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BREAK-UP AND CONTROL OF RIVER ICE

BY

G. P. WILLIAMS

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DÉGEL ET CONTRÔLE DE LA GLACE SUR LES RIVIÈRES

SOMMAIRE

L'article présente des renseignements de base sur le dégel des rivières et sur le controle de la glace durant cette période. Les principaux facteurs d'influence sur le dégel sont exposés dans leurs grandes lignes. Comme le processus de dégel dépend des variations climatiques et des variations dans la morphologie du chenal, le mode de dégel pour une section donnée de rivière varie d'une rivière à l'autre et d'une année à l'autre. Les limites et les principaux problèmes des diverses méthodes de contrôle sont résumées. D'une façon générale, les conditions économiques et l'emplacement déterminent non seulment la méthode à employer, mais aussi jusqu'à quel point le contrôle peut être poussé. L'exigence fondamentale de toutes les méthodes est la capacité de contrôler avec succès la pire des conditions, soit la débâcle. La prédiction des évènements se rapportant au dégel devient donc fondamentale au contrôle de la glace sur les rivières.

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BREAK-UP AND CONTROL OF RIVER ICE

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This review paper presents background information on the process of river break-up and control of ice during break-up. The main factors affecting break-up are briefly outlined. As the process of break-up depends on variable weather conditions and on local variations in channel morphology, break-up patterns vary from river to river and from year to year for a given section of river. The limitations and main problems associated with various control methods are summarized. Economic and local site conditions usually determine not only the method but also the extent to which river ice can be controlled. All methods of control have the basic requirement of being able to handle successfully the worst ice conditions likely to occur. Forecasting the different events associated with break-up is thus an important part of river ice control.

This review paper presents background information on the process of break-up and control of ice during break-up. Two major sources were used extensively in its preparation: a recent survey of literature on river ice jams by Bolsenga (1) and the U.S. Corps of Engineers bibliography on snow and ice (2) which contains abstracts of much of the voluminous literature available on these subjects. As most of the references on break-up are case histories, describing conditions at a particular site, only a few selected references have been cited.

Figure 1, showing the average dates of clearing of ice from rivers in the northern hemisphere (3), indicates the extent of the area in which river ice occurs. The zone where the mean monthly air temperature is 0°C during the

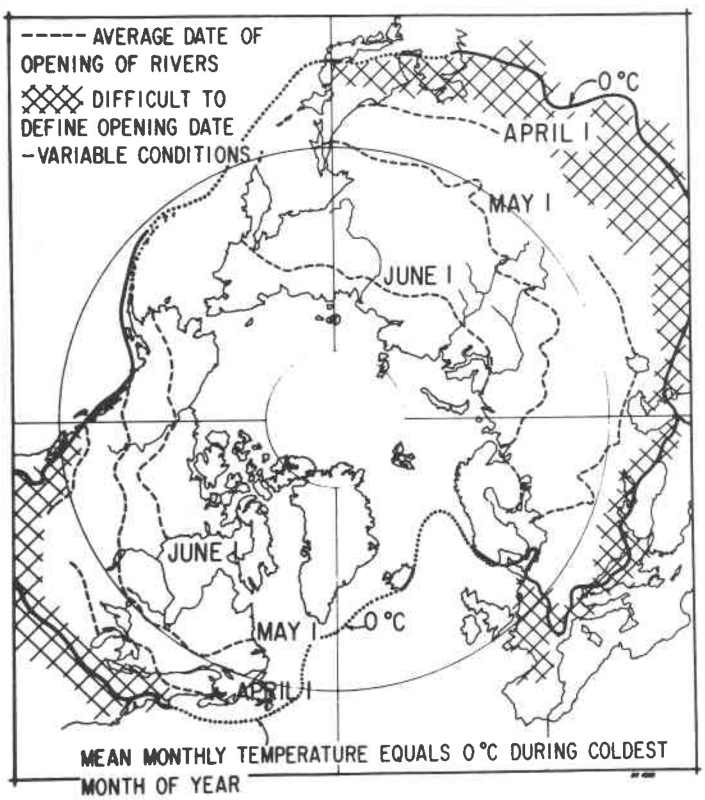

Fig. 1 - Occurrence of river ice in Northern Hemisphere.

coldest month of the year (4) marks the approximate southern limits of ice formation in rivers. The duration of ice on most rivers in this zone is about one month or less, depending on the severity of the winter. North of this zone of unstable ice, rivers are closed for several months of the year because of ice. Ice conditions on these rivers vary tremendously, ranging from massive ice jams extending over several kilometres in the large northward-flowing rivers such as the Mackenzie, (5), to the relatively minor ice formations in rivers such as the Po in Italy, where significant ice has occurred during only a few winters in this century (6). Patterns of break-up of rivers also vary from river to river, and from year to year for a given section of a river.

THE PROCESS OF RIVER BREAK-UP

The term "break-up" refers to a process that extends over a period of days or weeks, beginning when the ice in a river starts to move, break, or deteriorate, and ending when the water is completely free of all ice (7). The term, usually associated with the disappearance of ice in the spring, is used in this paper to include the movement and break-up of unstable river ice during the late fall or winter months.

The process of break-up is complex, depending on weather conditions that prevail during the ice season and on local variations in channel morphology. Figure 2 outlines the general sequence of events that end with the complete disappearance of the ice. The type of ice that forms, the pattern of movement, the

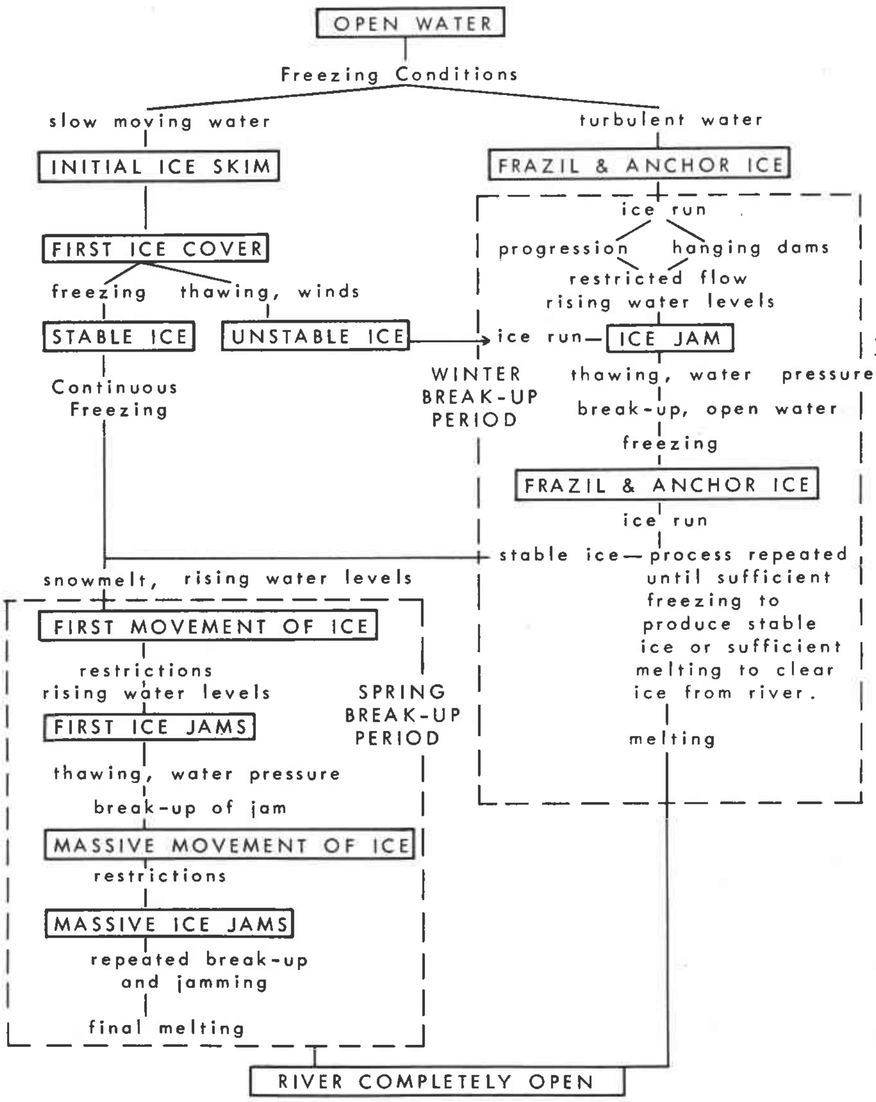

Fig. 2 - General sequence of events during winter and spring break-up periods.

process of jamming, and the type of jams that form, are quite different for winter and spring break-up periods. In both cases, however, serious ice problems occur when drifting ice in a river cannot be transported because of flow restrictions. The drifting ice accumulates and jams, resulting in high water levels, flooding, bank erosion, damage to structures and hazards to shipping and hydro-plant operation.

The first movement of ice can be considered as the beginning of the break-up period. For winter break-up, the movement of ice is more or less a continuous process as long as weather and flow conditions are favourable for frazil and anchor ice production. During spring break-up, the first movement and intensity of break-up of stable ice is determined primarily by snow-melt runoff.

The amount of ice available for movement past a site in a river usually determines the severity of break-up problems. The amount of ice produced during winter break-up depends primarily on the area of open water and on the rate of heat loss from the water surface in ice-producing rapids. Rivers with steep gradients and extensive rapids, exposed to frequent freeze-thaw periods, are subject to severe ice problems because of the vast quantities of frazil produced. Enormous quantities of frazil can also be produced in rivers before a stable cover forms if sudden intense cold weather with high winds occurs after a late fall when much of the river is open. During spring break-up the amount of ice available for movement depends on the thickness and areal extent of the ice covers which are fed to the site from upstream reaches of a river, including tributaries and lakes.

The channel morphology of a river determines whether it can transport drifting ice or whether jams will form. Jams usually start at restrictions to flow caused by bends in meandering rivers, islands, bridges or other structures, and by stable, immobile ice covers. They can also form at the mouths of rivers emptying into shallow, tidal estuaries or ice-covered lakes. In general, the jam is destroyed when the force from the head of water created by the jam is sufficient to overcome the forces resisting downstream movement of the accumulated ice. Once the jam is destroyed, the flood wave will move the masses of ice downstream until either the river is clear of ice or another jam is formed at another restriction.

The size of the jam, degree of deterioration of the ice in the jam, the extent of grounding of the ice, the pattern of drainage channels through the jam, and the configuration of the river channel are factors that determine how readily the jam will break up. The strength of the ice cover is especially important in northward-flowing rivers when southern tributaries choked with ice meet thick solid ice covers that have not yet started to melt. In contrast, the break-up of southward-flowing rivers can be quite gradual without appreciable jamming if ice covers in downstream southern reaches have had a chance to melt or deteriorate before spring runoff begins.

Jams formed from frazil and anchor ice are generally of lower strength than spring break-up jams. Winter jams can, however, consist of high strength ice if they are exposed to severe freezing weather.

Many local factors, too numerous to mention in this paper, are important in the break-up process. Wind and tidal effects have an appreciable influence on the break-up of ice at the mouth of large rivers flowing into the sea. Break-up is affected by watershed conditions, i.e. break-up of rivers in basins with extensive forest cover are considerably delayed because of delayed snow melt when compared with the break-up of rivers in basins with limited forest cover. Ice formation and break-up of rivers in mountains have special characteristics (8). Rivers that freeze to the bottom have unique break-up features. The break-up period on each section of every river is an individual event that can only be described adequately by considering all the factors that affect it during a particular year.

ICE CONTROL DURING BREAK-UP

River ice problems during break-up can be handled in three general ways:

(1) Ice Modification. - Ice covers or jams are melted or broken up by ice dusting, warm water discharge, explosives or ice breakers at locations in a river where break-up problems are known to occur.

(2) River Modification. - The river channel is modified and river control structures are built to control the formation and flow of ice and thus prevent ice problems.

(3) Design and Location. - Structures are so located and designed to withstand ice movements, jams, and flood conditions.

Economic conditions usually determine not only the method but also the extent to which river ice can be controlled. It is often impractical to attempt to control massive ice jams extending over several kilometres using any form of ice modification. In these cases structures must be designed or located to avoid serious ice damage. The complete control of serious ice problems by river modification usually requires extensive engineering investigations and major expenditures.

All methods of ice control have the basic requirement of being able to handle successfully the worst ice conditions likely to occur. Ice modification techniques are sometimes not completely reliable because they cannot be depended upon during years with adverse weather and ice conditions. The success of river modification techniques and the design and location of structures depends primarily on the ability to predict the most serious ice conditions that can occur.

ICE MODIFICATION TECHNIQUES

Control by Ice-Dusting

Early melting or deterioration of the ice cover may be induced at critical sections of a river by applying a thin layer of suitable dust to the ice surface during the early stages of break-up (9). The dust layer increases the melting rate by decreasing the reflectivity of the surface and hence increasing the amount of solar radiation absorbed. Almost any dark material applied in a thin layer on an ice surface will increase the rate of melt under suitable weather conditions.

Air temperature and the amount of sunshine during the early stages of break-up are critical factors in ice-dusting operations. Ice-dusting is not very effective if the daily minimum air temperature falls much below 0°C. If the air temperature is too low, heat losses from the surface by convection, evaporation and long-wave radiation will offset the increased solar energy absorbed by the darkened ice surface. Ice-dusting is most suitable for ice control of rivers in high latitudes as available solar energy can be high during early stages of break-up. Approximate calculations indicate that dusting can increase melting rates up to about 1.0 cm a day in latitudes of 45°N and up to 2 to 3 cm of ice a day in latitudes of 70 to 80°N (10). The thickness of stable ice will range from 50 to 70 cm in the south to 120 cm or greater in the far north. Several days of weather conditions conducive to increasing melt rates are needed to decrease significantly the length of the break-up period or weaken thick, stable ice covers.

As air temperature, snowfall and solar radiation at a site vary greatly from year to year, so will the success of dusting. In southern latitudes weather conditions are frequently completely unsuitable for dusting operations; even at high latitudes weather conditions can be quite unfavourable (10).

Successful dusting operations require detailed studies of past weather records, past ice conditions and dusting techniques. Information is needed on the frequency of new snowfall during potential dusting periods, the availability of suitable dusting material, and the cost of transporting and applying the dust. If potential benefits exceed anticipated expenditures, large-scale trials may have to be carried out before the most effective technique is developed for a site.

Chemicals such as calcium chloride have been combined with dusting to increase the rate of melting and deterioration of ice. As large quantities of salt are needed to melt ice, the success of chemicals may depend more on their ability to melt holes completely through the ice, creating zones of weakness that may expedite the natural process of deterioration. Research is needed on this aspect of ice control as there are few pertinent references in the literature.

Control by Thermal Discharge

The formation of ice in canals and rivers may be retarded or prevented by warm water discharge from thermal heating plants, atomic power plants and other sources. This method of ice control is attractive because extensive stretches of river can be kept completely free of ice. A major difficulty is locating thermal plants so that they can be useful for ice control and, at the same time, meet other more important requirements such as nearness to markets and adequate water supply during the summer months.

The main technical problem in ice control by thermal discharge is to estimate the length of river that can be kept open by a given discharge of waste water at a known temperature. The problem requires a reasonable estimate of heat losses from the anticipated area of open water using weather observations available for the stretch of river under consideration. Dingman, Weeks and Yen (11) have recently outlined a procedure for such estimates. The calculations are made for a steady-state ice-free reach when weather and flow conditions are relatively constant.

Other sources of warm water can be used to prevent or retard the formation of river ice. The success of these methods depends on the amount of heat available for ice prevention. Air bubbling systems, which bring warm subsurface water to the surface by various techniques (12), are especially successful in deep lakes or reservoirs where considerable heat is stored in the deep water under the ice cover. The method has serious limitations in rivers because the temperature of well mixed water under river ice seldom exceeds 0°C by more than a fraction of a degree. Warm water from deep wells (13) and waste water from sewage disposal plants have been used to help control river ice. Specially designed intakes that draw water at different temperatures from deep reservoirs (14) have some potential for ice control at particular sites.

Ice Control by Explosives

Explosives have been used extensively for removal of ice jams. The main requirement is to have sufficient knowledge and capability to place the charges in the right place at the right time. Unfortunately, the effectiveness of various surface explosives (dynamite, thermite, ammonium nitrate compounds, etc.) and the best procedures for placing them are still debatable (1). Explosives are best suited for breaking up relatively small jams where a small amount of explosive placed at key locations will clear a section of river of ice. An open channel and sufficient flow of water are needed to carry away the ice loosened by explosives.

One of the more comprehensive investigations on the use of explosives for river ice control was conducted in the Netherlands by Van Der Kley (15). His calculations, giving the size of charges for different ice thicknesses, indicate that explosives placed immediately beneath the ice cover are most effective. He concluded that explosives tended to make craters in the ice with very few cracks and, consequently, the ice was often not weakened enough to aid removal by ice-breakers. His conclusion that ice-breakers are always preferable to explosives for ice-control is of special interest; if explosives are not very effective in the shallow ice covers encountered in the Netherlands, they would be even less effective in the thick, solid ice covers of more northern areas. This conclusion may not be valid for all locations and problems; recent experiments with explosives in Alaska are somewhat more encouraging (16).

Aerial explosives (bombs, rockets, etc.), including conventional explosives dropped or placed from planes or helicopters, have usually been used on an emergency basis and have not been the subject of extensive investigations. Their effectiveness will depend on adequate preparation and organization based on knowledge of the river and the jams to be destroyed by such action.

Control by Ice Breakers

Ice breakers have been widely used to open up channels in an ice cover before natural break-up begins and to break up ice jams that have formed. Ice breakers are best suited for ice control on large rivers. Frequently, several ice breakers work together in a well-established plan of action. The ice breakers open up a channel by working upstream against ice jams and ice covers. Although ice breakers provide one of the most effective means of controlling river ice, economic considerations limit their use to rivers where serious damage, loss of hydro power or loss of shipping time will occur unless the river ice is controlled.

The many problems associated with the design and operation of ice breakers are beyond the scope of this paper. Waas (17) describes some of the design requirements for shallow draft ice breakers used on the Rhine River; other recent references are reviewed by Bolsenga (1).

Combined Ice Modification Programs

It is often advantageous to combine various techniques for breaking up an ice cover at key locations on a river. For example, explosives combined with ice cutting operations are used to control ice jamming on a section of the Rideau River draining through the City of Ottawa, Canada. Long narrow cuts are made in the ice by power-driven saws a few weeks before break-up starts. Sections of the ice cover between the cuts are blasted loose with explosives and then floated downstream. The operation starts at the mouth of the river and is gradually moved upstream until the section of the river, where jamming previously occurred, has enough open water to transport floating ice over the Rideau Falls into the Ottawa River. Figure 3 is an aerial view showing the start of operations near the mouth of the Rideau. This operation illustrates several basic requirements for ice control: potentially serious economic loss because of jamming, adequate preparation and organization before break-up, a relatively small section of river where the ice needs to be broken up, and a site where broken ice can be transported downstream.

ICE CONTROL BY BOOMS, STRUCTURES AND CHANNEL IMPROVEMENT

Booms

Ice booms are placed as barriers to ice flow in rivers to promote the formation of stable ice covers. If a stable ice cover is formed upstream from

Fig. 3 - Ice control operations, Rideau River, Ottawa, Canada.

the boom, the area of open water is reduced thus diminishing the rate of frazil production. Booms of this type range from log booms and artificial ice bridges or barriers (18) to massive ice control structures such as the one on the St. Lawrence River near Montreal, Quebec (19). Detailed engineering investigations are needed to determine the forces that will act on the boom and to determine the effect of the boom, barrier, or structure on water levels and ice movement.

Booms are also used to stabilize border ice and prevent the movement of lake ice into rivers and diversion channels. One of the most successful booms of this type has been constructed on Lake Erie to prevent funnelling of ice covers into the Niagara River (20).

Ice Control Structures

Ice control structures such as ice diversion dams, submerged weirs and dykes are used to hold ice accumulations or direct them during break-up to locations where the ice can melt in situ (21). The structures present obstacles to the movement of ice at certain predetermined water levels and flows.

A power dam can be considered as an ice control structure although its main purpose is power production. The dam may drown out rapids which previously had produced large quantities of frazil. Water levels and flows can often be controlled by power plant operations to minimize river ice problems or break up ice covers downstream from the dam.

The construction of a power dam does not always solve frazil problems. In some run-of-the-river power plants it is difficult to form a stable ice cover upstream from the dam and frazil problems occur every year. Frazil can still be produced in large reservoirs where a stable cover normally forms, if strong winds, combined with low air temperatures, occur at the time when a stable ice cover is just starting to form. This hazard from frazil, not always recognized because of infrequent occurrence, has resulted in power plant shutdowns for short periods of time.

Channel Improvements

Channel modifications that improve the flow of ice, or cause stable ice to form at chosen locations, provide a reliable, effective means of river ice control (22). Modifications include removing restrictions, deepening the channel, widening the river, stabilizing banks, straightening out bends and relocating bridge piers and structures. Hydraulic models are useful for determining the effect of proposed improvements on the flow of ice. The cost of extensive channel improvements can often be prohibitive on large rivers with severe ice problems.

THE ROLE OF FORECASTING IN BREAK-UP CONTROL

Efficient planning and design of ice control projects for hydro-plant operations, construction, and navigation require forecasts of ice movement, height of water levels, occurrence of ice jams, and the magnitude of the forces associated with ice movement (23). The success of various ice control methods often depends on the ability to forecast accurately the different events associated with the break-up of river ice.

The seasonal forecast of maximum water levels during break-up is one example of a basic forecast problem. The forecast of water levels during spring break-up is part of the more general problem of forecasting snow melt runoff, which requires: snow survey data from the watershed, snow melt equations relating weather parameters to rates of snow melt, and flood routing techniques to translate the snow melt forecasts into flow forecasts. Forecasting water levels during winter break-up requires information on the rate of ice production and on the behaviour of ice downstream from ice-producing rapids, i.e. whether ice will progress upstream to form a stable cover or move further downstream to form hanging dams or jams at restrictions (24). For both winter and spring break-up periods the usefulness of water level forecasts depends on the accuracy of short-term weather forecasts.

Forecasts of the probable occurrence of ice in rivers, occurrence of ice jams and probable date of clearing of the ice are especially useful in regions of unstable ice where serious ice problems do not occur every year. The probabilities of an ice-free winter and probabilities of obstructions by ice are an essential part of ice control for shipping in the navigable rivers of the Netherlands and Germany (25). The events associated with spring break-up tend to be more predictable on rivers where a stable ice cover forms each year, but even on these rivers the frequency and dates of occurrence of serious jams are often required.

In designing ice control structures or structures exposed to ice action during break-up, an estimate is needed of the worst ice conditions likely to be encountered. Most of the failures of structures because of ice could have been prevented if designers had been able to anticipate the severe conditions that caused failure. A classical example of a failure due to ice was the collapse of a bridge across the Niagara River (26) The collapse was caused by massive jams that created enormous lateral pressure on the bridge piers. The problem of designing for the worst ice conditions is similar to, but much more difficult than, the problem of predicting the so-called "100-yr. flood" for spillway design. In spillway design, past records of peak flood flows are usually available for statistical analysis. In designing for severe ice conditions adequate past records are often not available and designers must rely on information from local observers and on studies of the effects of previous high water levels and ice movements on rivers, banks and vegetation.

CONCLUDING REMARKS

The process of break-up of river ice depends so much on local site conditions that it is difficult to apply control methods and forecast techniques developed for a particular site to other locations. Several years of field observations of ice behaviour for different weather and flow conditions are usually needed for each stretch of river to develop reliable control methods. In the past, solutions to river control problems have often been necessarily empirical without developing a solid scientific basis for the advancement of ice engineering practice. It is only within the last few years that a more scientific approach has been taken in the design of ice breakers, the use of explosives on ice, the theory of ice movement and ice jam formation, and the many other problems associated with the break-up and control of river ice.

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DISCUSSION by G. FRANKENSTEIN

on paper by G. P. WILLIAMS (3rd Session)

I disagree with Mr. Williams that the strength and other properties of the ice are important or have to be known before effective blasting can be accomplished. Our tests were conducted on very strong clear ice of Northern Alaska and the weak river ice, which is typical during the breakup period, of New England and Minnesota. The results were approximately the same and are discussed in our paper (co-author, N. Smith).

AUTHOR'S REPLY

It is surprising that the strength of ice is not of importance in determining the amount of explosive to be used. I do not think that this point has been made in the literature I reviewed on the subject. The results of Mr. Frankenstein and Mr. Smith investigations are most useful for engineers who have to use explosives for clearing ice from rivers.