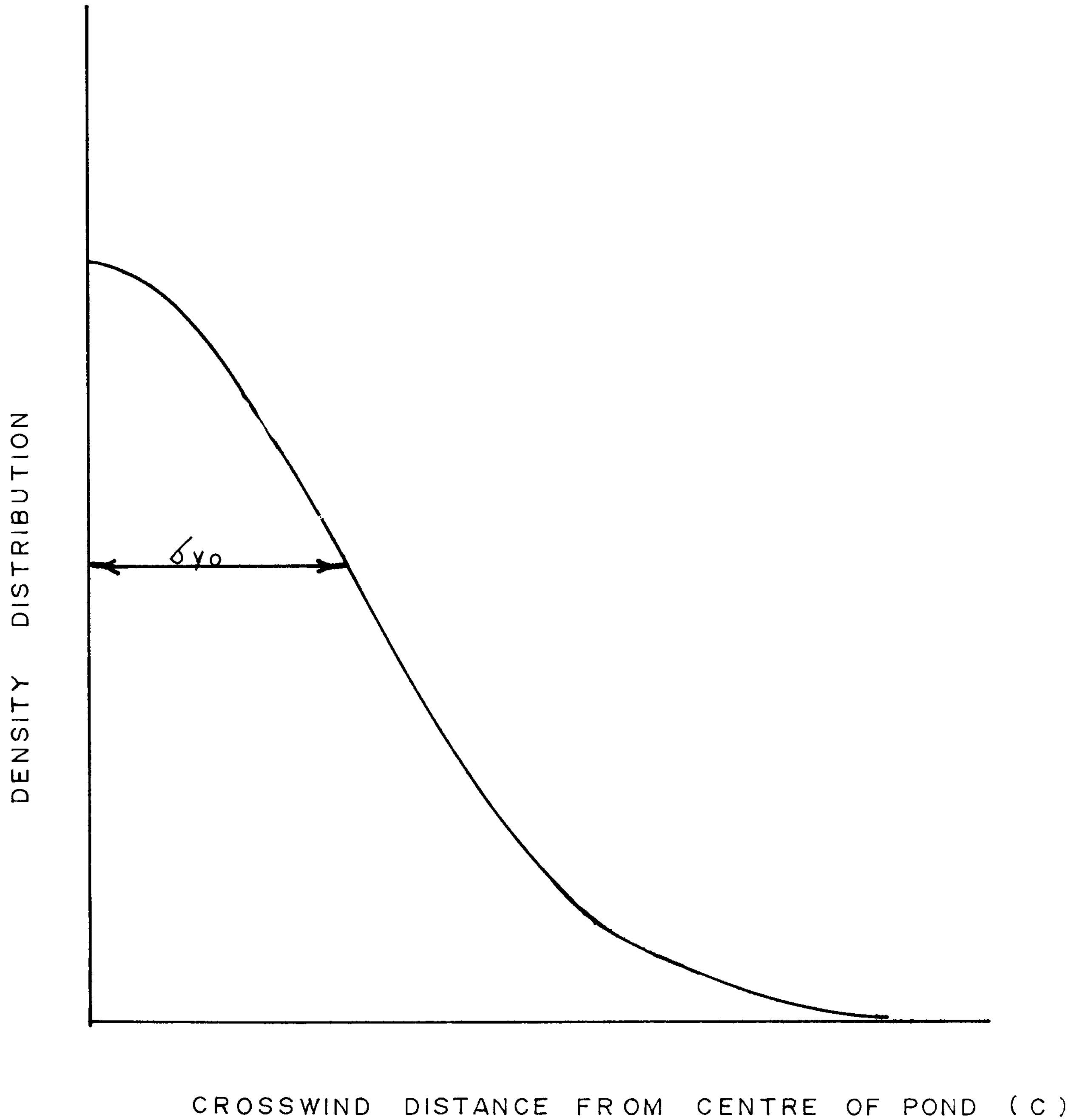


Figure 13 Assumed Density Distribution of Ice Fog Cloud (see Section 5.6).

6.0 IMPLICATIONS TO MILDRED LAKE

6.1 Ice Fog at Mildred Lake

An increased potential will exist for winter fogs at Mildred Lake due to increased moisture released to the atmosphere and increased nuclei concentrations. The projected output of water vapour to the atmosphere from the Syncrude complex is significant compared to that at other northern locations where ice fog has been experienced. However, the concentration and types of nuclei that may be present have not been determined.

The probability of extensive ice fog, however, does not appear large. For one thing the topography of the Mildred Lake area is not nearly as conducive to such persistent, strong thermal stratification as is the case in the city of Fairbanks, Alaska. Secondly, the number of days with sustained temperatures below -40^{o}C is far fewer than at Arctic settlements where large ice fog clouds commonly occur.

For example, at Fort McMurray Airport, 40 miles south of Mildred Lake, temperatures below -40^{o}C were observed for only 0.4 per cent of the hours during the months November through March for the period 1964-1975.

Although the frequency of extensive ice fog may not be high, there is a likelihood of localized ice fogs (eg. within the tailings pond and mining pit excavations) in combination with widespread water fog throughout the area. Onsite studies are required to obtain an understanding of the potential frequency and duration of these phenomena.

6.2 Ice Fog Prediction at Mildred Lake

The meteorological controls on ice fog vary from one location to another. The development of predictive techniques, then, should be based if possible on onsite observations and measurements by a trained observer. Determination of the local controls would require:

1. Daily records of fog in the vicinity of Mildred Lake noting the type, intensity (i.e. visibility), areal extent, apparent sources and topographic variations.

2. Monitoring of the diurnal variation of fog in terms of drift, growth or dissipation, thickening or thinning.

3. Concurrent records of temperature, humidity, wind, weather and sky condition across the area. Minisonde releases to determine temperature and wind profiles associated with fog.

4. Extent and behaviour of open waters.

Local and large scale controls on both ice and water droplet fog could be determined by correlating fog observations with meteorological and emission data.

A proposed prediction scheme for Fairbanks relates ice fog occurrence to a single synoptic (Large scale weather) feature: a northerly component to the 500 millibar flow over central Alaska (Ohtake and Suchannek, 1970). A similar synoptic dependence may exist for Mildred Lake as well.

6.3 Interaction with Pollutants

The stable atmospheric conditions which occur with low temperature fog are also conducive to poor air quality, but it is important to note that increases in pollutant concentrations during periods of fog are associated with low level sources of emission such as vehicular traffic or space heating.

Ice fogs are associated with extremely stable atmospheres. Under these conditions, the vertical diffusion of elevated plumes is very slow. As a result, the effluents from a tall chimney such as the 183 metre Syncrude stack would be embedded in the stable air far above the fog layer.

A ground-based ice fog layer generally ranges in thickness from 10-30 metres with a sharply defined upper boundary, its depth increases as the temperature remains below $-40^{\circ}C$ and it may on occasion reach 100 metres (Csanady and Wigley, 1973). Hence, it is improbable that elevated plume and fog will mix.

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