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The purpose of this paper is to summarize some of the information that is available in the literature on atmospheric icing, particularly information that will be useful to oil companies concerned with the design and construction of structures in areas where severe icing conditions can be expected.

TYPES OF ATMOSPHERIC ICING

In general, atmospheric icing can be grouped into three types: hoarfrost, rime, and glaze. In addition, there are combinations of rime or glaze with newly fallen snow as well as the type of ice that forms by the freezing of salt-water spray.

The following descriptions of hoarfrost, rime and glaze are abstracts from the articles in a glossary of meteorology (1).

Hoarfrost (commonly called frost or hoar) is a fluffy or feathery deposit of interlocking ice crystals (hoar crystals) formed by direct sublimation on objects, usually those of small diameter freely exposed to the air, such as tree branches, plant stems and leaf edges, wires, poles, etc. The deposition of hoarfrost is similar to the process by which dew is formed, except that the temperature of the befrosted object must be below freezing. It forms when air with a dew point below freezing is brought to saturation by cooling.

In addition to its formation on freely exposed objects (air hoar), hoarfrost also forms inside unheated buildings and vehicles, in caves, in crevasses (crevasse hoar), on snow surfaces (surface hoar) and in air spaces within snow, especially below a snow crust (depth hoar).

Rime is a white or milky granular deposit of ice formed by the rapid freezing of supercooled water drops as they impinge upon an exposed object. It is denser and harder than hoarfrost, but lighter, softer, and less transparent than glaze. Rime is composed essentially of discrete ice granules, and has densities as low as 0.2 to 0.3 gm per cm^3. Factors which favor rime formation are small drop size, slow accretion, a high degree of supercooling, and rapid dissipation of latent heat of fusion.

Rime is often described as soft or hard. Soft rime is a white, opague coating of fine rime deposited especially on points and edges of objects. It is usually formed in supercooled fog. On the windward side soft rime may grow to very thick layers, long feathery cones, or needles pointing into the wind and having a structure similar to that of hoarfrost.

Hard rime is an opaque, granular mass of rime deposited by a dense supercooled fog. Hard rime is compact and amorphous and may build out into the wind as glazed cones or feathers. The icing of ships and shoreline structures by supercooled spray usually has the characteristics of hard rime.

Glaze (also called glaze ice, glazed frost, clear ice) is a coating of ice, generally clear and smooth but usually containing some air pockets, formed on exposed objects by the freezing of a film of supercooled water usually deposited by rain or drizzle. Glaze is denser, harder and more transparent, than either rime or hoarfrost. Its density may be as high as 0.8 or 0.9 gm per cm^3. Factors which favor glaze formation are large drop size, rapid accretion, slight supercooling, and slow dissipation of heat of fusion. The accretion of glaze on terrestrial objects constitutes an ice storm; as a type of aircraft icing, it is called clear ice. Figure 1 shows a twig with glaze accumulation about 2 cm (3/4 in.) thick, even after some melting had taken place.

Several variations in these three basic types can occur. Some authors (2) classify rime into wind-orientated, free-growing aggregates and wind-orientated mixtures of rime and fallen snow. Free-growing aggregates growing at lower wind speeds are often called "soft" rime, in contrast to "hard" rime which forms at higher wind speeds (3).

Since sea-water contains salt, a salt-water icing deposit differs from fresh-water ice in that it may not wholly freeze. The ice that forms is nearly pure, resulting in an increase in the salt content of the remaining liquid, the freezing temperature of which steadily falls. This brine often becomes occluded in the intercrystalline crevices of the growing ice.

OCCURRENCE OF ATMOSPHERIC ICE

The following general comments on the occurrence of atmospheric ice in North America are based on the scanty information available in the literature on this subject.

As hoarfrost is of low density and does not adhere strongly to surfaces, it does not usually create serious ice loading problems. It is, of course, a common form of atmospheric ice occurring whenever the water vapour in the air sublimates on an object cooled below 0°C.

Heavy deposits of soft rime are most likely to occur in wooded regions sheltered from the wind where supercooled water droplets of small diameter occur quite frequently. It often creates problems in forested, mountainous areas which are in cloud with temperatures below freezing. This type of rime deposit sometimes combines with newly fallen snow to create problems with instruments such as anemometers, snow precipitation gauges, etc.

Hard rime forming at higher wind velocities will more probably occur at exposed locations on mountains which are often in clouds during the winter. These deposits growing on the windward side can have rapid growth rates, reported to be as much as 4 cm/hr (1.6 in./hr) (4). Japanese studies (5) indicate that the rime type of icing does occur on marine structures, but it is not considered by these authors to be a serious problem in the icing of ships.

Bennet (6) compiled an extensive literature review of glaze occurrence in the United States and other parts of the world. He reports that in the United States glaze occurs most frequently in a broad belt extending from north-central Texas to southern New England. Many parts of this area experience a glaze storm with ice $\frac{1}{4}$- to $\frac{1}{2}$-in. thick once every 3 years. He reported that west of the Rockies, glaze is not as common as rime or wet snow.

In 1955 Boyd (7) tabulated the frequency of freezing precipitation for 45 Canadian weather stations based on the two years 1951 and 1952. Some information on high winds and low temperatures during or following the icing storms was also given, but because of the short records available the values were considered preliminary indications rather than reliable frequencies.

More recently, the Climatology Division of the Meteorological Branch of the Canada, Department of Transport, prepared a map (8) showing the mean annual number of hours with freezing drizzle or freezing rain based on the 19 years 1942 to 1960 (Figure 2). More work is in progress in the Climatology Division on the frequency and duration of freezing precipitation.

Such frequencies and durations of freezing precipitation cannot be converted directly into ice loads, however; nor do weather observations ordinarily include the thickness or density of the accumulated ice. A subcommittee of the Canadian Standards Association and many communication and electric power organizations are now cooperating with the Division of Building Research in the collection of observations on the actual thickness of icing accumulations in Canada. The reports received in the first three winters are not enough to delineate the areas of serious icing, but the reports of glaze do seem to fit into the general pattern of the map showing frequency of freezing precipitation. Progress reports (8, 9) for the first two winters are available as Technical Notes.

It seems probable that the eastern half of Newfoundland suffers from more serious glaze icing storms than other areas, followed by an area around the southern Gulf of St. Lawrence. Southeastern Ontario, southern Quebec and the rest of the Maritimes suffer less frequently but do have serious storms. The reports of wet snow from the valleys of British Columbia and reports of heavy rime icing at high elevations do not, of course, correlate with the freezing rain map. The far North is not included in the project at present and hence no reports have been received on the rime icing which is believed to be rather common in high latitudes.

Vasil'yeva (10) reports that severe ship ice accretion, caused by the freezing of salt-water spray, occurs when air temperatures are from -1 to -14°C, with winds of force 6 (11 - 14 m/sec or 25 - 31 mph) or above and when the sea-water temperature is from +3 to -1.8°C. If water temperatures are higher than 3°C, shipboard icing is usually not a problem. It is reported that in the North Sea with water temperatures ranging from 5 to 8°C no serious icing of ships has been observed. Vasil'yeva notes that sever ship icing occurs in the northern parts of the Pacific Ocean - the Bering, Okhotsk and Japan Seas, where water temperatures are close to freezing. Severe icing also occurs off the coast of Iceland where water temperatures are close to freezing and severe storms with low air temperatures are relatively common in December and January.

DESIGN ICE LOADS

A question commonly asked by design engineers is what is the maximum thickness of ice that can accumulate on a specific structure in a specific location. Unfortunately, so many factors determine the thickness of ice that it is difficult to obtain reliable design values. It is almost impossible to calculate the amount of ice that can be deposited on complex shapes exposed to varying wind speed and direction, varying air temperature and varying droplet size, even when all these meteorological variables are known. To obtain a design load, the first step is to estimate from past meteorological records the worst combination of conditions that is likely to occur. This in itself is a very difficult problem, particularly in areas where adequate records are not available.

Kuroiwa (3) gives some theoretical accumulation rates for glaze and rime collecting on a single wire for different wind velocities. These calculations are useful but, as he states, "there are great differences between calculated and observed data because of the complexity and changeability of meteorological conditions."

The best source of information is actual measurement of ice accumulations under field conditions, even though such measurements are most limited. Rime deposits several centimeters thick are not uncommon in mountainous areas. Heavy fingers of ice extending well over a foot (30 cm) into the wind have been reported in British Columbia (Figure 3). Kuroiwa presents some observations of hard rime icing on a suspended wire on Mt. Nesiko in Japan where, under severe icing, the diameter of deposits reached 12 cm before the wire broke. The total weight of the deposit was 5.5 kg/m (3-7 lb/ft) of wire length. A maximum deposit of rime in the Tatra Mountains (11) was reported to be 209.3 kg/sq m (42 lb/ft^2) for an exposed surface. Bennett's study (6) shows that during a 10-year period about 2 in. of glaze is the greatest radial thickness formed on utility wires in the United States. Bennett also found that this was about the same as maximum deposits reported at various locations in the European portion of the U.S.S.R. during a 10-year period. It falls far short, however, of a report of ice on the guy wires of a tower in Newfoundland (8). This ice was 10 in. (25 cm) in diameter and is estimated to have weighed over 40 kg/m (27 lb/ft). Figure 4 shows the ice that had accumulated on the guy wires. Bennett also reports that several roofs were caved in by a severe glaze storm on 21-23 February 1922 which caused accumulated weights of from 80-100 kg/m^2 (16 to 20 lb/ft^2).

After an extensive study of shipboard icing, the Japanese recommend an icing load of 50 kg/m^2 (10 lb/ft^2) for an area of open deck exposed to extreme sea-spray icing (5). The U.S.S.R. design load for exposed decks is 30 kg/m^2 (6 lb/ft^2). The Japanese consider that the U.S.S.R. loading specification is less because it is recommended for regions where there is floating ice which has a dampening effect on wave action.

ATMOSPHERIC ICING COUNTERMEASURES

Before considering some general methods of controlling atmospheric icing, it may be worthwhile to define some of the problems created by atmospheric icing. In addition to being designed to withstand the expected weight of ice, the structure should be able to withstand any increased wind load which may result from the icing. The structure should also be designed to minimize problems such as galloping conductors or the hazards to the movement of men or vehicles created by slippery surfaces or falling ice. The freezing of sea-water spray on marine structures and ships not only creates a problem to normal working activities but has resulted in the capsizing of trawlers due to loss of stability (12).

If there is a choice, exposed locations should be avoided as the severity of glaze, rime and salt-spray icing increases with increased wind speed. Superstructures and wires exposed to the free flow of wind should be kept to a minimum. Power and communication lines should be placed so that if they break from icing, damage and disrupted service will be kept to a minimum.

Prearranged plans for removing severe icing loads should be worked out and, if possible, coordinated with meteorological forecasts. The control and prevention of atmospheric ice is generally the same as for the control of snow and ice in other problems, such as keeping parking lots free of ice. Considerable literature has accumulated on removing snow and ice from such areas by mechanical, heating and chemical methods. Recently a Manual on Snow Removal and Ice Control in Urban Areas (13) was compiled which presents useful summaries on ice melting by chemical and thermal methods.

The techniques would have to be modified for use at sites exposed to atmospheric ice, but the basic principles are similar. For example, Schaefer (14) concluded that the heat required to keep cylindrical rods free of ice on Mount Washington would be at a maximum about 10 watts/cm^2, which is much higher than the design heat requirements listed by Schneider (15) for keeping areas free of newly fallen snow (300 to 700 watts/sq m). Power companies have attempted to prevent atmospheric ice on power lines by heating the lines through increased current loads (16).

Considerable research has been carried out on the adhesion of ice to develop coating materials which would prevent snow or ice accumulations (17). Such coatings permit relatively easy ice removal because of low strengths of ice adhesion. These materials, however, seem to lose their effectiveness after repeated ice accumulation and removal cycles.

Some relative values for ice adhesion obtained by investigators (18) for several common materials are listed as follows:

Metals	88 - 120 psi
Rubber	20 - 50 psi
Plastics	10 - 40 psi

CONCLUDING REMARKS

The literature available on atmospheric icing has been reviewed briefly to define the different types of ice, the conditions under which they form and the general approach to control and prevention. Research underway in Canada on atmospheric icing problems is limited. The Low Temperature Section of the Division of Mechanical Engineering, National Research Council, has underway a study on the icing of fishing trawlers; the Meteorological Branch of the Department of Transport is studying past records of freezing rain; a survey of icing on wires and communication towers is being conducted by the Snow and Ice Section, National Research Council, through the cooperation of the Canadian Standards Association. It is hoped that this brief review will be useful to oil companies concerned with the design and construction of structures in regions where severe atmospheric icing can be expected.

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Figure 1 Glaze icing on twig

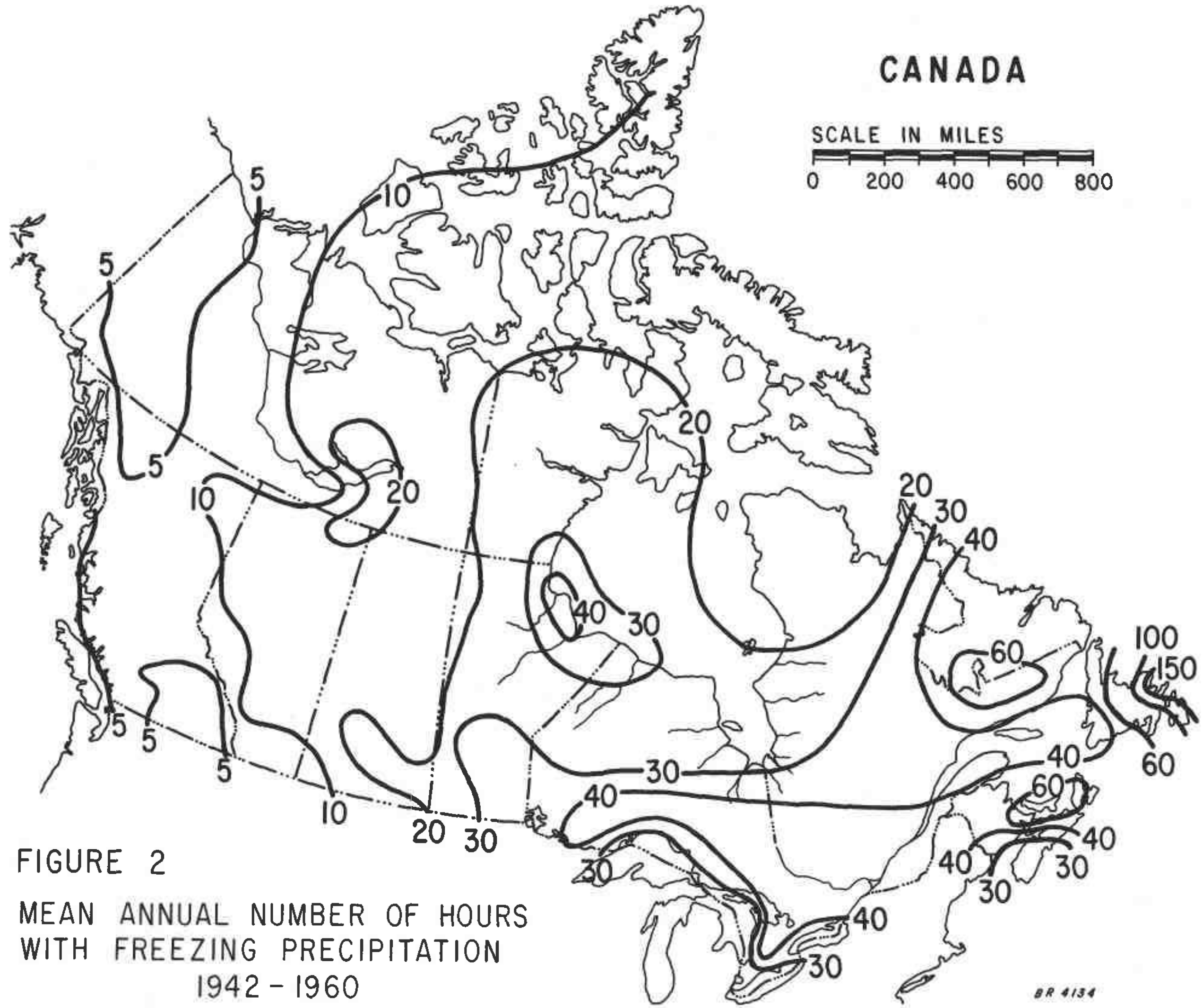

FIGURE 2

MEAN ANNUAL NUMBER OF HOURS WITH FREEZING PRECIPITATION 1942 - 1960

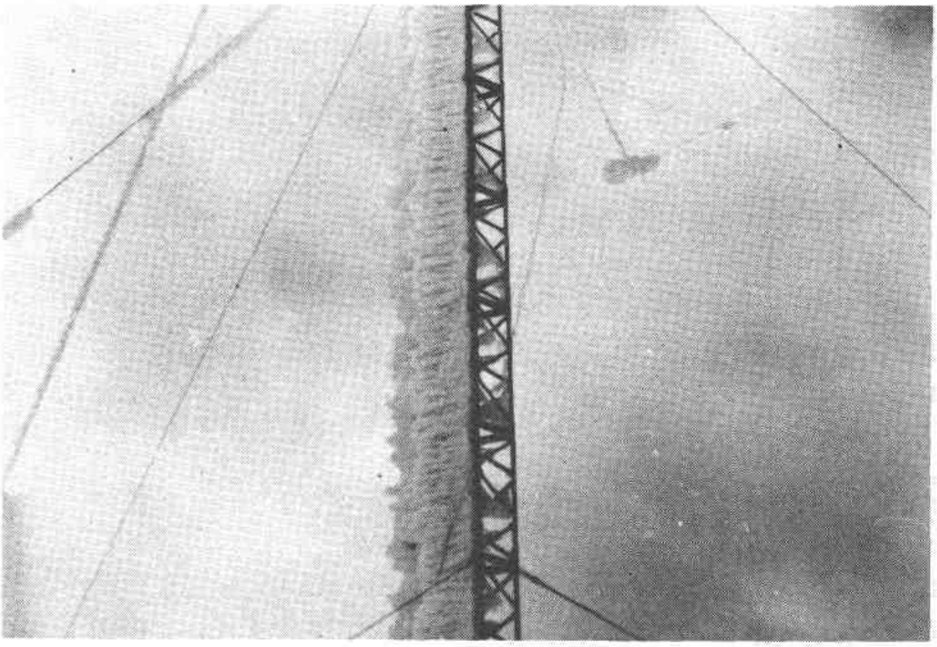

Figure 3 Rime icing on tower

Figure 4 Heavy glaze icing