THE USE OF DUST TO ADVANCE THE BREAK-UP OF ICE ON LAKES AND RIVERS

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In response to a general interest of several organizations in extending the navigation season, the Snow and Ice Section of the Division of Building Research, National Research Council undertook a study of the use of dust to accelerate the melting of ice covers in various areas across Canada. It was the purpose of the first part of the study, which is now reported, to obtain from published papers the information upon which could be based an opinion on the feasibility of the method, and recommendations concerning its use.

It has been known for many years that the melting of snow and ice covers can be accelerated by spreading a thin layer of dust on the surface just prior to the spring melt period (1). The Russians have used this technique to advance break-up in Arctic bays by as much as one month (2, 3). They report also that they have used dust to accelerate snow melt on airfields and at construction sites, and to open leads in ice covers as far north as Vil'kitskiy Strait (77° 40'N) (2).

The use of dust to advance the break-up period does not appear to have been used to any extent in Canada. Arnold carried out some field experiments in 1959 at Isachsen, Northwest Territories (latitude 78° 47'N, 103° 30'W) (4). Seven different materials were spread in varying amounts over test plots one square metre in area, on snow, sea ice and lake ice. The observations made showed that during the month of June the natural rate of melting was increased $2\frac{1}{2}$ to 5 times. Arnold discusses possible uses for this technique in Canada. He suggests that it would be useful to conduct similar studies in lower latitudes to see if it might have practical application in the more heavily populated areas of southern Canada.

A layer of suitable dust on a snow or ice surface will increase the amount of solar radiation absorbed, and consequently the amount of heat potentially available for melting. The cover will begin to melt when its surface temperature is 32°F and when it receives, on the average, more heat than it loses. The time and rate at which melting and subsequent break-up take place are determined by a number of inter-related factors. To appreciate the conditions under which dusting might be successful, and the limitations of the technique, it is necessary to discuss briefly the normal break-up of ice covers and the factors that influence it.

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SPRING BREAK-UP IN CANADA

The break-up of ice covers usually occurs in two stages. During The first stage, the cover deteriorates and weakens without decreasing appreciably in thickness (5, 6). It is believed that the deterioration is caused by the absorption of solar radiation by impurities at grain boundaries. During the second stage, open leads develop. Thereafter, the break-up is greatly influenced by water currents and wind.

The ice on a lake usually melts first near the shore. If this open marginal water is warmed above 4°C, it may flow laterally under the ice sheet and accelerate the melting. This flow, perhaps aided by wind action, can bring warmer sub-surface water to the surface and cause the final stages of break-up to occur very rapidly. The final disappearance of ice covers has occurred so quickly at times that some observers believed the ice actually sank (7, 8).

The break-up of ice on rivers is usually earlier than on lakes because only a portion of the ice has to be melted. Once the ice is free to move, the flow, usually increased by run-off water from the surrounding land, will accelerate the break-up. In large northward flowing rivers, run-off from the southern areas will affect the time of break-up in the more northern regions.

The melting of sea ice appears to follow the same pattern as for lakes and rivers (9). Weeks (10) states that during the first stage, interconnected cavities developed near the surface of the ice. As deterioration advanced, he noted that these internal cavities became large enough to insert a hand into them, and that they formed before the upper surface of the ice showed appreciable deterioration. When weakened sufficiently, the ice began to crack and break up along lines of weakness. This results in the formation of ice floes which eventually disintegrate. Air temperature, wind, waves and water currents have an important influence on the rate at which the final stages of break-up occur.

In recent years limited information has become available on the time at which break-up occurs at different sites in Canada. A circular published by the Meteorological Branch, Department of Transport (11), lists average dates of break-up of some rivers and the appearance of breaks along the shores of some lakes. Figure 1, reproduced from this meteorological circular, shows that on the average, break-up in Canada occurs in April in the south, and in June or July in the far north. The approximate location of the 32°F mean air temperature isotherms at different times in the spring is also shown in Fig. 1.

The time of break-up varies from year to year and with the type of water body. In Fig. 2 is shown the number of times break-up occurred at certain dates for a few selected harbours and rivers. This information was taken from Meteorological Branch Circular No. 3156 (12).

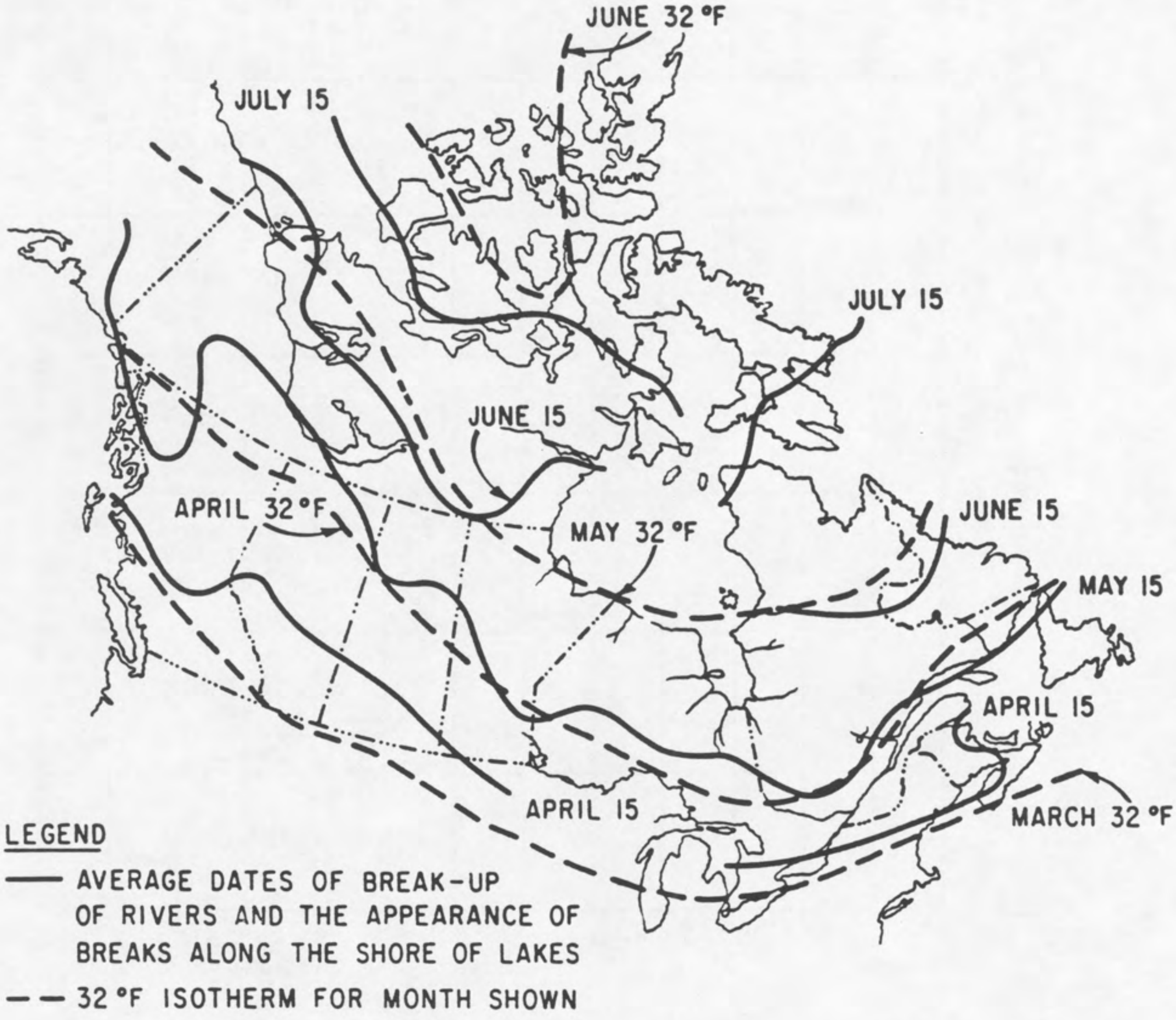


FIGURE I THE AVERAGE DATES OF BREAK-UP BR 2596-1
(REPRODUCED FROM REFERENCE No 11)

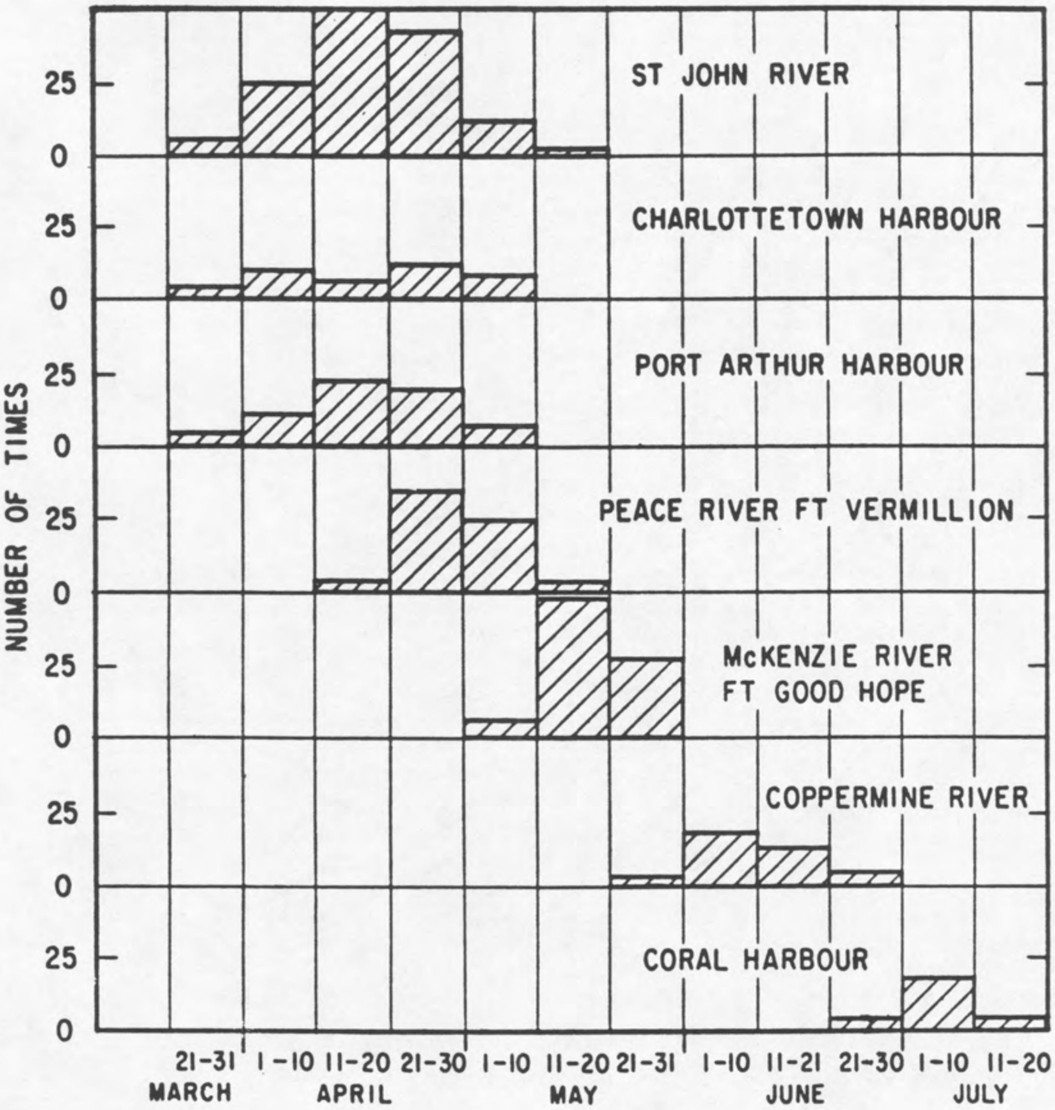


FIGURE 2
HISTOGRAMS SHOWING NUMBER OF TIMES BREAK-UP OCCURS IN A GIVEN PERIOD AT SELECTED SITES

BR 2586-2

A factor that affects the duration of break-up is the thickness of the ice to be melted. Because of the longer winter, the maximum thickness of ice covers is greater in the north of Canada than in the south. Some information on maximum ice thickness, obtained from Meteorological Circular No. 3195 has been plotted in Fig. 3 (13). It is seen that in southern Canada the maximum ice thickness is usually 1½ to 2½ ft; in the far north the maximum thickness of ice formed during one winter season is from 5½ to 7½ ft. Maximum ice thickness can be greater than this at specific sites because of ice jams and rafting.

The onset of the initial stage of break-up is determined by the rate at which heat is lost and received at the surface of the cover. The heat exchange occurs by radiation, convection and mass transfer (evaporation, condensation, sublimation). Whether there is a net loss or a net gain of heat by the cover will depend upon the magnitude and duration of these processes.

THE ENERGY BALANCE AT A MELTING ICE SURFACE

During the melt period, the heat associated with radiation is particularly important. Radiant energy is normally classified as short-wave and long-wave. Short-wave radiation is that associated with sunlight and is made up of wave lengths shorter than 2μ ($1\mu = 10^{-4}$ cm). The long-wave radiation is that emitted by the clouds, soil, snow, ice surfaces, etc. at their normal temperature, and is made up of wave lengths mostly between 5 and 50μ. Short-wave radiation is received by a surface during daylight hours only; long-wave radiation is received or emitted continuously.

If the temperature above the snow or ice surface is less than that of the surface, heat will be lost by the surface to the air by convection. If the temperature of the air is greater than that of the surface, the reverse will occur. Convective heat transfer, both positive or negative, can be quite large, depending on the meteorological conditions.

If the vapour pressure of the air above a snow or ice surface is less than that at the surface, heat will be lost from the surface by evaporation or sublimiation. If the vapour pressure of the air is greater than that of the surface, heat will be gained by the deposition of the solid or liquid. The gain or loss of heat by transfer through the vapour phase can be quite large, again depending on the meteorological conditions.

The net loss or gain of heat at the surface by radiation, convection, evaporation or condensation, must equal the sum of the heat associated with a change in temperature of the cover and the heat used to melt snow or ice. This requirement can be expressed as an equation, often called the energy balance equation. One simple form of this equation is:

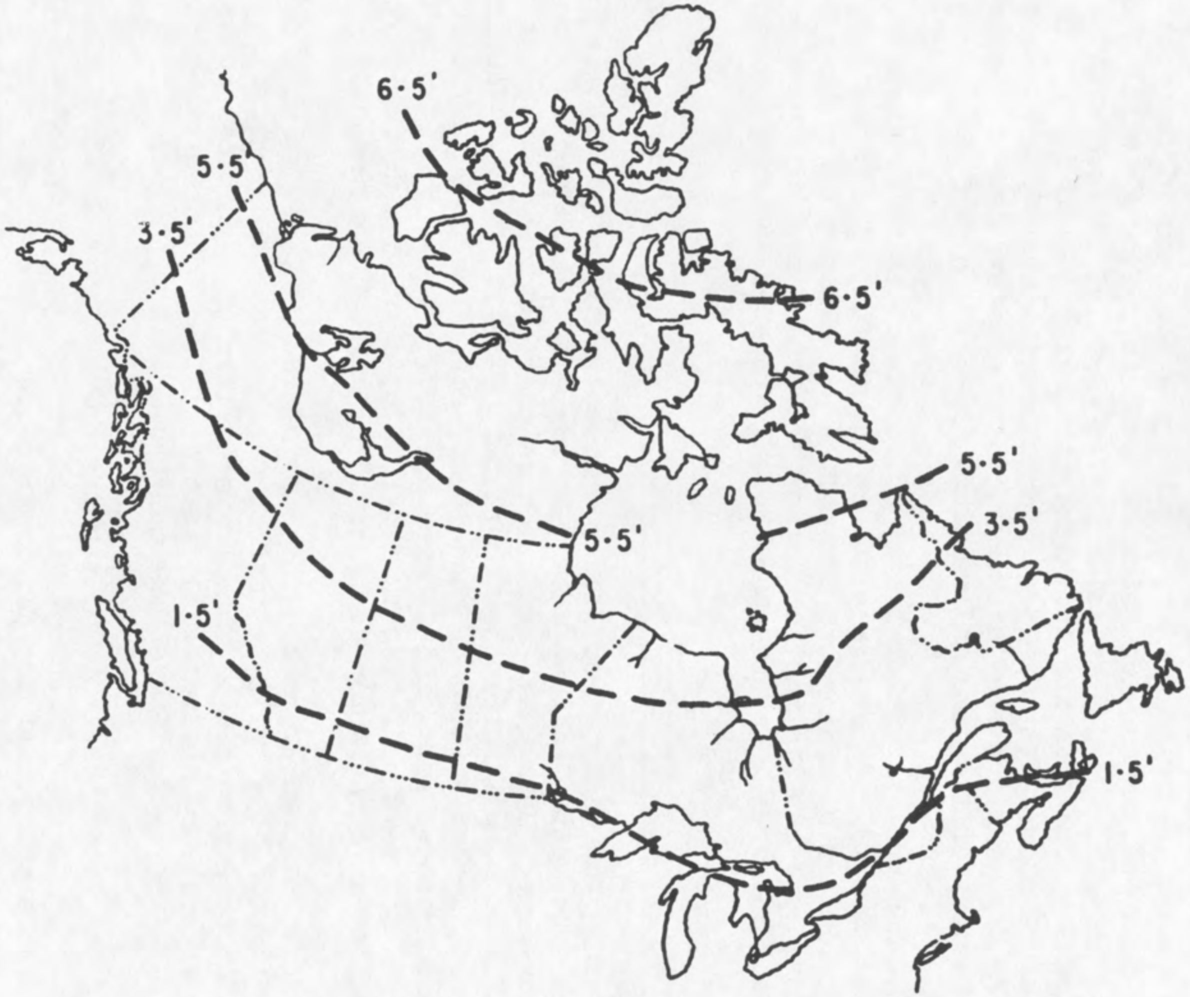


FIGURE 3

ESTIMATED AVERAGE MAXIMUM ICE THICKNESS (FEET) ON LAKES AND RIVERS IN CANADA *(OBSERVATIONS EXTRACTED FROM REFERENCE 13)*

BR 2586-3

$$Qsw = \pm Qlw \pm Qc \pm Qe + Qm$$

where

Qsw = net short-wave radiation
Qlw = net long-wave radiation
Qc = convective heat transfer
Qe = evaporative heat transfer (including sublimation)
Qm = heat used in melting ice, including heat required to raise temperature of the ice to the melting point.

This equation shows the various factors that affect the snow melt during the first phase of melting. For the second phase, account must be taken not only of the heat transfer between the air and the cover, but also of that between the water and the cover. For the present discussion, it is sufficient to consider the transfer between the air and the cover. Although it is not possible to calculate accurately the value of the various components of the balance, estimates are useful to discuss the inter-relationships between the components, and to show how changes in their magnitude will affect the balance, and consequently the melt rate.

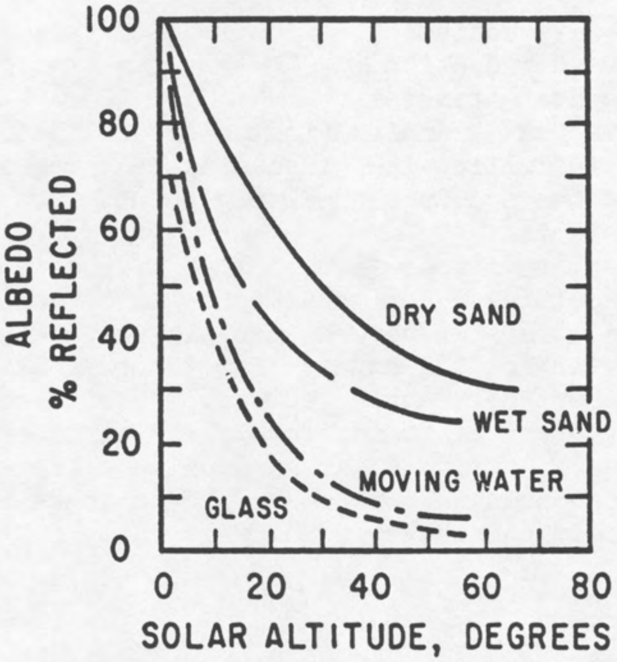
Short-Wave radiation

When short-wave radiation strikes the natural ground cover, part of it is absorbed and part is reflected upward. The percentage of the total incoming short-wave radiation that is reflected is called the "albedo." The percentage that is absorbed is the portion that is potentially available for melting snow or ice.

The albedo of natural surfaces depends upon the condition of the surface. In general, the brighter the surface, the higher the albedo. For new snow, the albedo or percentage of short-wave radiation reflected may be as high as 80 to 90 per cent; for melting snow the albedo varies from 40 to 60 per cent and for a water surface it is usually between 5 to 15 per cent.

The albedo depends also on the sun's elevation. Figure 4, taken from Geiger (14), shows that when the sun's altitude is below 10 deg, the percentage reflected is usually over 50 per cent, regardless of the surface.

The objective in applying a thin layer of suitable dust is to reduce the amount of short-wave radiation that is reflected from the surface, and thus increase the heat absorbed. It can be appreciated that dusting will be most effective in those circumstances where the albedo of the surface is normally high prior to and during break-up.



NOTE:

---- REFLECTION OF LIGHT BY GLASS (PAGE 2663 HANDBOOK OF CHEMISTRY AND PHYSICS)

FIGURE 4

DEPENDENCE OF ALBEDO ON THE ALTITUDE OF THE SUN (REFERENCE 14)

There are relatively few observations of the albedo of ice surface during the melting period. Yakovlev (9) suggests that the reflective capacity of drifting ice in the central Arctic fluctuates over a broad range. He states that "large fluctuations in the value of the albedo were discovered for approximately similar surfaces where visual observations showed no changes." He attributes this to the changing micro-relief of the surface of the snow or ice, especially during the melting period. Other observers (15) have noted that the albedo of melting snow or ice is highly variable. Untersteiner (16) suggests that because the surface of melting sea ice disintegrates into a layer of loose grains, 2 or 3 cm in diameter, the albedo tends to remain high.

Because albedo depends so much on the condition of the snow or ice surface, it is not possible to state exactly how much it will be reduced by darkening the surface with a suitable dust before normal break-up. Observations that have been reported however, can be used to estimate the change that will occur. Using this estimate and information that is available on incoming short-wave radiation, an estimate can be obtained for the increase in the absorbed short-wave radiation that will result.

The average short-wave radiation in cal/sq cm/24 hr received by various regions in Canada during the months when the average air temperature is 32°F has been calculated by Mateer (17). His values are given in Fig. 5. In the south the average short-wave radiant heat available during the early part of the melting period is 300 to 350 cal/sq cm/24 hr. In the far north, it is about twice as much for the same period of the break-up. Within a region, actual values will vary from season to season and from location to location.

Not only is there more short-wave radiation available during the melting season in northern Canada, but the sun is at an altitude high enough not to influence the albedo for a longer time during a 24-hr period. The following information taken from the Climatological Atlas of Canada (18), shows the number of hours the sun is above the given elevation for various latitudes during the spring melt period:

Melting Period	Latitude	Average Number of Hours. Sun's Elevation above given Elevation
March	45°	6 hr above 24° on March 21
May	60°	10 hr above 25° on May 21
June	70°	12 hr above 23° on May 21
July	80°	10 hr above 23° on July 21

The number of hours that the sun is above 23 to 25° elevation during the melting season increases with increasing latitude. It is only for high latitudes, where the melting period might be in July (above 80°N) that a decrease takes place.

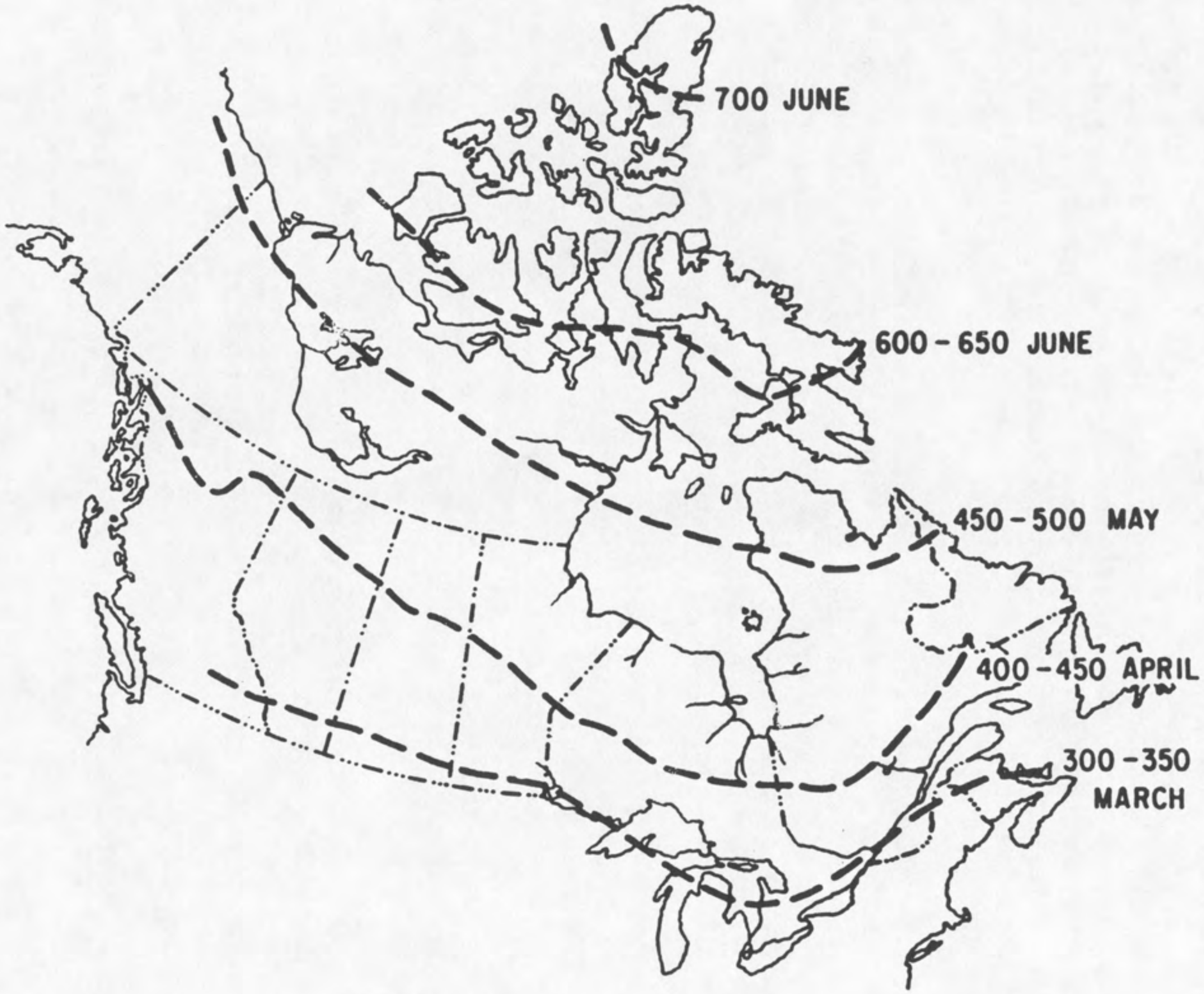


FIGURE 5

ESTIMATE OF AVERAGE DAILY INSOLATION DURING MONTH WHEN AVERAGE AIR TEMPERATURE APPROX 32°F (CALORIES / SQ CM / 24 HOURS)

BR 2586-5

If the incoming short-wave radiation is 300 cal/sq cm/24 hr and the albedo of an ice cover is reduced from 50 to 20 per cent by dusting, the value given by Peschonskii (2), the increase in the heat absorbed would be 90 cal/sq cm/24 hr. If the incoming short-wave radiation is 700 cal, under the same assumed conditions, the increase in the heat absorbed would be 210 cal/sq cm/24 hr. These approximate values show that the increase in the heat available for melting under the assumed conditions would vary from about 90 cal/sq cm/24 hr in southern Canada to about 210 cal/sq cm/24 hr in northern Canada. If the associated change in the long-wave radiative convective and evaporative heat losses is neglected, this corresponds to an increase in the melting rate of $\frac{1}{2}$ to 1.0 in. of ice per day.

Long-Wave Radiation

For long-wave radiation, snow, ice and water surfaces act very much like a "black body," i.e. they absorb or radiate approximately 90 to 97 per cent of the radiation a perfect radiator would when at the same temperature. Most dusts will not affect appreciably the long-wave radiation properties of snow and ice so that dusting a surface that is already at 32°F will not significantly change either the long-wave radiation emitted or absorbed. If dusting of the surface results in raising the average surface temperature, however, the long-wave radiation heat losses will increase, as according to Stefan-Boltzmann's law, every body radiates heat with an intensity proportional to the fourth power of its absolute temperature.

Evaporation and Convection

The main factors affecting the convective heat transfer are the temperature of the air, the wind velocity and the temperature and roughness of the surface. The application of a dust layer will not affect the air temperature or wind velocity directly, but it can increase the surface temperature and probably the roughness as well. This will increase the heat lost by convection.

Evaporation or sublimation from a surface depends primarily on the vapour pressure gradient, wind velpcity, and the roughness of the surface. If the surface temperature and roughness are increased by dusting, the rate of sublimation or evaporation will increase.

If the increase in the heat lost by convection and sublimation is great enough, it will balance the increase in the heat received by radiation before melting of the surface begins. This places a natural limit on how much the break-up of a cover can be advanced by dusting. The amount by which the break-up can be advanced will depend upon the conditions that prevail and will vary from place to place and from year to year.

The Lowest Temperature for which Dusting is Likely to be Effective

An estimate of the lowest average air temperature at which dusting will be effective can be made by calculating the evaporative, convective and long-wave heat losses at an ice surface for various air temperatures, and equating these losses to the possible gain in heat from the increased absorption of short-wave radiation. Unfortunately, estimating heat losses from natural surfaces requires detailed meteorological records that are normally not available for a specific site. Even when such records are available, the assumptions required for the calculations are such that the results are often unreliable. Although it is not possible to obtain precise answers, it was considered useful for discussion purposes to estimate the heat losses using available formulae. This was done for two sites, Resolute (75°N) and Ottawa (45°N). Appendix A gives the formulae used for the calculations.

The average incoming short-wave radiation values calculated by Mateer (17) were used to estimate the energy available for melting. It was assumed that the albedo of an ice cover can be reduced by dusting from 50 to 20 per cent. Evaporative, convective and long-wave radiative heat losses were calculated for various air temperatures and an assumed surface temperature of 32°F. The calculated difference between the heat available and the heat losses is shown on Fig. 6 for various air to surface temperature differences. It should be kept in mind that the calculations apply to the condition that the surface is at 32°F. Once the evaporative and convective heat losses exceed the radiative gain, there will be no heat available for melting i.e. the surface will be colder than 32°F.

The Armour Research Foundation has made a theoretical study on the use of solar energy for melting ice in the northern United States (19). Their calculated dependence of heat loss on the difference between the air and surface temperature is shown in Fig. 6 as are the measured melting rates obtained by Arnold (4).

Figure 6 shows that there is considerable difference between the losses calculated by the Armour report and those calculated with the formulae listed in Appendix A. This difference is due primarily to the value used for the heat transfer coefficient. The Armour report used convective coefficients that were obtained from laboratory tests. These values are higher than most of the values reported elsewhere.

The melting rates observed by Arnold for 78°N are lower than those estimated for northern regions. This may be due to incorrect assumptions in the calculations, unfavorable weather conditions for melting or to the fact that Arnold made only one application of dust.

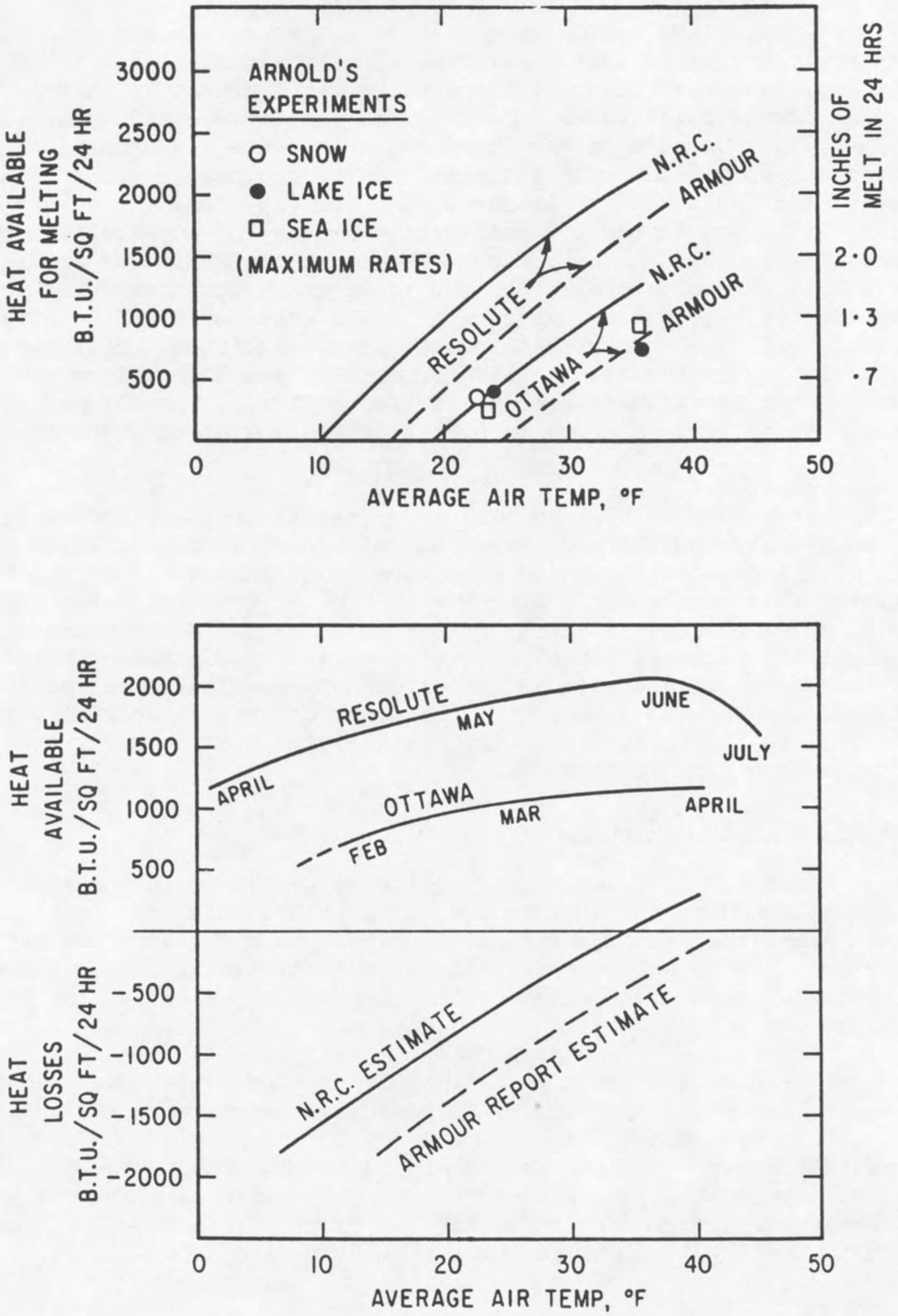


FIGURE 6

CALCULATED VALUES OF COMPONENTS OF THE ENERGY BALANCE FOR AVERAGE AIR TEMPERATURE BETWEEN 10 AND 40°F AND SURFACE TEMPERATURE 32°F

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Despite the approximate nature of the calculations, the following general conclusions can be stated. In the southern latitudes, melting will probably not occur if the average air temperature is below 20 to 25°F. In northern latitudes, the critical temperature will probably be about 5°F lower because of the increased short-wave radiation available in the break-up period. The estimate for the southern regions is supported by the report of the Armour Foundation (19) that states that for average conditions in the northern United States "it appears that it is not possible to maintain a surface temperature of 32°F, even if all the solar energy were obsorbed at the top layer of an ice sheet, if the air temperature is below freezing, except in the month of March." Arnold (4) and others (20) have shown that in the north, significant melt was obtained by dusting when the average air temperature was higher than 14°F (-10°C). If melting begins at these average air temperatures, the advance in the break-up period will be about two weeks in the south and about four weeks in the far north.

It should be kept in mind that the calculations presented are based on average conditions. For some melt seasons the available solar energy may be considerably higher or lower, and this would affect the amount of melting that occurs for average daily air temperatures below 32°F. For the 1959 and 1960 seasons, observations taken by the Meteorological Branch indicate that the radiation at Ottawa was greater and that at Resolute lower than the average values used in the calculations. In the calculations the albedo was assumed to be constant. In practice, its value will vary and will depend on the condition of the surface, the dusting material used and the frequency of application.

The Effect of Rain and Snow

Rainfall is usually not considered important in the melting process as the heat added to the snow or ice cover is probably not great (21). Rainfall can speed the melting process by helping to break down the structure of snow on ice. Nevertheless, rainfall can be detrimental if a dust layer has been applied, as it might wash the dust away from the surface or into uneven concentrations.

Fresh snow could have a significant effect if it covered the layer of dust applied to the surface. As fresh snow can have a reflectivity as high as 80 to 90 per cent, only some 10 to 20 per cent of the incoming short-wave radiation may penetrate the cover and be absorbed at the dust layer. Until the snow melts, the effectiveness of any material scattered on the ice would be greatly reduced. In Russia, the harmful effects of new snow are often minimized by dusting the ice cover after each snowfall.

THE REQUIREMENTS OF A DUSTING MATERIAL

Density of Application of a Dust

The decrease in albedo obtained by dusting will depend upon the amount of the surface that is covered by the dust. Let the density of application be W gm/cm^2, the average diameter of the particles d cm and the average density of each particle p gm/cc. Assuming that the particles are spherical, the average weight of a particle is $\frac{p\pi d^3}{6}$. For a density of application W, the average number of particles will be $N = \frac{6W}{p\pi d^3}$.

The average maximum cross-sectional area of a particle is $\frac{\pi d^2}{4}$.

The average actual area covered by the dust per unit area of surface is

$$A_d = \frac{\pi d^2}{4} \quad N = \frac{3}{2} \frac{W}{pd} .$$

If W, p and d are expressed in the same system of units, A_d is a dimensionless number whose value is independent of the a dimensionless number whose value is independent of the units used. From the expression for Ad, it is seen that the coverage obtained for a given density of application is proportional to the density of application and inversely proportional to the average diameter and density of the particles.

Williams has undertaken a study of the dependence of the change in albedo on average particle size and on the density of application of various dusts. Preliminary observations for two samples of Ottawa Valley crushed limestone, one with average particle size 1.2 mm and the other of 0.50 mm are shown in Fig. 7 where the observed albedo is plotted against the coverage A_d.

Figure 7 suggests that the albedo changes almost linearly with A_d, until it decreases to a value equal to the albedo of the dust. The extent of the linear range will probably depend upon the initial albedo of the surface and the albedo of the dust. For Ottawa Valley crushed limestone the maximum change in albedo occurs for $\frac{3}{2} \frac{W}{pd}$ equal to approximately .21. For dust of average particle diameter 1.2 mm, and density 2.4 gm/cc^3, this corresponds to a density of application of 1150 tons/sq mile and for average particle of diameter 0.5 mm, 475 tons/sq mile. Increasing the density of application of these dusts above this amount will probably have little further influence on the albedo of the surface.

The practical range for the average particle diameter of dusts that can be used to accelerate break-up is probably about 0.1 to 2.5 mm. Since the weight of material necessary to cover a given area varies approximately inversely with the average particle diameter, it will take about 25 times as much by weight to cover the same area with dust of an average grain size of 2.5 mm as with one of average grain size 0.1 mm, for Ottawa Valley crushed limestone of average grain size 0.1 mm. It would require a density of application of about 95 tons/sq mile to give the maximum decrease in albedo with the minimum weight of material. If the average grain size were 2.5 mm, the density of application would have to be increased to about 2400 tons/sq mile to give the same coverage.

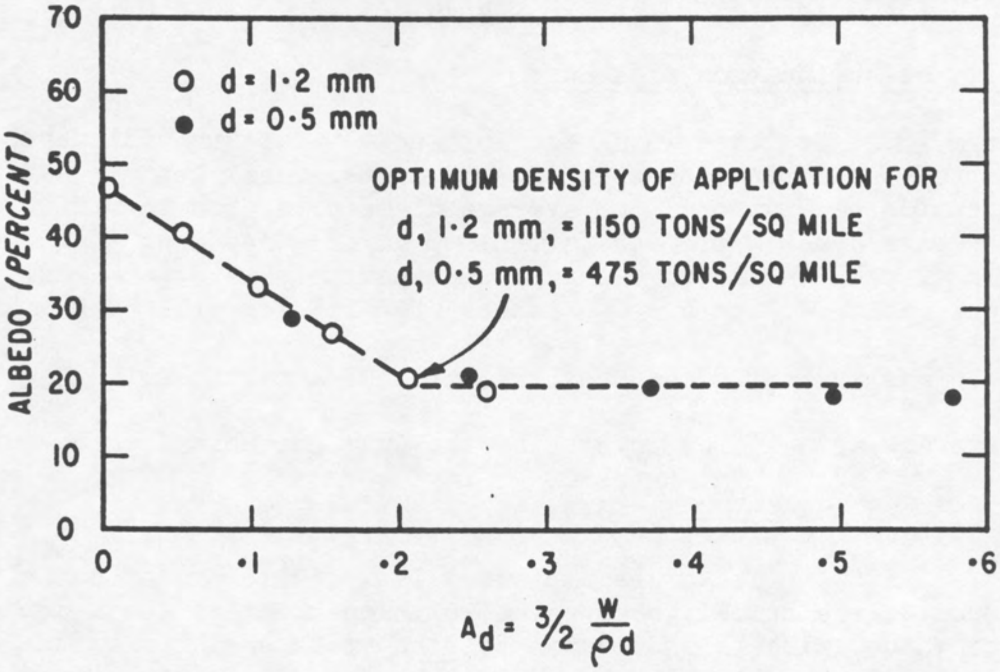

FIGURE 7

PLOT OF MEASURED ALBEDO VS THE COVERAGE A_d

$3/2 \frac{W}{\rho d}$ WHERE W = DENSITY OF APPLICATION
d = AVERAGE DIAMETER
ρ = DENSITY OF SOLID MATERIAL

For dusts with the same average grain size, the weight per unit volume varies directly with the density of the particle. The particle density of the heavier dusts, such as would be obtained from crushed rock or sand, is between 2.4 to 3.0 gm/cc. The particle density of the lighter dusts, such as soot, is about 0.5 gm/cm^3. It would require about half as much by weight of coal dust and about 1/5 as much of soot to produce the same decrease in albedo obtained with the Ottawa Valley limestone of the same average grain size. These figures are in general agreement with what has been used in practice. Table 1 gives some of the densities of application that have been reported.

The density of application required to produce the maximum decrease in the albedo is the maximum that should be applied at one time. If this layer of dust becomes covered with snow, its effectiveness will be greatly diminished and another layer would have to be applied. The amount of material that will have to be used at a site during a season will depend upon the weather. By consulting available weather records it should be possible, with experience, to obtain a rough estimate of this amount, but it should be kept in mind that the actual amount will probably vary appreciably from year to year. In regions of frequent but light snowfall, it might be advantageous to reduce the density of application but increase frequency.

Other Considerations

Because the main purpose in applying dust is to lower the albedo of the surface, the material must have a low reflectivity to solar radiation. Table I gives the absorptivity of different surfaces in the shortwave region. In general, the darker the color and the rougher the surface of the particle, the higher the absorptivity. Dark materials that might be available at a potential site, such as soil, sand, cinders, soot, have an albedo of between 10 and 20 per cent . This is probably the lower limit to which the albedo of a snow or ice surface can be reduced by dusting. Once melting has progressed to the stage where the ice surface is covered with pools of water, the albedo of the water-covered surface will probably be that of the water and independent of the dusting material.

The dust particles must be of such a size and density that they will not be easily blown by the wind or washed away by the melt water. Bagnold has found that there is an optimum diameter of about 0.10 mm for the movement of small loose particles by the wind (22). For particles of size greater than this, the resistance to dislodgement increases with increasing diameter.

Arnold found that the dusts he applied penetrated a considerable distance into the ice. Such penetration, if not too great, can be useful because of the particles become enclosed in thin walls of ice (2) and are not as liable to be disturbed by melt water or wind.

Care should be taken not to apply too much dust. Several authors report that if too much material is applied, the resulting layer can act as an insulator and slow down the rate of thaw (23,24). A check on the thermal conductivity of several materials (e.g. crushed rock) indicates that the rate at which heat is conducted through the dust layer to the ice surface can become a limiting factor if the layers are thicker than 1 cm. Lister reports that there is frequently a steep temperature gradient through dirt layers found on the surface of glaciers (25). In his observations he notes that 1 cm of dirt noticeably reduced the rate of melting if the sky was overcast, and that a dirt layer of 2 to 4 cm reduced the rate of ice melting if the sky was clear. If a dust layer forms a crust with a thin layer of air between the material and the ice surface, the rate at which heat can penetrate to the ice will be greatly reduced. A static air layer 5 mm thick, across which is the large temperature gradient of 10°C/cm will conduct heat at a rate of only approximately 2 cal/sq cm/hr under steady-state conditions. This is small compared to the short-wave radiation that a dust layer will absorb.

Mixing salt with the dust does not appear to increase appreciably the melting rate, and in some cases may reduce it. One reason for this is that salt is a light-colored material and so has a fairly high albedo (26). Arnold (2) reported that the addition of rock salt to dusting materials appeared to reduce the long-term effectiveness of the material.

If the dissolving action only of the salt is to be used to remove the ice cover, large quantities will be required. For example, one lb of sodium chloride will melt about ten lb of ice at 25°F (27). In Arnold's experiments, the maximum density of application of salt (750 gm/sq m) would have melted less than $\frac{1}{2}$ in. of ice at 25°F.

Method of Application

There is very little information available in published reports on the technique used to apply dust. Because these reports state only that the dust was spread "from an aeroplane" or "with a tractor," it must be concluded that standard dusting techniques were used. There is some indication that these techniques were not always adequate; e.g. Lang (23) states "while we knew that satisfactory results could have been obtained using a lesser amount of soot, the crude hopper used for this equipment would not effectively distribute the smaller amount."

Some attention has been given to applying the dust in patterns to reduce the amount required. Laktionoff (28) reports that radiation channels 33 miles long but only 100 to 180 ft wide were successfully opened through ice 6 to 15 ft thick, weeks ahead of the normal break-up. Such a channel has an area of about 1 sq mile. If channels are to be formed, consideration should be given to their possible closing by wind or currents.

RECOMMENDATIONS

It is clear that under some conditions dusting can be used to advance break-up. Economics will probably be the main factor that determines whether the technique can be applied at a particular site. This means that sufficient information must be available to assess properly the costs. Meteorological observations are now probably adequate for most Canadian sites to determine the thickness of ice to be melted, the best time to apply the dust and the climate during the break-up period. More information is still required on sources of suitable dusts, the minimum albedo that can be obtained with them, and the influence of particle size, and density of application. Laboratory investigations on the characteristics of some dusts have been initiated by the Snow and Ice Section of the Division of Building Research, National Research Council.

Sufficient information is now available to allow a potential user to undertake full-scale field trials. Such field trials would be useful as many of the factors related to the cost can only be fully appreciated and assessed through the experience gained in using the technique at an actual site.

Because of the large amounts of dust that will probably be spread and the dependence of change in albedo on the density of application, the technique used for spreading should be given careful consideration. A program of test and development of spreading equipment should be undertaken if the use of dust is to be exploited. Consideration should be given to integrate such a program with full-scale field trials.

In this report, only dusting has been discussed. Other techniques of reducing the albedo of the cover could usefully be considered; e.g. applying suitable dyes by spraying might be economical if they can be dissolved in water taken from under the ice cover.

SUMMARY

The application of suitable dust to an ice or snow surface decreases its albedo and increases the amount of short-wave radiation absorbed. The associated additional heat will increase the surface temperature and may cause the snow or ice to begin melting before the normal melt season. An increase in the surface temperature will also increase the heat lost by long-wave radiation, convection, and sublimation. If the average air temperature is too low, the increase in the heat losses will offset the increase in the heat received from solar energy and no melting will take place. This places a natural limit to the amount that the break-up period can be advanced by dusting. The length of this period is influenced as well by the amount of incoming short-wave radiation available at a site during the day and the thickness of the ice. A preliminary analysis, which is in general agreement with field observations, indicates that break-up can be advanced by about two weeks in southern Canada and about four weeks in northern Canada. The amount by which break-up can be advanced will vary from year to year because of natural variations in air temperature and ice thickness and incoming short-wave radiation.

The amount by which the albedo of a surface is reduced by dusting is probably directly proportional to the actual area of the surface covered by the dust. For a given density of application (e.g. 100 tons/sq mile) the actual area covered by the dust varies inversely as the average diameter of the particles and the density of the solid from which the dust is formed. This indicates that the smaller the average grain diameter and the lighter the solid, the greater will be the coverage for a given weight of dust. The action of wind and melt water probably places a lower limit to the size or particles that can be used. Field experience indicates that the practical range in average grain diameter is 0.1 to 2.5 mm.

The maximum amount by which the albedo can be reduced depends upon the albedo of the dusting material. Most naturally occurring dark materials, such as sand, soil, coal dust, soot, have an albedo of about 20 per cent. Once melting has advanced to the point where the dusted surface is covered with water, the albedo of the surface will probably be determined by the water and not by the dust and its density of application.

The cost will probably determine whether dusting is practical at a particular site. Sufficient information to assess the cost is therefore required. The Meteorological information, now available, is probably adequate. However, further information is required on the availability and characteristics of suitable economical dusts and on the equipment and techniques to spread them. The dependence of the change in albedo on the density of application and average grain size and density of the particles should be investigated further. Work on this aspect has already been undertaken by the Snow and Ice Section of the Division of Building Research. Experience with the use of dust should soon be obtained through full-scale field trials.

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TABLE I

INFORMATION AVAILABLE IN LITERATURE ON MATERIAL USED TO ACCELERATE THE MELTING OF SNOW OR ICE

Reference No.	Material	Particle Size	Application Rate		Albedo of Dust Layer
		mm	lb/100 sq ft	tons/ sq mile	%
(29)	Slag, coal	0.2-0.5			29
(23)	Soot		1-10	130-1300	
(24)	Wood ashes		0.5	65	
(30)	Ashes		1-2	130-260	
(30)	Soil		5-10	650-1300	
(31)	Soil or ashes		0.5	65	
(32)	Coal dust		0.1	13	on glacier ice
(33)	Cinders and dust	< 1	1-10	130-1300	
(3)	Foundry sand		0.5-1	65-130	
(34)	Carbon black				20-35
(35)	Coal dust		0.2-1	25-130	
(2)	Coal, sand		10	1300	20
(4)	Cinders, etc. Several materials	Range of sizes .2-2 optimum	Up to 22	Up to 3000	

TABLE II

ABSORPTIVITY OF VARIOUS SURFACES FOR SOLAR ENERGY

Material	Absorptivity (Per cent Absorbed)	Albedo (Per cent Reflected)	Source
<u>Natural Surfaces</u>			
Fresh snow cover	15-20	80-85	Geiger (14)
Cloud surface	10-30	60-90	"
Older snow cover	30-48	42-70	"
Fields, tilled soil	70-85	15-30	"
Sand	75-90	10-25	"
Forests	82-95	5-18	"
Surface of the sea	90-92	8-10	
<u>Concrete Tile Surface</u>			
Brown	85	15	Bonin and Teichmann (19)
Brown, very rough	87	13	"
Black	91	9	"
<u>Painted Surface</u>			
White (Pb CO_3)	12	88	Bonin and Teichmann (19)
White (A/2 0_3)	16	84	"
Yellow ($PbCrO_4$)	30	70	"
Green ($Cu_2 0_3$)	73	27	"
Red ($Fe_2 0_3$)	74	26	"
Blue ($CO_2 0_3$)	97	3	"
Lamp Black Paint	97	3	"

APPENDIX A

Calculations of Components of Heat Balance - Fig. 6

The Energy Balance Equation:

$Qm = Qsw \pm Qlw \pm Qe \pm Qc$

The heat used in melting equals the heat available from Qsw, the net short-wave radiation, plus or minus Qlw, the net long-wave radiation, Qe the heat associated with evaporation or sublimation and Qc, the convective heat. The heat required to raise the temperature of the ice cover to its melting point is neglected.

$Qsw = \alpha\,(Rsw)$ where α, the assumed albedo = 20%

= .123 (Rsw)Btu/sq ft/hr Rsw = short-wave radiation obtained from meteorological records cal/sq cm/24 hr.

Qlw = 1.0 (ΔT) Btu/sq ft/hr - Johnsson's approximation for long wave radiation (36) (assuming surrounding objects and terrain to be at the same temperature as the air, and an emissivity of 1.0 for cover).

ΔT = difference in temperature between surface and air (°F).

Qe = 121 ($e_s - e_a$) Btu/sq ft/hr - Penman's simplified formulae for evaporation from saturated surfaces when the average wind speed is 100 miles/day (37).

e_s = saturated vapour pressure at temperature of ice surface (inches of Hg)

e_a = vapour pressure of air (inches of Hg)

Qc = 1.21ΔT Btu/sq ft/hr - Obtain from Qe by assuming Bowne's ratio (38) is valid.

ΔT = difference in temperature between air and ice surface (°F).

Using these formulae and assuming various values for ΔT e_s, and e_a, approximate values for Qlw, Qe, and Qc were calculated. The surface temperature was assumed = 32°F.

THE USE OF DUST TO ADVANCE THE BREAK-UP OF ICE ON LAKES AND RIVERS

Discussion by C. E. Deslauriers,
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When the NRC's Snow and Ice Section undertook its systematic study of the use of dust to accelerate the melt of ice covers, the main foreseen application of the technique was the extension of navigation season. There are other useful purposes which could be served by this technique and it is my guess that many of those attending this Session have already in mind some past experiences or future applications in this field. Consequently, as soon as I will have completed what I actually consider a hard task to fulfil, we may expect an interesting and fruitful discussion of Messrs Williams' and Gold's paper by this audience.

Among the useful purposes that can be served by effective and economical acceleration of the melt of an ice cover in a river section, the reduction of ice-jam hazards during springtime break-up is certainly not the least in this part of the country. So, if a spread of dust on an ice cover can serve such a purpose, we may perhaps expect to see too many dirty spots on our rivers, in wintertime, within the next few years. But if the operation can be useful, it is not to be freely undertaken, since some bad results might also be experienced.

The use of dust or of any similar means for reducing ice-jam hazards is to be considered only as drugs, for their applications cannot correct fundamental causes nor prevent all damaging occurrences. Methods to combat ice-jam hazards should evidently be reserved to engineers' ordinance; at best, they can be auscultation aids for the preparation of a foreseen surgery.

Consequently, let the dust technique help when it can but, in the meantime, may the exposed riparian be convinced that the top of the nearest mountain is, in any case, the best place to be when an icy-flood is likely to come and also that the best assurance one may have to be out of danger in due time is to start climbing early during the preceding summer.

An investigation of the feasibility and limitation of such application of the technique now discussed is generally beyond the scope of this presentation; moreover, many of the necessary details would be here pure vagary. It seems, however, opportune to remark that for recognition of practicabilities and impediments, some further developments must be made to the outline of the break-up phenomena as given by Messrs Williams and Gold.

It is true that the break-up occurs in two stages and it is correct to identify them as follows:

<u>First Stage</u>: The cover deteriorates and weakens without decreasing appreciably in thickness.

Second Stage: Open leads develop and thereafter, the break-up is greatly influenced by water currents and wind.

It is true that deterioration of the cover during the first stage is caused by absorption of solar radiation, by impurities at grained boundaries. But the decisive influence of this process upon the breakup is mostly restricted either to languish river sections, or to springs characterized by their slow development of both air and water temperatures. In the latter case, the daily warmings alternate with night frosts, and on the whole, the thaw on the basin does not give high rates of run-off, so there is actually no wave associated with the snow melt.

More often, there is a certain daily flood wave in the river, at least during the later part of the first stage. By its repeated and progressively increasing hydro-mechanical action on the ice cover, said daily wave contributes much to the deterioration of the ice-slab. In the case of a fast spring development, this hydro-mechanical deterioration of the cover may have a decisive influence on the date of the break-up.

Whatever the characteristic of the spring, an application of dust for the reduction of some specific ice-jam hazards will generally prove its value if the enterprise is otherwise favorably supported by sunshine and climate.

But, since ice-jams are likely to occur during the later part of the first stage or during the earlier part of the second stage of the break-up, we may think that the efficiency of the operation can be compromised by fast developments of the spring and by persistent nebulosities. Therefore, the sole application of dust might not be sufficient for the purpose and, in such case, it might prove necessary to attack some spots of the ice cover with melting materials such as sodium chloride or calcium chloride.

The use of dust is cheaper than the application of a melting material; but, to a certain extent it would certainly be an economical decision to melt artificially specific spots of the cover, in order to prepare more effectively a possible early break-up. This is what we intend to do in a field experiment to be undertaken in a near future.

For five consecutive years, an operation was realized with the use of dynamite upon a certain section of a typical river, in view of reducing a specific ice-jam hazard. Up to now the gained experience can be summarized as follows: (a) No harmful effects were ever observed nor reported downstream; (b) No ice-jam did occur at this spot where, in the past, a certain jam occurred annually and where a more or less catastrophic jam was experienced since 1912, with an approximate mean recurrence interval of one in four years. Last year, a field experiment with dust was undertaken at this same site, while some minor spreads were also made at several other sites of some typical river. But, because of unfavorable circumstances, it was nearly impossible to perform satisfactorily the proposed measurements and observations. Nevertheless, the enterprise can be considered fruitful even if it was not supposed to contribute to the break-up. It gave out some lessons which will be carefully taken into account this year. Some of them can be figuratively stressed as folows:

1 - A wise wrestler attacks a known weakness and his choice of the opponent's member is governed by elementary anatomy and observations;

2 - Physics is somewhat related to ice cover formation and deterioration;

3 - Geometry is but a decorative art unless it is tied up with physical realities;

4 - Fish are perhaps more disturbed by dynamite than by dust even if the latter is metallic;

5 - It is better to use a highly conductive material if the dark spread is to be too thick;

6 - Modern roads have to be wide.

With such a scientific background and more particularly with the learnings gained from the report of Messrs Williams and Gold, we may expect a certain success with the coming 1963-experiment.

A detailed analysis of the 1962 enterprise reveals the following unit costs which are to be considered as somewhat high because of the primary character of this first attempt:

Operation	Unit cost
Clearing	1.5 to 2.0 mills/sq.ft.
Spreading	6.5 to 7.0 mills/sq.ft.
Material	(no valuable information because of (particular source of supply

One element of the cost estimate is the necessity of renewing the spread after each consistent snowfall. A statistical study of meteorological data for the region and for the last ten years reveals a fair expectancy of 8 renewals. Thus, the maintenance unit cost would approximately amount to 6¢ per sq.ft.. if the freshly fallen snow is not removed, and to 7¢ sq.ft. in the other case.

The concerned river section has an approximate length of $2\frac{1}{2}$ miles and a width varying from 200 to 300 feet, say a gross area of 4,000,000 sq. feet. It would not be practical nor useful to spread the whole area, so the patterns will be developed in accordance with the requirements demonstrated by a thorough sampling of the ice cover which is actually in progress.

As previously mentioned, some zones will be attacked with a melting material because past experiences and actual recognitions demonstrate the prudent necessity of a humanly controllable technique. Sodium chloride will be used under the assumption that, like men, fish prefer the taste of common salt to that of calcium chloride.

As to the method of application, it has to be adapted to the governing factors, extent and accessibility of the area, local availability of labor, equipment and material, quality requirements for the operation, cost of realization, maintenance and control. The first experiment has shown the advantages of farming methods and equipments over more modern practices. It seems that trucks, tractors and "snowgoes" are generally afraid of ice covers while horses and men do like them, even if the slab occasionally produce some troubling noises.

Lately, a fine sand source was luckily found and its granulometry seems to have been long ago tailored to measure. Its average grain size is 0.4 mm so, according to the findings of Messrs Williams and Gold, the density of application should be about 3000 tons/sq.mi. The remaining research is to find out the required quality spreader without going too far in administrative purchasing complications.

In spite of these encouraging circumstances, a question mark still remains and it cannot be humanly solved. So let us pray for maximum sunlight, since the albedo is to be at minimum.