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ICE ENGINEERING

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ICE ENGINEERING

BY

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BY

HOWARD T. BARNES

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THIS BOOK IS DEDICATED

TO

John R. Freeman, D.Sc.

CONSULTING ENGINEER

PROVIDENCE, R.I.

IN GRATEFUL ACKNOWLEDGMENT

OF UNFAILING FRIENDSHIP

THROUGH ALL THESE YEARS

PREFACE

In the Preface of my former book "Ice Formation with Special Reference to Anchor Ice and Frazil" published more than 20 years ago, appears the following: "I have every confidence that a thorough understanding of the laws underlying the formation of ice will lead to methods, as it has already done in part, which will so temper the effects of ice in our northern rivers as to render them no longer a bar to the full development and utilization of our vast water powers."

How far this prophecy has and is being realized the reader can best judge from the following pages. The delay in the publication of this book has come chiefly through the rapid advance which has been made in the science of ice engineering during the past few years. Even as we go to press there is much new and interesting material which might be included especially in regard to the ice forming power of water, the development of flood lighting methods for ice prevention and the use of new and powerful methods for ice control. It was thought inadvisable, however, to delay any further, and the present book it is hoped will be of assistance in directing the way towards a clearer understanding of the principles of the subject.

It is a pleasant duty to record the great help which I have received from the Department of Marine and Fisheries of Canada, the Hydro-Electric Power Commission of Ontario and the Cedar Rapids Power and Manufacturing Co. in the development of the new methods of ice control.

To my engineering friends I offer my grateful thanks and trust this book will prove of help in solving ice problems wherever they may occur.

Macdonald Physics Building
McGill University
Montreal

April, 1928.

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CHAPTER I.

EQUILIBRIUM OF THE ICE-WATER SYSTEM.

Colloidal Ice, the Crystal Structure of Ice.

When ice forms in water, heat energy is removed in a definite proportion, and conversely when ice melts heat energy is supplied in the same proportion.

$$\text{ICE} \rightleftarrows \text{WATER.}$$

is a reversible process, and proceeds theoretically without temperature change in the system.

Owing, however, to the poor conducting power of water and ice, a measurable temperature change is observed when the transformation of phase occurs either way.

In consequence when a so called freezing-point mixture is subjected to cooling, so that water is forced to pass over into ice, the temperature of the whole mixture falls slightly below the freezing point. Also when the mixture in equilibrium is supplied with heat ice melts and the mixture rises slightly above the freezing point.

We shall take O° Cent. or 32° Fahr. as the true freezing point of water at atmospheric pressure, and disregard the effect of a small amount of foreign matter dissolved in the water such as salts or dissolved air. The slight lowering of the true freezing point by such impurities in no way affects the result of our enquiry here. Thermodynamically considered it is necessary for a small temperature drop to be established between the water, on the one hand, and the ice particles on the other, to have a flow of heat across the boundary surface of the

two phases. Each particle of ice when growing in the mixture is surrounded with a mantle of heat which protects the solid ice from excessive cooling. The ice itself remains at O° Cent. But the heat flows down the temperature gradient to the cooled water from which it is extracted by the cooling agent. In a similar way the reverse takes place in the mixture, when heat is supplied from outside, the ice particles are surrounded by a mantle of cold or absorbed heat which prevents the ice rising appreciably above the freezing point.

When heat is withdrawn, or supplied, very rapidly, and the mixture is vigorously stirred, the ice itself shares in the temperature elevation or depression. It cannot remain exactly at the equilibrium point because of its inability to freeze or melt rapidly enough to keep up the heat exchange. The velocity of crystallization and of melting is finite, and is the determining factor in the temperature of the two phases when co-existing. The phenomenon can be observed by rapidly stirring a vessel of water outside on a very cold day in winter, and measuring the temperature of the water as the ice begins to form throughout the mixture. A temperature drop of a few hundredths of a degree below the freezing point will be first observed, then the temperature will rapidly rise as the ice increases in quantity until the ice particles have sufficiently increased to permeate the entire mixture. The temperature will then be not more than a thousandth of a degree below freezing. By repeating the experiment on a colder day a greater temperature depression will be observed.

The reverse effect will be seen, if the vessel is taken into the warm room, and stirred fast until the ice is all melted.

This simple experiment can be illustrated by a diagram, Fig. 1, which shows what goes on in regard to the temperature balance around the freezing point of a lake or river.

If a quantity of water is subjected to powerful cooling, which causes a uniform and definite loss of heat, and is continuously stirred so as to produce intimate mixing

between the ice and water, it will be seen how the temperature will fall slightly below the freezing point of the order of a hundredth of a degree. The temperature will gradually approach the freezing point as the quantity of ice increases, until finally as the ice predominates over the water the temperature will fall again.

Conversely, if it is imagined a quantity of ice melting and if possible subjected to intimate stirring of all its parts, then the temperature will rise slightly above the

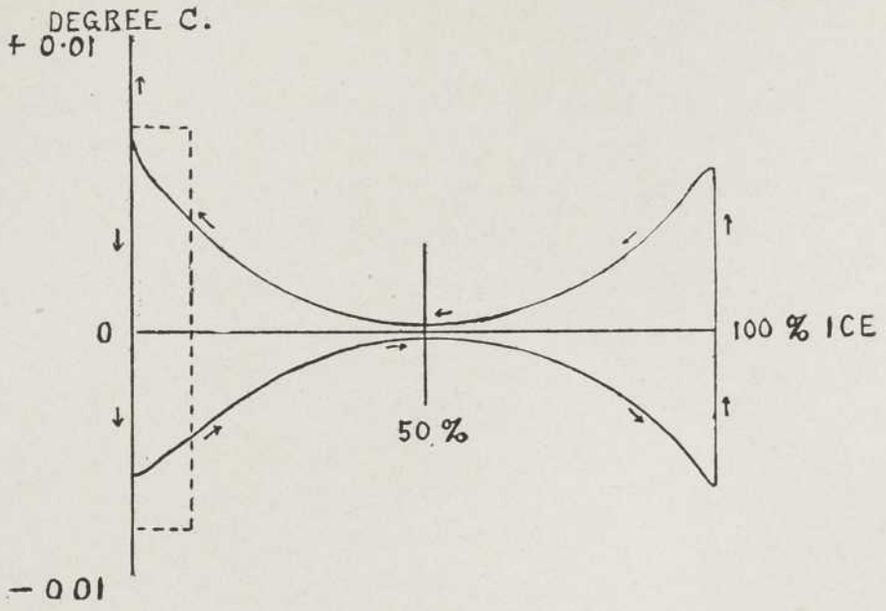


Fig. 1.—Diagram of Ice Water System.

freezing point depending on the rate at which the heat is being supplied to the mixture. As more water is formed and the ice becomes less in amount the temperature will fall nearly to the freezing point, and, when the water predominates over the ice, the temperature will rise again until the ice is all melted.

By a diagram the process can be followed in Fig. 1 by following the arrows. The amount of variation from the freezing point beyond 50% of ice is only conjectural, but is of little importance in the present study. All our natural ice conditions are of much smaller proportions than that except in the great solid ice packs, which do not come into this discussion as they cannot be stirred by mechanical means.

The dotted rectangle in the diagram represents about the range in a river like the St. Lawrence during the winter in the open stretches where the amount of ice rarely exceeds 20%.

Studies which were made many years ago in the St. Lawrence River at Montreal for the Monteral Harbor Commissioners gave the first measure of these small temperature differences. The microthermometer made it possible to find the relationship between the temperature variations throughout the winter and the amount and behaviour of the ice.

The sort of variations then recorded have been published, but it is interesting to recall that on Feb. 12th, 1897, at the Lachine Rapids when ice was forming rapidly in the water under an atmospheric temperature of $-2°$ Fahr. and a strong wind blowing against the current, the water showed a temperature of

$-0.0065°$ Cent.
$-0.0068°$ "

from the freezing point.

On February 7th the temperature was

$+0.0197°$ Cent.
$+0.0182°$ "

with a cloudy sky, and air temperature slightly above 32° Fahr. The ice was rapidly cleared out of the rapids by rain and mild weather. The next day the temperature of the water had risen to $+0.0547°$ and $+0.0415°$ Cent.

Whenever there was a bright sun it was noticed during this study that the water was always above freezing no matter what the air temperature was, a fact not entirely appreciated at that time, but which has come to be of such significance in the later development of the writer's work.

To fix the freezing point of water for accurate temperature measurements it is necessary to have equal quantities of ice and water, and the rate of loss or gain of heat must be reduced to a negligible amount. We must define

the true freezing point mixture then as *an intimate and equal mixture of ice and water neither gaining nor losing heat.*

Some experiments were made by the writer in the laboratory on mixtures of ice and water with accompanying measurements of the temperature on a microthermometer. The loss of heat was regulated and the proportion of ice to water. A vessel of water was cooled by a stream of liquid air passed through it. Weighed quantities of clean snow were added after the water had reached the freezing point. The readings obtained were for

ice just forming in the water	−0.0140° Cent.
ice 20%	−0.0060° "

During the time the water was subject to this rapid chilling, and was in the supercooled state, the fine particles of ice showed completely the phenomenon of agglomeration. They were in an adherent state and formed spongy masses like cotton wool. In every way this experiment reproduced what is observed on every cold day in winter on the open river, and was valuable in verifying the magnitude of the temperature changes in a body of open water in winter, which were carefully observed and measured for the first time by the writer in 1895 and 96.

This subject will be treated of later when the question of river ice is dealt with, and it will be shown how far it has been possible to control the ice forming power of the water by artificial heating methods. Strange as it may seem it was ten years after the writer first published his papers dealing with this small temperature effect in the water before any actual trials were made in a practical way to regulate the ice by means of heat. The first pioneer experiments were made in 1905 and 8 by Mr. John Murphy of Ottawa, who conceived of utilising heat in ice fighting through his long experience with power house operation in winter. Mr. Murphy deserves the best and most complete tribute for his courage in carrying out these experiments in the face of opposition and ridicule. He has been good enough to say that coming across one of my papers on this subject gave him courage

to go on with his plans and convinced him that he was right. The success that crowned his efforts made history in the science of ice engineering, and a description of Mr. Murphy's work will be given.

Colloidal Ice.

Until recently the nature of ice formation was not understood. It has been for long well known that water is an associated fluid, that its molecules are not simple H_2O molecules but molecular aggregates of complex form. Steam or water vapor consist of simple molecules which are called Hydrol. Water appears to be composed of double molecules called Dihydrol, while ice of triple molecules called Trihydrol. From studies of the physical properties of water such as specific heat, density and viscosity, it has been concluded that the associated water molecules of dihydrol contain varying proportion of the triple molecules trihydrol, and that the amount of the latter increases as the temperature falls from the boiling point. At the freezing point the proportion of trihydrol is estimated to be as high as 37% and at 100°C. about 16%.

Roentgen as early as 1892 stated that water contained ice in solution above the freezing point, and more recent studies have shown the identity of these ice molecules with the trihydrol. Before congealing, the water contains ice as a solution carries a salt, and the freezing point is the temperature where the solution becomes saturated with the ice and ready to produce the solid when the necessary energy is abstracted to enable the solid to precipitate out. To get this energy to flow out of the solution a small temperature depression is necessary, which we have already described. That the supercooling is not more pronounced is due to the rapid rate at which ice is formed tending to keep up the temperature so long as any water remains to form ice. Water supercooled by laboratory experiments to many degrees below O° C. is a highly supersaturated solution of ice, and readily precipitates on being agitated or by introducing a small particle of ice. It is exceedingly interesting to observe the nature of this first precipitation. The particles of

ice as soon as they can be seen under a microscope are devoid of crystal form and appear as a true colloid in small disc like particles. These flocculate and grow, passing through a crystal colloidal form to a true ice crystal. On allowing to grow slowly in quiet water they assume the form of a branching feathery snow crystal of most beautiful form. In rapidly moving water the crystals never become large, but are broken up and assume more and more a mass of broken spicules or spines. In nature, we find this first precipitation of ice in water appearing as a cloudy formation throughout the mass of the water. This is the beginning of the fine ice noticed in rapids or open water and called frazil or needle ice. It is the form which gives the most trouble in Power House operation, since it is produced all through the mass of the water and is of little or no buoyancy. It is readily carried into the racks and wheels, and adheres to the surface of machinery already cooled below the freezing point by the contact of the chilled water flowing through. When we treat of this interesting form of ice more will be said about the way in which this ice agglomerates and builds slimy layers and masses inside the wheel-case of a turbine, and resists all mechanical effort to be dislodged. It finally closes the water course entirely, or so far restricts it as to cause a serious fall in operating efficiency. In Fig. 2 we reproduce a microscopic photograph of this ice freshly grown which shows its colloidal form. When water is crystallized from a highly supercooled condition the particles grow to large size so rapidly as to mask the colloidal condition. A supersaturated vapor is very similar, and can be made to precipitate into a mist or fog by mechanical disturbance, or by introducing condensed vapor which in its turn starts the discontinuity necessary for the precipitation to take place. Colloidal ice is like the mist and appears to form suddenly in much the same way. I have called it a subaqueous fog, and it closely resembles that in appearance. The equally balanced forces of attraction or repulsion between water particles in a supersaturated atmosphere prevents their coalescing until a disturbance upsets the equilibrium. In the same way the equal distribution of the ice molecules in a supercooled quiescent water mass retards the

precipitation until mechanical agitation renders the approach of the molecular aggregates sufficient to set up the physical change necessary for the solid to form.



Fig. 2.—Microscopic reproduction of Colloidal Ice particles which form the subaqueous fog and eventually frazil.

Color of Water and Ice.

The color of natural ice, which in the case of icebergs is so vivid a blue in its real native purity, is deeper than the blue of sea water under a clear sky. Raman of Calcutta holds that this color is due to molecular scattering which appears to the writer to be the true explanation. The large size ice molecules in clear pure ice act like the particles in the sky and give to the mass the perfect shades so characteristic. Some authorities hold that the scattering of light in its passage through ice or water

(the Tyndall effect) is due to dust or impurities, and that it is impossible to get either ice or water entirely free from it. In the case of ice this criticism falls down for the deepth of the blue color of ice is a measure almost of the purity of it. Slight traces of foreign material alters the color rapidly to green, dull yellow and purple. From careful conductivity tests it is found that the ice which is formed on the underside of a surface sheet which is growing over flowing water is as pure as it is possible to get anything in nature. Indeed it is recommended by microscopic authorities that water be frozen in order to obtain it clean enough for the ultra-microscope. Water from melted clear ice is contaminated only by the vessel into which it is collected. Tests show such ice to be absolutely sterile, thus free from bacteria even when grown over polluted water.

In the glacier ice we find the pressure cracks often filled by melted glacier ice which has freed itself of air and comes from the purest form of ice. This refrozen mass gives the deepest blues so characteristic of the blue streaks in an iceberg. The green ice of an iceberg is the compressed glacier ice before the air has been expelled or freed from the interior of the ice mass. The presence of the air molecules in the ice changes the scattering resonant ratio and gives the changed hue. It is highly probable that Prof. Raman is correct, and the color of the ice is due to the large molecules, while the color of water is due to the presence of the ice molecules in solution. The glacial ice of icebergs is interesting because it shows no large crystal structure, being merely a mass of snow or frost nuclei grown to large dimensions. It is what we will call *pressure ice* as contrasted to *thermal ice* formed in a river or lake. Pressed down into a compact mass on the great ice plateau of Greenland the entangled air in amongst the snow and frost for countless ages is pressed into the ice and held in solution until the pressure is relieved as the icebergs melt. This air comes out in great quantities from iceberg fragments. The writer has shown that the amount of air carried by an iceberg is from 7 to 15% of the total mass and causes it to float much higher out of the water than ordinary ice would.

In the color of water it is more difficult to separate the effect of impurities from the true molecular scattering. Glacier streams and lakes are always the deepest blue and appear the deepest shade when coldest. The water of the St. Lawrence comes from the great lakes which are a gigantic settling basin for the silt and mud and its water is clear and blue wherever it is found.

It is a remarkable sight in winter to watch the varying shades of the river water as the temperature changes. Just at the freezing point the color changes rapidly and old river men can tell the approach of the ice forming period by the color.

The clearness of water has a great influence on the character of the ice formations as we will see later when the various forms of ice are described.

Mist, Fog and Hoar Frost.

All recent work on the nature of mist and fog is based on the nuclear theory, that is the precipitation of the water vapor by condensation on small particles in the atmosphere. Water contains the trihydrol up to the boiling point and in the process of evaporation a reasonable number of the ice molecules must be liberated into the vapor of the atmosphere. During very cold weather these ice molecules must persist and ultimately pass through molecular change to the true crystal form of hoar frost.

The highest clouds consist of snow crystals and the presence of minute ice particles in the upper atmosphere is shown in the phenomenon of sun dogs and moon dogs.

Halos are produced by colloidal particles of ice in the atmosphere, also the earth's shadows which are plainly visible in the north. The ordinary dense white fogs out at sea are probably colloidal water particles, but the white fog formed on water surfaces when the temperature is very low is the most beautiful fleecy cloud like form that is known.



Fig. 3.—White fog over open waters of the St. Lawrence.

A very interesting form of fog is the so called black fog which sometimes occurs in very cold weather over the open surface of the St. Lawrence river. Winter fog on the comparatively warm water of the river always appears when the temperature gets as low as 11° F. The river appears to be boiling, and the fog in columns and hair like forms rises from a few feet to as many hundred. The black fog occurs only at subzero temperature, and appears to be a precipitation of heavy semi-fluid water particles which, during their formation, absorb the entire rays of the sun. It is always preceeded by a white fog early in the morning before the sun is up and this white fog is known to rise in straight columns 1200 feet high. With the rising sun the white fog subsides and the color changes to a sulphur yellow like burning saw dust, and then rapidly to deep opaque black. It is the action of the sunlight which causes this transformation from the fine white colloidal particles to the deep black heavy forms.

Atmospheric conditions have been studied very carefully for information about the nuclei forming the starting point of these fog particles. In a dust free atmosphere it is difficult to attribute any cause other than the colloidal particles of ice and water in the vapour of the atmosphere. Under the action of daylight the nuclei and their condensation products are made to coalesce from the molecular state to the large aggregates of colloidal dimensions. It is hard to picture the intense action in the atmosphere when it is flooded with daylight in the early morning from the calm and serence condition of quiescence during the night. The light waves are projected into the sea of molecules with high powered energy impulses which tear their way through upsetting the stability, and interfering with the molecular equlibrium. The extent of the sun's spectrum is sufficient to supply wave lengths of energy which will suit a wide variety of particle dimensions. The resonant effects in the varying sizes of atmospheric aggregates are responsible for the beauty of the sunrise and sunset. Colorful effects due to selective resonant qualities of any medium are too well known to require extended discussion here.

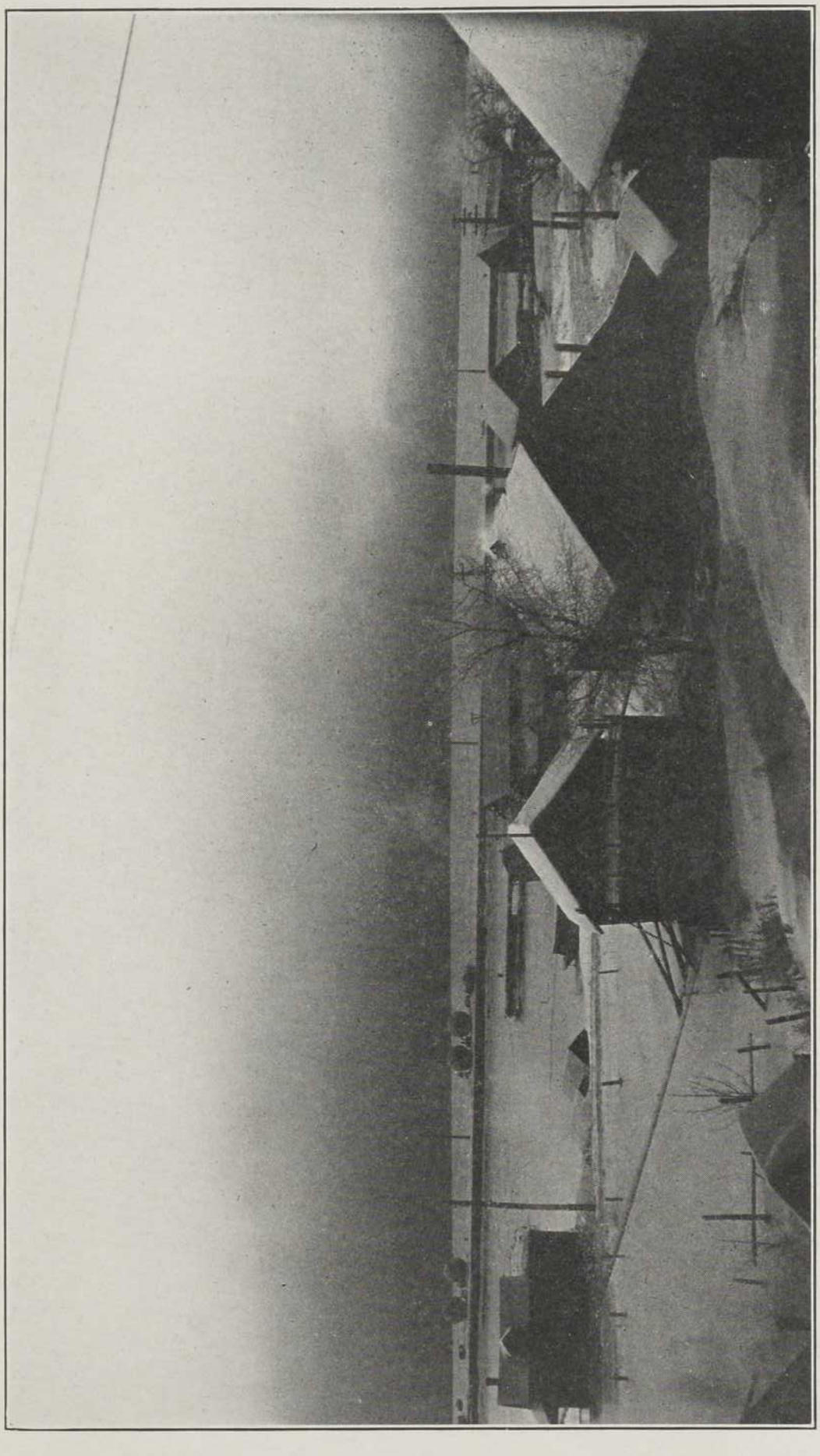


Fig. 4.—Black fog formed in subzero temperatures over open water.

Frost and Snow.

Frost patterns on glass offer an interesting study of the influence of colloids on crystallization. In the window frost pictures taken by Wilson A. Bentley for the writer, during his stay on the upper St. Lawrence river in 1925, may be seen typical cases of colloidal protective influence. Sodium chloride present in the atmosphere many hundred of miles inland from the sea produced distinct and well defined crystal alterations of form.



Fig. 5.—Old Window Frost showing fully developed Crystal patterns. Effect of Sodium chloride is shown.

The gradual change from the simple colloidal particles deposited from the air on the glass, to the fully developed crystals is well illustrated. The glass itself being a

colloid affects the crystal form, and the impurities left on the glass after cleaning produce abundant evidence of colloidal protection. In the study of snow crystals no

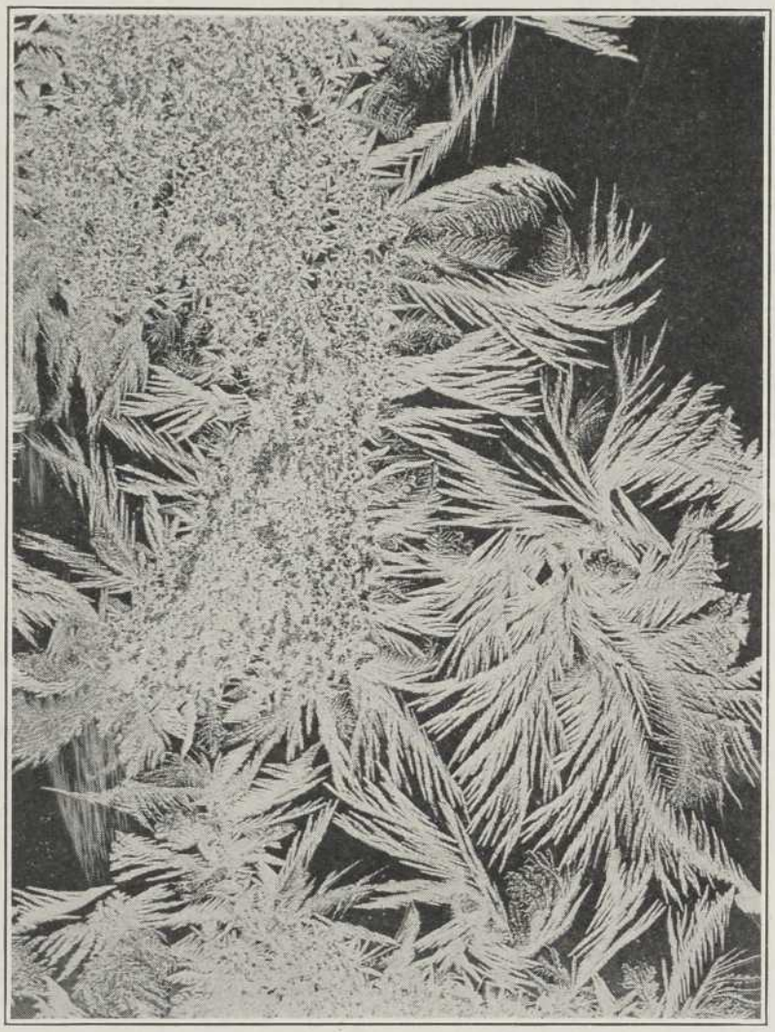


Fig. 6.—Young window frost forming from Colloidal deposits.

one can match the fine collection which Mr. Bentley has gathered for the last 45 years. His negatives run to over 4000 all different, and he tells the writer that he has never seen two snow crystals exactly alike. It is difficult to explain the origin of the snow crystal. The same nucleus which is the origin of the colloidal water forms must be at the same time the generating influence of the solid. Many snow-flakes show the nucleus very well and it is seen to be of the same shape as the first small particle that is precipitated out of water at the freezing point.

It has been pointed out how the moisture content of organic liquids gives rise to colloidal particles, and as an instance of this colloidal water and ice have been observed

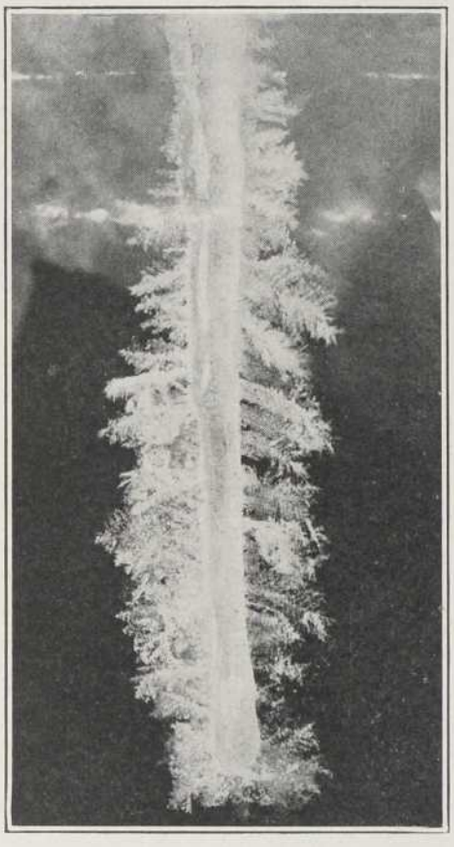
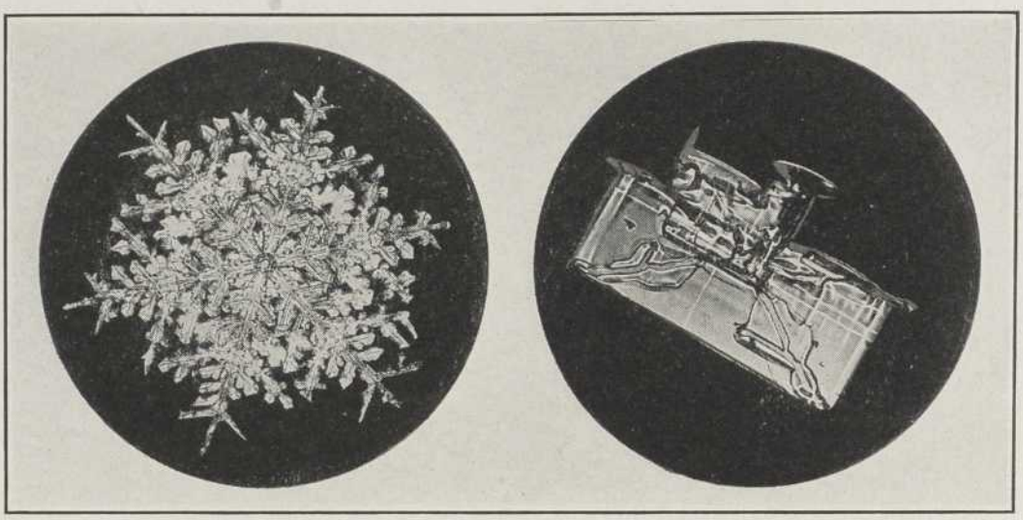


Fig. 7.—Hoar frost deposited on an icicle.

in chloroform when cooled. We are only at the threshold of our knowledge of the influence of colloidal water and ice on the whole subject of chemical activity. The trihydrol molecules, or ice particles as Roentgen first called them, are undoubtedley the basic nuclei for the many and varied forms in nature. And it may well be questioned whether or not the chemical activity of water is not due to the presence of these trihydrol molecules. At least we have several experiments which suggest such to be the case. It is highly probable that perfectly pure dihydrol would be chemically inert, and that the nearest approach to this is the so called dry water which was found by Baker to exert little chemical activity. If we

could find a way to destroy the trihydrol molecules in water that fluid would no longer be useful to living organisms nor would it ever freeze.

Fig. 8.



Feathery. Cubic.

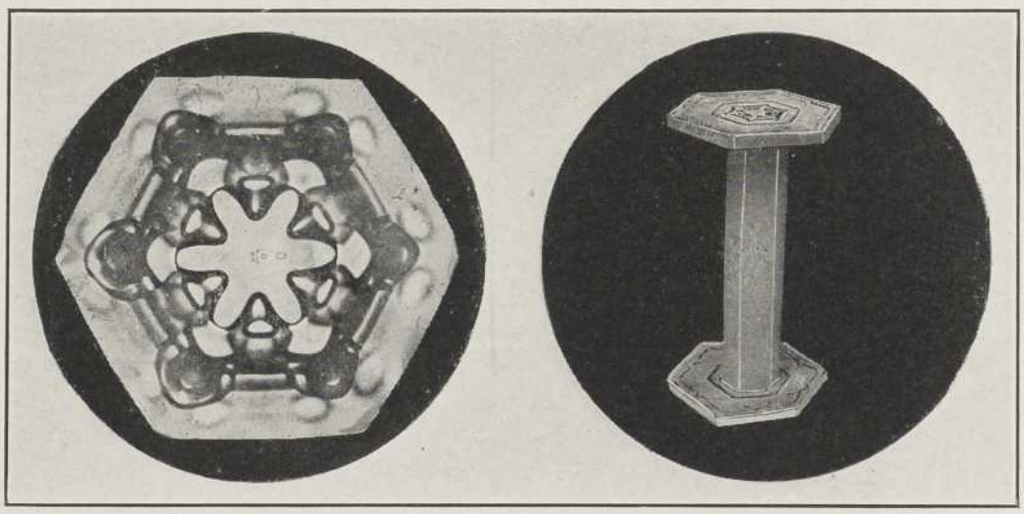


Plate. Cuff Button.

Crystal Structure of Ice.

An individual ice crystal may be of any size. Nearly everyone is familiar with the honeycombing of ice in the spring of the year by the sun, and how a large surface sheet will become like a lot of vertical spikes. These spikes are the large crystals of ice, separated by the melting of water films which contain the impurities and salts.

In the process of freezing on a still surface of water the crystals are all orientated with the main optic axis downwards as will be explained when we deal with the freezing of lakes and ponds.

In the neighborhood of the poles and on high mountains there exists often immense masses of permanent ice; and in some sections of Siberia, where a culture of the soil is possible in summer there are found below the surface of the earth strata of ice mixed with sand. In Alaska the subsoil never thaws out below about 5 feet in summer. When sinking a well at Yakutsk the soil was found frozen hard to a depth of 382 feet and consisting in some parts entirely of ice. These permanent masses of ice must be classed with rock as amongst the solid constituents of the globe. Fossil ice crystals are known to exist and were recorded by Udden in 1918.

The hardness and strength of ice is very great at low temperatures and it is reported that cannon of the calibre of six pounders were made in Russia in 1740. They stood an explosion of a charge of a quarter of a pound of powder with hemp or iron ball although the thickness of the ice was only four inches.

Ice treated as a mineral in Dana's Mineralogy, is given as belonging to the hexagonal system, probably hemimorphic. Distinct faces are rare and hard to measure. The hardness is given as 1.5, fracture concoidal, and lustre vitreous. It is colorless to white when pure and pale blue in large masses. Being transparent to light it is optically uniaxial, and shows a positive character as regards its indices of refraction. According to Reusch (1864) the indices of refraction are for the ordinary ray using red light 1.30598; for green light, 1.3120; for violet light, 1.317. For the extraordinary ray for the same three colors, 1,30734, 1.3136, and 1.321 respectively. The index of refraction increases with temperature.

The crystalline structure was originally studied by Tyndall who took slabs or plates of solid ice about half an inch in thickness. These were cut parallel to the freezing plane, and rendered flat by levelling and reducing by means of a warm and smooth metal plate. A beam of

sunlight was then focussed by a lens on the interior of the slab. The position of the focus was first found in air, the lens was then screened and the ice placed in position, the screen was removed and the effect watched by means of a magnifying glass. In this way the path of the light ray was instantly made visible by a great number of little luminous points resembling shining air bubbles. When the ray was sent through the edge of the plate the path of the beam could be traced by these brilliant spots.

In solid natural ice the planes of freezing are easily recognized by the stratified appearance which small air bubbles are seen to assume. This is particularly true in ice frozen rapidly in very cold weather. In solid clear ice frozen slowly, which contains no air, the ice must be exposed to sunlight for a short time in order to develop the minute cavities recognized by Tyndall. If these cavities after exposure to light are examined by a glass they are found to be cut by innumerable small parallel fissures, with here and there minute spurs shooting from them, which give the fissures a feathery appearance. These "flowers of ice" as they are called are found to consist of six petals with a central bright spot which shines with metallic lustre. It was found that these petals were composed of water, and the relation between the planes of these flowers and the planes of freezing was perfectly constant. They were always parallel to each other. It was found that the development of these flowers was independent of the direction in which the beam of light traversed the ice. Hence the freezing plane could always be told in a block of ice by sending a ray of light through it.

The more slowly artificial ice is frozen, and the less salt it contains, the more transparent it is and rigid, and the more difficult to split with a knife.

The planes of easiest cleavage in natural ice are those where layers of invisible salt solution have collected and congealed in the mass of the ice.

In recent years with the development of X-ray study of crystal structure some attention has been devoted to a determination of the structure of ice.

Wyckoff has pointed out that the existing X-ray data for ice are not sufficient to establish its structure with any degree of certainty although several series of measurements have been made by different workers. These consist of photographs taken by Rinne in 1917 by the Laue method, and interpreted by Gross in 1919; spectroscopic measurement made by Ancel St. John in 1918; and powder photographs obtained by Dennison in 1921. A theoretical study and revision of the structures proposed by St. John and Dennison was made by Sir William Bragg in 1922.

The Laue photograph of Renne showed complete hexagonal symmetry with an axial ratio of a:c = 1 : 1.678.

On measuring the plate again Gross assigned two molecules of H_2O to each unit cell in the structure, giving a = 3.46 Å. and c = 5.53 Å (a:c = 1:1.60), on the assumption that the original crystal was not twinned.

The spectrometer measurements of St. John indicate a unit cell containing four molecules of H_2O with a = 4.74 Å. and c = 6.65° Å. (a:c = 1:1.4026). The measurements were made from five good photographs of different samples. The specimens were obtained by freezing water in open pans and care was taken that only single crystals were selected. The photographs were taken with the samples at a temperature of −15° C.

Dennison obtained his ice by plunging a water filled capillary tube into liquid air. He used the Hull method in taking his photographs. The results showed a close-packed hexagonal lattice (a:c = 1:1.62), consisting of two sets of interpenetrating triangular prisms. The unit cell contains four molecules of H_2O, and has the dimensions a = 4.52 Å. and c = 7.32 Å.

Sir William Bragg proposed that the complete structure of the unit cell of ice is made up of four interpenetrating close packed hexagonal lattices. He confirms the figures of Dennison for the dimensions of such a cell.

Dennison has probably the best set of experimental values because of the danger of using twinned crystals in the other methods. The data of St. John are quite definite and sure, and he has remeasured his plates with great care. Since publication of his results and those of Dennison he has found no reason to alter his values.

It is highly probable that the difference between the values of Dennison and St. John is real and due to a real difference in the actual structure of the samples of ice used.

Taking a single crystal which had never been below -15° C. it might well differ from the small crystals formed at -181° Cent. with great rapidity.

We know that the first ice which is produced from a water matrix is devoid of all crystal form, and merges into the true crystal only on gaining considerable size. It is likely that the two methods will be brought into harmony when further work is done in this interesting field of investigation.

CHAPTER II.

PHYSICAL CONSTANTS OF ICE.

Density, Specific Heat, Hardness, Elastic Contents Heat of Fusion, Evaporation, Sublimation Color and Bacteriology.

The important influence of ice in the operations of nature has made a knowledge of its physical properties one of great interest. It is one of economic importance as well and the object of the present work is to bring together the most important results which are available from the literature in all countries.

It has always been the writer's contention that a knowledge of the physical laws governing the formation of ice would make the task of coping with the ice problem comparatively easy. Studies of the question in relation to ice-breaking, and winter navigation of the St. Lawrence river, has made this even clearer. People are too apt to judge of ice remedial work from the wrong end.

The enormous accumulation of ice masses in unprotected localities illustrates the large forces possible, from infinitesimally small beginnings, which warp the judgment and beggar the imagination. The well known saying "an ounce of prevention is worth a pound of cure" holds with pertinent force when dealing with the ice problem. In this chapter the writer merely discusses the properties of ice from the physical standpoint, and suggests the most probable value of the constants.

Density of Ice.

Passing over the earlier measurements of the denisty of ice by Boyle, Williams, Berzelius, Heinrich, Dumas

and Osann, we find one of the first attempts at an accurate measure was made by Brunner in 1845. His specimens were clear pieces of river-ice, which were weighed first in air and then in petroleum. The value he obtained was .9180.

Plucker and Geissler followed shortly after, using a dilatometer method and found the value .9158. Kopp in 1855 found, by the same method, .907.

Dufour in 1860 determined the density by submerging ice in a liquid the density of which he could vary and found the value .9175 and later using different liquids, he found .9178.

In 1870 Bunsen set himself to determine the value in connection with his well-known ice calorimeter. He employed a dilatometer of special design, obviating certain errors connected with previous dilatometers. He obtained the value .91682 and .91667, giving a mean of .91676.

Zakrzevski, in 1892, redetermined the value by Bunsen's method, using boiled water. He found the values .916710, .916713, .916708, giving a mean of .916710.

In 1899 E. L. Nichols made a careful series of measurements by various methods. He found that there were important differences in the density of new and old ice, and between natural and artificial ice.

Differences of the order of 1 part in 1000 were found for such forms of ice. Ice mantles, prepared by CO_2 and ether, gave a mean value of .91615, while natural ice, such as icicles, gave .91807. Natural ice from a pond, newly cut, gave .91804, while the same ice, one year old, was only .91644. Still another value found by Nichols, by a different method, for ice newly cut from a reservoir, was .91772.

The question of a possible difference between new and old ice was subjected to a careful study by Barnes and Cooke in 1901. They obtained large blocks of clear ice forming the under-side of the surface sheet on the St. Lawrence river. Such ice was obtained freshly formed

and compared with similar ice which had been in the cold-storage warehouse of the City Ice Company for one and two years. The method employed was to weigh the ice directly in water at 0° C. No difference was found due to age comparable with the values found by Nichols. The fresh ice had a density of .91674, the ice one year old was .91660, and the two-year-old ice was .91649. These values tend to show, as Hess points out, a relaxing of the crystalline texture with time. The mean of the various determinations give .916611 for the St. Lawrence river ice.

In 1902 J. H. Vincent determined the density of ice by weighing water in mercury. The water was weighed both as liquid at 0° C. and as solid at several degrees below zero. The mean value found was .9160.

In 1906, A. Leduc undertook a new determination of the density. The presence of air formed the basis of special study, and it was found that even boiled water contains a large quantity of dissolved air. As much as 1 cc. per liter was extracted by a special method. Leduc discovered that the density increases as the amount of dissolved air decreases, and he concludes that the density of gas-free ice is .9176. The influence of dissolved air helps to explain the small differences in the work of previous observers, and shows that the variations observed by Nichols may possibly be due to this cause.

We may conclude that the most probable values for ice formed in the usual way from boiled water, may be taken as follows:—

Bunsen	.91676
Zakrzevski	.91668
Nichols	.91615
Vincent	.91600
Leduc	.91720

while for natural ice we have

Nichols	.91806
Nichols	.91644
Barnes and Cooke	.91661

It is evident that the density of ice is not constant, but is dependent on the manner and rapidity of formation. It seems likely that varying quantities of air in the ice are

responsible for the fundamental differences found by different observers. A certain quantity of air can dissolve in the ice and can also be retained mechanically in the frozen mass. Under high pressure much larger volumes can be retained as is illustrated in the case of iceberg ice which retains as much as 10% of air. In recommending a general working basis for ice density the value of Bunsen *i.e.* .91676 seems to be a good average of all the latest and best measurements, and is here recommended as the most probable of this important constant.

Density of Snow.

On the Sonnblick (3106 meters) during the summer, A. Defaut in 1908 found the density of snow to increase from 0.280 at 12.5 cms., depth to a maximum of 0.632 at 87.5 cms., then a further increase until at 312.5 the value was 0.607. A minimum occured at 162.5 cms.

The increase of density with the depth is not linear as some suppose. The increase with depth is due to the squeezing out of air from between the snow crystals by the increased pressure.

The density of snow has been found to vary as would be expected. In 1909 Gheury gives the values between 0.045 and 0.105 from measurements made in England.

Maximum Density of Water.

The occurence of the maximum density of water, at a temperature above the freezing point, is one of the most important facts to be met with anywhere in nature. In our study of ice the determination of the density of water near the freezing point has attracted a great deal of attention, and many beautiful experiments may be performed to show that water ceases to contract at 4° Cent. or 39° Fahr., and expands from there far below 0° Cent. The classical experiment of Thos. Chas. Hope in 1805, which is familiar to every one, is one of the best.

Among the first precise experiments on the density of water, we may mention the work of Halström in 1825.

Depretz, in 1840, made accurate measurements with pure air-free water, which, when enclosed in a dilatometer, he succeeded in cooling to $-20°$ Cent., and found a perfectly regular expansion to this point. The sudden change of volume of water in solidifying at zero was shown to be a leap, as it were, to the gradual change of volume taking place when the water was super-cooled. The temperature found by Despretz for the maximum density-point was, from the mean of his experiments, 4.007° Cent. Halström found for the same point 4.108°, and Pierre 3.92°. Rosetti, in 1867-69, gives a summary of the various values found, and from this it may be concluded that 4° is as near the true point as the errors of the various experiments will allow us to come.

M. Chappuis, in 1897, determined the variation in the density of water very accurately by the dilatometer method, using an iridioplatinum vessel similar to the bulb of a gas-therometer.

Some of the values he obtained are given in the following table.

DENSITY OF WATER AT ATMOSPHERIC PRESSURE. AFTER CHAPPUIS.

Temp.	Density.	Temp.	Density.
0° Cent.	.9998674	6° Cent.	.9999691
1 "	.9999272	7 "	.9999294
2 "	.9999692	8 "	.9998760
3 "	.9999923	9 "	.9998085
4 "	1.0000000	10 "	.9997272

It was shown by Chappuis that the expansion cannot be accurately represented by a formula. M. Amagat, in 1893, in an exceedingly interesting paper, showed that, when the pressure is increased, the temperature of maximum density recedes towards zero, the amount being .025° Cent. per atmosphere. At 144.8 atmospheres the maximum density point was reduced to 0.6° Cent.

Many other accurate determinations have been made of the expansion of water, notably those of Marek in 1889, Thiesen in 1889, and K. Scheel in 1892, all showing good agreement.

Heat of Fusion of Ice.

With the density, the latent heat of fusion of ice has received a large amount of attention.

Black of Edinburgh, in 1762, was the first to draw attention to the latent properties of the heat in melting ice. His first rough measurement gave a value of 79.7 calories per gram. Strange to say this value is closer to the real value than those obtained by many later investigators. Lavoisier and Laplace, in 1780, determined the constant with their well known double-walled ice calorimeter. They obtained 75 calories. In 1842 Regnault obtained, by means of melting snow, the value 79.2 calories. Further experiments with small blocks of ice gave 79.06 calories.

L. F. Guttmann has recalculated Regnault's results by correcting for the erroneous value of the specific heat of ice used in the calculation since the capacity for heat of ice was taken as equal to that of water. He also corrected Regnault's value for the variation of the specific heat of water. This brings the latent heat of fusion of ice, as given by Regnault, 79.25, up to 79.59 colories per gram.

La Provostaye and Desains, in 1848, determined the constant and obtained 79.25, and 79.01 as mean values. They were somewhat uncertain of the amount of moisture adhering to their ice.

Hess, in 1848, avoided this uncertainty by using ice cooled several degrees below zero. He obtained 80.3 calories as a mean of his experiments. Person, in 1850, carried out some experiments by a similar method and obtained a value of 80.0 calories. Both Hess and Person required a knowledge of the specific heat of ice cooled below zero.

In 1870 Bunsen devised his well known ice calorimeter and determined the latent heat of fusion by adding known quantities of warm water. The value he obtained was 80.02 calories.

An accurate determination of the heat of fusion of ice was made by Prof. A. W. Smith, in 1903. Ice was broken into small pieces and cooled several degrees below zero. It was then transferred to a calorimeter containing light oil also cooled below 0°. The calorimeter and contents were then warmed slowly by a feeble electric current until the temperature was about 1° C. below zero. A larger current was then supplied for a sufficient time to melt the ice and raise the temperature of the water to half a degree above zero. Correcting for the specific heat of the ice and water, the heat of fusion could be obtained. The result thus found was 79.896 calories. This value, however, should be somewhat lower since it was worked out in terms of the Clark Cell = 1.434 volts at 15°C.

The measurements of Dickinson, Harper and Osborne were carried out very carefully in 1913 and are entitled to a great deal of weight. They took special pains with all the electrical measurements and used electrical resistance thermometers of great refinement. Their method was somewhat similar to Smith's but differs from it in the use of water instead of oil as the calorimetric medium, in the form and size of the ice specimens, and in the type of calorimeter.

The ice sample was put directly into the water and the approximate amount of energy required to melt the ice supplied electrically and measured. The temperature of the calorimeter water remained very constant although a large amount of ice was used.

Experiments as a control were made by the method of mixtures using refined electrical thermometers and served as a check on the electrical method, the value of which depended on the values which the author assumed for the calorie in joules.

Many different samples of ice were selected, prepared by different methods. That used for most of the determinations was commercial artificial can or plate ice frozen from city filtered water, which was distilled and boiled before freezing. The samples were selected for clearness and freedom from bubbles. Ice was also obtained from several sources. Natural ice about one foot thick was used which was not entirely clear or free from bubbles,

although conductivity tests showed it to be nearly as pure as double-distilled water. Specimens of ice used were prepared from double-distilled water frozen in tin-lined vessels exhausted of air. Although this method did not produce ice which was perfectly clear, yet the authors state that specimens of a very good degree of clearness were obtained. The experiment was made of freezing water purposely contaminated with a mixture of ammonia, sodium chloride and calcium chloride to the extent of 1 part in 1000. The results obtained by Dickinson, Harper and Osborne by the electrical method for the heat of fusion were 79.65 calories for the commercial plate ice and the same for commercial can ice.

By the method of mixtures on commercial can ice the value came to 79.61. For natural ice from Maine the value came to 79.64. All these results agree very well with one another and the mean 79.63 is probably very nearly right. They used for correcting for the temperature change in their ice, heating it up to O° Cent., the value for the specific heat of 0.52 which is a little higher than the latest measurements. If we take .49 as representing the specific heat, it brings the mean of their results up to 79.69. Under Specific Heat will be described determinations made by Dickinson and Osborne which confirm this.

In 1905 a determination of the heat of fusion was obtained by A. Bogojawienski when engaged in examining the specific heat of ice. His values lie between 79.41 and 79.91 and, while the mean is near the correct value, the wide divergence does not warrant our devoting any time to a full discussion of his methods.

E. Griffith in 1913 made a special study of the Bunsen ice calorimeter with a view to finding its limit of accuracy. He was prompted to do this owing to the wide divergences in the density of ice by Nichols, which we have already discussed.

He used electric heating in the calorimeter and obtained the value 80.30 which is much higher than the results obtained by using small pieces of ice directly. This he attributes to water occluded to an unknown extent in

the experiments such as Smith's. He does not explain how this occlusion is maintained for ice cooled many degrees below freezing. As pointed out by Callendar, Griffiths used too small a value for the density of ice. Taking a value of the density .9167 brings his result for the heat of fusion down to 79.5, a result in good agreement with the best determinations already described.

In 1905 Behns and Dieterici, using the ice calorimeter and electric heating, obtained the value for the heat of fusion equal to 79.69. In the same year, using the same method, Dieterici found 79.60.

W. A. Roth, in 1908, when discussing the most probable value of the heat of fusion gives it as 79.67. He misquotes at the same time Barnes and Cooke's value for the density of ice, giving it as .91649, while it should be .91661. This mistake has been reproduced in Glazebrook's Dictionary of Physics.

In 1923 Maass and Waldbauer deduced the heat of fusion from their experiments on the specific heat of ice. They found a value somewhat lower than the latest direct measurements. The figure they gave is 79.42 calories.

In 1927 Maass and W. H. Barnes redetermined the heat of fusion with the adiabatic calorimeter and found the value 79.4 at O° C. and 77.7 at —3° C.

Summarizing the values of the heat of fusion, we obtain the following:

LATENT HEAT OF FUSION OF ICE.

Year.	Observer.	Latent Heat in Calories per Gram. at O Cent.
1762	Black	79.70
1780	Lavoisior and Laplace	75.00
1842	Regnault	79.59
1843	de la Prevostaye and Desains	79.10
1848	Hess	80.00
1850	Person	80.18
1870	Bunsen	80.05
1903	Noyes and Sammet	79.20
1903	Smith	79.62
1905	Behns	79.69
1905	Dieterici	79.60
1905	Bogojawienski	79.61
1906	Leduc	79.20
1913	E. Griffiths	79.50
1913	Dickinson, Harper and Osborne	79.68
1923	Maass and Waldbauer	79.42
1927	Maass and Barnes W. H.	79.40

It is not good sense to take a mean of all these values, for we should be able to discriminate between the various researches. Thus the careful work of Dickinson, Harper and Osborne leads to a value which is beyond doubt very nearly the true one. The only doubt that might exist is the assumption for the specific heat of ice which enters as a very small correction. On account of the latest and very careful work of Maass and Waldbauer and Maass and Barnes on the specific heat of ice, which will be described in the section dealing with Specific Heat, it seems certain we are in possession of a value for the latent heat very near the truth.

Roth gives as the most probable value 79.67 and when, Black, Regnault, Smith, Behns, Dietrici and Bogojanlenski, by widely differing methods give such close values, it would seem that we now know this constant within 2 parts in 1000 at least.

The change of the value for the heat of fusion of ice was examined by Person who calculated that generally the heat of fusion of a body is smaller the lower the temperature becomes. Patterson verified this in the case of ice and found that for one degree of lowering of the freezing point the heat of fusion was lowered by 0.59 calorie per gram. At $-6°$ Cent. observation gave 76.0 calories.

Latent Heat of Vaporization of Ice.

Direct measurements of the heat of vaporization of ice were first made by Barnes and Vipond in 1909. It was well know that a great deal of evaporation takes place from ice and snow, but the nature of this change was not studied, for it was always assumed that heat of vaporization was the sum of the heat of fusion of ice, 79.69 calories, and the heat of evaporation of water, 598 calories.

Experiments were made to determine this constant by placing ice in a Bunsen calorimeter and evaporating by means of a current of dry air. The procedure was to continue the evaporation steadily over a sufficiently

long period to enable the conditions to become steady. The vapor carried over by the dry air was caught in sulphuric acid absorption bulbs. The heat absorbed by the evaporation was taken from the water in the calorimeter and caused a steady and regular increase in the mercury column in the graduated tube of the calorimeter. Readings were made during the most favorable period when the evaporation was progressing regularly and the amount evaporated was measured during a known interval of time. The values obtained from a larger number of readings showed some irregularity at first, but upon a lapse of time always quite uniform results. The various values obtained are shown in the annexed table. The evaporation in this case was carried out at a very slow rate, giving the vapor considerable time before leaving the calorimeter.

Heat of Evaporation of Ice.

Slow Rate.
702 calories
706 "
698 "
689 "
706 "

When the evaporation was carried beyond a certain rate, then it was found that a smaller value was obtained which persisted independent of the rate of evaporation. These were the most reliable measurements and were calculated as follows:

Heat of Evaporation of Ice.

Rapid Rate.
615 calories
608 "
597 "
607 "
612 "

It will be seen that these values, almost identical with the heat of evaporation of water at O° Cent. which is very nearly 600 calories, are very surprising and indicate

that the ice evaporates as a polymeric vapor. In other words, the vapor from ice has not passed through the liquid phase when it leaves the surface of the ice, but breaks down into ordinary water vapor when separated from the ice surface. In order to test this point, vapor from ice was passed rapidly through a tube over a heating current, and then over a sensitive electrical thermometer. The vapor issuing from the ice was several degrees below O° Cent. and the temperature was recorded by the thermometer bulb. When a heating current was applied so as to raise the temperature of the vapor to O° Cent., it was observed that more heat was absorbed by the vapor without changing its temperature, the amount of which exactly equalled the 80 calories per gram which had escaped with the vapor.

In order to show this, the heating current was increased by small increments and the temperature of the escaping vapor observed. These are straight lines with the exception of the flat portions which represent the absorption of the heat in the ice vapor without change of temperature.

It is probable that in ordinary evaporation from ice and snow the change of the solid vapor into ordinary vapor takes place just outside the surface and would, under ordinary circumstances, escape detection in vapor pressure measurements.

Specific Heat of Ice.

Of the early experimenters who turned their attention to the specific heat of ice, we may pass over the work of Desormes and Clement and of Avogadro as being too inaccurate to be included with the later work. Thus the former obtained the values 0.75 and 0.70, and the latter 0.92 by somewhat similar methods.

The two general methods which have been in use in the later work are, in one case the mixing of ice cooled below the freezing point, with warm water, and after correcting for the heat of fusion, to estimate the specific heat. The other is to mix cooled ice with oil, and arrange that the

minimum temperature of the mixture shall not be above the melting temperature. By this means a knowledge of the heat of fusion is avoided.

Person, in 1850, found between $-21°$ Cent. and $-2°$ Cent. the value 0.480, which agrees with the value of Regnault (1843), between $-78°$ and $0°$ Cent. Over the interval between $-20°$ and $0°$ Cent. Person also found the value .504, which led him to the conclusion that the specific heat near the melting-point was increased slightly, for according to his view, from $-2°$ to $0°$ Cent. a portion of the ice was melted, giving rise to a higher value of the specific heat.

Later determinations show, however, that there are no unusual changes in the specific heat of ice near the freezing point.

Desains, in 1843, found the value for the specific heat between $0°$ Cent. and $-20°$ Cent. to be 0.513; another value given by him is as low as 0.47 from which he concludes, although it is hard to see how he does so, that the correct value is 0.51.

In 1848, Hess found for an interval of temperature between $0°$ Cent. and $-14°$ Cent. the value of 0.533.

In 1853, Gadolin published his measurements of the specific heat for a mean temperature of $-8°.9$ Cent. which was 0.524.

Smith in 1903 made a comparative measure of the specific heat near the freezing-point for obtaining his measurements of the latent heat of fusion already described. He made his measurements between $0°$ Cent. and $-1.40°$ Cent., but obtained no indications of the great increase predicted from Person.

Dewar in 1905, carried on an interesting series of experiments on the specific heat of various substances at low temperatures. In this series he included ice. The calorimeter employed was a bulb containing liquid air or hydrogen, enclosed in an outer bulb also containing the same materials. The heat introduced by the body under investigation vaporized the liquid air and, from

the amount of air collected, the specific heat was estimated, knowing the heat of vaporization of the liquid air or hydrogen. The result of Dewar's work is to show that the specific heat of ice decreases rapidly but regularly with a lowering of the temperature as follows:—

Between° −18° Cent. and −78° Cent., 0.463
" −78° Cent. and −188° Cent., 0.285
" −188° Cent. and −252.5° Cent., 0.146

The agreement with Ragnault's value between O° Cent. and −78° Cent. which is 0.474 is remarkable.

In 1905, Bogojawienski gave some values for the specific heat of ice which he obtained for his determination of the heat of fusion already referred to. These are between the limits of O° Cent. and,

−45°	−35°	−25°	−15°C.
0.405	0.427	0.455	0.500

In 1910, Nernst obtained measurements of the specific heat of ice by using a vacuum calorimeter and succeeded in obtaining results for quite low temperatures. He obtained the following values:

−10° C.	0.533
20°	0.478
30°	0.451
50°	0.410
70°	0.374
80°	0.367
110°	0.309
140°	0.277
170°	0.214
180°	0.199

The ice was never raised quite up to O° Cent.

In 1910, some careful determinations were made by Koref which do not require any detailed description. He found between the limits of temperature:—

− 2.9° Cent. to − 76.9° Cent.	0.435
−15.3° Cent. to − 75.9° Cent.	0.417
−81.7° Cent. to −189.5° Cent.	0.266

In 1915 Dickinson and Osborne determined the specific heat of ice taking great care as to the purity of the ice. Their method was to freeze carefully prepared distilled water directly in their calorimeter vessel and then determine the heat capacity electrically. They avoided raising the temperature quite up to 0° Cent. but worked between −40° Cent. and −0.05° Cent. Their results are quite consistent and showed that for ice containing small traces of impurity the specific heat increased more rapidly as the melting temperature was reached. This agrees with the conclusions arrived at by A. W. Smith that ice tends to partially melt slightly below the true melting point temperature and hence the heat of fusion causes an apparent increase in the specific heat.

The values obtained for the specific heat of their purest samples, which they express in terms of the calorie at 20° Cent.
are as follows:—

0° Cent.	0.5057
−10° Cent.	0.4871
−20° "	0.4684
−30° "	0.4498
−40° "	0.4312

When expressed in terms of the standard 15° calorie these values are reduced a little, the result for 0° Cent. being 0.5050. They expressed the specific heat in a linear formula which reads

$$S = 0.5057 - 0.001863\ t$$

where t = the temperature in degrees Cent.

Dickenson and Osborne have corrected their values already described for the heat of fusion of ice, and expressed them using the new value for the specific heat which they obtained. These corrected values are in terms of the 15° Cent. thermal unit, 79.65, 79.62, and 79.70, giving a mean of 79.66. They express it, however, in terms of the 20° Cent. thermal unit as 79.74.

In 1923, some careful determinations of the specific heat of ice were made by Drs. O. Maass and W. Waldbauer. They were examining the specific heat of various

substances with a view to testing some of the theoretical formulae for the variations of the specific heat of certain well known solid crystalline substances at low temperatures.

The measurements for ice were made between the limits of O° Cent. and −190° Cent. While those of a large number of organic substances were made between other limits. The method used was one designed to completely overcome all calorimeter heat losses due to radiation and conduction, and consisted briefly in surrounding the calorimeter vessel by a jacket which could be so quickly regulated in temperature as never to differ by more than a small fraction of a degree from the calorimeter vessel itself. The substance whose specific heat was required was placed in a small silver or platinum vessel, called the "frigitor", and was precooled to the desired temperature. It was then quickly transferred to the calorimeter and the cooling observed by an accurately calibrated Beckmann thermometer. The temperatures of the cooling baths were measured by means of platinum resistance thermometers. In order to have the final temperature of the calorimeter always the same, 16.5° Cent. was chosen and the initial temperature of the calorimeter so regulated that the introduction of the cooled frigitor brought the end temperature to 16.5° or as near as possible, so that a small correction only was required.

By this means the ice was warmed, melted, and the water brought to a temperature of 16.5° Cent. All possible error due to partial melting of the ice at or near the melting-point was eliminated and this plan was adopted by these investigators in order to avoid what in other determinations appeared to be a possible source of error, and tended to make previous measurements at O° Cent. too high.

It may be safely assumed now that the specific heat of ice at the temperature of O° Cent. is not greater than 0.50 and probably equal to 0.49. The change with temperature is represented by the values given next and by the formula found by Maass and Barnes.

Maass and Barnes W. H. (1927) have repeated the specific heat of ice for various temperatures down to −80° C. by using a adiabatic calorimeter of improved design. Their results are given in the following table of specific heats.

They modify somewhat the values of Maass and Walbauer and agree very closely with Nernst values. A careful check was made on the value around 20° C. and the work repeated.

TABLE OF SPECIFIC HEAT.

Temp. C.	M. & B.	M. & W.	Nernst	D. & O.
0	0.4873	0.485	.....	0.5057
−10	0.4770	0.475	0.533	0.4871
−20	0.4647	0.465	0.478	0.4684
−30	0.4504	0.453	0.451	0.4498
−40	0.4340	0.444	.....	0.4312
−50	0.4160	.....	0.410	.....
−60	0.3958	.....	.....	.....
−70	0.3737	.....	0.374	.....
−80	0.3496	.....	0.367	.....

$Cv = 0.5017 - 0.0063032\ T + 0.000009828\ T^2$ where T is the absolute temperature t°C = 273.1 abs.

THE SPECIFIC HEAT OF WATER.

The specific heat of water, owing to its great importance, has been the subject of much study.

The change of specific heat is not a simple one, and from 0° Cent. to 40° Cent. it drops rapidly, passing through a minimum value near 40°, and then increases up to, and beyond the boiling-point. In Fig. 9 the mode of variation over the range of temperature from −10° to 100° Cent. is shown.

Various points have been decided on for the selection of a thermal unit, and it seems that the best one is the temperature at which the specific heat is equal to its mean value between 0° and 100° Cent. It will be seen by inspection of the curve that this occurs between 15° and 16°. The one-hundredth part of the specific heat between 0° and 100° being taken as unity, then that between 15° and 16° Cent. is equal to 1.0002.

In the table given below the specific heat of water is given in terms of such a unit.

TABLE OF SPECIFIC HEAT OF WATER.

-5° Cent.	1.0158	50° Cent.	0.9980
0° "	1.0094	60° "	0.9991
10° "	1.0023	70° "	1.0004
20° "	0.9989	80° "	1.0017
30° "	0.9976	90° "	1.0031
40° "	0.9974		

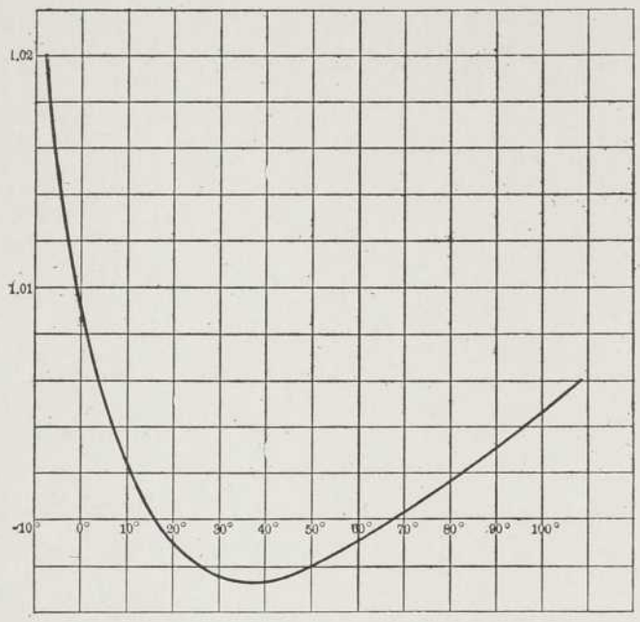


Fig. 9.—Variation of the Specific Heat of Water.

The specific heat of water is of special interest in the neighborhood of the freezing-point. Several determinations of this, by absolute methods down to a few degrees of the point, and also by the method of mixtures, to temperatures of several degrees below zero have been made. In these experiments supercooled water was used and it was shown that the variation curve which had been deduced for large ranges of higher temperatures was continued regularly below zero. This is shown in the figure just given, where it will be seen that the curve is continued below zero without any discontinuity. We have shown from consideration of the association of water that at O° C. water is a saturated solution of ice. The presence of ice molecules in water completely explains the rapid decrease in the specific heat of water as the temperature rises, as well as the maximum density point.

In the first case, superimposed on the heat-energy necessary to cause an expansion of the molecules as the temperature rises, we have the heat absorbed in breaking up the molecules of ice (trihydrol) to form water-molecules (dihydrol). The relative amount of ice-molecules grows less as the temperature rises, and consequently the specific heat apparently grows less. At 37.°5 C. there is an exact balance between the two effects, the normal increase in the specific heat, and the decrease in the heat absorbed in breaking up the ice-molecules.

Dealing with the position of the point of maximum density, we are observing the resultant of two effects,—one the change in volume of the water due to the decreasing number of ice-molecules, and the other the natural increase in volume due to the increased space required by the molecules of water as the temperature rises.

From 0° Cent. up there are so many ice-molecules present that we find an apparent decrease in volume. At 4° C. there is a balance of the two effects, to be followed by an increase in volume as the temperature rises, the normal thermal expansion masking the effect of the ice. The position of maximum density occurs therefore at 4° Cent. or 39° Fahr., while above and below this temperature the density decreases.

The effect of pressure on the viscosity of water can also be explained by the ice simile. It was observed by L. Hauser (1901) that below 30° Cent. an increase of pressure decreases the viscosity of water, whereas above this temperature the reverse is the case. No precise point was obtained for the balance of the effects, but the author places it at about 30°. It is well known that the effect of pressures on a mixture of ice and water is to melt some of the ice. Pressure here changes the ice-molecules into the less viscous water-molecules, and we find the effect apparent on the water below 30°. At or near this temperature there is a balance between the decrease in viscosity due to the squeezing back of the ice-molecules into water-molecules, and the normal increase in the viscosity due to increasing pressure.

Thermal Conductivity of Ice and Snow.

A knowledge of the thermal conductivity of ice and snow is of great importance in many problems of meteorology. The protection to the ground afforded by a layer of snow or ice against the severe temperatures of northern winters has, as we have shown, considerable bearing on practical questions. Thus the character of the underground temperatures in the crust of the earth, is influenced to a large extent by the thickness of ice or snow that accumulates over the ground in winter. The nocturnal cooling of the soil by radiation which goes on to so large an extent under ordinary conditions of soil-exposure, is without influence when the ground is covered with snow.

The loss of heat from a river is checked by the rigidity of the surface-sheet of ice which prevents the direct contact of air and water, and reduces the loss to that of conduction through a mass of ice. And, although ice is a better conductor of heat really than water, the process of conduction-loss is so slow, compared to convection and wind-currents that the heat-loss is checked at once. As the ice-sheet grows thicker the heat-loss grows slower. Accumulations of snow, fallen, blown, and drifted over the ice-sheet, still further reduce the loss of heat, as it is a poorer conductor than solid ice, and it checks radiation through the clear ice.

Conductivity of Ice.

The thermal conductivity of ice was first determined by Forbes in 1874, using a method proposed by Kelvin. A disc of ice, 12 inches in diameter, was formed by placing a freezing mixture about a vessel of water kept constantly at O° C. With suitable thermometers in the ice disc, the value of the conductivity, K, which he found was the following:—

Along principal axis.....	0.134
Perpendicular to axis.....	0.128

these were expressed in C.G. minute units.

Mitchell, in 1885, used Ångstrom's method of periodically heating and cooling the end of a bar of ice and de-

termining the period of the waves set up in the bar. He found in C.G.S. units the value .005 for the conductivity. F. Neumann used the periodic method with more success. He found for K. the value .00573 in C.G.S. units.

Straneo, in 1897, using the guard-ring method, found values for the conductivity of ice in two directions to be nearly the same, *i.e.*,

Along principal axis..... .0050 and .00517
Perpendicular to axis.... .00514

THERMAL CONDUCTIVITY OF ICE.

Observer.	Direction not given.	Along axis	Right angles to axis.
Forbes	.....	.00224	.00214
Michell	.005	.....	.....
Neumann	.00573	.....	.....
Straneo	.....	.0050	.00514
Straneo	.....	.00517	.....

Trouton found the conductivity of ice best along the principal axis in the ratio 22:21 thus confirming Forbes.

On account of its importance in meteorology, the conductivity of snow has received a great deal of attention.

Andrews, in 1885, determined the relative conductivity of ice and snow, found that of ice to be about 122 per cent greater than that of snow. In 1889, Hjeltström determined the conductivity by burying four thermometers, at different depths; and observed the temperature with great care from time to time. Taking the specific heat of snow as 0.50 and the density as 0.183, he found as a mean the value .00507 in C.G.S. units.

In 1891 Abels found that the conductivity was proportional to the square of the density of the snow, or that $K = .0067\ D^2$ in C.G.S. units.

Jansson, in 1901, determined the conductivity of snow by considering it as a fine powder and applying a method which had been worked out by Christiansen in 1881. The snow was placed between three circular copper plates into which thermo-junctions were inserted. The outer plates were maintained at the required temperatures in order to cause a measureable flow of heat across the snow. It was found that the conductivity K could

be represented by the following expression.

$$K = .00005 + .0019d + .006d^4$$

in C.G.S. units, where d is the density of the snow. It was further found by Jansson that the conductivity depended on the form and size of the crystals.

In 1905 Okada published the results of a careful series of measurements. He found that the density of snow varied with the depth according to the following order:

at	5 cm.	0.13
	25 cm.	0.24
	34 cm.	0.29
	45 cm.	0.35

Between 10 and 20 cms. the conductivity was found to be .00028, while for a depth of 20 to 30 cms. the value of K was .00045 in C.G.S. units. These results were found to agree with Abel's formula, which gives for the density determined by Okada the value, in one case of .00022, and in the other the value .00039. The formula of Jansson is not in such good accord.

Okada continued his studies of snow in 1907 and 1908 with thermometers buried vertically in the snow at an altitude of 113 meters. He measured the heat exchange and found it confined to the upper 30 cms. of snow. The average daily heat exchange is 19 calories per sq. cm. Whereas for other materials there is:

Moor soil	15 cals.
Sandy soil	24 "
Granite Rock	134 "
Snow clear day	24.3 "
Snow Cloudy	11.5 "

He found that the effect of density on the heat was small. The effect may be expressed in the formula—

$$D = .0039 + .00021\ t$$

Where D is the diffusivity and t the temp. centigrade.

Conductivity of Water.

The first absolute measurement of the conductivity of water was made in 1869, by Lundquist of Upsala, who

obtained, by a method due to Angstrom and used by him for metals, the value 0.0933 at a temperature of 40.8° Cent., in C.G. minute units.

Winkelmann in 1874, using Stefan's method for gases, obtained the value 0.0924 in the same units.

In two papers which were published in 1880 by H. F. Weber there is described a very careful series of measurements of the conductivity of water, and several other liquids. He placed the liquid between copper plates, which were maintained at a steady difference of temperature, and had suitable thermometers immersed in the liquid. A most careful study of the method was made previous to, and during the course of the work, and many possible sources of error corrected. He found that the conductivity decreased rapidly as the temperature was lowered, but the results he expressed in terms of the specific heat equal to unity over the range of his experiments. He determined the diffusivity at 4.1° Cent. to be 0.15619, which is a mean of ten determinations. Taking with him d = 1, s = 1, the value of K comes out to be 0.0745 in C.G. minute units. At 23.67° Cent. he finds for the diffusivity 0.17909, a mean of ten determinations, which gives for K the value 0.0857, taking d as 0.998 and s as 1.

When we take the true value of the specific heat of water, for the two temperatures at which Weber worked, we find at 4° Cent. his value changed to 0.0741, and for 23° Cent. 0.0859, the correction being to increase the difference between the values. In a third paper, published in 1880, Weber compares his results with those of Lundquist and Winkelmann, and in the case of the former investigator, he shows a very good agreement. After deducing a linear expression from his two measurements at 4° and 23° Cent., Weber exterpolated to 40.8° Cent., the temperature of Lundquist's experiments, and obtained the value 0.0953, or, corrected for the specific heat, the value 0.0950. This is quite close to Lundquist's value, which was 0.0937.

Winkelmann's value, which was 0.0924, does not agree with Weber's for the same temperature, which was 0.0745, or, corrected for specific heat, 0.0741.

A later determination of the thermal conductivity of water has been made by R. Weber (1903). He found the value 0.00131 in C.G.S. units between 35° and 12° Cent. The method employed was the usual one, and the author tried a large number of liquids as well as water.

TABLE OF THERMAL CONDUCTIVITY OF WATER.

Name	Date	Temperature	Value C.G.S. units.
Lundquist	1869	40.8° Cent.	.00156
Winkelmnn	1874	4.0° "	.00154
H. F. Weber	1880	4.0° "	.00124
"	1880	23.6° "	.00143
R. Weber	1903	24.0° "	.00131

COEFFICIENT OF EXPANSION OF ICE.

The earliest determinations of the coefficient of expansion of ice were made in 1845, by Brunner who obtained the value 0.0001125; in 1845, by Struve who obtained 0.0001593; in 1845, by Marchand who found 0.0001050; and in 1852, by Plucker and Geissler who found 0.0001585. These values represent the cubical expansion for ice near to the freezing-point in centigrade degrees.

Pettersson of Stockholm, in 1883, found that ordinary distilled water ice had a linear expansion of 0.000053 between −12° and −2° Cent. He claimed to have found that ice begins to contract at some point between −35° and −25° C. With ice made from the purest water the coefficient between −17° and −10° C. was .000055, which increased to .000057 between −4° and −3° and then decreased until it changed sign at a point just near the freezing point.

Andrews, in 1885, found that the coefficient of expansion increases rapidly towards the freezing point and becomes quite small at low temperatures. He obtained as his highest value .0002203 and lowest .0001064, giving a mean of .0001633.

Zakrzevski, in 1892, found the value for the cubical coefficient as low as .000077.

Nichols, in 1899, determined the expansion and found the value .0001620, while Vincent, in 1902, found .000152. We may safely assume that the coefficient is not far from .000160.

COEFFICIENT OF CUBICAL EXPANSION, PER 1° CENT.

Observer.	Coefficient.
Brunner	.0001125
Struve	.0001593
Marchand	.0001050
Plucker and Geissler	.0001585
Pettersson	.000159
Pettersson	.000168
Andrews	.0001633
Zakrzevski	.000077
Nichols	.0001620
Vincent	.000152

PLASTICITY OF ICE.

Early observations of the plasticity of ice were made by Bianconi in 1871. He caused rods and plates to be pressed into ice masses and, by having various shaped holes in the plates, observed prisms of ice issuing from these opening and bending over to meet the surface of the plate.

Pfaff, in 1875, made observations on the bending of ice bars. He noticed that when the temperature was near zero a very small force produced permanent deformation. A bar, 1.3 cm. thick and 51 cm. long, suspended with both ends free, bent in 24 hours about 2 mm. when the temperature ranged between $-12°$ and $-3.5°$ C. With the temperature between $-1°$ and $0°$ C., the bending was 9 mm. in the same time.

Some very interesting experiments were carried out in 1885 by Andrews, while engaged in measuring the conductivity and other physical properties of ice. He used a large ice block, on which he placed a polished steel rod, 16 inches long by 0.292 inch in diameter. The rod was made blunt at the end and rested under a weight of 181.5 pounds; this served to press it into the ice at a rate depending on the hardness. This experiment was carried

out at different temperatures and the depth to which the rod penetrated the ice under the varied conditions of temperature, compared with the penetrability at 0° C.,

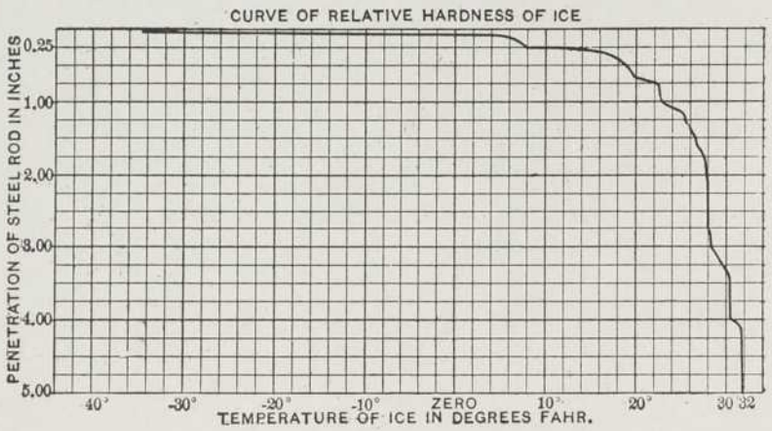


Fig. 10.—Andrew's Curve for Relative Hardness of Ice at Different Temperatures.

afforded a means of calculating the relative hardness of the pure ice. He found that ice is exceedingly hard from about −40° C. to about −9° C., after which its power of resistance rapidly decreases, giving way almost entirely at the melting point, where it becomes relatively very soft and plastic.

McConnell and Kidd in 1888, and McConnell alone in 1891, proved the plasticity of ice under tension. They showed that an ordinary bar of ice, composed of several crystals, will yield continuously either to pressure or tension. They found, however, that a bar, cut from a single crystal, with its length at right angles to the optic axis, showed no signs of continuous stretching, even under half the breaking tension; and this was also true of pressures, a crystal yielding in neither direction, for forces applied at right angles to the optic axis. A single crystal of ice has been termed by McConnell to be of perfect "brittleness."

The explanation offered by James Thomson, to account for the plasticity of ice, in the light of what is termed regelation, that is, the melting of ice under pressure, and the water flowing to other parts of the crystal to freeze again when relieved of the pressure, was found

not to accord with McConnell's experiments. This was especially so for his experiments carried out at very low temperatures.

The bending of a bar of ice was shown to take place by the sliding of a number of layers of finite thickness. To account for the distortion of the ice-bars in his experiments, McConnell was led to believe that a shear or slipping of the planes took place, giving rise to the observed plasticity. He proved this by obtaining the direction of the optic axis of the various crystals by polarized light.

One of the most interesting features of McConnell's work is the large amount of bending and recovery of ice, which was out of all proportion to known effects in other substances.

McConnell determined from his experiments what he called the plastic coefficient, or inverse of the viscosity. He gives as a value for this coefficient the number $A \times 10^{-11}$ cm. grm.$^{-1}$sec., where A lies between 1 and 10.

Elasticity.

The measurement of the elasticity of ice is a matter of some difficulty, on account of the permanent change of form which takes place under load. Using the method of bending moments, which is perhaps the most convenient one, far too great values for Young's modulus are obtained unless the readings are taken during the first few seconds. Thus Moseley, in 1871, give a value of 92700 in kilograms per square centimetre and Bevan the value 60000 Kg/cm^2.

Making use of sounding ice plates Reusch found the value 23632 Kg/cm^2, which was subsequently verified by the careful work of Hans Hess in 1902, who made an extended study of glacier ice. His work is of considerable interest and importance. He found that an ice bar cut from a block, when mounted in the usual way and loaded in the middle, showed a slow settling with time, after the first small deflection due to bending had taken place. The slow change went on regularly with time and

represented the gradual shearing of the cyrstals. The rate of change due to the shear was widely different for different loads. On removing the load the bar recovered somewhat at once and then continued to recover slowly for a few minutes. This was put down by Hess to residual elasticity.

The work of Hess was carried out on bars about 1.2. cm. thick, 2.5 cm. wide, and from 4 to 16 cms. long. The loads varied from 1 to 5 kilograms. The bars were cut with the crystalline axis parallel to the width, to the length, and to the thickness. Determinations of the modulus showed that this varied in the proportion of 1 to 3 to 5 for the cases where the principal crystalline axis was at right angles to the plane of the bending force in the direction of the bending force and when the plane of the axis was at right angles to the direction of bending force.

The values obtained by Hess are contained in the following table taken from his work "Die Gletscher." (1904).

MODULUS OF ELASTICITY.

Temperature.	Position of principal axis	cm^{-1} g sec. $^{-2}$	$\frac{kg}{cm^2}$
0 to −1	Length	$(1,82 \pm 0,10)10^{10}$	18200
−2 " −5	Length	$(5,90 \pm 0,50)10^{10}$	15900
0 " −1	Breadth	$(3,83 \pm 0,22)10^{10}$	38300
0 " −5	Breadth	$(4,18 \pm 0,23)10^{10}$	41800
−1 " −5	Thickness	$(2,54 \pm 0,12)10^{10}$	25400
−1 " −3	Large Grains	$(2,85 \pm 0,12)10^{10}$	28500
0 " −3	Small Grains	$(2,26 \pm 0,16)10^{10}$	22600

As a mean for all his observations in the three directions he gives

$$E = (2.76 \pm 0.17) \times 10^{10} \text{ cm.}^{-1} \text{ gr. Sec.}^{-2}$$

or expressed in the other units

$$E = 27600 \text{ Kg/cm}^2$$

K. R. Koch in 1914 made some experiments on the Elasticity of ice determining the bending moment on different specimens and at the same time finding their torsional oscillation. Great difficulties were found in the elastic after effect, and in permanent deformation even under small forces.

The results for ice cut with axis parallel to the frozen surface is

$$E = 957.6 \text{ Kg/mm}^2$$

For bars cut the other way

$$E = 1120.3 \text{ Kg/mm}^2$$

Results he obtained the previous year were about 50% different, which the author tries to account for in the actual temperature of the ice on the two seasons' results. He comes to the conclusion that ice may show differences in elastic properties especially as it is a crystalline substance.

The torsional modulus of a rectangular bar with its axis parallel to the frozen surface is

$$F_{90} = 300.15 \text{ Kg/mm}^2$$

For the bar the other way

$$F_{90} = 278.0 \text{ Kg/mm}^2$$

Viscosity of Ice.

It has been well established that ice behaves as a viscous solid quite apart from any effect due to regelation on the movements of glaciers. This matter has been the subject of some controversy. Tyndall claimed that ice was not viscous, basing his argument on the fact that glaciers always cracked when subjected to tensile stress no matter how slow.

McConnell was among the first to show that ice is capable of being deformed without fracture by a stress. He showed that an ice crystal can be sheared by very small stresses in a direction at right angles to the optic axis. His main results show that the viscosity of the ice becomes greater as the temperature falls and that the cube of the friction of the sliding ice molecules varies as the square of the velocity. The coefficient of viscosity, as determined by McConnell, has recently been recalculated by R. M. Deeley, and is found to lie between 3×10^{10} and 134×10^{10} in C.G.S. units.

Hess, in 1902, determined the viscosity and found that under the loads he used the viscosity coefficient in-

creased a little with the duration of the experiment. With large loads, near to the breaking point, he found that the viscosity coefficient decreases with the load. Over the range of his experiments he found the viscosity to be of the order 10^{10} in C.G.S. units, the exact values depending on the load and on the duration of the experiment.

B. Weinberg, in 1905, determined the viscosity of ice by a torsional method. Ice was cut into cylinders and prismatic rods with their lengths parallel to the optic axis. One end was fixed and the other subjected to a twist. Attention was paid to the effect of temperature and the following expression was given

$$u = (1.244 - 0.502T + 0.0355T^2) \times 10^{13} \text{ gm./cm. sec.}$$

He gives Young's modulus also as

$$5 \times 10^9 \text{ at a temperature of } -1^\circ \text{ C.}$$

In a further study of the viscosity of ice, Weinberg, in 1907, discusses the relation with the shearing rate and shows that this has a connection with the relaxation theory as developed by Maxwell and Schwedoff. Judging from the value of the coefficient of viscosity, the author concludes that the critical velocity of the ice current in a glacier must be of the order of the velocity of light.

Small values of the rigidity, of the limit of elasticity and the viscosity, and the greater influence of the temperature, is regarded by the author as an indication of the weakness of the limiting regions between the individual grains, and of a "wet" friction produced by regelation in addition to the "dry" friction. He shows that the latter form of friction is possible in ice on account of the gradual shearing in directions normal to the optic axis, when local excess of pressure is quite excluded.

R. M. Deeley, in 1908, has given some calculations of the viscosity of the ice of the Swiss glaciers. A viscosity of 125×10^{12} is as near an estimate of what he calls the average effective viscosity of such a form of ice as can be given. In winter he concludes that it is probably doubled owing to low temperature.

From actual experiments carried out with pitch, which he compares with McConnell's experiments, he considers that the nature of the shear produced in an ice crystal at right angles to the optic axis very closely obeys the law of viscous flow. If this view is further verified he points out that it means, in the case of crystalline ice, that a solid may be liquid along one plane only, resembling the case pointed out by H. A. Miers, that a liquid of low viscosity may have a crystalline structure.

Deeley gives, as a result of a study of McConnell's work, the viscosity of an ice crystal in a direction at right angles to the optic axis as

$$2 \times 10^{10}$$ at the freezing point.

At this temperature, the viscosity of a glacier is about 12500×10^{10}, or some 6250 times as much. This, he thinks, may be due to the fact that the optic axis of glacier grains are at all angles and lock each other.

Hess showed that the admixture of sand and dust with ice increases the viscosity; hence he concludes that the plasticity of glacier ice near the ground is less than for that higher up. Since the viscosity of ice increases with the time for slow steady application of small loads, Hess calculates from his experiments that the coefficient for long flowing glacier ice must be of the order of $a \times 10^{15}$ where a lies between 1 and 100. Hence he concludes that for long continued loads the viscosity of ice compares with steel, being 6×10^{18} and that for zinc being 4×10^{11}.

ELASTICITY AND VISCOSITY.

Observer	Kind of Ice.	Young's Modulus.	Viscosity.
Moseley		92700 Kgs cm-2	
Bevan		60000 "	
Reusch	Clear ice	23632 "	
Hess	Clear ice and glacier ice	27600 "	
McConnell	Ordinary ice		$\frac{3 \times 10^{10} \text{ gm}}{\text{cm.sec.}}$
McConnell	"		134×10^{10} "
Hess	"		order of 10^{10} "
Weinburg	"	5000 "	1.24×10^{10} "
Deeley	Glacier ice		1.25×10^{10} "

Observations were made by Hess to determine the dependence of the velocity of flow on the pressure. For this purpose an iron tube 25 cm. long and 6 cm. wide, with a conical orifice running down to 4.5 cm., was ar-

ranged. Pure air-free water was frozen in the tube, and a piston was fitted in one end to which a long arm weighted with 87.5 kilograms, was attached. During the experiment the tube was surrounded with pure snow. The flow was found to increase very rapidly with increased pressure, and it was found that, once the flow had started, a comparatively small pressure was sufficient to maintain it.

With a pressure increasing 28.6 to 42.0 kilograms per square centimetre the piston moved from 0.000013 cm. per second after the first four minutes, to 0.00717cm. per second after four hours. The portion of the ice forced out of the narrow orifice was found to be quite different in structure to the ice inside the cylinder. The latter was clear and homogeneous, while the expelled ice was cracked and broken into grains.

After long-continued pressure, however, the outflowing ice was as compact and clear as that in the cylinder which must indicate some definite change in structure with time under the increased pressure.

Similar to the experiments of Hess, and at about the same time (1902), G. Tammann studied the velocity of flow of ice, during the course of his experiments on the flow of crystalline substances. It was clearly demonstrated that the plasticity of ice is relatively small, but that near the melting-point it rapidly increases. Like Hess, he enclosed ice in a steel cylinder with a small orifice at one end, out of which it was made to flow under pressure. It was observed that, no matter what the pressure, up to the pressure corresponding to the melting-point for the particular temperature of the experiment, a sudden rapid increase in flow took place.

He obtained the following results for different temperatures indicated in the table.

Temperature	Pressure in kilos per sq. cm.	Highest pressure of steady flow.	Melting pressure in kilos per sq. cm.
− 5.7° Cent.	665	642	678
−10.7 "	1130	1116	1225
−15.7 "	1729	1611	1681
−21.7 "	2100	2000	2070
−27.6 "	2240	2220	....

The second column shows the pressure at which the rapid increase of flow took place, and represents very nearly the pressure which would be required to bring ice down to the melting-point corresponding to the temperature of the experiment. The third column represents the highest pressure of steady flow corresponding to the particular temperature, and, by comparison with the second, shows how suddenly the ice yields. The last column gives the pressure from the melting-curve.

Viscosity of undercooled water was obtained by R. H. Twining in 1913 by a new viscometer. Values for water from 0° to −9.30° C. as well as from 0° −20°. No particular anomaly is noticed in the experiments.

Tensile Strength and Compressibility.

From the researches of Pfaff it was shown that an ice bar stretched under a force of 1 Kg. per sq. cm. in seven days by .022 of its length during a time when the temperature was near 0° C.

Fabian, in 1877, showed from a study of the extensibility and elasticity that under a load of 0.5 Kg. per sq. cm. ice behaved very nearly as a completely elastic body. Under a load of 30 Kgs., which was 1.5 Kgs. per sq. cm., the temporary extension was 0.0633, while the permanent extension amounted to .030 mm. A rupture of the bar took place when it had extended by 1/5000 of its length under a load of 2.5 Kgs. per sq. cm.

As a result of his experiments Hess placed the tensile strength of ice as high as 7 to 8 Kgs. per sq. cm., and the compressibility as 25 Kgs. per sq. cm.

The crushing strength of ice, as determined by U.S. testing machine, has been given as ranging from 327 to 1000 pounds per square inch.

The strength of surface ice has been lucidly expressed in the following way: 1.5 inches will support a man; 4 to 5 inches will support cavalry and guns; 6 inches, wagons drawn by horses; 18 inches a railroad train, (Compare Chapter 7 on Ice Pressure.)

Colour and Refractive Index of Ice.

Pure ice is colourless to white and pale blue in large masses. It is transparent, being optically uniaxial, crystallizing in the hexagonal systems and showing a positive character as regards its indices of refraction. Passing over the early work of Brewster, Wollaston and Fraunhofer we have that of Reusch, in 1864, who measured the indices of refraction for the ordinary and extraordinary ray and found:

	Index of Refraction.	
Character of Light.	Ordinary Ray.	Extraordinary Ray.
Red	1.30598	1.30734
Green	1.3120	1.3136
Violet	1.321	1.321

The effect of temperature is to decrease the refractive index slightly.

Electrical Properties of Ice.

Insulating Properties.—Ice appears to be a good insulator. Thus telephone cables, which are defective through moisture, become perfectly right when the air temperature falls below freezing. S. P. Bouvier, in 1803, showed that ice could not be used to replace water in the dry pile. Dellmann, however, in 1864, investigated the insulating properties of ice and found them the same as water even down to 8 or 10 degrees below freezing, which does not seem to accord with practical experience.

Dielectric constant.—The dielectric constant of ice at $-24°$Cent. has been found to lie between 60 and 78, values not far from pure water.

F. Beaulard, in 1905, made a determination of the dielectric constant of water, which he extended to ice in 1907. His method was to contain the substance in an ellipsoid glass vessel, suspended in a high frequency alternating electrostatic field. The axes of the ellipsoid were all inclined to the field. The couple acting on it was determined when the vessel was empty and then when it contained the substance. The result obtained is given at 11.04, the low value of which as compared to the gen-

erally accepted value 80, the author puts down to polarisation effects in the usual methods of measuring dielectric constants.

The best work which has been done on the conductivity of ice was by J. H. L. Johnstone in 1912 at Halifax in H. L. Bronson's Laboratory of Physics.

The fall of potential method was used similar to the well-known Kelvin conductivity bridge which made the results independent of polarization. This fault was found by Bronson to be very large and difficult to handle in a conductivity cell. The temperature coefficient of the resistance was also measured, and found to be much larger than for an ordinary electrolyte. The procedure was to fill a special cell with completely purified water and freeze it *in situ*. To avoid cracking the glass walls by the expansive force of the freezing, a rubber tube was inserted, and acted as a lining. The water was introduced and then frozen, the air liberated through a small hole in the rubber tube.

Special prepared conductivity water was used which measured, as high as,

$$1.4 \times 10^6 \text{ ohms at } 17.9^\circ \text{ C.}$$

The specific resistance of the ice was found to be at 0° C., 0.367×10^8, and at -19.3° C., 3.86×10^9.

Its value at 11° C. being very nearly one thousand megohms or one thousand million ohms.

Johnstone's values agree very well with those of Ayrton and Perry in 1877.

P. Thomas in 1913 determined the electrical properties of ice, amongst a number of materials, and found for the dielectric constant at 1000 cycles, the value 86.4.

The resistance found was 7.22×10^7 ohms, and the break down voltage $.011 \times 10^6$ volts per cubic cm.

Vapor Pressure of Ice and Water.

Measurements and calculations of the vapor pressure of ice and water have been made by Regnault, Jublin,

Marvin, Theisen and Sheel, and Ekholm. Dr. Washburn in his paper on the subject 1925, calculates the v.p. from thermodynamics based on the measurements of Weber, (1915) and Sheel and Heuse (1909).

TABLE OF VAPOR PRESSURES.

Of Ice.			Of Water.	
0°	4.579	Washburn	4.579	Washburn
−10	1.950	"	2.149	"
−20	0.776	"	0.960	Sheel.
−30	0.286	"	.....	
−40	0.097	"	.....	
−50	0.030	"	.....	

Experiments by S. Weber (1916) carry the vapor pressures to −193° C. His values are given at the following temps.

Temp.	V. Press.	
0° C.	4.579	mm.
−25	0.480	"
−63	0.003	"
−98	0.000015	"

His results agree with the Nernst vapor pressure formula.

BACTERIOLOGY OF ICE.

Ice is a crystalline solid and cannot therefore contain foreign material. The persistant tirade against the safety of using ice as a food is foolish and unwarranted by the facts. The chemist crystallizes his product to purify it, and nature purifies water by the same process.

Public distrust is fostered by the absurd general statements in medical books on bacteriology as to the danger of using ice for cooling drinks, but when the facts are sifted, it is found that in history only two epidemics have been directly caused by using ice, and they were by no means severe ones.

Ice is a far safer food than either water or milk, and the public runs much less risk from its use, than from its milk supply. The trouble comes from improper harvesting of natural ice from localities infested with weeds and dirt, which become frozen in between the ice crystals.

In the manufacture of artificial ice there is usually an opaque core into which all the foreign matter from the water has been thrust, and in which it is retained. In natural ice, frozen from a flowing river or deep lake, all foreign matter is expelled, on the underside, and it is only the top dressing of snow ice, which contains the impurities.

An ice crystal cannot form unless it is absolutely devoid of foreign matter, and in a large sheet of clear ice, it is the space between the crystals where salt or bacteria can be retained. There are several things which keep ice free from infection: (1) The temperature is below the point, where bacteria can multiply; (2) The manner of formation, layer by layer, tends to expel both bacteria and air; (3) The rigidity of the structure prevents the bacteria from moving, and consequently they soon perish in an air free environment; (4) Solid ice cannot be infected by handling for the surface is continually washing itself free of polution.

There is no possibility of even an obnoxious odor penetrating the ice, any more than so much rock.

All these factors contribute to the safety of using ice and nature has nowhere provided a substance of greater purity, or beauty.

The bacteria which are found frozen in impure ice are:

1. B. Colis Communis
2. Typhoid bacillis
3. Sewage Streptococci

These three indicate sewage contamination.

There has been a considerable amount of work done on the question of the safety in using ice. It has been found these bacteria are reduced in number vary rapidly, when frozen into a mass of ice, and are killed or rendered non-virulent, after a few weeks storage.

Thus Dr. Sedgwick finds that B. Coli are killed after 12 weeks, and Typhoid after 9 weeks storage. That ice purifies itself on standing is well known, and even sea water ice will become quite pure after 5 years. Storage

of water is also found to have a purifying influence, and it is now known that an adequately stored water is a safe water. Ice which is stored for three months, has the additional advantage of the initial purification, when first frozen.

My own tests on the water from melted ice shows it to be so closely allied to the purest distilled water, that it is indistinguishable from it by a chemical examination. Provided ice is clear of air pockets, it may be safely used, even when frozen from a polluted source.

Bujwid, in Warsaw, found hailstones to contain 21000 bacteria per cubic centimetre, and Foutin, in Petrograd, found 729. While rain was found to contain only a small number, from 4.3 −19 per c.c.

This is what we would expect, as the hailstone is frozen around a mass of slush ice, and retains the original nuclei, from which it was started.

Repeated tests of the bacterial content of great blocks of clear St. Lawrence river ice give negative results, that is, complete sterility. Ice cut on Lake Ontario, in Toronto Bay, shows a high bacteria count on the upper snowy crust, but a few inches lower in the clear ice, absolutely sterile, which proves the immobility of the imprisoned bacteria.

Melted ice makes an excellent substitute for distilled water or rain water, for washing, or as a solvent, and it is useful for storage batteries. Indeed the writer has frequently added the acid to solid ice in mixing battery fluid and thus avoided the great heat which accompanies the same thing with water.

CHAPTER III

RATE OF GROWTH AND MELTING OF SURFACE FORMED ICE.

Infra-red Absorption of Ice, Various Kinds of Ice.

The formation of a surface sheet of ice on an expanse of quiet water, with the advent of cold weather, is exceedingly beautiful. As the season advances, the mass of the water drops in temperature, lagging somewhat behind the temperature of the air. The loss of heat to the cool atmosphere takes place by radiation and conduction from the surface. In the interior the convection currents play the most part in causing the temperature to fall, and these result in a fairly uniform distribution of temperature throughout the mass.

The convection process stops when 4° Cent., or 39° Fahr., is reached and passed, and the colder layers remain at the top. The surface in contact with the air then becomes cooled more than the interior, and finally reaches the freezing-point.

The abstraction of heat from the surface goes on at a rate much faster than can be kept up from the interior of the mass, and very soon long needle crystals of ice shoot out over the top of the water from the banks towards the centre. These ramify and divide, and form lateral crystals until the whole surface becomes coated with ice. The process of solidification then proceeds, the surface layer becoming more compact, until the water is entirely protected by a thin blanket of ice. Thickening of the ice sheet takes place downwards by conduction of heat through the ice, and to a certain extent upwards by accumulations of snow.

It is a most interesting sight to observe the approach of the ice mantle from all sides towards the centre. In

the case of very large bodies of water, it happens that frequently the border ice never meets, being prevented from doing so, either by the mildness of the climate, or by continual wind agitation. The formation of the first ice near the shores is helped very much by rapid convection of heat by the air. Cold currents of air, warmed by the water, rise rapidly from the centre, and are replaced by cold air which sweeps in from the sides. On account of the increased temperature, which the air attains as it moves over the open surface towards the centre, it follows that the centre is subjected to less cooling than the edges, over which the cold air sweeps from the countryside. Without doubt the direction of wind affects the conditions, and its direction may be observed in the formation of the first ice on an open lake or river.

The conduction of heat away from the water to the shore, which has been given as the cause of the formation of border ice, can have but an infinitesimal effect when compared with the immense stream of convection currents. We know what bad conductors rock and sand are, and what a small quantity of ice could be formed by conduction of heat to the edges.

Probably the most usual way for the first ice cover to form, particularly on a flowing stream or on a wide lake where the full effect of a strong cold wind is felt, is the accumulation of frazil or anchor ice together with snow or scum ice formed by the wind. This floats down on the surface, and gradually accumulates in great fields which quickly "set" in a solid frozen sheet.

The ice sheet grows continually in thickness as the winter advances, and this growth is brought about almost solely by conduction. Radiation ceases when the ice forms, because it is seldom clear, and is usually covered by snow. The heat-rays do not penetrate such an opaque mass, but are reflected back by the irregular masses of ice crystals or snowflakes. A clear ice-sheet, however, would readily transmit some of the heat-rays and make the loss of heat go on faster.

We have seen that the conduction of heat through ice is very small, and, were it not for the accumulation

of snow and rain on the surface, and the freezing to the under side of fine crystals of ice carried under by currents in a river, the ice sheet would grow in thickness very slowly.

It is possible to calculate approximately the rate at which a sheet of ice will thicken by conduction alone to a cold atmosphere.

The problem has been worked out by Dr. S. Tetsu Tamura, in a paper on "The Mathematical Theory of Ice Formation," published in the Monthly Weather Review for February, 1905, where it is shown how difficult it is to obtain an adequate mathematical expression which can be applied to actual conditions in nature.

Considering a surface of open water subjected to a cold atmosphere, the problem is to calculate the thickness of ice, E, which will form in a time t. After the first formation of ice the sheet increases in thickness by conduction through the ice. If it is assumed that the temperature of the ice increases uniformly from its upper surface downwards, the quantity of heat, $\frac{K\theta}{E}dt$ will flow upwards through the ice in a time dt.

In the same interval of time a layer of ice whose thickness is dE is formed. Here K represents the thermal conductivity of the ice, and θ the temperature of the air, or upper surface of the ice, which must be less than O° Cent. The quantity of heat, $\frac{K\theta}{E}dt$ is drawn from the water which is in contact with the ice at O° Cent., and is equal to $LSdE$, where L is the heat of fusion, and S is the density of ice.

Therefore $$\frac{K\theta}{E}dt = LS\,dE$$

from which $$E^2 = \frac{2K}{LS}\int_0^t \theta\,dt$$

As long as θ remains constant,

then $$E = \sqrt{\frac{2\theta Kt}{LS}},$$

a simple formula for calculation.

A useful formula, for calculation, which is based on an analysis of the actual observed data for the growth of an ice-sheet, and which we have found to hold quite accurately for fairly large temperature differences, is as follows:—

$$t = \frac{LSE}{K\theta}\left(1 + \frac{E}{2}\right)$$

where t is the time in seconds for the ice sheet to attain a thickness E centimeters;

L is the heat of fusion, 80 calories;

S is the density of ice, 0.9166;

K is the conductivity of ice, 0.0057 calorie per degree difference of temperature, per square centimeter, per second;

θ is the difference in temperature, centigrade, between the under side of the ice sheet, O°, and the air temperature. (Equivalent simply to the air temperature.)

In the following table will be found the time taken for an ice sheet to grow in thickness, indicated in the first column, when the air temperature is that given by the upper line.

The calculations are made on the assumption that the surface is clear of snow, and water at O° C.

The table is useful in giving a maximum value for the thickness of ice that would form at any place, having found the mean air-temperature over the period of time considered.

RATE OF GROWTH OF ICE-SHEET.

Thickness of Ice.	TEMPERATURE			
	−10° Cent.	−20° Cent.	−30° Cent.	−40° Cent.
1 inch.....	2.06 hours	1.03 hours	41.2 min.	30.9 min.
6 inches.....	1.95 days	23.41 "	15.61 hours	11.71 hours
10 inches.....	5.19 days	2.60 days	1.73 days	1.29 days
1 foot.....	7.38 "	3.69 "	2.46 "	1.85 "
2 feet.....	28.60 "	14.30 "	9.53 "	7.15 "
3 "	63.69 "	31.85 "	21.23 "	15.92 "

The following treatment of the problem is due to Prof. L. V. King, of McGill University, who worked out this method while engaged in making ice observations during one of our Government ice breaking expeditions, in the St. Lawrence river in 1910. The results are of much interest and importance in directing further scientific work in this line.

Mathematical theory of the Rate of Growth of Surface Ice as developed by Dr. King

Although it would seem to be a simple matter to measure the rate of thickening of a sheet of ice over water, the difficulty is, rather, one of lack of opportunity than difficulty of measurement, especially if it is desired to obtain data under conditions which actually exist in the formation of ice over rivers and lakes. A series of measurements of the rate of growth of surface ice from the Canadian Government ice-breaker, "Lady Grey", stationed at Quebec lead to an investigation of these results which extended the theoretical formulae representing the formation of surface ice hitherto given by introducing the effect of small temperature effects in the water, radiation and humidity effects.

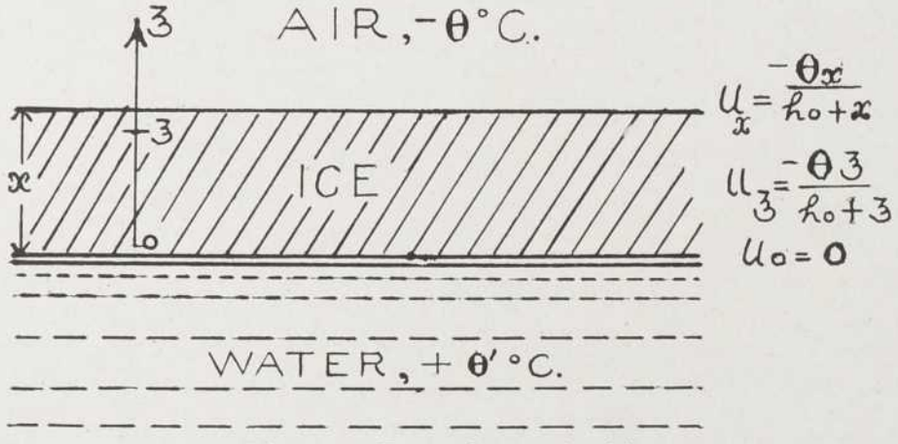


Fig. 11.—Rate of growth of ice.

Let us consider a sheet of thickness x cms. exposed to the air at temperature $-\theta$°C. and to water at temperature $+\theta^{01}C$. Taking a vertical prism of unit cross section we examine the loss or gain of heat to which a layer of water about to turn into a thickness dx of ice is subject.

(1) The main factor in ice formation is the loss of heat from dx due to conduction through the ice into the air.

(2) The growth of ice will be affected by loss or gain of heat due to convection-currents in the water.

(3) There will be a cooling effect due to evaporation from the surface of the ice. This will be affected by the relative humidity of the atmosphere and by the velocity of air-currents over the surface of the ice.

(4) Finally there will be a loss or gain of heat due to radiation. This will include the effect of radiation to the layer dx from the atmosphere and conversely.

The effects (2), (3), and (4) are small in comparison with the loss or gain of heat by conduction and may be regarded as small corrections to the latter. Although it would be possible to include terms representing these corrections in a general differential equation, the result would be too complicated to be easily intelligible. Hence we will work out the growth of ice when it loses heat by conduction alone, and then estimate how the result is modified by each of the factors (2) and (3) taken separately.

The Formation of Ice due to Loss of Heat by Conduction alone.

The variation of θ^{01} from zero is so small that as far as conduction of heat is concerned we may consider a slab of ice of thickness, x kept at zero on one face and losing heat to the air at the other. Taking an origin in the face kept at zero and measuring ζ vertically upwards, we have, if u be the temperature at ζ, $\frac{d^2u}{d\zeta^2} = 0$ with $u = 0$ when $\zeta = 0$.

The quantity of heat dQ_1 flowing through unit cross-section in time dt is

$$dQ_1 = -K\frac{du}{d\zeta}dt$$

where K is the conductivity of ice.

The boundary condition between the ice and air is specified by Newton's Law of Cooling, which states that, at the boundary the rate of loss of heat is proportional to the difference of temperature between the surface of the conductor and the air-temperature at a distance. This law holds fairly well so long as this temperature-difference does not exceed 20° or so. Thus at the boundary $\zeta = x$ we have an equation of the form

$$\left(\frac{du}{d\zeta}\right)_{\zeta=x} + \frac{u+\theta}{h_0} = 0$$

where h_0 is an experimental constant depending on the surface conductivity between ice and air, the suffix$_0$ indicating that the water is exactly at the freezing-point 0° C.

We find at once that

$$u = -\frac{\theta\,\zeta}{h_0+x} \qquad (1)$$

so that the rate of loss of heat due to conduction is given by

$$dQ_1 = \frac{K\,\theta}{h_0+x}\,dt \qquad (2)$$

In general h_0 will depend on the velocity of air-currents, relative humidity, etc. In order to make the problem precise we take h_0 to refer to ice forming in still air, saturated near the surface of the ice, so that there is no cooling effect due to evaporation.

If the surface $\zeta = x$ were kept at a temperature $-\theta°$ we should have $h_0 = 0$ and $u = \frac{-\theta\zeta}{x}$, with $dQ_1 = \frac{K\theta}{x}\,dt$.

The physical interpretation of h_0 is now obvious; the flow of heat from the ice into the air at temperature $-\theta$ is the same as if a thickness h_0 were added to the conductor and the surface kept at the temperature $-\theta$, the water-ice surface being at zero.

When the layer dx has become ice, the latent heat given out is $\rho L\,dx$, where ρ is the density of the ice and L its latent heat of fusion.

Equating this to (2) we have

$$\frac{K\theta}{h_0+x}\,dt = \rho L\,x \qquad (3)$$

giving at once the expression,

$$\frac{K}{\rho L}\int_0^t \theta\, dt = x\left(h_0 + \frac{x}{2}\right) \tag{4}$$

which makes $x = 0$ when $t = 0$.

In this form the result corresponds to the formula given by Barnes and gives the same result if we take $h_0 = 1$ cm.

In order to calculate x being given t and corresponding values of θ, the formula may be written

$$(x + h_0)^2 = \frac{2K}{\rho L}\int_0^t \theta\, dt + h_0^2 \tag{5}$$

The equivalent layer h_0 may be determined from a series of observations of the growth of an ice sheet: thus if we have an observed (x, t) curve, h may be determined in terms of the initial slope, since

$$h_0\left(\frac{dx}{dt}\right)_{x=0} = \frac{K\theta_0}{\rho L} \tag{6}$$

In terms of the initial slope (5) may be written

$$(x + h_0)^2 = 2h_0\left(\frac{dx}{dt}\right)_0 \frac{1}{\theta_0}\int_0^t \theta\, dt + h_0^2 \tag{7}$$

or

$$\frac{x^2}{2h_0} + x = \left(\frac{dx}{dt}\right)_0 \frac{1}{\theta_0}\int_0^t \theta\, dt \tag{8}$$

which shows the character of the curve of growth when x is small.

The Effect of Convection on Ice Formation.

Precise measurements to $\frac{1}{1000}$th of a degree have shown the existence of variations of the order of $\frac{1}{100}$ th of a degree C. about zero in the temperature of the St. Lawrence River during winter. θ' is usually positive, but in very cold weather the water may become slightly undercooled, and θ' may become negative. Although the effect of θ' is negligible in the conduction effect, this

contribution of heat to the layer dx may become considerable, should the water under the ice be in motion, as for instance, in the case of a fixed sheet forming over running water. If we assume, as we have done, in the case of the air-boundary, that the escape of heat from the water at θ' into the layer dx at 0° is proportional to the temperature difference θ' we may write, if $dQ_2 = C dt$ represents a gain of heat due to convection,

$$dQ_2 = C\,dt = \frac{K\,\theta'}{h^1}\,dt \qquad (9)$$

Here h^1 refers to the surface conductivity between ice and water and will in general depend on the velocity of currents under the ice.

In order to take into account the effect of convection we must subtract a term $C dt$ from the left hand side of (3), in which h refers to the ice-air surface conductivity in the new conditions. The differential equation is modified

$$\frac{K\,\theta\,dt}{h+x} - C\,dt = \rho L\,dx \qquad (10)$$

to θ and C are in general functions of t and the differential equation is of the type

$$\frac{d\zeta}{dt} + \frac{P}{\zeta} = Q$$

where P and Q are functions of t. This equation cannot be integrated in full generality.

If we take C = const. and θ = const. the solution of the differential equation (10) may be written,

$$\frac{Ct}{\rho L} = -\frac{K\theta}{C}\log_e\left\{1 - \frac{Cx}{K\theta - Ch}\right\} - x \qquad (11)$$

giving $x = 0$ when $t = 0$.

In practice θ may be taken to be the mean temperature throughout the interval 0 to t. The solution in this form shows that, if C be positive, as when there is a gain of heat due to convection, the ice will attain a *limiting thickness* given by

$$\bar{x} = \frac{K\theta}{C} - h = \frac{h'\,\theta}{\theta'} - h \qquad (12)$$

In integrating the above equation we have assumed θ constant. The limiting thickness $\bar{x}$ will depend on the

average value of θ throughout a long interval, and will be practically independent of fluctuations of temperature throughout short intervals. In terms of $\bar{x}$ the differential equation (10) becomes

$$\frac{\rho L}{K\theta}\frac{dx}{dt} = \frac{1}{h+x} - \frac{1}{h+\bar{x}} \tag{13}$$

and when $x = 0$

$$\left(\frac{dx}{dt}\right)_0 = \frac{K\theta_0}{\rho L}\frac{\bar{x}}{h(h+\bar{x})} \tag{14}$$

The solution, equivalent to (11) may be written

$$\frac{K}{\rho L(\bar{x}+h)}\int_0^t \theta\, dt = -(\bar{x}+h)\,\log\left(1-\frac{x}{\bar{x}}\right) - x \tag{15}$$

or

$$\frac{h}{\bar{x}}\frac{1}{\theta_0}\left(\frac{dx}{dt}\right)_0 \int_0^t \theta\, dt = -(\bar{x}+h)\,\log\left(1-\frac{x}{\bar{x}}\right) - x \tag{16}$$

which takes into account to a first approximation, the variations of θ with the time.

The departure of an observed (x, t) curve from the theoretical parabolic curve (7) and (8) enables us even in the early stages of ice formation to calculate the limiting thickness $\bar{x}$, if the actual curve is such, that we may attribute its defect from the parabolic curve, to a convection effect from water to ice.

In order to calculate $\bar{x}$ from an observed value of x and t we must solve a transcendental equation.

We suppose as a first approxination that the water is exactly at O° C. so that h_0 may be calculated from the initial inclination of the (x, t) curve by (6). Substituting in (14) we find

$$\bar{x} = \frac{h^2}{h_0 - h} \tag{17}$$

Substituting for $\bar{x}$ in (16) we have to find h from the transcendental equation

$$f(h) = \frac{-h^2}{(h_0-h)^2}h_0\,\log\left\{1-\frac{x}{h}\left(\frac{h_0-h}{h}\right)\right\} - x\frac{h}{h-h_0} - \frac{1}{\theta_0}\left(\frac{dx}{dt}\right)_0\int_0^t \theta\, dt = 0 \tag{18}$$

The Effect of Atmospheric Humidity.

The effect of evaporation from the surface of the ice, is to diminish the surface temperature, by an amount η°C. depending on the relative humidity of the air, in immediate contact with the ice. This diminution is of the order of the depression of the dry and wet bulb thermometers, under the conditions of temperature, and relative humidity, existing at the surface of the ice. An inspection of hygrometric tables shows that this depression η° may amount to as much as 1° C. Now the surface temperature above zero of ice forming in saturated air, is for a thickness x.

$$u_x = \frac{\theta x}{h_o + x}$$

It will be seen later that, h is of the order 6.5 cms. Thus when x is small in comparison with h, u_x is a small fraction of a degree above freezing, so that η° may be quite comparable with u_x.

It will be seen that the cooling due to surface-evaporation will have a very sensible effect on the early stages of ice formation. The temperature drop η due to evaporation will in general, depend on the air temperature at the surface of the ice, and so long as x is small will be a function of x as well as of t.

In reality the temperature at the surface of the ice, is higher than the recorded air temperature at same distance from the ice, especially when the ice is thin. The relative humidity of the air at the surface of the ice, will be diminished; evaporation will take place with greater rapidity, so that the cooling effect will be greater than the depression of the dry and wet bulb thermometers. This statement is supported by the fact that dense clouds of hoar-frost emanate from the surface of open water and *thin ice* in cold weather, (θ below +10° F.) The air in contact with the water and thin ice is warmed to some extent, and so is able to take up more water vapor than it can contain when it is carried by convection into the colder portions of the atmosphere. Thus even when the relative humidity of the air is 100 per cent., evapor-

ation may still go on over water, and over ice which is thin enough to transmit sufficient heat to warm sensibly the air in immediate contact with it.

Let u_x' be the surface temperature of ice of thickness x for a relative humidity corresponding to a cooling effect η. The loss of heat from the layer dx is $dQ_3 = \frac{K u'_x}{x}$ if η be the cooling effect we have $\eta = u_x - u'_x$ where u_x refers to the surface temperature in a saturated atmosphere, *i.e.*

$$u_x' = \frac{\theta x}{h_o + x} + \eta$$

and
$$dQ_3 = K\left(\frac{\theta}{h_o + x} + \frac{\eta}{x}\right)dt,$$

where h_o refers to the surface conductivity in a saturated atmosphere with the water at O° C. while the differential equation becomes

$$K\left\{\frac{\theta}{h_o + x} + \frac{\eta}{x}\right\}dt = \rho L\, dx \qquad (18)a.$$

We notice at once that the effect of η is to make the (x, t) curve cut the axis of t at right angles and to influence greatly the first part of the curve.

To obtain a *lower limit* to the effect of relative humidity, we may take η° to be the actual depression of the dry and wet bulb thermometers, corresponding to temperature $-\theta$ and the observed relative humidity. We have seen that the cooling effect will be considerably greater than this, especially when x is small.

We have
$$\frac{K}{\rho L}dt = \frac{1}{\theta + \eta}\frac{x(x + h_o)}{x + \epsilon h_o}dx$$

where
$$\epsilon = \frac{\eta}{\theta + \eta} \qquad (19)$$

With the solution

$$\frac{K}{\rho L}\int_0^t (\theta + \eta)\, dt = \frac{x^2}{2} + h_o(1 - \epsilon)x - h_o^2\epsilon(1 - \epsilon)\log\left(1 + \frac{x}{\epsilon h_o}\right) \qquad (20)$$

expressing to a first approximation the variation of θ and η with the time.

A more exact theory should be based on the rate of evaporation from an ice sheet under known conditions

of air temperature, surface temperature, relative humidity and wind velocity. Such data, of great meterological interest, are, however, still lacking.

The Effect of Radiation

The layer dx is capable of losing heat to, or gaining heat from the atmosphere by direct radiation through the ice. Owing however, to the lack of experimental data on the diathermancy of ice for long heat rays, and how the transmission of radiation is affected by its thickness, it is difficult to estimate the effect on ice formation, arising from this cause. We know, however, that both ice and water, transmit radiant heat poorly. A very small thickness of water (1.8 mm.) will cut down 90 per cent. of the radiation, from a red-hot platinum spiral, while the remaining 10 per cent. is transmitted without much loss by increasing thickness of water. The general effect of thickness on transmission, is shown in the table given below.*

*Preston: "Heat," p. 559.

TABLE I.

LIQUID	THICKNESS IN CENTIMETRES.				
	.051	.10	.18	.36	.69
Carbon Bisulphide	94.5	91.6	87.5	84.8	82.7
Chloroform	83.4	75.0	65.0	60.0	55.2
Benzole	56.6	44.3	57.5	29.5	26.4
Water	19.3	15.9	11.2	9.0	9.0

It would seem by plotting the curves from this data that the loss (or gain) of heat from (or to) the layer dx may be represented by a term

$$dQ_4 = C_4 (1 - \alpha e^{-\mu x})\, dt \qquad (21)$$

C_4, α and μ being constants referring to the transmission of radiation through ice. The curve for water shows that the exponential term becomes very small as soon as x has attained an appreciable thickness. If we assume that ice is transparent to the heat waves emitted by water

at zero, so that the contribution due to radiation may be represented by a term of the form

$$dQ_4 = C_4 dt \qquad (22)$$

representing a loss of heat for C_4 positive, C_4 will be independent of x, and so the effect of radiation may be included with that due to convection by writing $C - C_4$ for C in (10).

C_4 will of course depend on the state of the sky, the amount and intensity of sunlight, the condition of the surface as regards snow, etc.

Numerical Results.

The Effect of Conduction.

Observations were made on the rate of growth of surface ice at Quebec. On entering into dock, the ice-breaker "Lady Grey" clears away all ice for a distance of 50 feet or more, in the neighborhood of the slip. In very cold, calm weather, surface ice forms very rapidly. It is only necessary to break up a small area of surface ice, and take a few pieces on board, where they can be easily measured up. The results are given in the following table, in comparison with values calculated theoretically.

Table II.

Time of day	Time from zero at 12 noon	Water Temp.	Air Temp.	$\int_0^t \theta\, dt$	x calcul. from (7)	x calcul. from (16)	Observ.
11.30 a.m.	.....	+.092° C.	−20° C.	.....	.....	.....	.....
12 noon	0.0	.....	−19.4	[0]	0	0	.....
12.30 p.m.	.5 hr.	.068° C.	−19.0	34300	.29cm	.29cm.	.31cm.
1.05	1.1	.053° C.	−18.3	14400	.62	.61	.62
1.35	1.6	.053° C.	−18.1	107100	.88	.85	.9
2.05	2.1	.....	−18.3	139700	1.13	1.07	1.1
2.35	2.6	.....	−18.3	172800	1.38	1.29	1.3
3.05	3.1	.045° C.	−18.3	205900	1.62	1.51	1.6
3.35	3.6	.....	−18.6	239200	1.86	1.73	1.8
4.05	4.1	.....	−19.0	273300	2.11	1.92	1.9
5.05	5.1	.....	−19.7	343100	2.58	(2.30)	2.3

The curve of these give the observed values of x against t and begins practically as a straight line, cutting the axis at 12^{00} which may be taken as the origin of time. The fifth column gives $\int_0^t \theta\, dt$ calculated in centigrade-second units. The sixth column gives the values of x calculated from

$$(x + h_0)^2 = 2h_0 \left(\frac{dx}{dt}\right)_0 \frac{1}{\theta_0} \int_0^t \theta\, dt + h_0^2$$

From the curve we see that $\left(\frac{dt}{dx}\right)_0 = \frac{5}{3} \times 60 \times 60$ in cm. sec. units $\theta_0 = 19.4°$ below O° C.

K = .0057 in C.G.S. units, ρ = .9166, L = 80

So that

$$h_0 = \frac{K\theta_0}{\rho L} \left(\frac{dt}{dx}\right)_0 = 9.07 \text{ cms.} \qquad (23)$$

It will be observed that the actual values of x are less than the calculated ones (in the sixth column) towards the end of the curve.

This deviation may be attributed either to a convection effect, or to the effect of relative humidity, which was about 75 per cent. at the time of the observations. The observations are not extensive enough to decide the relative parts played by these two effects. In the following sections, we will examine the results obtained by considering each of these two effects, taken separately, although both must contribute towards the actual state of affairs.

The Effect of Convection.

To find the values of h and $\bar{x}$ corresponding to a representation of the observed values x and t by (17) we solve (18) for h taking

$$x = 2.3 \quad \theta_0 = 19°.4 \quad \frac{dx}{dt} = \frac{3}{5 \times 60 \times 60} \int_0^t \theta\, dt = 343100$$

$$\frac{1}{\theta_0} \left(\frac{dx}{dt}\right)_0 \int_0^t \theta\, dt = 2.95 \qquad h_0 = 9.07 \text{ Cms.}$$

Thus to a second approximation we have to find h from

$$f(h) = -\frac{h^2}{(9.07-h)^2} \times 9.07 \log \left\{ 1 - \frac{2.3}{h}\left(\frac{9.07-h}{h}\right)\right\} - \frac{2.3\,h}{9.07-h} - 2.95 = 0$$

We find $\begin{matrix} f(6.40) = +.013 \\ f(6.50) = -.023 \end{matrix}\Big\}$ hence by interpolation $h = 6.44$ Cms. (24)

and thus $$\bar{x} = \frac{h^2}{(h_0 - h)} = 15.7 \text{ Cms.}$$

t is then calculated for given values of x. from (16) by using the formula in the form

$$\frac{[\theta]^t_0}{\theta_0}\frac{h}{\bar{x}}\left(\frac{dx}{dt}\right)_0 t = -(\bar{x}+h)\log\left(1-\frac{x}{\bar{x}}\right) - x \qquad (25)$$

$[\theta]^t_0$ denoting the average value of θ between 0 and t.

Substituting numerical values t is given by

$$t = \frac{78.98}{[\theta]^t_0}\left[-22.18 \log\left(\frac{15.72-x}{15.72}\right) - x\right] \qquad (26)$$

By means of this formula the following table was drawn up.

TABLE III.

x (obs.)	$[\theta]_0^t$	t (calc.)	t (obs.)	x (calc.)
.31 cm.	19.2° C.	.55 hr.	.5 hr.	.29 cm.
.62	18.9 C.	1.14	1.1	.61
.9	18.7	1.73	1.6	.85
1.1	18.6	2.18	2.1	1.07
1.3	18.6	2.62	2.6	1.29
1.6	18.5	3.33	3.1	1.51
1.8	18.5	3.80	3.6	1.73
1.9	18.6	4.04	4.1	1.92
2.3	18.7	(5.11)	5.1	(2.30)

The results of the first and third column when plotted give a theoretical curve. From this curve the value of x corresponding to the observed values of t are read off. The entries of the last column are entered in the seventh column of Table II for comparison with the results obtained from the parabolic formula (7).

We are now able to estimate C from (12) and obtain

$$C = \frac{K\theta}{\bar{x}+h} = \frac{.0057 \times 19}{22.2} = .005 \text{ calories per sq. cm. per sec.} \quad (27)$$

This represents the quantity of heat flowing into the layer dx per unit area per second.

The average temperature of the water, during the formation of ice was $\theta' = +.05°$ C.

Thus
$$h' = \frac{\theta'}{\theta}(\bar{x}+h) = .057 \text{ cms.} \quad (28)$$

The value of h' is most easily measured from the results of a laboratory experiment, by observing the rate of diminution of weight of a block of ice melting in water kept at a constant temperature, (say $+1°$ C.) and kept constantly stirred. By observing the rate of change of weight, h' could be calculated with a fair degree of accuracy. The value of h' will in general depend on the velocity of the water in contact with the ice. It seems probable that owing to viscosity, the velocity of the layer in immediate contact with the ice, will not vary very much between certain limits of the water velocity at some distance away. As soon as the velocity of the water, in contact with the ice, exceeds the "critical velocity", and the viscous stream-line motion becomes turbulent, we should expect a sudden decrease, in the value of h', *i.e.*, heat will be conveyed to the ice much more readily and the ice will melt much more rapidly.

Since we have estimated the values of h and h' it is possible from (28) to find the limiting thickness, corresponding to any pair of values of θ and θ'.

It will be noticed that, $\bar{x} \gtreqless 0$ according as $\frac{\theta}{\theta'} \lessgtr \frac{h}{h'}$. This may be interpreted to mean, that under these conditions, no ice will form. The result may be shown graphically by taking θ and θ' as coordinates and drawing the line $\frac{\theta}{\theta'}, = \frac{h}{h'}$ as in Fig. 12. No ice will form if θ

and θ' be such that the point, (θ, θ') fall on the right hand side of the line $\frac{\theta}{\theta'} = \frac{h}{h'}$ in the region marked "no ice".

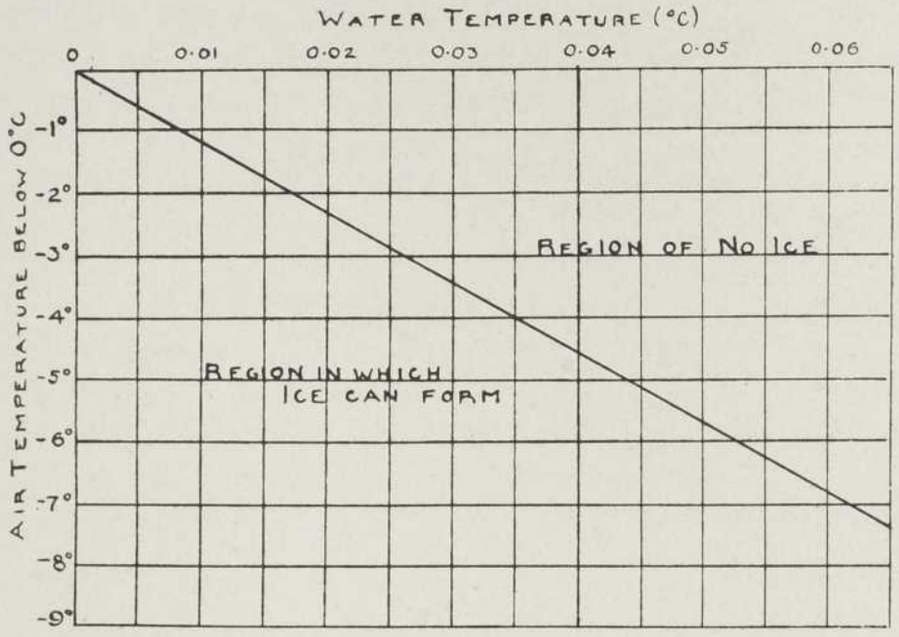


Fig. 12.

The limiting thickness $\bar{x}$ corresponding to a pair of values of θ and θ' can easily be found by a graphical construction. Taking θ and $\bar{x}$ as coordinates as in Fig. 13,

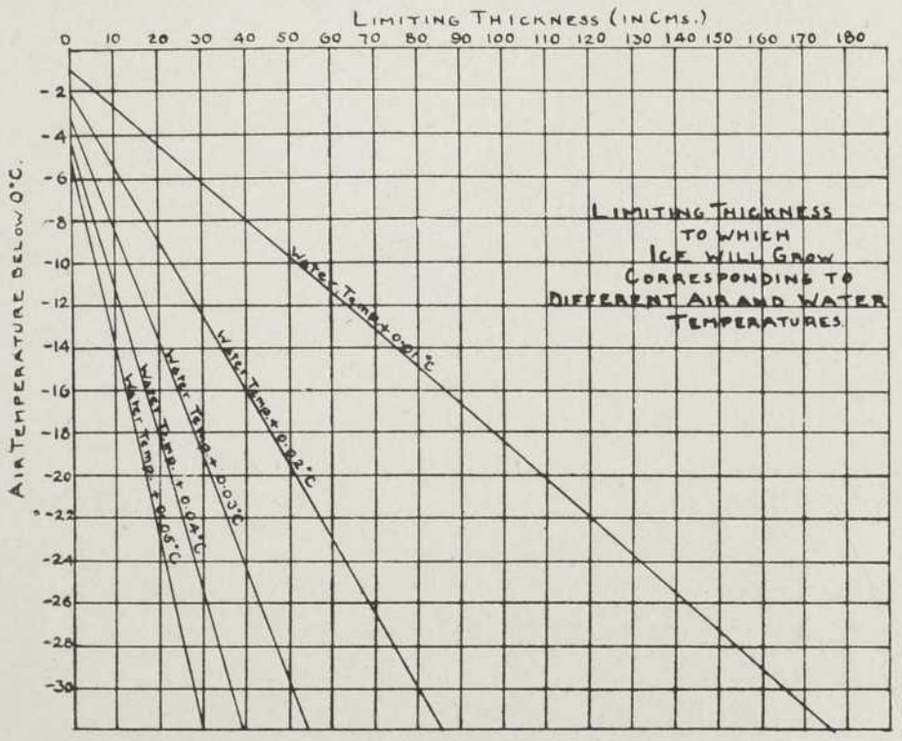


Fig. 13.

and considering θ as a variable parameter, the equation

$$\bar{x} + h = \frac{\theta}{\theta'} h'$$

represents a family of straight lines all passing through the point $\bar{x} = -h$. The intercept included between any one of these lines (corresponding to a given value of θ') and the axis of $\bar{x}$ on any straight line parallel to the axis of θ is proportional to θ' By suitably choosing the position of this straight line, we may mark a scale θ' on it in such a way that $\theta = 1000\ \theta'$. This gives $\bar{x} = 50.6$. Thus if we mark off θ' on this scale and join this point to $\bar{x} = -6.44$ we obtain a straight line giving the values of $\bar{x}$ corresponding to various values of θ for that value of θ'. An inspection of Fig. 13 will make this clear. From the constructions, here given the following table of limiting thickness for various values of θ and θ' was drawn up.

TABLE IV.

θ / θ'	−20° C.	−15° C.	−10° C.	−5° C.	−4° C.
0.00°	∞	∞	∞	∞	∞
.01	107.8 cm.	19.3 cm.	50.6 cm.	22.2 cm.	16.5 cm.
.02	50.6	36.5	22.2	7.9	5.0
.03	31.7	22.2	12.6	3.2	1.2
.04	22.2	16.0	7.9	0.7	no ice
.05	16.5	10.9	5.0	no ice	"

θ / θ'	−3° C.	−2° C.	−1° C.	0° C.	
0.00°	∞	∞	∞	Indet.	
.01	10.9 c.m.	5.0 cm.	No ice	No ice	.....
.02	2.2	No ice	No ice	No ice	.....
.03	No ice	"	"	"	.....
.04	"	"	"	"	.....
.05	"	"	"	"	.....

It is interesting to draw a family of curves showing the effect of water temperatures in affecting the growth of ice. From a series of curves, calculated for air temperature, $\theta_0 = -19°.4$ C, $h = 6.44$
from the formula

$$\frac{[\theta]^t_0}{\theta} \frac{h}{\bar{x}} \left(\frac{dx}{dt}\right) t = -(\bar{x} + h) \log \left(1 - \frac{x}{\bar{x}}\right) - x \qquad (29)$$

For the following values of θ' the limiting thicknesses given in Table V. are shown:

TABLE V.

Curve	θ'	$\bar{\alpha}$
I.	+ .05° C.	15.72 cm.
II.	.04° C.	21.5 cm.
III.	.03° C.	30.1 cm.
IV.	.02° C.	50.0 cm.
V.	.01° C.	105. cm.
VI.	0.00° C.	∞
VII.	− .01° C.	−118 cm.

The Effect of Relative Humidity.

In very cold weather η is small and θ large, so that we may neglect $\frac{\eta}{\theta}$ and consequently ϵ except in the logarithmic term of (27). We may then write, approximately,

$$\frac{K[\theta]_o^{t}}{\rho L} t = \frac{x^2}{2} + h_o x - h_o^2 \epsilon \log\left(1 + \frac{x}{\epsilon h_o}\right)$$

If t_o refer to the time taken for the ice to attain the thickness x in a saturated atmosphere, *i.e.*, when $\epsilon = 0$, we have

$$\frac{K[\theta]_o^{t}}{\rho L} t_o = \frac{x^2}{2} + h_o x$$

thus

$$\frac{t_o - t}{t_o} = \frac{h_o \epsilon \log\left(1 + \frac{x}{\epsilon h_o}\right)}{\frac{x^2}{2 h_o} + x} \qquad (30)$$

while

$$t_o = \left(\frac{dt}{dx}\right)_o \left(x + \frac{x^2}{2 h_o}\right) \qquad (31)$$

In estimating numerical values, we may suppose that, to a first approximation, the results of observation are repeated by the parabolic formula (31) for which $\left(\frac{dt}{dx}\right)_o = \frac{5}{3}$ (in hour, cm. units) and $h_o = 9.07$ cms.

We then estimate t_o for various values of x (31) and hence by (30) we find $\gamma = (t_o - t)$ (for these values of x)

corresponding to different states of relative humidity. If we take the observed (x, t) curve to refer to relative humidity 75%, we can by adding τ to the observed values of t obtain the "reduced" (x, t_0) curve corresponding to relative humidity 100 per cent. This curve is drawn as in Fig. 14.

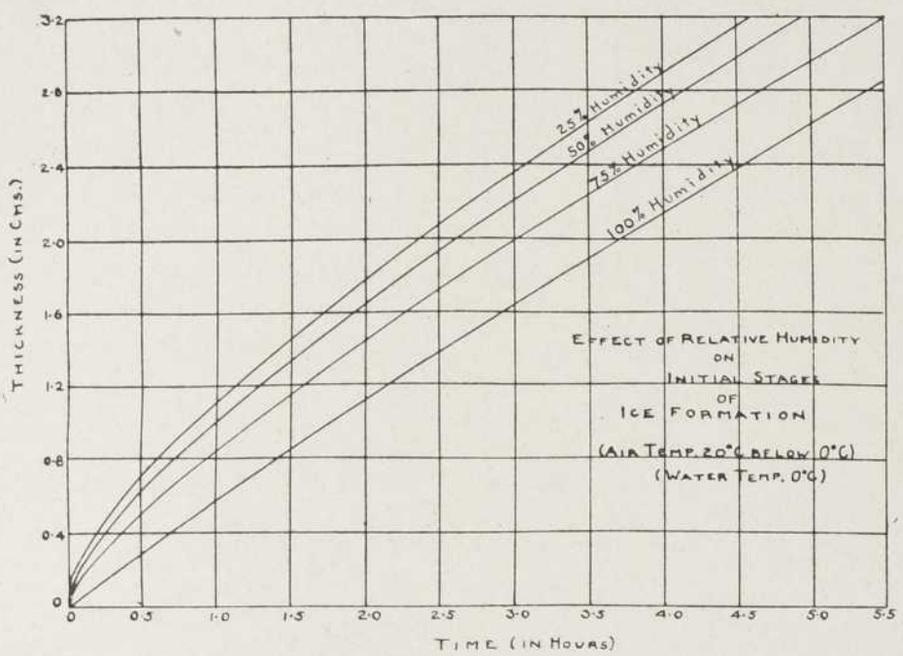


Fig. 14.

It is seen to cut the axis at +.05 hour from the origin previously chosen at an inclination $\left(\frac{dt}{dx}\right)_0 = \frac{.95}{.42}\left(\frac{\text{hour}}{\text{cm}}\right)$. This curve can be represented as far as the observations go by a parabolic curve, for which $h_0 = 12.26$ cms and

$$t_0 = \frac{.95}{.42}\left(x + \frac{x^2}{2\,h_0}\right).$$

We may if we choose, push the calculations to a second approximation, by using these last-found values, to calculate t_0 and τ in (30) and (31) and then proceeding as before. The observations are not, however, complete enough to warrant this degree of accuracy.

In this way, the values of t_0 given in the Table VI. are obtained. We may then find $t_0 = t_0 - \tau$ and compare the results with observation.

TABLE VI.

x	t_o	τ	$t = t_o - \tau$	t observed
.31 cm.	.710 hr.	.26 hr.	.450 hr.	.45 hr.
.62	1.44	.42	1.02	1.05
.9	2.11	.51	1.60	1.55
1.1	2.60	.55	2.05	2.05
1.3	3.10	.59	2.51	2.55
1.6	3.85	.64	2.21	3.05
1.8	4.37	.66	3.71	3.55
1.9	4.64	.67	3.97	4.05
2.3	5.68	.74	4.94	5.05

The observed and calculated values give as good an agreement, as in Table III. The fact that the last two calculated values of t are less than the observed values, seems to indicate a gain of heat to the ice by convection. The observations have not, however, been carried sufficiently far to admit of an estimate of its effect being made.

The effect of humidity becomes small as soon as the ice has attained an appreciable thickness.

The preceeding calculations can only be regarded in the light of a very rough estimates, and are given as an indication of how observations on the rate of growth of ice sheets, under specific meteorological conditions, can be utilized to obtain valuable ice-constants. Further observations taken throughout a considerable length of time, are very much to be desired.

Another treatment of the problem was sent by Prof. G. T. Becker, in 1908, and this deals with the problem as one of straight heat conduction.

He gives a formula

$$t = \frac{12885}{E} x \left(1 + \frac{x}{2}\right)$$

E is practically the temperature difference of the ice surface exposed to air, as constrasted to the water. X is thickness of ice sheet. t is time in seconds for ice to grow to thickness X. The equation is essentially the same as the one already given.

Rate of Growth of Ice for Large Thicknesses.

Observations were commenced early in December, as soon as the first ice had taken, to determine the rate of growth of the ice. For this purpose, a suitable place was selected on Lake St. Francis, and a stake frozen into the ice to serve as a datum plane from which the measurements could be obtained. In spite of the surface coating of snow, it was always comparatively easy to obtain an approximate measurement of the ice thickness, since the upper surface of the ice was well frozen, hard and level, and served very well as a datum plane, from which to locate the desired thickness, but as much of the ice varied in thickness from place to place, it was necessary to keep the comparative measurements located at one spot. The following observations were obtained and plotted in the accompanying curve. It will be seen that a steady growth continued up to about the middle of February, after which the thickness began to fall off. Some discrepancy exists, for the observations about March 24th, which may have been due to a slight shift of the datum plane owing to some melted snow followed by a hard frost. I have omitted these readings from the present results. The last reading was taken direct from the shifting ice sheet, without reference to the datum plane, and was obtained with considerable difficulty. It can be regarded as approximately correct. The attainment of limiting thickness is here shown clearly for the first time, and illustrates the fact that a gradual small elevation in water temperature takes place under the ice, due to the greater power of the sun. The effect of snow is shown clearly in a flattening of the curve early in January. The limiting thickness appears to be at the point about 25 inches, but in other places, as much as 30 inches was measured. It is unlikely that the ice in Valleyfield Bay ever becomes much thicker than this, since it grows with great slowness at this thickness. The limiting thickness will depend on the mean air temperature, and on the depth of snow resting over the ice. The mean water temperature was measured through the ice at this point in March, and showed no deviation from the freezing-point, greater than about a 2/100ths, the thermometer

was not capable of determining with certainty a deviation of less than this from the freezing-point. Judging by measurements made on Lake St. Peter by means of a microthermometer, it is probable the water temperature was slightly above the freezing-point under the ice all winter. Fig. 15.

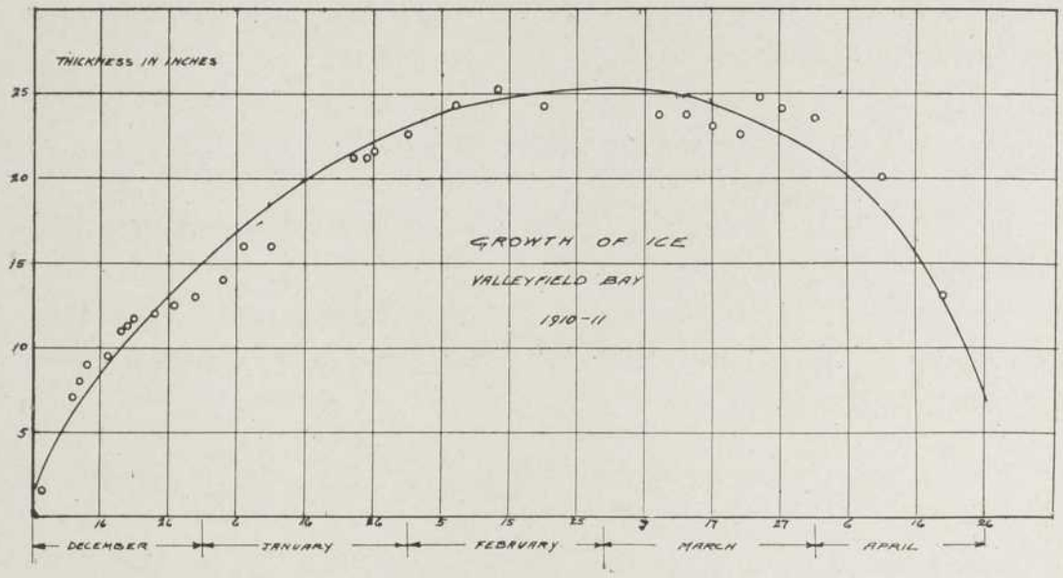


Fig. 15.—Growth and Melting of Surface Ice.

Rate of Growth of Ice.

Date	Thickness	Date	Thickness
Dec. 7th	1.5 inches	Jan. 7th	16.0 inches
12th	7.0	11th	16.0
13th	8.0	23rd	21.25
14th	9.0	25th	21.25
15th	9.0	26th	21.50
17th	9.5	31st	22.50
19th	11.0	Feb. 7th	24.25
20th	11.25	13th	25.25
21st	11.75	20th	24.25
24th	12.0	Mar. 9th	23.75
27th	12.5	13th	23.75
31st	13.0	17th	23.00
Jan. 4th	14.0	April 20th	13.0

Ice Survey of the Bay and Lake.

One of the most important features of the work was to determine the presence of any accumulation of frazil

or anchor ice under the surface ice. For this purpose, lines of holes were bored along the main channel of the Bay and across the Bay, about 200 feet apart, and sections were made out as far as the lighthouse. The borings were carefully watched for any evidence of frazil, but absolutely none was found. In addition to this, borings were made at Lancaster, Ont., and at Summerstown, Ont., about 8 miles below the end of Cornwall Island, but no evidence of frazil was found.

The Infra-red Absorption of Ice.

E. K. Plyler in a recent paper has measured the absorption of ice for heat rays. This work taken with that of Professor J. R. Collins on the heat absorption of water furnishes us with valuable evidence of the constitution of water and ice.

The absorption of ice is dependent upon the direction of the plane of polarization for the near infra-red region. Crystals were cut with the optic axis parallel to the surface. Plane polarized radiation was allowed to fall upon the crystal and the per cent. transmission determined. The crystal was set in three positions: first, so that the transmitted radiation constituted the ordinary way; second, so that the transmitted radiation constituted the extraordinary ray; third, so that the incident energy was about equally divided into two rays. For the first position, with a thickness of 5 mm., absorption bands were observed at the following wave lengths with the corresponding per cent. transmission: .81 μ −55 per cent., .92μ −54 per cent., 1.06 μ −46 per cent., 1.29μ −27 per cent.

For the second position the values were: .79μ −93 per cent., .89μ −94 per cent., 1.02μ −93 per cent., 1.26μ −57 per cent. For the third position the transmission curve fell between that of the first and second positions and showed both sets of bands. The region from 1.4 to 1.7μ was studied by using a specimen 1 mm. thick. The position of maximum absorption was located at 1.5μ. The incident energy was unpolarized.

Plyler assumes Sutherlands theory of association of water which we have already described in Chapter I. In this water vapor is $(H_2 O)$, water is a mixture of $(H_2 O)_2$ and $(H_2 O)_3$. and ice is 100 per cent. $(H_2 O)_3$. In water 16 per cent. of $(H_2 O)_3$ is present at 100° C. and 37.5 per cent. at 0° C.

From M. Hettners investigations the position of the maximum absorption in the bands of water vapor is given, while Collins has determined the maximum absorption of water at 0° C. and 100° C., and from measurements for ice a curve can be made with per cent. trihydrol as ordinate and wave length in microns as abscissa. In Fig. 16 Plyler's curve is given for bands in the region of

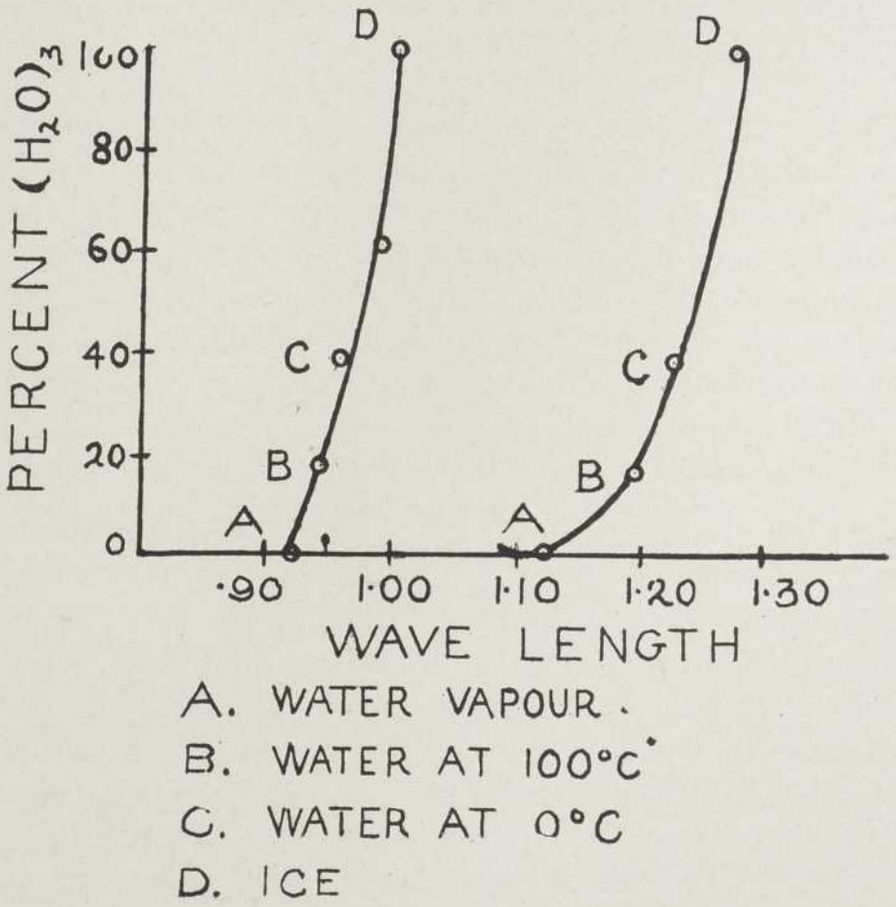


Fig. 16.—Curve from E. K. Plyler's work on Infrared Absorption of Ice.

1 and 1.2 microns. The values for ice are for the extraordinary ray. The curves are particularly interesting and regular.

G. Bode found that 1 mm. of ice, absorbed 93 per cent. of the incident energy at 1μ. Plyler's work shows that 5 mm. of ice at 1μ absorbs only about 5 per cent. of the energy for the extraordinary ray and about 47 per cent. of the radiant energy in case of the ordinary. It is difficult to explain this variation in values except on the basis that surfaces of the ice used by Bode must have been very irregular, and also the ice must have contained air bubbles.

Absorption of Water for Infra-red Rays.

J. R. Collins has obtained by the use of two constant deviation spectrometers in series and a Coblentz linear thermopile, the absorption coefficient of water for various temperatures from 0° to 95° C. The bands found showed maximum absorption at the following wave-lengths:

At 0° C.	.775	....	.985	1.21	1.45	1.96
At 95° C.	.74	.845	.97	1.17	1.43	1.94

There is a shift toward shorter wave-lenghts as the temperature increases, and also a marked increase in magnitude of the maximum absorption for the bands at .77, .98 and 1.21μ. These changes are qualitatively explained by Roentgen's and Sutherland's hypothesis that water is a mixture of at least two kinds of molecules, presumably $(H_2\ O)_2$ and $(H_2\ O)_3$, whose relative amounts change with a change of temperature.

Five Varieties of Ice.

Dr. P. W. Bridgman of Harvard University has shown the existence of five different forms of ice. His work which is an extension of that of Tammann is of the greatest interest and importance. A method was devised which enabled the compressibility of water to be measured up to 12,000 Kilogrammes per sq. centimetre, or ninety tons per square inch. Under this pressure a dimunution of volume of about 20 per cent. was produced. At a temperature of 20° C. many irregularities were observed which could only be explained by admitting the freezing of the water by the high pressures.

It was Tammann who first found that when ice is subjected to pressure at temperatures lower than −22 C.

it is no longer possible to cause it to melt, but that, instead, it changes in form, passing over to another kind of ice which is more dense than water, instead of less dense, as is ice at atmospheric pressure. The pressure needed to produce this second kind of ice is about 2,200 kilogrammes per square centimetre. The new forms of ice are comparable to the two forms of carbon coal and diamonds, with this difference, however, this new kind of ice changes to ordinary ice just as soon as the pressure on it is removed, in the same way that ordinary ice will change into water when a sufficient amount of heat is applied. Tammann succeeded in discovering two new kinds of ice, each denser than water.

Tammann's discovery was that at high pressures there are two modifications of ice, each of which is denser than water. Bridgman expected that the freezing-point of his modified form would be raised by the application of pressure, so that possibly the irregularities could be explained by the freezing of water to this new form of ice at 20° C. under the very high pressures reached in this work, which were about five times those reached by Tammann. But the fault in this explanation is that Tammann had predicted from measurements on this new kind of ice that no pressure, however great, could possibly raise the freezing-point of water higher than −17°, and a temperature of 20° C. was here being employed.

The pressure at which the piston used by Bridgman falls into the cylinder without producing a rise of pressure is the pressure at which the water freezes to ice at the particular temperature of the experiment. For every temperature, the pressure at which the water freezes is different. When the ice is denser than water, the freezing temperature increases as the pressure increases. In this way it is possible to find at what pressure water freezes for any given temperature, and so to construct so-called "melting curves."

Fig. 17 shows more clearly the relation between these different kinds of ice. It will be noted that in this figure there are five regions, numbered according to the kind of ice to be found within the region. Thus, for

example, if in an experiment the pressure be raised to 10,000 or 10 kgm. and the temperature maintained at O°, these corresponding to the point 10.0 on the diagram, the

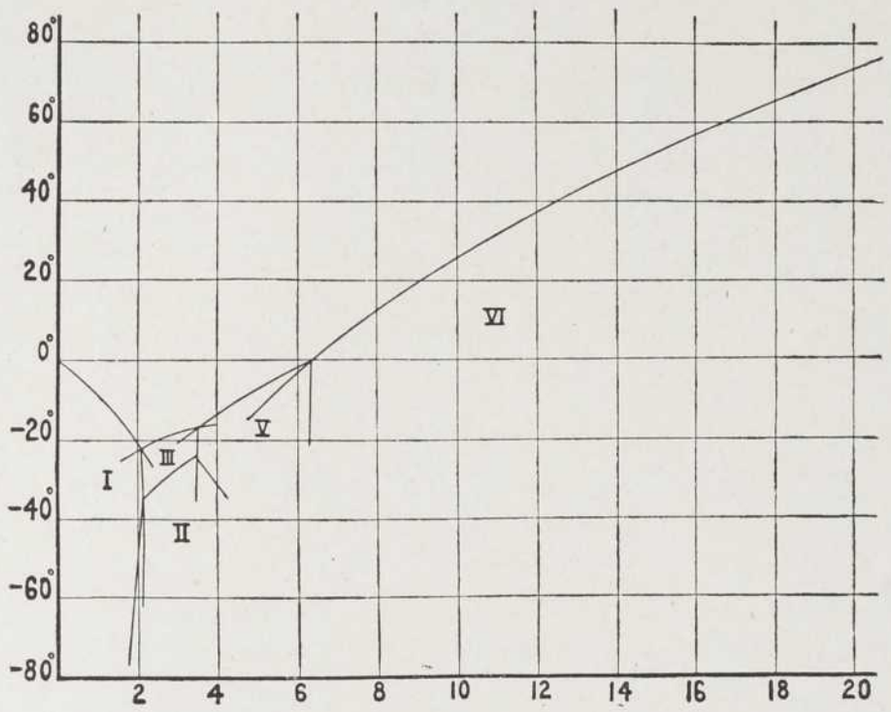


Fig. 17.—Curves from P. W. Bridgman's work on Five kinds of Ice.

water substance will be found to exist in the form of ice VI. Or again, if the pressure is 2000 kgms. and the temperature 20° (point on the diagram 2, 20), then the water substance is in the form of ordinary liquid water; or, thirdly, if the pressure is 1000 kgms.; and the temperature −20° (point on the diagram 1, −20°), then the water substance is in the form of ice I, the form we are ordinarily familiar with.

On any of the boundary lines of the regions in Fig. 17 the two adjacent forms of water substance are in equilibrium with each other, but if the state of the mass be changed slightly so that it is represented by a point within either of the regions, the kind of ice in that region prevails and the other disappears. Thus, let us suppose that there is ordinary ice, ice I., at say −10° and atmospheric pressure in the apparatus at the beginning of an experiment, then if the pressure be increased (keeping the temperature constant at −10°) at about 1000 kgms. (point 1, −10°), the ice melts to water. But if now we

continue to increase the pressure, at about 4400 kgms. (point 4.4, $-10°$), the liquid water freezes again to a new kind of ice, ice V., which is denser than water. If we still further increase the pressure, at about 6300 kgms. (point 6.3, $-10°$), the ice V. suddenly changes to ice VI., the volume again decreasing during the change. Or, if we commence at atmospheric pressure and $-30°$ (point 0, $-30°$), and increase the pressure, we first change ice I. (ordinary ice) into ice III., then, on still further increasing the pressure, ice III. changes to ice II.; on further increase, II. changes to V., and finally V. changes to VI. The high temperature to which the curve between ice VI. and the liquid runs is of interest; by the application of 20,000 kgms. we may freeze water, although it is nearly boiling hot.

The four varieties of ice denser than water have several interesting properties. Thus it will be noticed in Fig. 17 that the curve separating region VI. from the region of the liquid, L, is prolonged into the region where V. is stable. The interpretation of this is that it does not always hold that when one of the modifications is carried into a region in which another variety exists as the stable form, the unstable form will immediately disappear; thus it is possible to carry either liquid water or ice VI. into the region in which V. is the stable form, and to maintain it there for a considerable time without the change to V. taking place. We are all familiar with a similar property shown by liquid water at atmospheric pressure; it is possible to cool liquid water considerably below O° without the water freezing, particularly if care is taken not to subject the water to any mechanical disturbance. The fact that liquid water and ice VI. may both exist in the region in which V. is the stable form was the cause of considerable trouble during the first experiments, when it had not yet been established that there really was another form of ice, ice V. On the melting curve of ice VI. below O° a number of irregularities were found for which the only explanation seemed to be that there was a new variety of ice. At first, however, the experiments could not be repeated, and it was only after some time that it was discovered that an apparently

unessential variation was sufficient to determine whether VI. or V. would freeze out of water at temperatures a little below O°. If the experiment was performed with the water contained in a glass bulb, ice V. would freeze out of the liquid, but if the water was enclosed in a steel bulb, then ice VI. almost always froze out of the water. The presence of a few splinters of glass was sufficient to ensure the appearance of V. instead of VI. The explanation of this strange phenomenon has not yet been found. The phenomenon is simply an illustration of a fact with which chemists have been familiar for a long time; namely, that if a substance is capable of existence in two or more forms, it usually holds that the more unstable form appears instead of the stable form.

There is one exception to the statement that it is possible to carry one modification into the region of another and maintain it stable. None of the varieties of ice can be carried into the region in which liquid water is the stable form without the solid melting. It seems to be impossible to superheat a solid with respect to a liquid, although it is almost always possible to subcool a liquid with respect to a solid. This rule has been hitherto found to be of practically universal application at atmospheric pressure, and it is here seen to apply at high pressures also. Ice II. behaves in a similar way with respect to ice III. Ice II. may not be superheated appreciably with respect to ice III., but III. may be very considerably subcooled with respect to II. That is, III. behaves with respect to II. as if it were a liquid, although we know, by direct proof, that III. is really a solid.

The manner in which one ice changes into another is truly remarkable. We know that water freezes slowly or that ice melts slowly, but some of these kinds of ice will change into another kind so rapidly that the reaction reminds one of an explosion. For instance, if ice I. is changed to ice III. at $-25°$, the reaction takes place so suddenly that it is impossible to follow the change of pressure which takes place after the reaction. On several occasions a click in the apparatus has occurred when the transformation took place, so rapid was it. Still another

remarkable thing is that the effect of temperature on the velocity of the reaction is very great indeed. If ice I. is cooled to about $-50°$, the reaction occurs so slowly that it takes hours for its completion. Similar behavior is found also on the curves III.-V. and V.-VI.; the reaction from one solid form to another is very rapid indeed at temperatures near the melting temperature, but as the temperature is reduced the speed of the reaction becomes very much less. This is the reason that the curves separating the domains of the different kinds of ice could not be followed to lower temperatures than are shown in the diagram. At lower temperatures the reaction becomes so very slow that it would have taken days to obtain a single point. It is to be expected that the curves separating II. and V. and V. from VI. will continue to run to lower temperatures, that they will finally meet, and that from the point of intersection a new equilibrium curve, the curve between II. and VI., will start. The point at which any three curves meet in the diagram is called a triple point. It will be noticed from the figure that two curves never meet without a third curve starting from the point of intersection of the other two.

The fact that ice I. gives place to ice II. at a certain pressure has one practical application. We have often heard of the immense pressures developed when water is allowed to freeze in a closed vessel. Burst water pipes are a familiar example of this, and there are also well-known experiments in which cannon balls have been split open by freezing water. It is of interest to inquire how much pressure might be reached in this way. The diagram furnishes an answer to the question, as it shows that if the pressure on the ice during freezing should rise to much over 2000 kgms., corresponding to 30,000 pounds per square inch, the ordinary ice would change to ice III., which has a much less volume, so that the ice would tend to shrink and the rise of pressure would be arrested. Thirty thousand pounds per square inch is, therefore, the highest pressure that can be obtained by freezing water in a closed space.

It may be of interest to give a rough idea of the difference of volume between the different forms of ice.

To indicate the change of volume accurately, it is necessary to specify the pressure and the temperature at which the change from one variety to the other takes place, because the change of volume depends somewhat on both these factors. Roughly, ordinary ice,—ice I.,—is from 10 to 13.5 per cent. less dense than water. Ice III. is on the average 3 per cent. denser than water and 20 per cent. denser than ice I. Ice II. is about 22 per cent. higher in density than ice I. Ice V. is about 5.5 per cent. denser than ice III. and perhaps 6 per cent. denser than water. Ice VI. is 4 per cent. denser than ice V. and from 9 to 5 per cent. denser than water.

The latent heat is about the same for all the varieties denser than water than it is for the ordinary kind. The various modifications of the solid have, however, this remarkable relation to each other; namely, that the one may change to another in a large number of cases without any appreciable transfer of heat. Wherever, in the diagram, there is a transformation curve running vertically, then on that line the one solid form passes to the other without appreciable heat transfer. This fact allows the very sudden change from one solid form to another that has been commented on, because if there were any heat of transformation it would be set free during the reaction, and would have to be conducted away, which would take time.

Therefore the reaction could not run faster than the heat could be conducted away. In those cases in which there is no heat to be conducted away the reaction might be very fast indeed. But the fact that there is no heat of transformation does not explain why the reaction is very rapid; it simply makes a rapid reaction possible, provided that the other factors are favorable. This is shown by the fact that at the lower temperatures on the transformation curves there is still no heat of reaction, but the reaction, nevertheless, runs slowly.

CHAPTER IV.

THEORIES OF THE FORMATION OF ANCHOR ICE.

EFFECT OF LIGHT AND HEAT ON ITS DISINTEGRATION.

The form of ice which has attracted the most attention of all the forms to be met with in nature, is that known in this country as anchor ice. As its name implies, it is ice which is found attached or anchored to the bottom of a river or stream. It seems to have been observed in nearly all countries where river ice is formed, and goes by the name of ground ice, bottom ice, ground-gru,—a name given it by the inhabitants of Aberdeenshire,—and lappered ice by the people of the south of Scotland, who apply the epithet to the natural coagulation of milk. In France it goes by the name of glace-du-fond, and in Germany as grundeis. The French-Canadian expression is moutonne, as it resembles the white backs of sheep at rest.

The phenomenon of ice forming on the bottom of rivers has been known for a very long time, and, although the majority of the early philosophers of France denied its existence, it was well known to every peasant.

In 1788 M. Beaun wrote several papers to establish the existence of ground ice from his personal observations. He reports that the fishermen on the Elbe used to find the baskets, which they let down into the river for the purpose of catching eels, were often, when brought up to the surface, incrusted with ice. Anchors used for mooring their boats, when lost during the summer, frequently appeared in the following winter, being raised by the mass of ice which had formed about them. Their signal-buoys sometimes became displaced from the raising of the large stones by the ground ice, and caused great inconvenience.

Desmarest, a member of the French Academy of Sciences, was among the first of the scientists to make observations on the formation of ground ice. He reports having observed flakes of ice, formed at the bottom of running streams, increase in thickness five or six inches in a single night.

In Ireland's "Picturesque Views of the River Thames," published in 1792, where he speaks of the ground ice of that river, he states "The watermen frequently meet the ice-meers, or cakes of ice, in their rise, and sometimes in the under side enclosing stones and gravel brought up by them ad imo."

In February, 1827, M. Hugi, President of the Society of Natural History at Soleure, reports that while standing on the bridge over the Aar, when the river was clear of ice, he observed large ice tables continually rising from the bottom in a vertical direction, and with such buoyancy as to rise considerably above the surface, when they immediately sank into a horizontal position, and floated down-stream.

This is in almost perfect accord with what takes place in our northern rivers, during the daytime under a bright sun or during mild weather.

In 1833 the great philosopher, M. Arago, published an interesting paper on the subject in the Annuaire du Bureau des Longitudes. He mentions the following rivers where ground ice was met with, and the date of such observations: In the Thames, by Hales, in 1730; in the river Deonie, France, in 1780; in the Elbe, by Beaun, in 1788; in the Teine, Herefordshire, in 1816; in the Rhine, at Strassburg, in 1829; and in the Seine in 1830.

In the Edinburgh Philosophical Journal for 1834 there is an interesting paper on "Observations on Ground Ice," by the Rev. Mr. Eisdale, who attempts to explain the phenomenon by an original theory of his own. He states that the ice commences on the bottom and extends upwards to the surface, and is produced only in the most rapid and most rugged streams.

The Rev. Dr. Farquharson published two important papers on ground-gru in the Philosophical Transactions of 1835 and 1841. His observations were made of the ice in the rivers Don and Leochal in Aberdeenshire. The conclusions he arrived at are that ground-gru is formed by radiation at night, and he endeavored to substantiate his reasoning upon the principle of the formation of dew.

The first use which I have been able to find of the name *anchor ice*, is in the Encyclopaedia Americana, published by Carey and Lea, of Philadelphia in 1831. Under the article on Ice, the author, after referring to ground-ice, states that "a kind called anchor ice appears to be formed at the bottom, or at least under the surface of rapid rivers, perhaps owing to the comparatively slow motion of the water at the bottom of a stream."

The term anchor ice, then, seems to have originated in America, and is applied to ice anchored on the bottom of streams and rivers, flowing too swiftly for surface ice to form. Much confusion exists in regard to the relation of this ice to frazil ice, brought about partly by a misuse of terms, and partly from the fact that immense quantities of frazil ice become attached to the bottom by freezing to the layers of ice already formed there. The term anchor ice we shall use to designate all ice found attached to the bottom, irrespective of its nature of formation. Thus, frazil becomes anchor ice when it attaches itself to the bottom. The birth of frazil or colloidal ice is in the water itself through wind or rapid agitation, and by radiation. Anchor ice may form *in situ* on the bed of a river, and may grow by attaching to itself frazil-crystals carried by currents, and by the process of radiation.

In the report of the Montreal Flood Commission we have the terminology clearly defined, and it cannot be too strongly emphasized, the importance of adhering to this distinction, for clearness of expression. Thus, referring to the important report published by the Commission as early as 1888, we find the following: "Frazil as distinguished from anchor ice is formed over the unfrozen surface above and below Lachine Rapids (St. Lawrence River at Montreal), between Prescott and

tide-water, and wherever there is sufficient current or wind agitation to prevent the formation of bordage ice.

We find that as early as 1810, writers of that time drew a distinction between three kinds of river-ice, if we may judge from an early edition of the Encyclopaedia Britannica published at that date. Under the article on Ice we find the following: "Ice forms generally on the surface of the water, but this too, like the crystallization, may be varied by an alteration in the circumstances. In Germany, particularly the northern parts of that country, it has been observed that there are three kinds of ice: 1. That which forms on the surface; 2. Another kind formed in the middle of the water, resembling nuclei or small hail; 3. Ground ice, which is produced at the bottom, especially where there is any fibrous substance to which it may adhere. This is full of cells like a wasp's nest, but less regular, and performs many strange effects in bringing up very heavy bodies from the bottom by means of its inferiority in specific gravity to the water in which it is formed. The ice which forms in the middle of the water rises to the top, and there unites into large masses; but the formation both of this and the ground-ice takes place only in violent and sudden colds, where the water is shallow and the surface is disturbed in such a manner that the congelation cannot take place. The ground ice is very destructive to dykes and other aquatic works. In the more temperate European climates these kinds of ice are not met with." These are what we call in America sheet, frazil, and anchor ice.

Frazil crystals are formed during extreme weather, when anchor-ice is frozen down and rapidly growing, and not, as is sometimes supposed, when moderate weather occurs, and the latter becomes loose and rises to the surface. It is often thought useless to distinguish frazil from anchor ice. They are certainly both ice, but the conditions under which anchor-ice will form are not the same as for frazil, and vice versa. Methods to obviate the one will not meet the exigencies of the other. So long as the ice problem lasts we shall find circumstances conducive to the formation of either one or the other, or both. We should therefore keep clearly in our mind how

each is likely to be formed in order to be prepared to distinguish the conditions most likely to favor the growth of either. In a smooth-flowing river we are more likely to have anchor-ice formed in excess, whereas in turbulents streams, we are likely to have more frazil. It is hardly likely, however, that there will be a great difference in the amount of frazil formed in either case; it will probably be that more or less anchor ice will appear in proportion. In a river 40 feet or more deep anchor ice is unknown, although large quantities of frazil are met with.

Everything indicates that nocturnal radiation is the most active cause of anchor-ice, and it is a great question whether it would form at all, or except in very great extremes of cold unless the first coating of ice was placed over the rocks, by the radiation of heat, from the bed of the stream.

The radiation of heat from a river goes on all the time to the colder air above, and to a much colder space. During the daytime under a clear sky the sun's heat radiated down through the water offsets the cooling effect produced by the sky radiation; and on a cloudy day the heat-rays are reflected back again by the clouds. On a clear night in winter, with little or no moisture in the air, the circumstances are conducive to excessive radiation.

The influence of the sun is everywhere observed in the formation of both frazil and anchor ice. In the former by warming the water, and preventing it from becoming undercooled, and in the latter by loosening the masses of anchor ice, and causing them to rise. Frazil is never observed to form under a strong sun, nor anchor ice during the day time.

A common sight in the early morning, after a cold clear night, when the sun rises,is the appearance of masses of anchor ice. These rise and float down the current in great quantity. Boatmen are very careful when crossing a river not to go when these masses are rising, in fear of being surrounded and caught in a mass and carried down by the stream into the rapids.

Anchor ice grows so rapidly during periods of excessive nocturnal radiation and low humidity that it may attain a thickness of five feet or more during the night. So compact does it become, that it is often very difficult to thrust a sounding rod through it. It is granular and plate-like in structure. Fig. 18. Through clear water

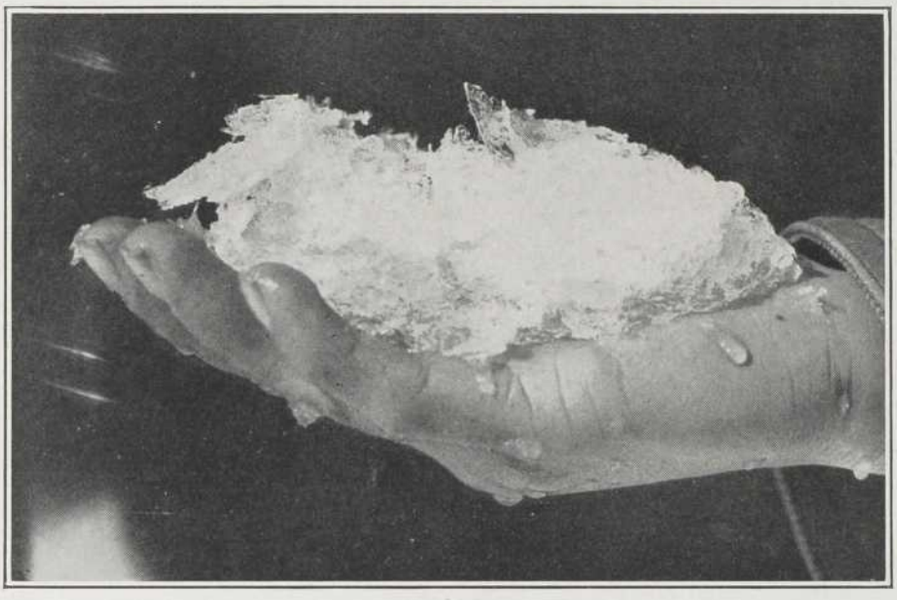


Fig. 18.—Anchor ice taken out of the water and held in the hand.

the ice looks like weeds with long tentacles rising up out of the mass. It often has great power to lift rocks and boulders up bodily, and many of these are carried far downstream attached to irregular masses of ice. Fig. 19. The spongy character of adhering frazil crystals attached to anchor ice, or the underside of a surface sheet, causes them to accumulate slime from the water. The characteristic color of these masses is brown. When melted in a vessel the slime settles to the bottom, where it is seen to be of a very fine structure consisting probably of infusorial growth.

The Cause of Anchor Ice.

We shall now briefly consider the main facts in connection with the formation of anchor ice in relation to frazil.

The experimental evidence is now sufficiently great to enable us to recognize two distinct agencies at work in the production of these two forms of river ice. In the

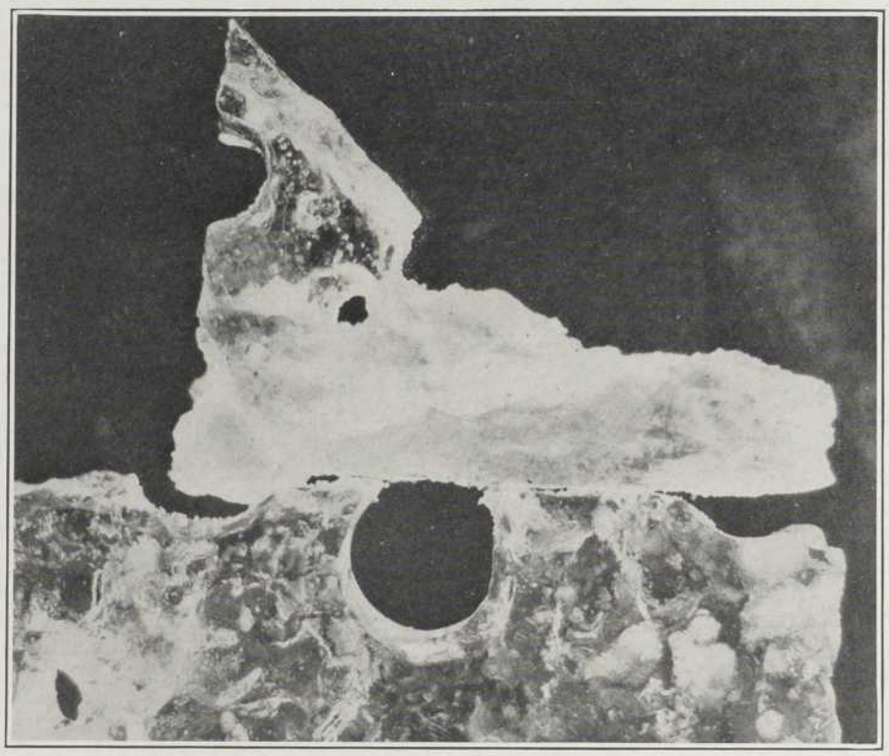


Fig. 19.—Solid masses of Anchor ice where it has been frozen to rocks under water.

first case, we have the production of frazil by the direct cooling of the water, whereby the heat is abstracted by agitation either by wind, or flowing over rapids. Its formation is the result of a small temperature depression in the water, which increases with the degree of atmospheric cold. The appearance of the frazil is the relief offered by nature to offset the excessive cooling of the water, and the extent of undercooling of the water is an indication of the amount of ice being formed. Another form of relief supplied by nature is the absorption of a portion of the sun's heat in the water during such time as it is clear. By this means the surface-cooling effect is offset by the powerful volume effect of the sun's rays.

The agglomeration of the frazil in the water is caused by undercooling, whereby each little particle of ice becomes the centre or nucleus for further growth. Two

such ice nuclei coming in contact at once freeze together, and very soon firm compact lumps are formed. Some particles of denudated material in the water may become the nucleus of an ice crystal, and frazil masses have stones, particles of mud, or portions of vegetable matter mixed in with them. The first run of frazil has a remarkable cleansing effect in the water.

With the advent of warm weather, and especially under the influence of rain, the temperature rises slightly above the freezing-point, and the agglomerated masses rapidly fall apart and disperse in the currents.

The second and greatest cause of river ice formation is that of terrestrial radiation, whereby an immense quantity of heat is radiated off into space under a clear sky.

We have never, to my knowledge, observed the formation of anchor ice under a layer of surface ice. Yet there is no valid reason why it should not form in a shallow river, provided the ice is clear and free from snow, and the water is flowing sufficiently rapidly to be at or very near the freezing-point along the bed. Usually this is not the case and anchor ice is not formed. It is reported, however, in 1730, and quoted in a paper on "Ground ice" by M. Arago in 1833 that, "during an atmospherical temperature of 15.8° Fahr., Hales saw at Teddington the surface of the Thames, near the banks, covered with a layer of ice one third of an inch in thickness. There was also, at the same time, a second layer below of greater thickness, which followed the depth of the river as it adhered to the bottom. This sheet was united to the upper one even on the waterside, but it was gradually separated in proportion, as, in proceeding into the river, the depth of the water increased. It was not so solid as the first, and was mixed with sand and even stones, which the flakes sometimes carry with them in their movement upwards."

Again, we find quoted by the same authority, that in the beginning of February, 1830, M. Duhamel, on breaking the ice which covered the surface of the Seine a short way below the bridge at Grenelle about 10 feet from the

banks, found a layer of continuous ice 4 cm. thick. The water was upwards of a yard deep. At every depth the water was found to be at zero, and the current was tolerably rapid. In both these observations no means are available for us to find out whether the ground ice was formed previous to the formation of the surface sheet or after. It is quite possible that the river was open, and, after becoming cooled to zero, ice was formed on the bottom during the earlier part of the night by radiation. The surface sheet may have been of a later growth, formed more slowly from the sides, and of sufficient clearness to admit of radiation. On the other hand, the surface sheet may have been formed first and the ground ice later, although the thickness of the surface ice which was found on top, indicated a very recent formation. Both rivers were shallow, and it is unlikely that there was any accumulation of snow on the surface of the ice, which as we have seen, is the chief obstacle to the heat loss.

Another case is quoted by Mr. Farquharson in his second communication to the Royal Society, 1841, as observed by Colonel Jackson, of the presence of ground ice in the Neva, under three feet of ice and three feet of snow. He considers, however, that ground ice was formed previous to the surface ice, and on account of the severity of the weather it had not been dislodged during the time of formation of the surface ice.

In experiments to detect the cooling of the bulb of a thermometer, when left undisturbed at night in the water, the temperature was observed to fall one thousandth of a degree in 15 minutes, and when the bulb was withdrawn ice was seen to be formed on it. I have also observed that ice grows more readily, and to greater depths on dark colored rocks, which is in accord with what we know of the greater radiating power of dark objects. This was also observed by Farquharson. It is also well known that anchor ice does not grow on cloudy nights, although frazil may be produced at such times.

In experiments on the absorption of the earth's radiation in water and in ice, I have found that a con-

siderable amount of heat can penetrate through clear ice. Having established the fact that some of the heat-rays can penetrate, we would naturally turn to the question whether such heat loss would be shown by its effects on the bed of a river in contact with ice-cold water. It requires a cooling of only a thousandth of a degree or less to start the formation of ice, and it would be a matter of some surprise if the radiation did not produce this minute effect. In deep rivers anchor ice is unknown, the limit of formation appearing to be from 40 to 45 feet. The depth, however, would depend on the clearness of the water.

Fairly recently (1923) a Russian physicist, B. Altberg, published an account of his observations on the cause of the formation of ice at the bottom of lakes. He also gives several experiments, conducted in the laboratory, to prove that ice will form in supercooled water with no radiation. He concludes that the radiation theory of anchor ice is unnecessary, and without foundation.

It is hardly necessary to point out the lack of experience in forming a conclusion so prejudicial to reason and experience. Undoubtedly, ice will form on objects immersed in supercooled water, and it is just this, which takes place in nature, when the water and objects in it, become supercooled. Where Altberg forgets his experimental acumen is in attributing to the water an ice forming power devoid of causation. In his experiments a refrigerant acted as the cooling agent, and was the direct cause of the water's becoming supercooled. In nature, it is the earth's radiation which is the cause of the supercooling, and the ice growth as the following experiments, made in 1910 by Prof. L. V. King, while making ice studies on the Canadian Government ice breaking ship "Lady Grey" working on the St. Lawrence river above Quebec, will show:

The observations are of great importance in establishing the full significance of radiation, as the dominant factor in anchor ice formation. Simultaneous observations were being made at the time of solar and nocturnal

radiation, and water temperatures. A vacuum thermometer on deck was used for the radiation records while a microthermometer served to obtain accurate records of the water. On these occasions the ship was anchored in mid-stream below the ice barrier at sundown, and observations were made up to midnight.

On March 10, 1911, the progress of events from 12 noon until 11 p.m. showed a steady fall in solar radiation until the earth radiation predominated over the solar, and after sunset caused a cooling of the vacuum thermometer below that of the air of 4° Fahr. A similar drop in water temperature took place towards the freezing point to within +.015°., from +0.082° F. The temperature never reached the freezing point, as the current flowed strongly from under the ice barrier above the ship.

The interesting feature of this experiment is that a crust of anchor ice formed over the rope, holding the thermometer, down to the bulb itself, which was a distance of three feet under the surface, and the ice was produced in a current of water actually *above* the freezing-point. No other explanation of this experiment seems possible, except that of the influence of terrestrial radiation, through three feet of water.

As an important confirmation of this experiment, the following day, March 11, observations were continued in exactly the same way. Curves were obtained from 7 a.m. to 12 midnight. The night radiation was only 3° F. below the air temperature, and the water fell from +.060° to +.020° F.

In consequence of the diminished radiation and higher water temperature little or no ice was found on the rope of the thermometer, in contrast to a crust of 2½ inches the previous night, with 4° of radiation cooling.

These two experiments are sufficient proof of the influence of terrestrial radiation through water, which is in itself sufficiently above the freezing-point to preclude any possibility of ice forming directly in it. Of course the whole phenomenon is one of degree, and the depth and extent of anchor ice depends on the intensity of the

radiation loss, as well as the temperature of the water. Thus in the experiments above cited, water at $+.02^\circ$ F. with cooling represented by -3° F. gave no ice while with water at $+.014^\circ$ and a cooling of -4° F., ice was formed *in situ*.

Objections to the Radiation Theory of Anchor Ice.

Since the publication of the authors' book on Ice Formation in 1906, in which the suggestion was made of a selective penetration of long heat rays through water, many writers have objected on the ground that water is so opaque to the long heat waves that it could not possibly transmit sufficient energy to generate ice. Thus W. W. Coblentz and others have quoted their own and other authorities to show how opaque water really is to waves beyond 2μ. Now the radiation from a body at the temperature of the earth in winter, lies between 8μ and 20μ. The solar radiation consists of visible heat rays (light) and infer-red rays down to 2μ which are transmitted through a considerable thickness of water. In measurements made by the author in 1897 it was shown that solar rays are half absorbed in three feet of water, and reduced to a very small quantity in 15 feet according to an exponential law. The green and blue rays are almost solely transmitted beyond thirty feet in the clear water of the St. Lawrence.

The infer-red spectrum of water shows undoubted indications of a transparent band beyond 2μ. Now the ice balance is so delicate in water, at 32°, and more so in supercooled water, that an amount of energy too small to be measured on a thermometer, would easily occasion a growth of ice, which when once started continues to grow at a fairly rapid rate. It is sufficient to know that no one cause is operative to produce ice on the bed of a river, and it is only common sense to treat all causes for each alone, or collectively, may produce anchor ice.

Effect of Sunrise on Anchor Ice.

The writer has for a special reason taken much interest in the light of the sunrise. The atmosphere just before

dawn is cleared of most of the water vapor and dust which leaves the returning rays free to penetrate the intervening space. The rush of returning light stirs everything again and causes an agglomeration of the colloidal particles of water and ice, precipitating fog in an otherwise clear air. During the entire day the light is stirring up the atmosphere by the great energy input. By the sunset period the water vapour is in the form of large coalesced particles, giving the characteristic color to the sky. The entire color gamut of the sky is due to water vapor and, were the sky free of vapor, no color at either sunrise or sunset would be seen. The kind of color is dependent on the size of the particles through which the light passes, and hence a study of the varying colors of the sunrise and sunset gives some idea of the state of the water vapor in the air.

My attention was directed to this for many years from the wonderful influence of the early light on the disintegration of anchor ice. This ice is as has been pointed out a product of the great nocturnal radiation under a clear sky whenever the weather is cold. In the early morning, however, the first light which tinges the eastern sky causes the ice to rise, before even a delicate thermometer can detect any temperature change in the water. Thousands of tons of ice are brought up from the bed of the St. Lawrence river every morning in winter in the open reaches, and are floated down stream to add their quota to the great packs at restricted points.

As the sun rises higher and the rays penetrate into the water greater quantities of ice come up until the bed is clear. This is repeated almost every morning, but the exceptions, which cannot be explained by a casual observer, were the object of special study on my part, involving a careful examination of the color of the sunrise during every month of the year. This was carried out from May, 1925, to April, 1926. Color plates were exposed during such time as the sunrise was evident on clear and characteristic days. This difficult and laborious work was done for me by Mr. Walter A. Connolly, of Morrisburg, where the anchor ice is very abundant, and the atmosphere unusually clear and free from smoke.

This series of pictures is of exceptional beauty, and has been the subject of much careful study.

At sunrise a red sky intimates the presence of great water particles which readily agglomerate into rain drops by the sunlight, and hence a red sky in the morning indicates rain. On the contrary the reverse takes place at sunset for a red sky shows the water vapor in a state of subdivision below the rain drop size which during the dark hours of the night become still further divided, and finally deposited as dew. The air is cleared for a dry and pleasant day. The sunlight tends to collect and grow the water particles, while the darkness under the full influence of the great nocturnal radiation tends to reduce the size of the particle to the colloidal condition, when they are deposited readily on the chilled surfaces of the earth.

This remarkable influence of the sunrise on ice was the occasion of the writer's first conceiving the idea of using artificial radiant heat for destroying ice. During a two weeks' observation of a single iceberg off the coast of Newfoundland, it was remarked how much cracking was heard in the period from darkness to dawn, and how during this time large pieces of ice came off. The day witnessed no such effects, and the heat of the sun was washed off by the running water from the melting surface. At night the iceberg dried, and the surface became cold and hard again. As morning approached much fog was precipitated on the ice, and when the light first appeared the cracks started again. The sunlight was able to penetrate the ice surface, setting up strains in the huge mass which contributed to its destruction.

On returning to Montreal after this experience the writer determined to use an exothermic mixture (thermit) generating a high temperature, and to apply this locally on the iceberg in the hope of causing the strains artificially and thus breaking the mass of ice just as heat will shiver a mass of hard glass. This is described in Chapter 10.

Various ice formations which come from nocturnal radiation such as hoar frost and the exudation of ice

from stems of plants, have been described by Coblentz, Columnal ice from soil is very interesting and varied. Fig. 20.



Fig. 20.—Ice exuded from the ground in winter.

Flood Lighting for Ice Prevention.

It is highly probable from experiments now in progress that some form of selective radiation will be found of high photochemical activity, which will imitate sunlight in destroying the ice forming power of water by breaking up the trihydrol. Already a "sunrise" lamp has been made to burn under water, emitting powerful red, green and ultra-violet rays which are active in destroying ice.

CHAPTER V.

FRAZIL ICE. WINTER ICE FLOODS.

Frazil is a French-Canadian term for fine spicular ice, derived from the French for cinders which this variety of ice most resembles. When formed in salt water it is known as "lolly ice". It is composed of fine particles which, when first formed, are colloidal and not seen in the water in which they are floating. The ice at first possesses little or no buoyancy, by Stoke's Law, but soon grows to a larger size in agglomerated masses like snow clusters which can be seen floating on the surface of the water. They resemble small flat discs.

Frazil is the natural result of the effect of a cold atmosphere on a river which is flowing too rapidly for a surface sheet to form. In rapids where water is agitated a great deal of frazil is produced. It is carried a long distance in the current, and with the accumulation over a long open stretch the water becomes loaded to the bottom during a period of intense cold and wind agitation. The water has the appearance of being loaded with sand. Measurements of the number of frazil particles found in the open water on an average cold day in winter vary from five to ten per cubic centimeter, but may rise as high as twenty or thirty.

The distance to which frazil will be carried by the current from open water to the under side of the surface ice covering the quieter parts of the river is shown by the formation of hanging dams. At Montreal, the frazil generated for the most part in the Lachine Rapids is traced for at least twelve miles beyond the barrier ice. The crystals become attached to the underside of the surface ice, and build down sometimes to the river bed. In one locality we have observed a depth of ninety feet. In taking soundings through the ice over these dams, the lead may usually be forced easily through the spongy

frazil, but often the ice becomes so hard as to resist all efforts at penetration. It is this winter pack which causes so much trouble along the St. Lawrence River. The ice bridge, once formed, causes a rise of water level and an upheaval of the surface sheet. Frazil is formed not only on the surface, but also throughout the body of the river when the water is supercooled. The supercooling is never more than a few thousandths of a degree, but notwithstanding this, it produces great physical effects. It is during such a time that the ice becomes adhesive, agglomerated, and produces trouble for the operators of water powers. The strength and tenacity of the frazil, as long as the temperature remains below the freezing point, is enormous. It wants but the very smallest change of temperature in the water, however, to make it soft and spongelike, and easily disintegrated.

The sun is the most powerful agent in imparting the necessary small fraction of temperature to the water to relieve ice troubles. Thus water wheels which have been securely cemented during the night are soon running again the next day when the sun comes out.

Theories of Frazil Ice Formation.

In the discussion before us the writer will adhere closely to the distinguishing terminology, which has already been adopted in this book, to designate frazil and anchor ice.

The need of such a separation will impress itself more and more on practical men as time goes on.

The writer in 1901, endeavored to bring about an official recognition in a paper on "Ice Formation in Canadian Waters," before the Canadian Society of Civil Engineers. Although the Society took no action, it was a matter of satisfaction to observe in the discussion following the paper, that every one fell in with the suggestion, consciously or unconsciously, and clearly made the desired distinction in describing personal experiences. It is important, I think, to have a name for the two forms of ice, being as they are products of two different agents of heat transfer, and I have adhered to the term "frazil"

because it is one universally accepted in Canada. Going back in history, we find the first to apply a name to the ice found on the bed of a river were the Germans, who called it grundeis. Following from this suggestion later writers adopted the name ground ice. The name anchor ice originated in North America, and I have chosen to use this name in preference to the much older one—ground ice, because I think it more perfectly fits the facts of the case. Ground ice might be ice formed anywhere on the ground, but anchor ice readily suggests ice which is held down or anchored to the bottom.

The need of a distinctive name is more readily seen after considering the facts brought forward by a number of observers. In quoting the personal experiences of any author I shall, where it may be necessary, add in parentheses the true term to the author's use of the word frazil or anchor ice, according as it appears to represent either form of ice contrary to the terminology of this book.

It will be well now briefly to consider various theories which have been advanced from time to time to account for river ice formation.

Turning our attention to papers on the subject, we find several valuable ones written from 1881 to 1887. These are all descriptive of the ice problem as it has presented itself to the practical engineer in the development of water power, or water works in this country.

Naturally the conditions of formation have been more severe and the ice growth on a much vaster scale than could be expected in the countries where—like England, France, or Germany—the winters are comparatively mild, and the rivers small. In Russia much attention has been devoted to this problem.

In 1881, in the presidential address before the American Society of Civil Engineers, at Montreal, Mr. J. B. Francis devotes a short section to a consideration of anchor ice. He makes no mention of the term "frazil", but states in regard to anchor ice: "The ice is formed in small needles on the surface, which would remain there

and form a sheet if the surface was not too much agitated." He then goes on to explain the production of whirls and eddies and the general mixing of the currents, whereby these needles of ice are carried to the bottom and adhere there by regelation. As an explanation of regelation, he refers to the observations of Faraday and Forbes. To explain why the small crystals freeze so readily, as compared to a larger mass of ice, he says: "In the minute needles formed at the surface of the water the tendency to adhere would be much the same as in larger masses touching at points only, while the external forces acting upon them would be extremely small in proportion." Thus they would become frozen down more easily.

He states that the adherence of the ice to the bed of the stream or other objects is always down stream from the place where it is formed, which is true, of course, in respect to the freezing down of frazil crystals. He then goes on to say that in large streams it is frequently many miles below, which is quite correct, but he overlooks the growth of anchor ice in places where frazil ice is formed only in small quantity, and immediately swept away by currents from under the barrier ice. After speaking of the agglomeration of these needles (frazil) into spongy masses drifting along with the current, causing troublesome impediments to the use of water power, he points out the value of having water powers supplied directly from ponds, rivers or canals frozen over for a long distance immediately above the places from which the water is drawn. In the entire paper no reference is made to the effect of radiation.

Dr. Robert Bell published a paper in 1886, in the "Transactions of the Royal Society of Canada," on "Ice Phenomena," and in it devotes some space to a discussion of frazil—or anchor—ice. He points out many facts in support of the radiation theory of anchor ice, which he states was first suggested by Dr. T. Sterry Hunt, who mentioned to him that he regarded it as analogous to the formation of hoar frost. Dr. Bell considers that the surface-formed ice in the rapid may aid the formation by being carried down by currents. He speaks of the excavation caused by the removal of stones and boulders

by anchor ice. Dr. Hunt has been given the credit for suggesting radiation as the cause of anchor ice formation. We have no means of knowing whether he was familiar with Farquharson's papers, or whether he came to the same conclusion independently.

The first paper to be written solely about frazil ice is that of Geo. H. Henshaw, in the Transactions of the Canadian Society of Civil Engineers for 1887. The paper is on "The Nature of Frazil and the Prevention of its Action in Causing Floods." Written at the time of the work of the Montreal Flood Commission, it is of value in bringing out expressions of opinion on the subject from well-known engineers, and of offering a theory to account for its varied formation.

After complaining that in a study of this kind, which is more physical than engineering, the scientific men neglect the subject or "leave us in the dark," he points out "that the haziest notions, if any, regarding it prevail among our highest scientific authorities." As an illustration, he refers to the explanation of frazil ice, offered by Sir William Thomson, (Lord Kelvin) then President of the British Association Meeting in Montreal in September, 1884. This explanation was that it was supposed to be the product of currents of water passing over and disintegrating solid anchor ice, exposing its "bones," just as a rock is worn into irregular forms by the removal of its softer parts. The incorrectness of this explanation is manifest to any one who has experienced this kind of ice.

All through Mr. Henshaw's paper we find the terms frazil and anchor ice used in the exact sense of the terminology adopted in this book, and it is only in the discussion following the paper that any confusion arises. The author gives his opinion that ice (frazil) never forms in water without an independent nucleus and that, like anchor ice, it may form below the surface of the water. When it appears free on the surface the nuclei are supplied by minute particles of vapor, which, becoming frozen in their ascent and falling back upon the water, form the stars seen in Tyndall's experiment, when the sun's rays

are focussed in the interior of a block of ice. The author refers then to the observations of Mr. Frank Gilbert, engineer and contractor, who was engaged in deepening the channel through the Gallops Rapids, showing the presence of masses of frazil frozen down to the anchor ice on the bottom. He says that it covered the bottom in dense masses of a spongy appearance, through which his pole swept with scarcely perceptible impediment. Masses of frazil cannot be described better than "spongy". Any one who has dislodged this ice from the under side of surface ice where it has accumulated, and seen it rise slowly to the surface, cannot mistake it. It can readily be distinguished from anchor ice by its much more feathery texture. Anchor ice is coarser and full of grains formed of much larger crystals. Mr. Henshaw offers an explanation of frazil in order to account for its formation at some points more readily than others. He considers generally that frazil ice is formed in currents cold enough not only to preserve its crystals, but to induce their formation.

On account of the irregular nature of the bed of a river Mr. Henshaw considers that there are formed currents and streams of different velocity to the surrounding layers, just as in a wind-storm the snow is drifted and sweeps in long lines, or streaks, with bare places between. Thus there may be formed in a rapidly flowing river streaks composed of currents colder than their surroundings. He regards these currents as forming "an irregular network with meshes of every size and threads of every thickness." The frazil appears in the currents, which he calls supercooled by the "sudden cooling of the water upstream." At the same time he is careful not to commit himself to the statement that the water itself is below the freezing-point. He considers that such water is always charged with minute icy particles, which may cause in themselves the refrigeration of the bottom. Objects found in the threads of colder water become nuclei about which ice forms, and masses of frazil are produced. Similarly, when warm weather sets in, these currents become warmer than their surroundings, and the ice is dislodged.

The main idea connected with Mr. Henshaw's explanation is quite correct, that is, the existence at certain times of currents of different temperature, and no doubt the slight undercooling of the water set up at the surface of an eddy results in a colder current passing downwards. To go further and state that his theory has "at least the merit of accounting for all known facts in connection with the nature and action of frazil" is wholly incorrect. All that he attempts to do is to try and explain why frazil appears to mass at some points and not at neighboring places; to do this he produces from his imagination a picture of a river, divided off into innumerable parts, separated by a skeleton of ice-laden, supercooled water. The remainder of the paper is devoted to a discussion of the ice-floods along the St. Lawrence, and of methods to obviate them.

The discussion which follows Mr. Henshaw's paper is of a very interesting character. It brings out, better than anything else I have ever seen, how different observers may arrive at totally different conclusions about the same phenomenon. The collection of facts here found is of the greatest value, and I shall give, as far as possible, the essential points in connection with it as follows:—

Mr. Herschel states that anchor ice is the New England equivalent of frazil, which is probably correct, owing to the lack of terms then existing. The word frazil is wholly of Canadian origin. Mr. Herschel then goes on to describe conditions for the formation of anchor ice (frazil), where he had observed it in the Connecticut River, and at the Detroit Waterworks. He observes that it forms in the river only at times when there is no covering of solid ice, and generally, only for the 12 to 24 hours just preceding the formation of such a covering. He gives as its most distinguishing characteristics, its low specific gravity, and its adhesiveness. The first is obviously his way of describing the fact that masses of frazil float low in the water, to which we have already referred and explained; and the second is probably the result of having always observed frazil on days when it was forming.

Mr. G. W. Ranney stated that frazil was never observed by him to form in still water or smooth current. He considers that it is formed in rapids where the water is broken up and intermixed with air. Referring to personal observations at Cow Bay, Mr. Ranney says: "At O° Fahr. prisms of ice begin to form about 200 feet down-stream from the surface ice. The anchor ice (frazil) begins to form as soon as the rapid commences, but does not adhere to the bed of the river until it has traveled 500 to 600 feet down the rapid, and commences to settle on the bed of the river and adhere to everything with which it comes in contact."

This is no doubt all correct, for the water would require an appreciable time to become sufficiently undercooled for the frazil to form, after flowing from under the surface ice. And its adhesive properties would be very much increased after traveling 500 feet down the rapid in contact with a cold atmosphere.

Dr. Robert Bell brought forward the idea of radiation as the real origin of frazil (anchor ice), and stated the necessary conditions for its formation.

Mr. Hannaford stated that frazil ice is to be found at the foot of rapid currents, and in broken and shallow water, rather than in currents of great depth. He says that frazil ice (anchor ice) is practically unknown at the Niagara River. He then compares the conditions at Montreal, and speaks of the ice floods.

Mr. Lesage described the conditions at the Montreal Water-works' aqueduct above the Lachine Rapids, where the river in winter is always open for a distance of seven miles to Lake St. Louis. Immense masses of frazil and anchor ice are drawn into the aqueduct, and frequently completely cut off the supply of water. So much trouble was experienced that the mouth of the aqueduct, was moved higher up to a bay, and a large basin was formed by part embankment and part cribwork, which allowed the surface ice to be formed over an area of about ten acres, and no further trouble has been experienced.

He has observed large masses of anchor ice attached to boulders, the general bed of the river, and in all places

where there were eddies. "It assumes a fungus shape," he says, "gradually growing upwards." A rise of a few degrees in the air temperature will cause the whole mass to break away from its anchorage, often carrying with it a boulder or any substance to which it is attached. He has observed that sometimes the river is nearly covered with these floating masses, plainly showing that they had formed in the open water of the river. "The formation was most marked on cold bright days, and the frazil (anchor ice) rose to the surface on a cloudy day, with a slight rise of temperature. Every year," he states, "when ice first covers the aqueduct, frazil forms in the settling-basin and is carried into the wheels, which have to be stopped a few hours until the ice has covered the basin."

Mr. Poole related one of his experiences at the Acadia Colliery, N.S., when the feed-pipe, supplying the boilers from an artificial pond, was stopped up in the morning after a clear, cold night, and a wind sufficient to prevent surface ice from quickly forming. It was found that the netting was coated over with coarse crystals of ice and the sponges were solid lumps. He says "the crystals of ice had every appearance of growing *in situ*." The current was so weak that he considers they could not have been drawn down. This observation of Mr. Poole's is clearly one of radiation.

Mr. Murdock stated that he had never seen anchor ice on clay bottoms, but only on shallow rapid rivers with rocky beds. Frazil, he considers, the same as anchor ice and has the property of floating under the surface of running water. He speaks of the case of the uplift and overflow of the Saskatchewan by the anchor ice, which came under his notice.

Mr. Steckel remarked on the origin of the word "frazil" and considered it to be a purely French-Canadian expression for "slush ice." He advised adopting a name common to both French and English and suggested "Frasis."

Mr. Sproule then followed, and remarked that only a small part of the frazil blocking the channels has at any time been attached to the bottom. He considered that frazil is formed only at very low temperatures, and seems to differentiate it from a surface ice film, which is forming all the time when the temperature is a few degrees below the freezing-point. It is the disintegration of this surface ice that he thought caused the most obstruction. We cannot see where to draw the line of separation in Mr. Sproule's suggestion. Frazil is distinctly a product of surface agitation as well as, what we have termed nucleation in the mass of the river when undercooled, so that no distinction really exists.

There is no doubt that Mr. Sproule was entirely correct in attributing to frazil the main agent at work in obstructing river channels.

Mr. Keefer, after describing anchor ice and frazil and the meaning of the terms, gave some of the conditions necessary for their formation. He says: "Anchor ice will form on the bottom in shallow streams whenever there are about 15 degrees of frost or more." At Montreal he considers that there is little doubt that the depth of formation extends in severe weather to 45 feet. The thickness to which it will grow depends on the duration of the cold. In comparing his observations of anchor ice and frazil, Mr. Keefer refers to the fact that there is often an abundant formation of slush ice (frazil) on the surface in the main channel at the setting in of winter, which collects in masses by mutual attraction or cohesion of the spicules. He goes on to say: "If this be the raw material from which the growth of anchor ice is made at the bottom, the fact still remains that this ice is most abundant on the surface when there is no anchor ice at the bottom; on the other hand, the growth of anchor ice at the bottom is most rapid when and where there is no visible ice of any kind floating upon the surface." He considers that it may be possible for surface-formed crystals to build up anchor ice, but the first layers must be formed on the bottom *in situ*. He then goes on to give his reasons for holding the radiation theory. He states that intelligent and reliable mill owners assert

that this troublesome ice is never found in their mill-races no matter how cold the weather is whenever the sun is shining or whenever there is a cloudy sky at night.

In concluding his remarks, Mr. Keefer stated that anchor ice is not an unmixed evil; from the large amount produced and the enormous quantity of heat set free in its formation, he considers that it plays a very important part in tempering the severity of the climate. A closed river or lake is practically shut off from heat loss, while an open river is an abundant source of heat.

Sir William Dawson stated that the best name for frazil would be "spicular ice," which is used by geologists in discussing the subject. It floats in the water and is perfectly soft and mobile. "Such ice," he said, "may consist of thin blades or needles of a crystalline character, which may form in a separate or detached manner in water, which is cooled below the freezing-point, and which is agitated by the wind, or by a rapid current, so that the ice cannot become compact." The spicular ice may further grow on the bottom in the manner in which crystalline needles form in some saturated saline solutions. He stated further: "The fact that it forms most readily in open water without any covering of ice, and in clear cold weather, indicates that radiation from the bottom has an important influence in its formation, but where the water is sufficiently cold it may crystallize on any nucleus presented to it, and more especially, it would seem, on metallic bodies and stones which are good conductors of heat. Hind states that on the coast of Newfoundland anchor ice forms in large masses in the sea, at depths of sixty and seventy feet, and it has been known to raise stones and anchors from the bottom, and to freeze around fish caught in nets. He also states that when the salt water has been cooled below the freezing-point, the fresh water of streams pouring into it from the land is at once converted into lolly or floating frazil. In this last action there is something analogous to what takes place when water at about the temperature of 32° is tossed about in a rapid and mixed with air at a still lower temperature, perhaps below zero. These are merely desultory observations from the point of view of a geolo-

gist; but they may serve to show that there are different kinds of spicular ice, and that they may be formed in various ways. It seems certain that several of these modes of formation are concerned in the production of the spicular ice so troublesome in our river, so that it is not prudent to limit ourselves merely to one theory of formation, any farther than the general principle that they all depend on the somewhat rapid crystallization of water, under circumstances in which it tends to form groups of spicular crystals rather than solid sheets."

Mr. Tate remarked that whenever water, at a temperature of 32° Fahr. or less, was passing over the riverbed at a higher temperature, a formation of ice might occur after the manner of hoar frost, possessing great cohesiveness and tenacity, until disturbed by a higher temperature or other forces.

Mr. W. Bell Dawson pointed out the influence which the point of maximum density would have on the formation of ice in quiet waters, and the absence of this condition in a rapid, tended to make ice crystallize on the bottom and sides. He considers that the frazil in the water is produced mostly from crystals so formed.

Mr. T. Guerin gave as his theory of frazil that it consisted of particles which must have been frozen separately. To bring this about, the water must have been divided into distinct particles at the time of freezing, such as when violently agitated into foam and spray. He did not believe that frazil is always formed at the bottom. We notice here the confusion of terms. He also found it difficult to believe in the amount of frazil (anchor ice) observed lying on the bottom near the Canadian Pacific Railway bridge at Lachine.

Mr. P. A. Peterson, in reply to Mr. Guerin, described his personal observations of the anchor ice at the C.P.R. bridge. He stated that in taking soundings in depths of water varying from five to forty feet, the bottom of the river was frequently covered over its entire area with frazil (anchor ice) from two to three feet in thickness; when the sounding-rod was let down upon it the frazil (anchor ice) was of such a consistency as to sustain the

rod, which could be forced through it by a couple of strong men without much difficulty. He describes the rise of the ice in mild weather, when it could be seen all over the open surface of the river. He observed that it formed during a period of intense cold, when the thermometer was below zero.

Mr. W. McLea Walbank described the anchor ice as being visible at Lachine in the open water on a clear day, and that it always came up to the surface on cloudy days, turned upside down.

Mr. Irwin considered that air mixing with water was the main factor in the production of frazil ice. Such ice, he thinks, would be very cold and therefore dense enough to sink and be carried to the bottom. Under surface ice frazil does not form, which Mr. Irwin considers is in direct support of his theory. It is not clear whether he refers to air absorbed by the water or air which has become churned up with it. In any case, it is impossible to conceive of an ice crystal forming, and being so cold, that it sinks readily in the water. How could it be so cold, a question we may well ask ourselves. If the cold of the air bubble forms the ice crystal, why should the crystal not grow by the addition of more ice, rather than remain below the freezing-point.

In his concluding remarks Mr. Henshaw stated that frazil and anchor ice were of common origin. Anchor ice, he thinks, forms when the current is too swift to allow "efflorescence," and may be likened to "an accumulation of roots when branches and foliage have been swept away." He does not consider that the loose masses seen floating in our rivers can ever have been attached to the bottom, "even if it is assumed that the nuclei have, by some means, reached the necessary temperature, and still more so that the particles from the surface should arrange themselves in forms suggestive of luxuriant vegetable growth."

We must now turn to the very valuable report of the Flood Commission, and there we find a section devoted to a discussion of anchor ice, as it presented itself to the engineers in charge of the work.

I regard their observations of much value and the section is reproduced since the report is difficult to obtain.

Article on Anchor Ice, Extracted from the Report of the Montreal Flood Commission, 1886-87.

"The terms 'anchor ice' and 'frazil' (cinder ice) are indifferently applied to the same material, but the first evidently is most applicable to this ice when found in the bottom of the river. Large quantities are formed by a comparatively moderate degree of cold upon the surface of the open water and never reach the bottom, but a still larger quantity in the same area and with much greater rapidity becomes attached to the bottom in the coldest weather only, and leaves it on the approach of a higher temperature. In one respect the two are identical, that is, both are exclusively the production of open water. There is no formation of either when and where the surface is covered with ice, and, whereas large formations of both take place in the beginning of winter, over the vast surface below the Lachine Rapids, the further formation of this ice ceases as soon as and wherever the ice-bridge is formed. Frazil, as distinguished from anchor ice, is formed over the whole unfrozen surface above and below Lachine Rapids between Prescott and tide-water, and wherever there is sufficient current or wind agitation to prevent the formation of bordage ice, while anchor or anchored ice, except in the shallowest portions of the current, does not appear in the deeper water until zero weather sets in.

"This continued low temperature brings the whole body of the water to or even below the freezing-point, and it is then filled with needles of ice, which are carried from the surface to the bottom and from the bottom to the surface by the rolling motion of the descending water. The contact of this frigid current with the bottom brings the latter into a condition when this form of ice adheres to and commences to grow rapidly upon it, as an icy fungus or moss attaining a growth of several feet in depth within the duration of a severe cold term, which may extend from three to five days. On the approach of

mild weather it becomes detached from the bottom, sometimes bringing up with it gravel and stones, and may be seen a dark-colored mass bursting up all over the open surface with considerable force and with a hissing sound, which rises a foot or more above the surface, but falling back shows only a few inches floating above it. Out of the portion above the surface the water quickly drains and it becomes as white as snow. The river surface then presents the appearance of a meadow dotted with low white haycocks, which pass over the Lachine Rapids and go under the fixed ice below. This is repeated several times during the winter, the number of the 'crops' and the thickness of each depending on the severity of the winter.

"One of the principal objects of our survey has been to ascertain what became of this anchor ice, as well as of the surface-formed frazil, after they disappeared under the ice-bridge. Holes were cut through the ice in March last and lines of cross sections, over fifty in number, were taken at various points between Lake St. Peter and the Lachine Rapids. Through these holes the thickness of solid ice and of frazil, as well as the depth of water underneath both, were ascertained. The frazil or anchor ice, was always found immediately underneath the solid ice and attached to its under side. Chopping was always necessary to get through the solid ice, but as soon as the frazil was reached the water came up to its winter level. A pole could be forced through the frazil and a heavy sounding weight could be 'churned' through it until the clear water was reached, or the bottom of the river, where, as in some cases, this deposit extended to the bottom. The first trial cross sections showed that the deposit of frazil was comparatively small in quantity below Varennes. The cross sections, therefore, were taken chiefly above Varennes, and more frequently where the greater deposit was found. The great bulk of the frazil was found above Longue Pointe, and above that point, therefore, the great majority of the cross sections were taken. The greatest quantity in proportion to the free water was found in the Laprairie Basin. Here there was more frazil than clear water, the proportions being

one hundred and seventy millions of cubic yards of frazil to one hundred and thirty million cubic yards of water. The next greatest quantity was found between Ile Ronde and Longue Pointe, where there was about half as much frazil as clear water, the proportion being forty-five millions of cubic yards of frazil to ninety-one millions of water. The next most congested section of the river was that between Victoria Bridge and Ile Ronde, where there was found about thirty per cent. of frazil. The next in order of congestion was between Longue Pointe and Pointe aux Trembles, where the frazil was about twenty-seven per cent. of the clear water. The last section measured was between Pointe aux Trembles and Varennes, where the frazil was reduced to a little over six per cent. of the clear water.

"These proportions of ice and water are confined to the frazil alone, and do not include the solid ice covering of the river, which, weighed down by snow, thaw, and rain, is thereby depressed below winter water-level, and by so much encroaches on the discharge at its widest point. In these comparative quantities no account is taken of the water with which the frazil is saturated when suspended in the channel and underlaid with clear water. When grounded and compressed by the weight of the solid ice overhead, little water can penetrate it, and this grounding is shown by "hummocks' on the river surface where the frazil is holding up the crust when elsewhere it has been lowered by the falling water.

The greatest depth of frazil below Montreal was found immediately opposite Longue Pointe. Here the downward growth from the under side of the solid ice covering of the river extended to a depth of thirty-five feet. It was found nearly as deep at the foot of the Lachine Rapids. In these cases it reaches nearly to the bottom, but, of course, not all the way across the channel, otherwise the river would be driven out of its banks. Opposite this great 'undergrowth' at Longue Pointe the main channel is about sixty feet deep, overhung with about twenty feet of frazil, but having a clear waterway under it nearly forty feet deep, through which it finds relief. That this downward growth of frazil is, in the

situations most favorable for its accommodation, only limited by the depth of water seems probable from the results of our soundings above Beauharnois, where the enormous winter run of frazil between Lake St. Francis and Lake St. Louis is arrested as soon as the latter is permanently closed. Here we found the undergrowth over eighty feet deep and reaching within a few feet of the bottom.

"On the basis of our cross sections the estimated quantity of frazil between the Lachine Rapids and Varennes, in March last, was two hundred and fifty-three million cubic yards. Besides this frazil, there were one hundred million cubic yards of surface ice, between the Lachine Rapids and Varennes, making a total of ice in this section exceeding three hundred and fifty million cubic yards. Of this amount two hundred and twenty millions were above the line between Moffatt's Island and Windmill Point, but as the ice went partially out of Laprairie Basin before the flood and shoved in front of the city, about half of this two hundred and twenty million cubic yards must have slipped down below Ile Ronde before the ice-bridge gave way, and thus contributed to the flood of April last. The quantities of March, 1887, were probably in excess of average winters; but our investigation of temperature shows just as severe winters not followed by flood. There may have been as great, or even greater, quantities of frazil in some non-flood years, when it was differently distributed, or when it moved off in different order.

"We endeavored to ascertain whether there was any diminution of this body of frazil before the ice went out, for which purpose it was remeasured up to the last day on which it could be safely done. Warmer land-water is coming in, it may be weeks before the ice goes out, but apparently it had no effect upon the frazil or upon the channel-water, which maintained a temperature almost at the freezing-point to the last.

"Thus there was in April last, during the flood, about three million cubic yards of ice masses in that portion of the river extending from Montreal to Varennes, forcing the river to rise over nine feet higher than when the ice-

bridge formed at Hochelaga in the end of December, 1886. Probably one third of this total had been let down below St. Helen's Island from that portion of the river between it and the Lachine Rapids, which contained over two hundred million cubic yards of ice. This was an obstruction compared with which St. Helen's Island, Ile Ronde, and Moffatt's Island are insignificant. The whole cubical contents of these islands above low-water mark is under twelve million cubic yards.

"This ice obstruction causes the river to rise until its increased sectional area and additional head give the necessary discharge, and, whereas the river, when not burdened with ice, varies its sectional area, surface slope, and velocity, as it narrows or widens, shoals or deepens, we find that when congested with ice, with all lengths, of cross sections and all depths of frazil, there was remarkable uniformity in the area of the free water-way left, everywhere between Lachine Rapids and Varennes. The river evidently disposes of the downcoming frazil, where it will be least in the way. A very large proportion of that we found in March, perhaps the greater portion, had been carried down there after the ice-bridge was formed. All through the winter we found from observations at the air-holes that frazil was passing down below the city. This undoubtedly had come over the Lachine Rapids and had gone through the whole length of the Laprairie Basin. How far it travels from Montreal we cannot determine. It probably follows the main channel current until it is wheeled out of line by some eddy or counter-current, and is thrown into lower water, where it will be allowed time enough to attach itself to the ice overhead. There is no means of getting current velocities under the frazil, but the presumption is that when this encroaches upon the channel to a certain extent, the local current is quickened and no more frazil allowed to stop there. In whatever way it is done the cross sections prove that the river, like a judicious stevedore, disposes of the frazil as it arrives, and so places it as to maintain a thoroughfare for its water.

"Uniformity of water-section suggests uniformity of current during this state of ice congestion, which we know

does not exist when the river is free from ice. The summer current opposite Montreal is much stronger than it is in the Laprairie Basin above or in the river below Hochelaga. The one is reduced and the other increased by the ice pack, and it is owing to this increase of current in Laparirie Basin chiefly that so much frazil is carried down below Montreal and so far below that city.

"The sources from which this enormous amount of frazil is derived are, first, the whole river above Montreal until Lake St. Louis is closed, then the river-section below this lake as far as Laprairie Basin, with its twenty-nine square miles of water surface, nineteen square miles of which remained open until the ice pack from below ascended to the Victoria Bridge. After this space is filled up with ice the open area from the foot of the Lachine Rapids to Lake St. Louis above Ile Dorval, containing about twelve square miles, remains open all winter. Lake St. Francis is permanently closed in December, but the fifteen square miles of open water between it and Lake St. Louis sends down the frazil in such quantities that the channel opposite Beauharnois is blocked, raising the water about thirteen feet, the flow of the Ottawa River, on the Vaudreuil side of Ile Perrot is stoppped, the current reversed, and large quantities of St. Lawrence water pour down the Back River (the main stream of the Ottawa), and re-enter the St. Lawrence at Bout de L'Ile, fifteen miles below Montreal."

Mr. T. C. Keefer, C.M.G., C.E., in his presidential address before Section III., of the Royal Society of Canada in 1898, took as his subject, "Ice-floods and Winter Navigation of the Lower St. Lawrence." No one is more competent to speak to us on the subject of the ice problem than Mr. Keefer, whose vast experience in handling the matter has won for him the greatest praise. As one of the prominent engineers of the Flood Commission, he aided in bringing about a most complete understanding of the conditions giving rise to the floods we have already described, out of which have developed effective methods of prevention.

Mr. Keefer devotes a section of his paper to the subject of anchor ice, and in this we find what he terms a

supplement to the paper by Dr. Bell, which we have already referred to. The points brought out are so important that I cannot do better than reproduce them here.

"1. The greater formation of anchor ice, both in area and thickness, is often in the deeper open water above the rapids. In the shallower rapids it forms and rises more frequently, and in less severe frosts, probably because of radiation, is more rapid and sun penetration greater in shoal than in deep water, and from the more rapid flow of the ice-cold water chilling the stony bottom. In long-continued, extremely cold spells of several days' duration it may grow, in a rapid, to a very considerabe depth and form a dam, raising the whole water-surface. When this gives way we are not able to say whether it has yielded before the increased head of water, or from the relaxation of its hold upon mother earth, which follows a change of temperature.

"2. It has been known to continue for days and nights on the bottom and attain great thickness, without a clear sky overhead, but with the thermometer always below zero, Fahr.

"3. The very large boulders which are picked off the shoals below the rapids and dropped in the ship channel below Montreal are lifted (I believe) by anchor ice lodged under the surface ice. By the sudden, and often considerable, elevation of the field ice to which it is attached (which may be caused by a 'shove' before the river 'takes' in January), the whole may be driven upon or over a boulder shoal and settle down with the falling water enveloping a boulder with its saturated slush, out of which all water is pressed, by downward pressure of the surface ice, during the winter fall of river-level and thus form a solid mass. These icy 'islands' are seen as 'hummocks' after the winter lowering of the river, when the compressed anchor ice beneath holds up the surface ice much above the water-level. When the whole field is lifted by the spring rise of water the boulder accompanies it (a mere pebble in proporation to the size and lifting-power of acres of ice perhaps twenty feet thick in

some places), and is dropped as soon as warmer water in the river releases it from its icy matrix.

"4. It is not only 'in the rapids,' but everywhere where there is open water in the river, that the colder surface-water is carried to the bottom. Anchor ice has been found at least two feet in depth on the bottom in over twenty feet of water in the river above the Lachine Rapids. This is only during the severest weather. Although the temperature of the water may not descend perceptibly below the freezing-point, while that of the air is over twenty below zero, it is under these circumstances this deep river bottom produces anchor ice, and when this ice rises, as it does in floes of considerable size, it does so with decided force from such a depth, projecting its top into the air and falling back with a hissing sound due to the rapid drainage of its above-water portion. It is also known that at the time of this formation upon the river bottom, the flowing water is loaded with fine ice crystals (to the formation of which, I think, the cold surface-air is a necessary factor) and, as these are carried to the bottom, the presumption is that they are picked up by a condition of river bottom which does not exist at other times, which, if not actually frozen, has this power of attraction for these passing crystals by which alone, I believe, anchor ice is formed. Whether the river bottom is frozen by radiation into space or into an intensely cold atmosphere at the surface of the water, or whether this is produced by the continued friction of an ice-laden current of the coldest possible water, the result is the same and is fortunately limited to short and infrequent periods of severe winters.

"After the spring break-up, when large masses of ice are driven ashore by the final 'shove', ice-floes have been found on the beach, partly composed of several feet of anchor ice, to the bottom of which frozen gravel was attached."

A most interesting observation is reported by Mr. Keefer, which illustrates the immense growth of frazil crystals in the water during a very cold day. He describes crossing over the river below the Lachine Rapids

in an open boat, when the thermometer was twenty below zero, Fahrenheit, and noticing the frazil ice spiculae so thick that their resistance to the paddle could be felt, and when the paddle was withdrawn the needle-like spiculae stood out at right angles to it. The crystals seemed to be attached only by the point, like iron filings to a magnet.

During this time the river must have been slightly under-cooled and the frazil forming rapidly. The constant withdrawing of the paddle into the cold atmosphere chilled it to such an extent that these crystals at once attached themselves, and grew to considerable dimensions.

Mr. Keefer refers to the disastrous effects of anchor ice, during a winter of great severity, in driving a river out of its bed, and this, he thinks, accounts for some of the "ancient channels," "lost channels," and "high-water channels" to be found near some cataracts and rapids.

He draws attention to the yearly closing of the outlet of the St. Lawrence at the head of Lake St. Louis by the frazil manufactured in the Cedar Rapids, and the consequent overflow of the St. Lawrence around the head of Ile Perrot into the channel of the Ottawa.

Depth of Formation of Anchor Ice in Fresh and Salt Water.

The depth to which anchor ice will grow seems to be about the same in the clear waters of the ocean, according to the observations recorded by Captain Robert F. Scott, in his "Voyage of the Discovery," as we observe it in our northern rivers. In his log of September 12th, 1902, we find that his attention was drawn to the fact that his nets and ropes, whilst under water, became coated over with ice-crystals. He describes it as "a very curious phenomenon." One line, only an inch in circumference, was pulled up covered with a cylinder of flaky ice nearly a foot in diameter. This cylinder of attached ice extended five or six fathoms (30 to 36 feet) below the surface, after which it gradually dwindled away. Captain Scott describes the ice as very delicate and of a flaky structure, the

axes of the leaves being at right angles to the rope, while their planes were inclined and intersected at an angle of crystallization of 60. The whole thing, he says, "looks like some beautiful lace fabric, and, held up to the light, we can see through it the most gorgeous prismatic coloring. It falls to pieces at a touch, and each leaf can be split to the thinnest layers." The likeness to anchor ice, as we observe it, is at once apparent.

He further describes similar crystals formed on the townets, where each minute fibre forms a nucleus for the ice to grow around.

Temperatures were taken of the water at the time, which indicated something below the freezing-point of the salt water, but he did not place much reliance on these readings, for he says, "I do now know that they (the temperatures) are very reliable for such small differences." At a later date he states that the explanation was given to him as due to the supercooling of the sea, when ice would form around nuclei, such as the ropes and nets, "just as a saturated solution can be made to crystallize." "In this light," he says, "it would be natural enough that the effect should increase as the water grew colder towards the spring, and it is interesting to note that Hodgson found that at one time these crystals formed as deep as 17 fathoms (102 feet) below the surface."

It is quite possible that the open sea, not being affected by currents of any magnitude nor agitated in its depth, might become supercooled, but with the presence of so much ice it is difficult to imagine it so. Captain Scott's most frequent observations were made of the flaky ice which diminished beyond 40 feet, which is quite in accord with the data we have in regard to nonformation of anchor ice beyond 40 or 45 feet in our rivers. If radiation played no part in the formation of the ice around his ropes and nets, then it is difficult to see why the ice should not form beyond this depth if it grows in the way he suggests. It is possible that the sea was above the freezing-point at these depths, but there is certainly a close agreement with well-existing data for

anchor ice. The one observation of ice 102 feet is very interesting, but this was not observed by Captain Scott personally.

It was pointed out by Sir Wm. Dawson, in the discussion of Henshaw's paper on page 118, that on the coast of Newfoundland anchor ice is known to grow in large masses at a depth of 60 or 70 feet in the sea. This compares with the observation of ice at a depth of 102 feet. Sea water is usually very clear, and will permit of the transmission of radiant heat from a greater depth than in the case of the more turbulent waters of a river.

To account for anchor ice and the fact that spongy masses of frazil crystals float low in the water, it has been suggested that the density of these forms of ice was greater than normal. The production of a very dense ice that apparently sank in the water of an ordinary cryophorus was recorded by Professor John Cox in 1902. Prof. A. N. Shaw has repeated this experiment many times, and has on occasions attained ice which apparently sank. Experiments made of the density of frazil ice, directly withdrawn from the water, which were made by Dr. John R. Freeman, yielded in every case normal results. This taken in connection with the known buoyancy of anchor ice leaves little doubt that the ice which is commonly met with in nature is of ordinary density.

The Buoyancy of Frazil Ice in Water.

It now appears quite clear why very small ice crystals such as frazil appear to have little buoyancy, and, therefore, are easily carried about in the water by the various currents. A body moving through a fluid is subject to a viscous resistance which retards the motion. Under the influence of the gravity pull, a body falling or rising through water will acquire a constant velocity called the terminal velocity which represents the equilibrium between the gravitation force and the viscous resistance. Since the gravitating force is a volume effect while the viscous drag is a surface effect it follows that the former decreases more rapidly than the latter as the diameter of the body decreases.

Stokes has worked out the expression for the terminal velocity of small spherical drops of water falling freely in air and has shown that fog particles may thus remain suspended in air for long periods when they are very small.

The viscous drag on a small sphere of radius r is a force given by the expression: $f = 6\pi\mu r V$
where μ = cœfficient of viscosity
V = terminal velocity of the sphere.

Suppose a sphere of density σ falls under gravity in a fluid of density ρ the force pulling it down is $\frac{4}{3}\pi r^3(\sigma-\rho)g$ Hence when the viscous drag balances the downward pull $6\pi\mu r V = \frac{4}{3}\pi V^3(\sigma-\rho)g$ from which $V = \frac{2g r^2(\sigma-\rho)}{9 \quad \mu}$ the expression generally used.

Zeleny and McKeehan have carefully verified the truth of this expression for small spores, powders, and spheres of wax and mercury. When we apply the expression to the movement of ice we can do so only approximately since these particles are not spherical. Nevertheless, it furnishes us with some idea of the size of a small ice sphere which would not rise through water.

For drops of water in air where $\mu = .00018$ and $r = .001$ cm. the velocity is only 1.2 cms. per second. When the radius increases to .01 cm. the velocity becomes 121 cms. per sec. which is considerably larger. This explains why fog particles settle so slowly and rain drops fall so rapidly.

Ice being lighter than water the effect of gravity is of course to lift it upwards. Taking μ for water at O° C. as .01793, the density of ice as .9166 and that of water as 1. then for an ice sphere of .01 cm. radius,

$$V = \frac{2}{9}\frac{981\,(.01)^2\,(.9166-1)}{.01793}$$

which is very nearly .1 cm. per second. A sphere two-tenths of a millimeter in diameter could probably be seen at close range in water, and be practically suspended in the water. It is evident that very small ice crystals can be regarded as having no buoyancy, although their

density is quite normal. Some actual experiments on spheres and cylinders of ice would be of considerable interest.

Winter Ice Floods.

The narrow portions of the river below Montreal are entirely inadequate to carry off large quantities of floating ice, and a consequent damming of the waters annually occurs.

As to the character of the floods, I cannot do better than turn to the Report of the Flood Commission: "The St. Lawrence River is not subject to floods in the ordinary sense in which this term is applied to other rivers, such as the Ohio and Mississippi. The floods with which we have to deal are not due to excessive quantity of water but of ice, and are entirely local, being confined to a comparatively insignificant extent of the river. Although due to ice formation, they differ from ice gorges in the more southern rivers, which are of short duration and often more destructive, and are produced only by the breaking-up and departure of the ice. In the St. Lawrence, on the contrary, there is a permanent elevation of the river level in the affected districts, while the volume of the flow is diminishing, which elevation, though not maintained at maximum height, continues throughout the winter. Although this takes place every winter, and the wharves of Montreal are submerged about four months in the year, this winter rise of the river is not always accompanied by what may be called a flood. The river reaches its highest winter level from the packing of the ice in December or January, and its highest spring level, arising from the breaking-up and departure of the ice, in March and April. The spring break-up resembles the ice gorges of other rivers, in that it is an accompaniment of the departure of the ice, but this winter elevation is peculiar to the more northern rivers, and, when it reaches the proportions of a flood, is the result of an unusual burden of ice blocking the channels and requiring a temporary rise before the river can force open a larger area of waterway and settle down to its winter bed."

The strength of the water-current really determines the formation of a continuous surface sheet, and the barrier ice, which forms at the foot of rapids where the river widens out, encroaches on or recedes from the open water in direct proportion to the severity of the weather. It is when the strong floating ice meets the barrier ice that the winter packing sets in. The packed surface of the channel presents a ragged section both in air and water. All interstices are filled with frazil, which is also drawn in under by the current, but very soon rises to the under side of the ice and freezes there. So deep and firm becomes this accumulation of frazil that at one time it was the custom of the railroads to construct a track across the river for the carriage of freight.

The accumulated mass of frazil, though porous and saturated with water, is as effective an obstruction to the flow of a river, with respect to the area occupied by it, as so much rock. The obstruction it creates may be inferred from the fact that it compels so great a river as the St. Lawrence to back up in winter fifteen feet at one point below Montreal before it can force sufficient way for its low water discharge through "these miles of monstrous tubercular growths within its ice-covered bosom."

Extract from the Report of the Montreal Flood Commission.

The St. Lawrence is a river of such width and depth that, notwithstanding the great volume of water which it carries (its low water discharge above Lake St. Peter being 315,000 cubic feet per second) its extreme range between highest and lowest water marks is only about six feet, or one-tenth that of the Ohio at Cincinnati. Wherever this range is exceeded, as at Cornwall, Beauharnois, and Montreal it is only in winter, and is due to the packing of the ice. The river below Montreal is affected by ice from tide-water to the foot of the Lachine Rapids—a distance of eighty miles—and, with the exception of what are called air holes, the whole surface is covered with ice. But above the Lachine Rapids the winter level is only elevated by ice for a short distance opposite Cornwall and Beauharnois. All the remainder, embracing both open water river sections and ice-covered

lake ones, with rare exceptions, maintains the ordinary level. The exceptions are where an ice-bridge or jam may occur in the narrower channels above the Cornwall Canal in very severe winter, or where a bridge is formed artifically by sawing off enough bordage ice and swinging it across the channel to an island, to give communication with the mainland. These bridges do not affect the river-levels at their site, but by arresting floating ice may advance the bridge upstream to a point where shallower water and a swifter current may cause a pack and form a dam. The open water sections are about forty miles in length between Cornwall and Prescott, about fifteen miles between Lakes St. Francis and St. Louis and about ten miles between the ice-covered portion of the latter and the foot of the Lachine Rapids. There is no case of a permanent winter dam where there is open water immediately below it (as in the case of a gorge at the break-up of the ice), but the permanent winter rise at Cornwall and Beauharnois takes place under the same conditions as that at Montreal, namely, the junction of a river section open with one which is closed, and of a strong current with comparatively dead water.

It is when the ice-bridge approaches a rapid which is fighting for its life, that the grandest effects of its convulsive efforts are seen. The large ice-floes, as they approach the ice-bridge, are nipped between it and the moving ice behind them and are broken, tilted on edge, forced under the bridge, or packed against it. When this moving mass is excessive it grounds on to the shoals and piles in the channel, thus throttling the only waterways left to the river; the latter then rises rapidly, backing up to deliver an effective blow and drives the obstruction before it and on to the bordages or under them out of the channel. Sometimes the solid bordages are lifted, cracked, and the edges driven over each other or on the shore, where piles of great height and volume are suddenly formed, sweeping everything movable before them.

These collections of frazil are the most important factor of the flood question, and, indeed, it may safely be asserted that they are the sole cause of them. In other words, if there were only field or bordage ice to deal

with, no matter how often they were broken up or broken off by wind or thaw, there would be little chance of floods. The tendency of field or bordage ice is to float, and it resists submersion with great force, while the tendency of frazil and anchor-ice is to sink upon the slightest provocation and follow submerged channels, taking all the windings of the currents until grounded in shallow water or arrested against the under side of the fixed ice, to which it freezes and forms a nucleus for further accessions of the same material, until this spongy downward growth reaches many times the thickness of the surface ice to which it is attached. Fig. 21.

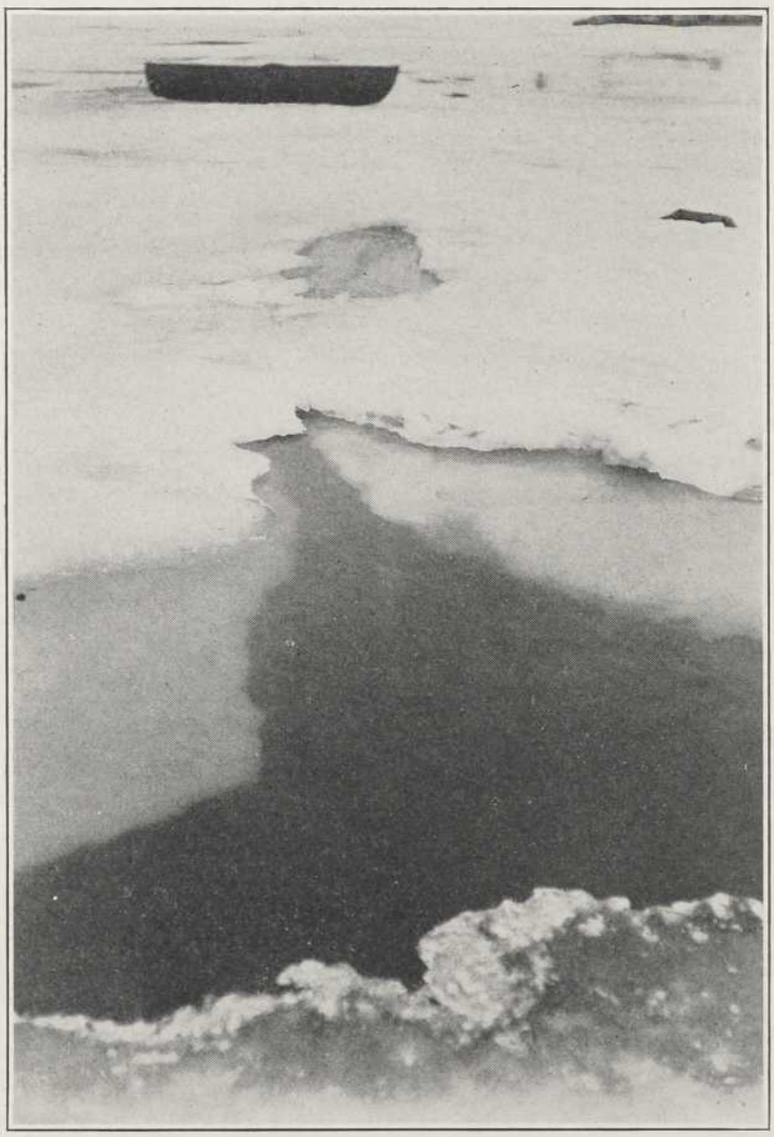


Fig. 21.—Frazil showing through the clear water of the St. Lawrence attached to the underside of the surface ice.

Snow carried in the water of the open river is a very important factor not only for the actual accumulation of ice, but in the chilling action of the ice crystals falling from a very cold atmosphere. Much of this snow ice is responsible for the growth of frazil and during a heavy snow fall the water may carry great masses of ice. These masses sometimes are rolled along by the currents and become like great snow balls. At other times the ice takes the form of large discs called "pancakes" which roll horizontally with flat centers and ruffeled edges.

Turbulence in Relation to Frazil Formation.

In rapids where the water is broken and mixed with air there is an increased formation of ice. The disturbed water is equivalent to an increased area of exposed surface, while the violent agitation of the falling water tends to precipitate the colloidal particles.

Anchor ice is also observed to grow in great abundance in rapids and more readily on the upstream side of rocks. This is no doubt due to the deposit of ice particles on the face of the rocks, which the water strikes first. Running water in thin layers is cooled rapidly by nocturnal radiation, and the rock surfaces are cooled also by the same means.

It has been observed that anchor ice forms on a dry cold clear night when the night radiation is excessive, in rapids over which water is flowing when the temperature of the water in the main body of the stream is two or three degrees above freezing. The night radiation is so great at times that the first run of anchor ice comes in the morning when the river is above the freezing-point. With the sunrise all this ice is rapidly dissolved in the water.

Ice Forming Power of Rivers.

While this is treated elsewhere in this book it is worthy of note here that rivers differ in the amount of ice produced during an average winter according to their depth, turbulence and amount of natural heat which is conserved

in the stream. Thus the St. Lawrence river produces on an average about 10 to 16 cubic feet of ice for each square foot of exposed area in the International Section mostly in the rapids. While the Moira river at Belleville, Ontario, which is a shallow stream of much smaller size, but full of rapids, has produced as much as 23 cubic feet of ice.

CHAPTER VI.

ICE REMEDIAL WORK.

Use of Steam, Hot Water, Thermit, Calcium Chloride and Other Chemicals.

Attention must now be devoted to a consideration of various methods which have been used to control conditions, which have resulted from ice troubles in hydraulic work, and winter floods.

It is generally not a difficult matter to find out the precise nature of the ice troubles which annually cause curtailment of the output of power developments, or which result in damage from winter floods, in settled communities.

The writer has always claimed that a careful scientific study of ice problems would lead to remedial methods of importance. Changes of climate, however, bring about variations of condition in any locality, which complicates the problem as it is presented to the engineer. It is only by gathering and discussing experiences, and interpreting such in the light of our present knowledge of ice formation, that we may expect to do the most good; and it is hoped that, in due time, the ice problem will be conquered, and it will no longer be necessary to view with alarm, the advent of cold weather.

Considering the important role played by ice in the economy of nature, it is surprising that more attention and study has not been devoted to the effects of ice, in designing new hydraulic developments. As a rule the ice is regarded as a possible source of potential trouble, but rarely is the question squarely faced, and the water

courses studied with a view to ice prevention and ice control. Much can be accomplished at the inception of the problem and subsequent loss avoided.

In northern countries an ice engineer is as essential as a highway engineer in laying out new roads.

Use of Heating Devices in the Form of Steam and Hot Water.

It is interesting to review the work of those who have so far perfected heating methods for ice prevention. All methods are included here, especially those of foreign design, but the main ones outlined.

A notable example of the early efforts to combat frazil ice is to be found in the 16th Annual Report of the Board of Water Commissioners, of Detroit, Mich., published in 1868. After discussing suitable pipes to be used, the report, which was by S. G. Wright, and J. Owen, refers to the trouble from stoppage by ice, and their efforts to overcome this, is interesting reading.

"The water is drawn from the well by a steam pumping engine. When the engine is pumping, the water is required to pass through the holes in the strainer at the rate of one hundred and twenty barrels per minute, to furnish a full supply.

"Under certain circumstances during extreme cold weather, it is with difficulty a supply of water can be obtained, in consequence of the accumulation of ice on the strainer, frequently requiring the speed of the engine to be reduced, and at times to stop it for several hours together, no water passing through the pipe into the well, notwithstanding the bottom of the well is twelve feet below the surface of the river. The size of the well is about forty feet long, eighteen feet wide, and twelve feet deep. The circumstances under which the difficulty occurs are cold weather, ice forming in the lake above and on the shores of the river, and the river free from ice over the strainer. But when the river is covered with ice over the strainer, the difficulty does not occur at any degree of cold. The greatest

difficulty occurs when the thermometer ranges from seven or eight degrees to eighteen or twenty degrees above zero, but when the mercury rises above twenty degrees the difficulty soon ceases. The greatest number of detentions, it has been observed, occur at night, and when the sun is obscured by clouds; but when the sun is unclouded, no difficulty is ever experienced. This peculiar stoppage to the flow of water to the pump well has been encountered for many years—first on the strainer of the inlet pipe laid in 1840, again on the one laid in 1850, both of which were located so near the wharf that the ice which formed on them was removed by means of long poles kept at hand for the purpose.

"The present inlet pipe was laid in 1858, which, extending farther out from the wharf, and in a greater depth of water, when ice formed as before, it could not be so removed and all that was done up to a year and a half ago was to wait for the action of the elements on the ice to remove it, which usually takes from three to four hours.

"With the rapidly increasing consumption of water, it cannot but be evident that the time will very soon arrive when it will not be safe to permit any detention to the pumping engines, and that this remarkable phenomenon must be solved and the difficulty overcome. Your committee has adopted every accessible means of investigation to obtain suggestions and information on this subject. Attention has been called to it in our published reports, and by the Press. Men of science have been seen and corresponded with, and scientific associations have been requested to investigate the subject, but as yet no complete remedy has been discovered. As no experiments had ever been previously made, and the theory was so strongly presented to us that the trouble was wholly from anchor ice forming on the strainer, we, in the summer of 1866, caused a submarine diver to cut an opening through the downstream side of the strainer, and hang a self-acting door. Under similar circumstances in the winter, when the engine had heretofore been stopped, this door gave a limited supply of water; but from unforeseen causes, it had to be abandoned and

permanently closed. When the river was entirely covered with ice, no trouble was experienced. This fact induced us to suspend a line of booms from the wharf some distance above and outside the strainer, so as to retain a covering of ice over it when the rest of the river was not covered. This boom was successfully kept in position until the ice firmly formed inside of it, but failed to accomplish the object. The theory that the covering of the entire surface of the river by ice prevented radiation, and by that means the ice did not form on the strainer, was strongly urged; and, if so, any covering over the strainer would answer the same purpose. To test it, we, last summer, employed the submarine divers, Messrs. Harrington and Phillips, to build a submerged platform of planks immediately over the strainer, which they successfully accomplished, but which, however, proved of no avail, for the stoppages occurred at a higher temperature than before.

"On the 29th of December last, while but a small supply of water could be produced, we induced Mr. Harrington to go down to the strainer and make an examination of its condition. Owing to the extreme coldness of the water and atmosphere (the thermometer on the wharf marking twenty-six degrees), it was impossible for him to remain down but a short time, but long enough to discover the fact that the strainer, with its surrounding spiles, was one mass of ice particles collected into a mound some ten feet high, and about fifteen feet in diameter, and that large quantities of minute crystals of ice were rapidly passing, and adding to the mass already collected. Specimens of the ice were brought to the surface in a bag. It was in sheets and particles thin as paper, translucent, with sharp, pointed edges. A further examination developed the fact that the small amount of water the pump was then receiving came through the lower or downstream side of the strainer, this being the only point where he could approach it, and which was found but slightly covered with ice. When these facts were ascertained, we thought we were about to solve the problem and provide a remedy for the difficulty, especially as a similar experiment to the one

we then proposed to adopt had been successful at the Buffalo Water Works. It was to enclose the strainer, except a part of the downstream side, so as to prevent these floating particles from collecting on and around it. To do this, a large piece of canvas was prepared of suitable size, and firmly fastened by the diver around the spiles, which, with the platform, completely covered and encircled the strainer, except on the downstream side. This was but just completed when the weather became colder, and during the night the thermometer indicated several degrees below the freezing-point, and before daylight the engine stopped for want of water. Preparations were made as speedily as possible for another descent to the strainer. At half past eleven o'clock a.m. the diver went down, and this very important fact was ascertained, that with the temperature of the atmosphere at twenty-nine degrees, the water at the surface was thirty-three degrees, whilst at the bottom of the river it was thirty-five degrees. At this descent much less ice was found on the strainer and its surroundings than the first time. The lower side was clear, but on the upper side the action of the current had worn the ice into elongated cones, pointing up stream. At this time the pump was receiving a full supply of water. About three hours later, the diver again descended (thermometer thirty-three degrees); he found the ice had entirely disappeared. The wooden platform was removed, since which time no trouble was experienced up to the evening of the 24th inst., when the surface ice of the river was in motion. From one o'clock a.m. of the 25th inst. (thermometer sixteen degrees), no water could be obtained until daylight, when the engine was again started, and no further delays have since occurred.

"Your committee, by the aid of the submarine diver, has ascertained the fact that at certain temperatures these ice particles are ever present in the river, and are continually passing down by the action of the current, and whatever obstructions they meet with in their passage they collect upon. This being the case, we recommend for the coming summer, the entire removal of all spiles and other substances adjacent to the strainer, believing that with

nothing but the smooth dome of the strainer for these particles to lodge upon, the quantity that will accumulate cannot very seriously prevent the flow of water to the inlet pipe.

Patented Heating Devices.

The first recorded patented device appears to be that of R. A. Chesebrough, U.S. No. 90727, granted in 1869, for a Steam Heater. This constituted a method for laying steam pipes along the bottom of a canal, to prevent surface ice from forming. Two 2″ pipes were placed and connected with a boiler, but as this method could never heat the bottom water above the maximum density temperature it could not have been practical.

In 1883 a patent No. 279901, was granted to Alfred H. Martine, of Fall River, Mass., for an apparatus for melting anchor ice. It is stated that his invention relates to means for removing the anchor ice which forms, or accumulates, at or near the screens of water courses, or aqueducts, and in the flumes, or gateways of mills; and it consists, first, in a jet of steam applied under water directly to the ice, by means of a pipe or hose; secondly in a flume, canal, aqueduct, or water course provided near its gateway or screen with a steam pipe, or pipes arranged in such a manner as to enable steam to be brought into direct contact with the anchor ice under water; and thirdly a perforated frame work of pipes to be inserted in the water. Steam is forced through this pipe, and emerges through the holes into the water around the screens.

It will be seen this is a method solely for throwing a steam jet into water to loosen the ice. A very crude arrangement, but interesting historically.

In 1906, Mr. John Murphy, of Ottawa, Ontario, was granted patent No. 838564, for heating racks to prevent ice accumulations in, or on, water power apparatus. Mr. Murphy also took out subsequent patents on a cored turbine through which steam could be passed. At

the Ottawa Power Co. large quantities of frazil are made in the rapids above the Chaudiere Falls, which have to pass through the turbines.

Mr. Murphy has demonstrated the success of his methods in the severest weather. We shall describe his methods in his own words:

"Holes were bored through the end plates which serve the purpose of keeping the water in the penstocks from entering the power-house, and which also form the bearing through which the turbine-shaft runs, and through these holes steam pipes were led. Steam is admitted when a unit begins to lose capacity, and normal load is picked up again within five minutes of the time of the admission of the steam. Water wheels, which were shut down during the night when frazil was running in great quantities, have been started up as soon as steam was injected, in spite of the fact that the frazil had filled the penstock and settled on the wheel cases, and blocked up the openings between the chutes.

"It is not necessary to keep steam passing all the time, but only on such occasions, usually at night, when the frazil is agglomerating and in an adhesive state. The occasional injection of steam is often all that is necessary".

Experiments were tried by Mr. Murphy on the electric heating of racks.

"We have made with a couple of bars of the rack the following trials." (The rack is the same one subjected to the steam tests.) "They (the bars) were covered with hard ice above the water-line, and also for a short distance below it. Two heavy iron wedges, used as 'terminals' were driven between them, and current from an exciter sent through the bars. Ten minutes after the current was started the ice was removed with a pocket-knife, while the adjacent bars could only be cleaned with much difficulty with a heavy chisel. 600 amperes at 0.3 volt, i.e., 180 watts, were used for this trial. The temperature of the air was just about the freezing-point, and so also was that of the water. Another day when the

air was at 15° F. ice was immediately melted from a single rack-bar by sending 500 amperes through it. Both of these trials showed that if a small amount of energy was continuously applied to the bars, ice would not form on them, and that the amount of energy would be lessened very considerably if the bars were kept away from the cooling effect of the atmosphere."

In 1908, Frank C. Pierece of Shoshone, Idaho, was granted U.S. patent No. 888924, for electrical heating deflector grates, to impart heat to water to prevent ice sticking. These grates are placed at a suitable angle in the stream to deflect the ice. This method is a simple one effective enough in small streams where the volume of ice is not great.

Mr. Ed. Gjerstad, of Norway, sent a description to the writer in 1908, of a method he had patented, of leading steam, or hot air through hollow racks on the river Glommen. The ice, he reports, is prevented from sticking to the bars at the inlets to the turbine and power houses.

In 1923, Mr. R. S. Hyatt of Valentine, Nebraska, was granted U.S. patent No. 1475389, for preventing ice sticking to the metal parts of the large turbine cases. His method is an arrangement of turbine parts, to form a closed magnetic circuit, with the runner as the central portion, and the flux returning through the gates and spacing bolts, similar to that found in the core type transformer.

By placing a stationary coil about the runner, we have a transformer with the non parts of the turbine forming the secondary, and absorbing a large percentage of power in the form of alternating current, applied to the primary coil. This he claims is a very efficient and effective means of heating the turbine, for preventing the adherence of ice. The coil and principle of application has been applied to a plant operated by the Cornell Hydro-Electric Company, on the Niobrara River near Valentine, and has abundantly demonstrated the feasibility of the method.

This plant consists of two vertical thirty-seven and one-half inch Leffel Sparks turbines operating under twelve foot head directly connected to umbrella type generators. A test coil has been attached to one of these turbines without alteration of the parts in any manner and no interference or decrease in output has been experienced. The coil has an input of 3 K.W. at approximately 60% power factor with coil losses of 0. 3. K.W. giving an efficiency of approximately 90%. The runner of the turbine is considerably worn with attendant large air gap in the magnetic circuit. A turbine with the proper air gap would materially increase the power factor of 60%.

A number of runs have been made under actual frazil ice conditions with the result that the turbine equipped and heated with the electric power showed no signs of ice while the one not so equipped was completely shut down several times and required thawing to place it in service. As a more severe test the turbine equipped with the coil was allowed to become partly clogged with ice; the gates having become inoperative at .8 opening and the power of the wheel diminished to about 25% at which time the switch was closed supplying current to the coil. In approximately five minutes the gates loosened and shortly the wheel picked up load in proportion to gate opening. The turbine was examined fifteen minutes after closing the switch, and found to be entirely free from ice. Frazil ice has been eliminated, in so far as it interferes with hydraulic turbine operation.

Having reviewed thus far various methods for applying heat at a low temperature, it is right to say that all of these have found uses under particular circumstances.

Mr. Hyatt's induction heating should prove very useful, and deserves extensive trials. Steam and hot air have been generally employed in power houses for some years, without regard to patent rights and, indeed, it seems a difficult matter for a patentee to protect his rights, so general is the practice today.

The method of bubbling compressed air at the base of racks has met with some favor, and is quite extensively

used. This owes its effectiveness to the heat of the compressed air, as well as to mechanically bringing up the lower and warmer layers of water from a considerable depth.

We shall now turn our attention to methods of dealing with the ice problem by using high temperature sources of heat, which has formed the basis of U.S. patent No. 1562137, granted in 1925, to the writer.

Thermit Heat Units for Ice Control.

The heat from reacted thermit is so intense that the mass of molton iron which carries the heat is too bright to look at without dark glasses. A temperature which varies from 2500° to 3500° C. is produced in a few seconds. The actual number of heat units per pound of material is only 1500 and is much less than for coal, but the temperature being so high this small amount of heat is very effective for the purposs of ice control. Then the energy back of the reaction, while not great compared to carbon, is sufficiently large to give a powerful energy flow for a considerable time. Such energy when delivered from a body at so high a temperature is far more effective than many times more actual heat units at a lower temperature, such as steam or burning coal would impart.

As soon as the molton iron comes in direct contact with the ice or water a second reaction takes place which decomposes the H_2O into oxygen and hydrogen. The oxygen is fixed by the iron to form the oxide again, and the hydrogen is liberated and burns with the oxygen of the air. There is such a rapid evolution of gas that a slow explosion results, which has proved most effective in loosening and cracking ice masses. It is well known how steam is dissociated into O and H when passed over red hot iron, and this gives a convenient way of preparing hydrogen gas. The thermit does the same thing with ice or water on account of its very high temperature, and imparts two very important properties for ice fighting, *i.e.*, heat and explosion. The reaction makes little or no noise and is admitted by experts to be the slowest explosion known. On account of this fact it can do no

harm to concrete structures, or bridge piers in immediate contact with the reacting thermit, and no harm has ever been done to fish in rivers or lakes where it has been used.

For ice control in thickly settled communities it offers no unpleasant or dangerous features. There are no detonating noises to break windows, and the thermit is itself absolutely non-explosive and safe to handle and transport. The writer does not attach importance to the amount of ice which thermit actually melts for the heat liberated is small compared to the heat of fusion of ice. The important fact is the output of energy in a penetrating heat ray which overcomes the exceedingly small temperature effects, in the water responsible for the pranks and inconveniences caused by ice. It is possible to see thermit heat units glowing through several feet of water and ice masses, which proves the penetrating power of the radiation.

The reaction of thermit has been studied in solid ice and Fig. 22 shows a block of ice weighing 400 pounds, blown to pieces with a charge of two pounds of thermit reacted in a hole cut in the block about half way through, but not sealed. The picture shows the great volume of hydrogen gas driven out and upwards to a height of 70 feet with the heavier molten slag and iron falling in a shower of fire all around. When this reaction is made in a closed bomb the hydrogen can be collected and burnt with ease. Balloons can be filled with the gas.

The reacting charge when first fired glows with an intense white heat inside the ice for several seconds before the explosion occurs, and proves how powerfully the rays are sent out through the ice for the whole block seems to be white hot. The ice becomes highly phosphorescent before the explosion. A slow motion picture of the reaction shows a vapor given off from the outside of the ice immediately preceding the upheaval. Undoubtedly temperature strains are set up in the ice, especially when it is very cold, and to these temperature strains is attributed the great cracking which goes on in an iceberg for many hours after a thermit heat unit has been used in it. An iceberg gives the best example of the effects of the

strain, as it is by far the largest mass of solid hard ice that could be experimented with. See Chapter 10.

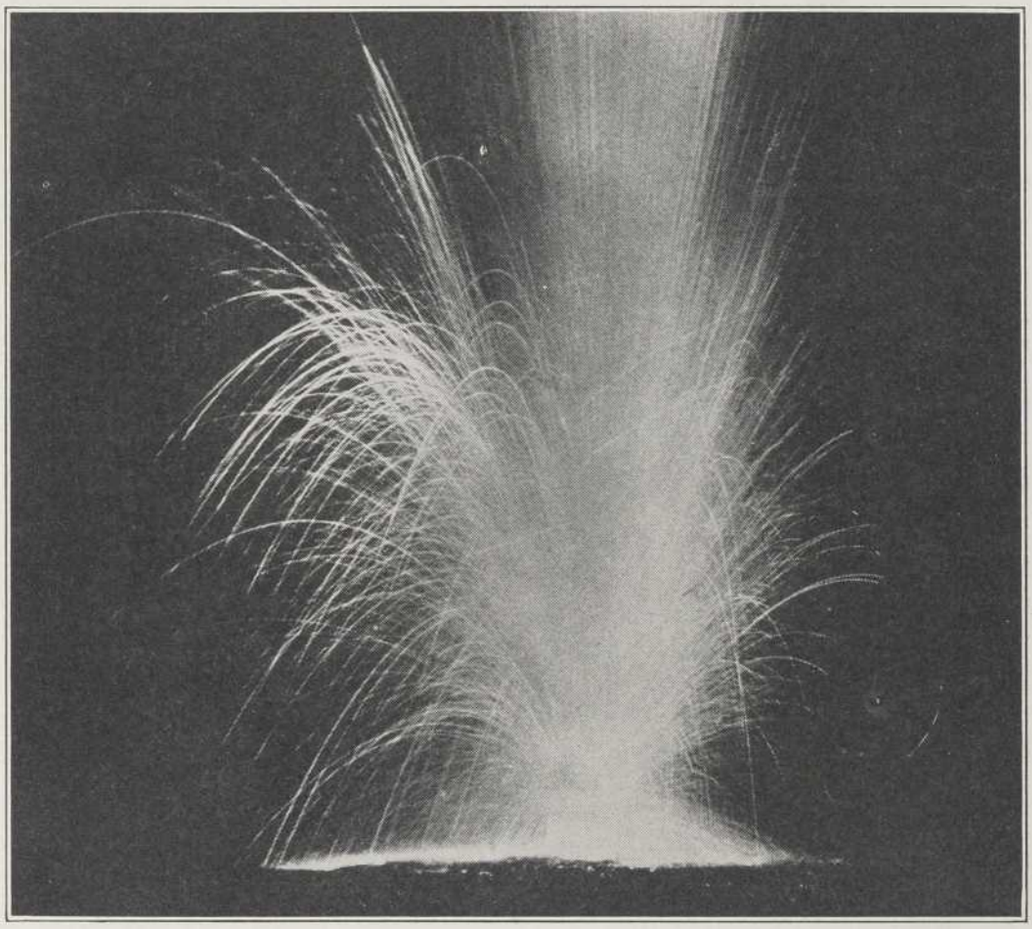


Fig. 22.—Solid block of ice burning and exploding by the intense heat of a thermit charge.

The result of bringing a body at such a high temperature in contact with cold ice was quite unknown to the writer before these experiments were tried. In fact, the passage of heat across a very steep temperature gradient has never been studied, nor the mechanism of transfer determined. Ordinarily we would regard it as conduction, but what this method of heat transfer becomes when the gradient is several thousand degrees across a face of perhaps molecular dimensions is difficult to visualize.

Spectrum of Ice Gas.

Through the kindness of Prof. D. A. Keys of McGill University I have been able to study the spectrum of the

gas from the thermit ice reaction as well as the continuous spectrum of the molten thermit itself.

The former shows the characteristic hydrogen lines mixed with traces of oxygen and carbon monoxide, while the latter shows strong emission in the yellow, green and blue which I believe to be particularly effective in destroying the ice structure.

Thermit Reaction in "Dry Ice."

It was a matter of interest to try the effect of the intense heat reaction of thermit on solid carbon dioxide ice

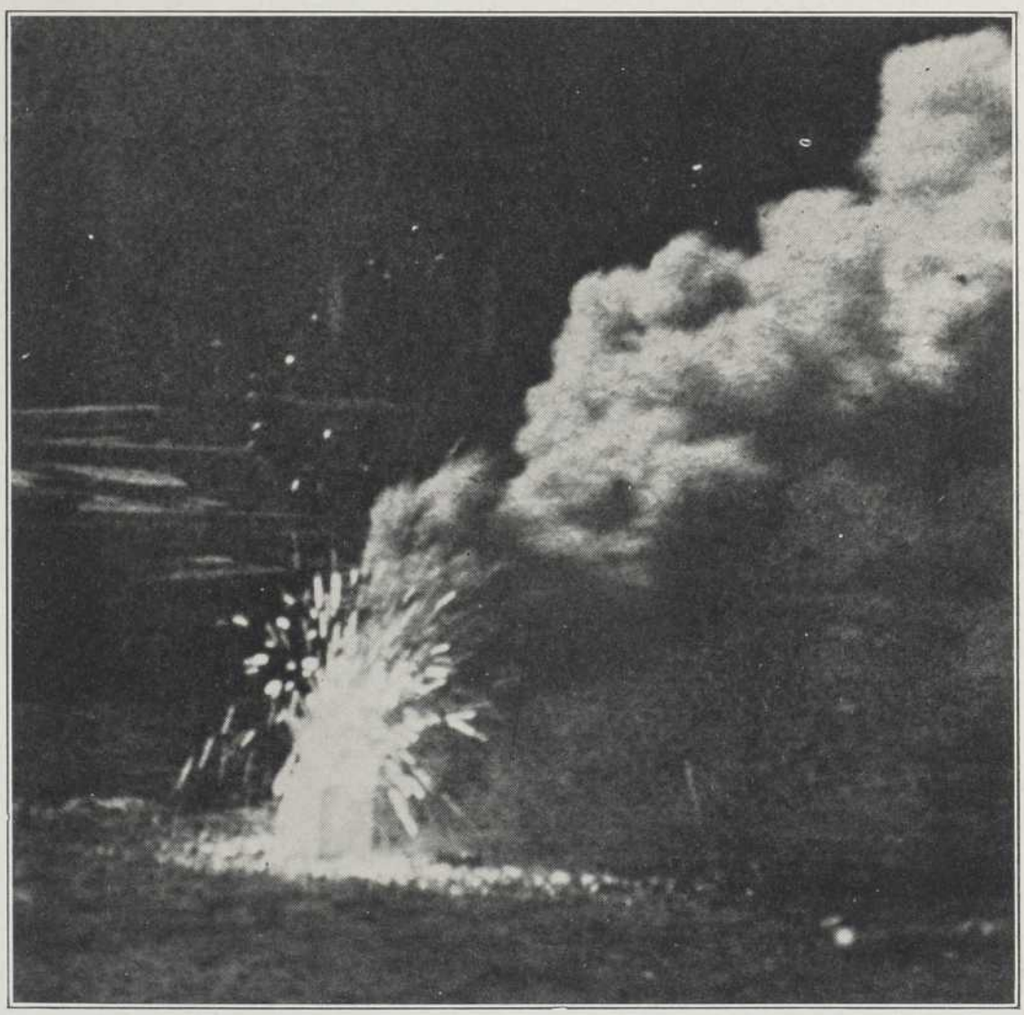


Fig. 23.—Solid block of carbon dioxide "dry" ice burning by the heat of thermit.

called in the trade "Dry Ice." For this purpose a block of compressed CO_2 ice was prepared, of about a cubic

foot in size. The thermit was inserted directly into a cavity in the centre of the block and reacted. Three successive charges were required to explode the block, and it is doubtful whether the explosion would have resulted, but for possible moisture pressed into the block when it was prepared.

The first charge reacting is shown in Fig. 23 where the heat of the thermit is seen burning the ice and forming dense carbon smoke, very much like the smoke

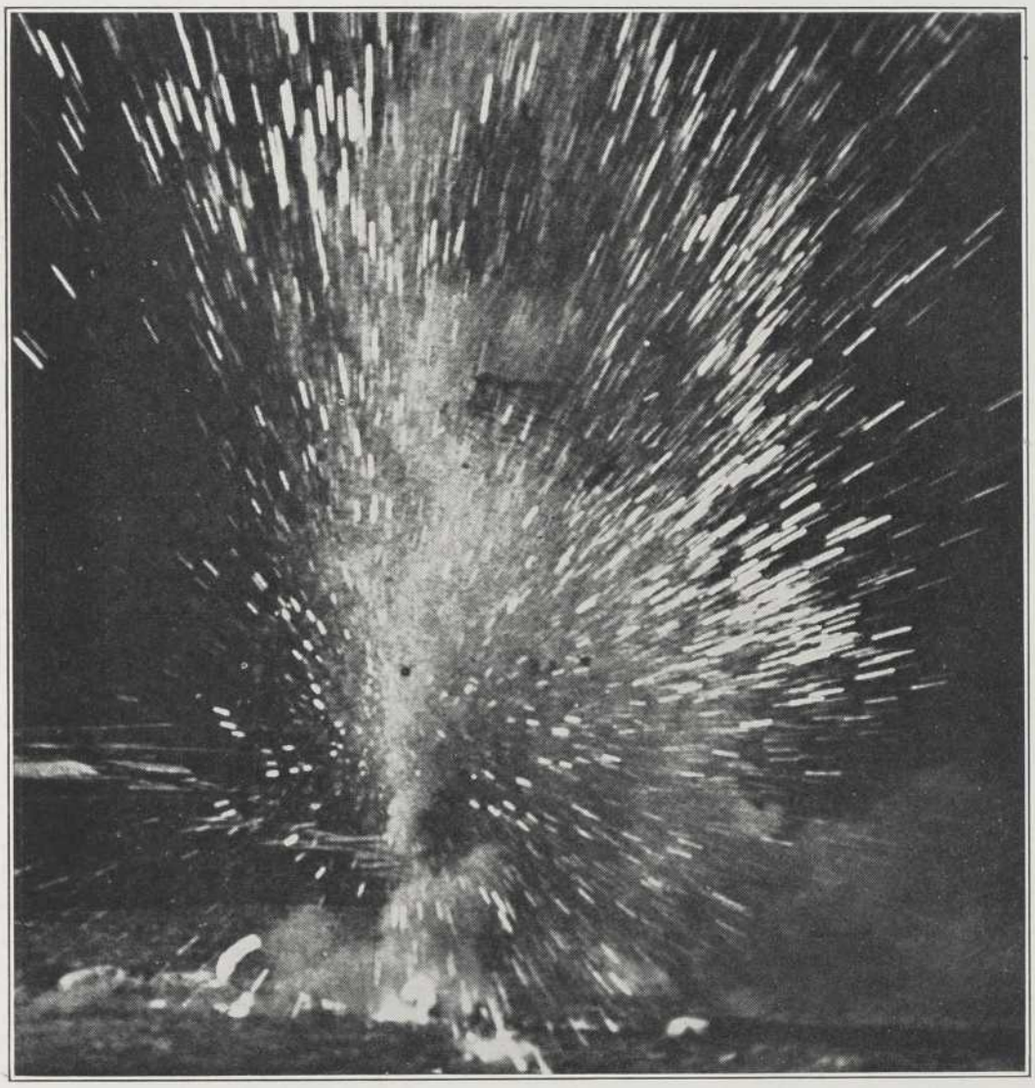


Fig. 24.—Solid block of carbon dioxide ice exploding after the third charge of thermit.

obtained by burning dried leaves. The second charge in the enlarged cavity cracked the block in three places,

while the third charge exploded the ice as shown in Fig. 24. Further attempts to explode "dry ice" have failed.

First Experiments with Thermit in Ice Jams.

The first experiments made on the St. Lawrence in February, 1925, were approached with great caution. The explosive action of the heat input in ice was not entirely anticipated, and the design of a suitable container and the best method of applying the charge were largely a matter of trial.

I was fortunate in being able to consult Major H. B. Faber, Director of Military Pyrotechnics of the U.S.



Fig. 25.—First two thermit heat units used. February 1925

Army, who rendered invaluable help, and through his interest and cooperation greatly faciliated the experiments. Mr. J. H. Deppeler of the Metal and Thermit

Corporation of New York also rendered very valuable help in developing the container. See Fig. 25.

Quarter Million Tons of Ice Removed.

The first experiments were tried at Waddington, N.Y., on February 24, 1925, in a great ice jam in the south channel of the St. Lawrence River, Major Faber being present during the experiments. The location selected lay between the main shore of New York State and Clark Island, where a large accumulation of ice blocked the channel, just below the Pulp Wood Dock. A large field of ice, which had formed on a shoal between Ogden and Clark Island, became detached with a temporary rise of water and lodged below the Pulp Wood Dock, completely closing the south channel. This occurred on or about the twentieth of January. Thereafter a considerable accumulation of the usual floating ice packed firmly along the head of the lodged ice sheet, creating a head of water of a foot or more. The process of accumulation continued, causing a pack which was further accentuated by shoves.

At the time of these experiments the jam was approximately 1000 feet in length and 500 ft. in width. The accumulated mass under the ice sheet was carefully measured, showing depths varying from six inches to 43 feet. The head, foot and sides of the jam were lodged solidly on the bottom, so much so in fact that the upper portion of the underhanging mass was compacted appreciably. In choosing locations for the operation of the heat units, two points were selected near the head of the jam in the centre of the channel and the third was located near the foot also in mid-channel, but in the centre of a solid mass of slush ice 38 feet thick, resting on the bottom.

The first container, see Fig. 26, holding about 90 pounds of thermit, was inserted through a hole about two feet square cut at the first location through the surface ice eight inches thick. On the under side of this sheet was found underhanging slush ice to the depth of 13 feet. The container was lowered into the hole, suspended

by four ropes and with difficulty pushed through the under-hang to a depth of eight feet; the wires were fastened to four wooden stakes driven into the ice. The



Fig. 26.—First heat unit being prepared for treating the Waddington ice jam Feb. 24th, 1925.

wires for igniting the thermit were 50 feet long and connected to a storage battery. This length was considered a safe one as no violent outward reaction was anticipated.

Doctor Faber took charge of the firing, See Fig. 27, and when it was estimated that the reaction was complete, the ice was observed to upheave and a great wave passed through the entire ice field and a column of water and slush mixed with hard ice, was hurled 20 feet into the air, mushrooming to a diameter of 40 feet.

After the reaction had subsided in the course of four or five minutes the container was removed with difficulty owing to the disintegrated character of the ice near the hole. It was found that the molten iron had gone right through the bottom directly into the ice mass. The hole in the ice had been blown to 25 feet in diameter through the solid ice, but slush ice from below had risen

in a dense compact mass which enabled the men to support their weight in a reclining position to rescue the con-



Fig. 27.—Major H. B. Faber shown adjusting the wires for firing the first heat unit.

tainer for examination. Further examination revealed another crack 50 feet in diameter surrounding the original hole, and perfectly circular.

The time being late, the other experiments were put off until the following day. The writer expected that owing to the distribution of the heat generated it would take at least twenty-four hours to see outward visible effects under the ice at outlying parts of the jam. The head of water was expected to seep in through the openings made by the heat unit and gradually wash its way along, undermining the pack. That this surmise was correct was not only substantiated in this case but has been in all other cases of subsequent use of the units.

Every unit put off in an ice pack acts as a point of infection which spreads over a greater and greater area

until the water melts its way through and comes out through the hole blown in the ice. It then cuts its way down the pack whenever the ice remains long enough in position for it to go on acting so. In the Waddington jam, however, the other two containers put off brought out the entire mass of ice within twenty-four hours, but this cutting and undermining action of the flowing stream under the surface was noticeable. The second experiment was made by inserting a unit in the mass midway between the scene of the first unit and an opening in the middle of the jam cut out by the heat of the first unit. Longer wires were put on, and two extra batteries were attached. The unit was put down three feet in slush under the surface ice. The reaction resulting from this firing was different from the previous one. There was noticed two primary and three secondary upheavals which shattered the surface ice and then a huge flame 15 feet in diameter and six feet high was emitted which burned for several seconds over the hole. This was interesting and startling, as it was the first demonstration of the decomposition of the ice into its gases with actual phenomenon of burning ice.

The last experiment was carried out within a few minutes of the second, and it was placed at the lower extremity of the jam down 20 feet in the huge mass of slush forming the foot and main support of the jam.

On firing no outward sign of the reaction was visible, but the whole pack was shaken by the upheaval like an earthquake with a dull, low, rumbling sound. As the time was late, the party returned across the river to their homes and the jam was left for the heat to act during the night. It is proper to mention that following the experiments the weather turned intensely cold, which was a condition favorable to holding the jam in place, strengthening the mass and adding to it by infiltration of freshly formed river ice. A close watch was kept all the next day to detect any visible sign of the heat action. Nothing of importance was noticed until the afternoon, when some floating masses of ice were seen moving away from the foot of the jam. After an interval of about half an hour the whole jam, of about 250,000 tons

of ice, moved out, and passed quietly down the river, leaving the channel clear. As the ice moved away some heavy masses grounded about two miles down stream, where they remained firmly in place in a current of high velocity. The river at these points is of sufficient depth to pass the usual river ice without obstruction. An examination of these grounded masses showed evidence of the heat units, for the slag from the molten thermit was embedded therein.

It is well to point out also that the jam was an old established one which was wedged in precisely in the form of a cork in a bottle. The sides were sustained by heavy natural field ice of unusual strength firmly locked in position and in the ordinary course of events no movement would have taken place until the spring break-up. As proof of this there was no other movement of ice fields observed along the river and the jam at Chimney Island was reformed and strengthened concurrently with these experiments.

One Million Tons of Ice Moved.

During February and early March a heavy pack had formed in the south channel between Chimney Island and the New York shore below Ogdensburg, which had gradually filled with snow and loose pack ice from the river above. The river level had been lowered below by about a foot and in consequence was backing the water up into Lake Ontario. There was no immediate prospect of this jam moving out, as it was securely wedged by very heavy barriers of pack ice grounded in some places in 70 feet of water. Some of this pack ice was shoved up from the bottom to a height of seven feet above the water level. A more difficult or unpromising field of operation could hardly be selected. On February 19th, the jam was visited and preliminary measurements made with photographs. On March 11th, and 12th, a rough survey was made and the key of the jam located. On March 13th, 1925, two heat units of 90 pounds each were set off at two places considered the most vulnerable. The first shot was placed under the surface ice, which was 27 inches thick and exceedingly hard with no under-

hanging ice. The hot iron passed directly into the running water without much explosion, but directly afterwards the water could be heard flowing violently along the channels cut under the ice by the heated material.

The second shot was placed about 200 feet south in an underhanging mass of slush. The surface ice was 20 inches thick here and the depth of the underhang was eight feet. The unit was forced down four feet and tied



Fig. 28.—Ninety pounds of thermit reacting in the Chimney Island ice jam March 13th, 1925.

to four steel ropes attached to stakes as before. On firing, a heavy explosion ensued and a hole 15 feet in diameter was blown in the hard ice. A flare of intense

heat and flame shot out to a height of 45 feet and 20 feet in diameter. (Fig. 28.) After this, flames played over the hole for five or six seconds. This shot cracked the ice for a distance of 600 feet and a three-inch surge of the water was observed in the opening 200 feet away, where the first unit had been fired.

Having completed the firing of all the remaining units which we had to use in these experiments, the scene of operation like that at Waddington was left for the night for the effects of the heat to have full play. In exactly nine hours after the key of this jam came away where it had been treated, and during the night the whole jam moved out as well as two larger ice fields which were loosened above probably by the change of water level which resulted. The fields being large areas of surface ice dislodged above. The channel was quite clear by the evening of the next day and in a week's time all the ice and moved down the river. With the removal of this jam the river levels below were restored to normal in a day or two. An estimate of the amount of ice liberated in this jam by the heat units was one million tons, not counting the other two floes which passed through and which would have packed into the ice jam had it not been taken out by the units.

Ice Pan Removed at Clark Island.

One heat unit of 90 pounds of thermit was placed in a heavy pan of ice grounded in nine feet of water near Clark Island. The pan was approximately 8,500 square feet in area. The unit was sunk to a depth of four feet in the underhanging slush. The firing resulted in an explosion which lifted the entire pan off the botton, cracking it and floating it down the river with the men on it. In addition another pan 60 feet away was also lifted off and floated down by the surge from this shot. In this experiment the heavy iron container rifled and shot into the air over 100 feet, pulling out the four stakes and snapping the four steel wires like threads. The operators rescued themselves in the boat which they had used to land on the pan. See Fig. 29.

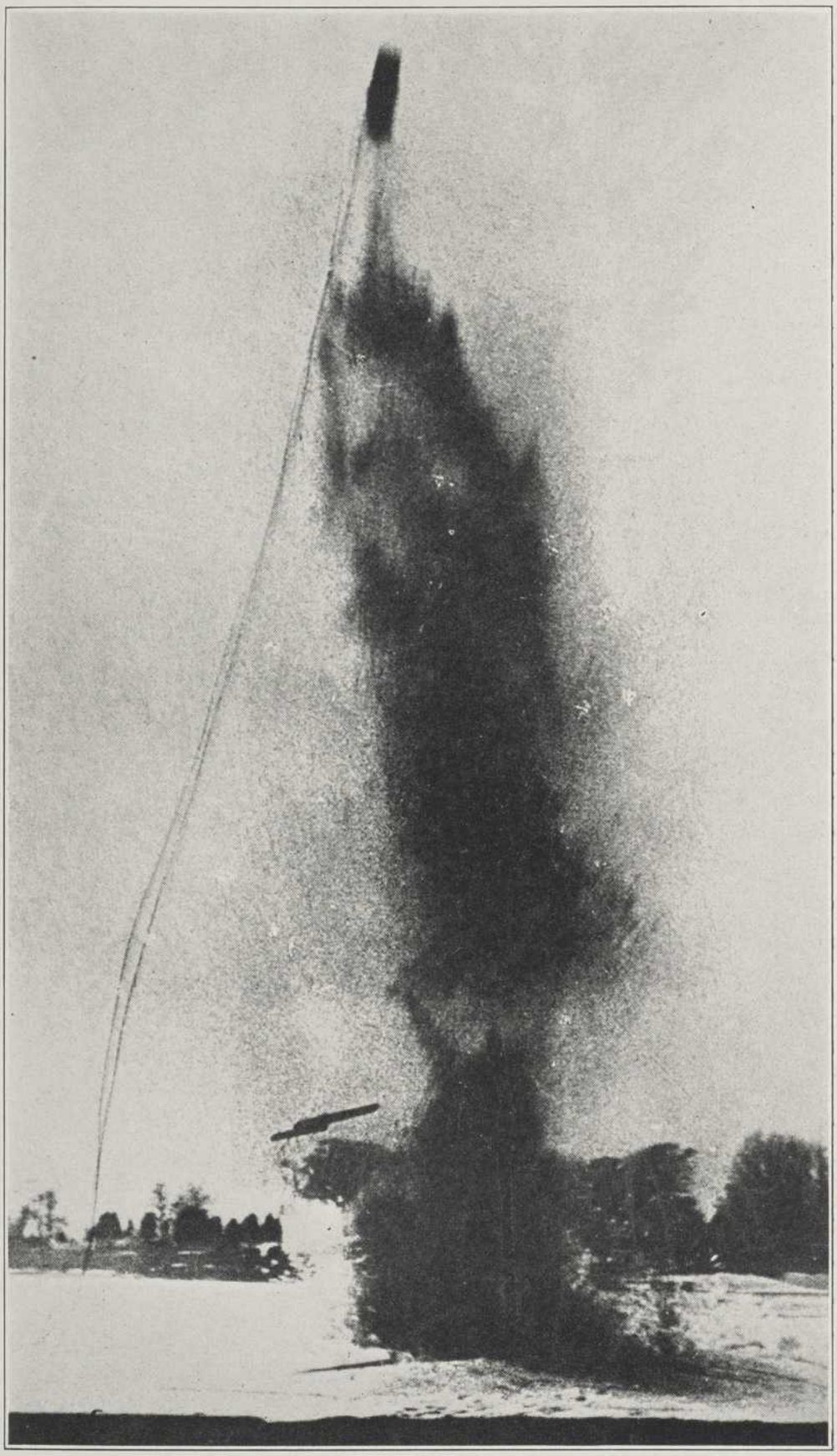


Fig. 29.—Thermit heat unit of ninety pounds reacting in the Clark Island ice jam. Note the container 125 feet in the air.

Removal of the Allegheny Ice Gorge with Heat Units.

In March, 1926, the writer was called out to Oil City to treat the huge ice gorge which was threatening Oil City and Franklin on the Allegheny River. This was a dry jam holding back in flood the waters of the river and placing both cities in great danger as well as the whole extent of the Pennsylvania Railroad track for 25 miles between Oil City and Brandon. The treatment of this mass of ice with its subsequent removal without damage forms an important chapter in the history of ice engineering written for the first time.

Description of the Gorge.

Early in February, 1926, the surface ice on the Allegheny river broke and moved down over a distance of some 50 miles above Oil City and Franklin, Pennsylvania. The restriction of the river at Brandon, 14 miles below Franklin, caused the ice to stop and jam in such a way that the entire mass above filled the gorge to that city, causing the river to rise, but not enough to cause apprehension. The character of the river is typical of these mid-state streams, and winds for miles between high cliffs with shallows, islands and deep hollows interspersed. The normal flow is in the neighborhood of 3,000 second-feet, but in the rainy season or with a sudden storm the level rises 20 feet or more in a few hours.

Towards the end of February a large quantity of ice came down from Kinzau, and quickly jammed into the pack which held below Franklin without dislodging or moving it. This caused the river to become packed from Franklin to Oil City, a distance of 8 miles, with a rapid rise of water level, higher than had ever been experienced by these communities. So serious was the situation with the flooding of Oil City and Franklin that the entire water works was put out of commission and Oil City was left without water or lights for several hours. The Pennsylvania Railroad put its locomotives to work supplying steam for the pumps, and the city fire apparatus

was used to assist in the same work. The two cities were in very grave danger, apart from the uncomfortable condition of the lower streets caused by the high water and floating ice. Fig. 30.



Fig. 30.—Street scene in Oil City, Pa., during the height of the first flood.

This second run of ice blocked the river up to Oil City, and left a solid ice gorge for 20 miles. In a few days more ice came down and blocked for 5 miles above Oil City, making a solid and almost dry ice jam 25 miles in extent. See Fig. 31.

Grave fear was evinced by the citizens over the situation, as it would have been impossible to cope with a heavy rain, and the normal run-off from such rain would have very materially increased the flood condition. Fig. 32.

On the first of March a telegram was sent to me from the Mayor of Oil City asking for aid, and on the same day I left for New York, and got in telephone communication with Oil City. From New York, I explained over the telephone that my methods were unknown to engineers, and that I felt certain the flood level could be relieved, as had been done elsewhere. Later on in the day a message was received from the Oil City Chamber of Commerce by the secretary, Mr. L. H. Gavin, to come

out to the Allegheny Valley to look over the situation. Accordingly, I arrived in Oil City at noon on the third of March and at once met the combined Chambers of



Fig. 31.—Part of the Allegheny ice gorge from a hill at Veuango, Pa.



Fig. 32.—View of a part of the flooded area, Oil City yards, Pa.

Commerce of Oil City and Franklin. After describing the principles of the method of ice control, which I had worked out during many years of study and experiment

on the St. Lawrence, it was unanimously decided by the Chambers of Commerce to finance the work, and that same afternoon a special train was put on by the Pennsylvania Railroad, whose tracks followed the gorge for the entire length, and during the afternoon I inspected every part of the gorge. In the evening I again met the members of the Chambers of Commerce, when the method of attack was outlined and the various committees of co-operation were organized. A special Ice Gorge Committee was formed, which met every evening in the Chamber of Commerce at Oil City and at Franklin on alternate evenings. Reports of committees were received each evening, and the work laid out for the following day.

Such a large jam could not be moved easily with no water to float the ice, and indeed, during the first week the weather was so cold that it was useless to send large masses of ice down the river, as they merely jammed lower down. The river was free of ice below Brandon, and when I arrived the Pennsylvania Railroad had been using dynamite in an effort to break out the foot of the jam.

Methods of Attack.

As explained to the Chambers of Commerce, every known method of attack known to me would be used in forcing a passage for the water through the gorge. In my experience, thermit had proved the most powerful tool, and while other agencies were employed they were all of small value compared to that.

Until March 5th, I was engaged in gathering material on the nature of the ice, plotting the findings on the government maps of the river, and planning the best method for the attack. The containers for the thermit were being constructed and filled with the first ton ordered from New York. Up to this time the dynamiting alone had been carried out, and a small channel had been opened through the lower end of the gorge with its use.

In a broad general way the use of the heat units at first was for the purpose of opening up the channels under

the ice and weakening the surface before taking the ice out in order to bring down enough water to float the ice and afford relief to the high water at Franklin and Oil City. As soon as the weather moderated the various sections of the gorge were treated, and large patches opened, but when the warm weather set in the final removal of the sections was effected with large charges of thermit.

The use of dynamite was continued for a while to free as much of the restricted area below Brandon as possible in preparation for the final removal of the pack. But dynamiting had to be discontinued shortly after the thermit was applied on account of the excessive bleeding of the ice running under the gorge and coming out at the lower end.

Calcium chloride was used to open channels in the surface ice near the bridges, and was found quite effective.

The mixture of sand and gravel was used for the same purpose, and was spread on the surface so as to gather the sun's heat to melt the ice faster. It was remarkable to see the rapidity with which the gravel sank into the ice, and at these treated points patches of water opened when the weather moderated.

Water levels were carefully observed at Franklin and Oil City and at points higher up, and the writer was kept constantly informed of these. At the same time, weather reports were received during the day from various stations along the river as well as from the Weather Bureau at Washington.

The Boy Scouts were organized into groups for observation at the various bridges near Oil City and Franklin to report on the fluctuations of levels and the surges from hour to hour. The entire river during the first ten days was constantly surging and pulsating, due, no doubt, to the high head of water seeking channels through the ice in the lower pack. The boys also ran lines of stakes across the river at two points near the railroad bridges at Oil City and Franklin. These stakes were capped with red, and were accurately placed in alignment so that the

slightest movement in the upper pack could be at once detected. Long before the ice was moved out the whole gorge was slowly moving down stream like a glacier, and the stakes gave me the first sign of this movement.

The Thermit Operations.

The writer will now try to give some idea of the way in which the general attack on the gorge was carried out with the use of the thermit heat units.

Some experimenting had to be done during the first few days. Special containers were constructed by Mr. J. P. Coffman, Superintendent of the National Transit Pump and Machinery Company, of Oil City. See Fig. 33. Arrangements were made by Mr. Coffman to have



Fig. 33.—Placing a large heat unit in the Allegheny ice gorge.

the containers loaded at the shops. Before the containers were finished, some charges were prepared in 10 gallon oil barrels.

After a careful survey of the gorge, the points of greatest resistance were selected in the old jam below Franklin which had resisted the onslaught of the second

gorge. These points were about five to six miles apart, beginning at the foot of the pack. No attempt was made to treat the upper pack from Franklin to Oil City, because this was being weakened by the effect of the open water above Oil City at the head of the jam. The sun's heat was being carried into the pack, and the greatest danger lay in this upper ice under high water shoving down on the older pack, still hard and solid, and causing great damage to the city of Franklin, situated in the jaws of the mass.

The water, when it reached the lower pack, had had its heat all taken out of it by passing through the upper pack, and hence its melting action was reduced to a small amount. The entire gorge was divided into two parts. The lower, represented by the older gorge, which was dry and grounded with the water forcing its way around through side-channels, and the newer gorge, lifted high on flood waters accumulating above Franklin. The object of the first thermit treatment was not to dislodge the ice, as the dynamiting operations had shown the uselessness of this while the cold weather lasted, but to open channels under the surface. The water had to be brought down into the old pack and by its presence do two things: relieve the flood level above; and afford water enough to lift the lower ice and get it ready to be passed on down the river, without gorging and causing more floods.

With this in view, all work was concentrated on the heavy packs and the thermit containers fired as low down in the ice masses as possible. Fig 34. The liberation of this great heat had the effect of burning out great areas under the ice, and the force of the explosions, which resulted from the heated metal in contact with the ice and water, caused cracks and disruption which allowed the water to force its way through these places under a high head and gradually work its way down, clearing and melting a channel much larger than was evident to the eye at the time.

In the accompanying curve figure 35, it will be seen how the levels of water at Franklin and Oil City dropped

after the thermit was applied. Each charge was noticed to produce its effect in reducing the flood water.



Fig. 34.—Sinking a large heat unit in the ice.

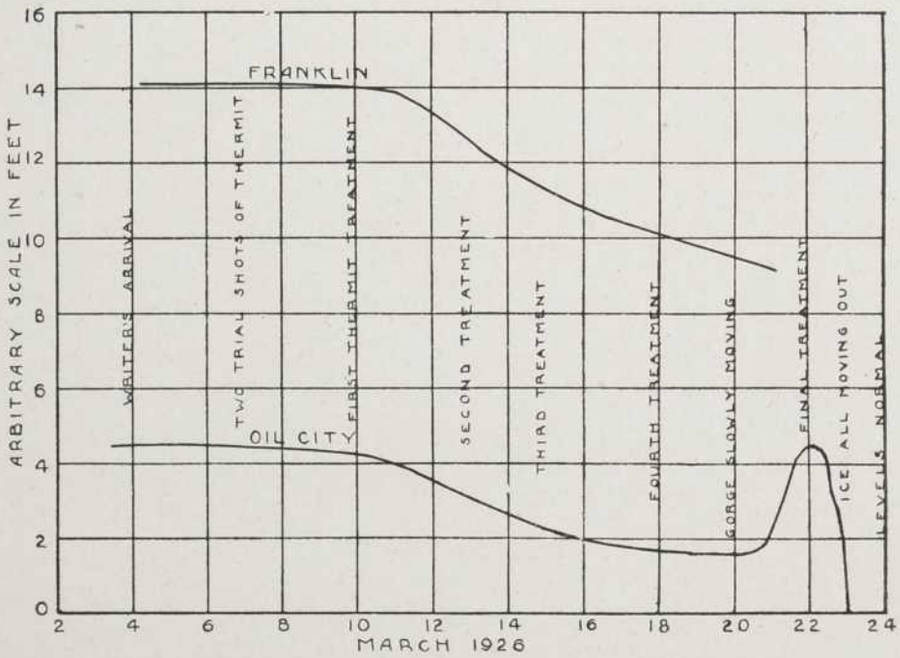


Fig. 35.—Diagram to show the drop in flood levels immediately following the thermit treatment.

With the fall of water in the upper pack there was a rise of level in the lower end, and care had to be taken not to let the water down too fast so as to avoid flooding the Pennsylvania Railroad tracks at the lower part of the gorge.

All of the time up to March 18th was taken up with use of the thermit at the critical points and the operations regulated by the daily watch of flood levels. The drop in level occurred simultaneously with the thermit treatment.

From the 10th to the 20th, when the weather turned very mild, the gorge was held in control in this way, and the whole pack was observed to move very slowly downward as the water was brought down. From this glacial-like movement much valuable information was obtained as to the hardest and most resistant points. By the 20th, great areas had opened up, and it was found desirable to begin the final attack to remove the gorge. The writer was criticised for not taking the ice out at once, but this was unwise, for reasons already given. The whole situation was under control and the river levels held down until such time as nature could aid in the removal of the ice.

On the afternoon of the 20th, the upper pack began to move under the weakening action of the sun. This was a little sooner than the writer had expected, and in consequence new tactics had to be adopted. Everyone thought that the entire gorge would move out, but so strong was the ice still holding between Oil City and Franklin that it gorged into the ice at that point under a high head of water without moving beyond Reno. The citizens had a taste of what might have occurred to them in a much worse way had not the lower gorge been opened and the previous flood waters taken away. A considerable flood ensued at Oil City, although Franklin did not experience this flood in the least.

The same night the water began to rise, and early the following day Oil City was in flood, with rain falling. The Reno traction bridge was in grave danger, and stood

18 inches off its piers, resting on the ice, while the power house was partially submerged and in grave danger also.

On Monday, March 21st, two heavy charges of thermit were set off at the two points in the new jam at Reno where the pack was greatest, and these were effective



Fig. 36.—Reno traction bridge lifted 18 inches off its piers by the ice.



Fig. 37.—Same bridge put back again safely by careful control of flood levels by thermit.

in relieving the flood in Oil City, and were so gauged with other charges to lower the level without moving the

ice in order to put the Reno bridge safely back on its piers without damage of any kind. Figs. 36 and 37.

On that day, March 21st, more thermit was rushed from Pittsburgh by motor truck and special train, and all night long the men worked heroically to fill containers for the morning.

On Tuesday, additional charges inserted in the pack to bring the ice level down to a safe distance below the bridge, and then a concentrated attack was made on the gorge to remove it entirely.

Two thermit crews were sent out, one below Franklin at Indian Bend, the last remaining points of resistance, and the other to loosen the pack holding between Oil City and Franklin.

The men in charge of the work, Messrs. Geo. L. Bannon and Fred. Wenner, deserve the greatest praise for the courageous way in which they went at the attack in the rain and bad weather. The ice was none too firm to go on to place the charges, and frequently planks had to be used to effect a safe passage.

Under the terrific action of these thermit charges, the gorge was shaken loose in great patches and sent down the river safely, the lower pack giving just ahead of the upper, thus avoiding any flooding except for a short time at Indian Bend, where some of the track embankment was washed out. This was caused by the great rush of water from the upper pack meeting the resistance of the slowly-moving ice below. Very little damage was done, however, and by 6.30 o'clock in the evening the river levels at both Oil City and Franklin were back to normal.

On Sunday night, March 21st, two spans of the Big Rock bridge were taken out by the ice movement, but this could not have been prevented as the understructure, which had been condemned as unsafe, was a prey to the slowly moving ice and the flood waters above. It was a matter of great satisfaction that no loss of life or injury resulted from the whole operation, and the property

damage was comparatively small, compared with what it might have been.

Heat the Natural Ice Fighting Tool.

It is reasonable to look to heat as the natural fighting tool, and nature points the way in directing us to the powerful influence of the sun. Great power houses, shut down during a cold night, are at once relieved in the morning with the sunrise. The penetrating power of the sun's rays unbinds the forces of freezing between the ice crystals, honeycombs solid ice, without necessarily melting them. The actual energy radiated into water by the sun is not so great as can be supplied locally by steam, but the character of the radiation from a high temperature source is such as to give it great penetration and widespread influence. Water is almost opaque to rays which come from a radiant below a low red heat, but the energy from a high temperature source has great penetrating power. When steam or electric heaters are put in water the action is confined to the surface in mechanical contact, and the spread of the heat is only brought about by steam lines of flow.

In selecting a radiant beam for ice control, the selective absorption of water for heat rays has to be carefully considered. In solid ice the problem seems to be a similar one, and the whole matter appeared to the writer in a new light in 1924, when making iceberg studies off Newfoundland.

As sunlight is scattered by the surface ice of a lake, or river, the energy, so valuable for ice prevention, is entirely lost and cannot be recovered. Could we direct the sunlight under the ice where the water is comparatively warm as contrasted with the air above, then little or no ice could form and that which did on a cold night would be rapidly dispersed on a clear day.

City of Belleville, Ont., Protected Against Flood in 1927.

In the winter of 1927, the writer was called in consultation with the City of Belleville and the Engineers of

both the Canadian Pacific and the Canadian National Railways, with a view to preventing what appeared to portend a flood of unusual size. After a careful survey of the ice condition at the mouth of the Moira River, which discharges through the harbor of Belleville into the Bay of Quinte, the writer agreed to relieve the situation, and free the city from flood.

This fact is mentioned as showing that as a purely engineering feat, ice control methods are capable of financial rating.

The method adopted and results achieved are perhaps best described in the report of the City Engineer of Belleville, Mr. Charles D. Campbell, who took very careful notes and surveys during the progress of the work.

Records of currents, water flow and levels as well as records of maps showing how spring freshets have affected the Moira River banks and mouth have been collected at the City Hall in City Engineer Campbell's department. This data has been assembled for the first time with great patience and trouble by the City Engineer.

His report to the City Council refers in particular to the operations when thermit was used under the my direction. The report is invaluable as a record of conditions and of this year's undertakings. Mr. Campbell says:

"The work of treating the Moira River at its junction in the Harbor with the Bay of Quinte with thermit was carried out under the direction of Dr. Howard T. Barnes in accordance with the Council's orders and the results noted by a study of definite observations.

"Subsequent to the demonstration of February 9th, when 600 pounds of thermit were discharged under the ice surface of the Harbor, the council received and adopted a report from Dr. Barnes and he was engaged to carry to completion his treatment of the river on the instructions of the council.

"Between Wednesday, March 2nd, and Saturday, March 5th, Dr. Barnes discharged 10 one hundred

pound containers of thermit in the deep portion of the channel from the front of the jam of slush ice near the lighthouse to a point within 1200 feet south of the railway bridge and 15 fifty pound containers in approximately two parallel lines 50 feet and 100 feet south of the railway bridge. The purpose of this discharge was to remove the under mass of slush by dissolution and dislocation, and incite a movement of the water of the Moira river from upstream into the main channel of the river, the expectation of this water movement being to erode the surface ice which was $2\frac{1}{2}$ feet in thickness. Five tons of calcium chloride were placed in rows forming a checker work approximately of 50 feet squares underneath and to the north side of the railway bridges between the third and fifth piers from the east end of the bridge. The action of the calcium chloride dissolved the surface ice along the lines and enabled the heavy ice under the bridge to be easily shoved through whenever a mass from upstream exerted any pressure against it.

"A line of cinders about 15 feet in width and spread very thin was placed on the surface ice directly over the main channel and extended from the railway bridge 1800 feet south. The action in this case was the absorption of the heat rays from the sun and the consequent penetration of the surface ice and the weakening of same.

"The results were as follows: An observation was taken daily of the elevation of the top of the surface ice at a point in the fourth panel of the east end of the Canadian Pacific Railway bridge. The water level under the ice was also noted. Following the discharging of the thermit, March 2nd to 5th, there was a subsidence of nine inches in forty-eight hours which increased to sixteen inches, at the end of the fourth day. The water level receded between the 5th and 12th of March sixteen inches.

"The lines of calcium chloride did very effective work in weakening surface ice. As soon as the first direct pressure from above the field treated was exerted the lines of cleavages showed themselves to follow directly along the calcium chloride treated line, in one case following the same line for a distance of 150 feet and

the whole mass moving out without any heaving of the ice field. This is particularly noteworthy inasmuch as the field of ice that was broken was that section lying adjacent to and under the railway bridge where it was not possible for the sun's rays to reach.

"The slush ice from the lighthouse to the railway Bridge which was at the beginning of the treatment from twelve to fifteen feet in depth and very tightly compacted was observed by a test made every few days in each of the holes where thermit had been discharged. On Thursday, March 10th, the report showed practically every hole clear in the main channel, and the slush ice having all moved out. This movement of the slush ice premitted the free movement of the increasing water to flow from upstream with its powers of erosion acting on the surface ice and the freedom of this movement of water permitted surface ice from upstream being carried underneath the solid field of ice in the harbor.

"We found in testing on March 9th, that the surface ice from upstream was present in some of the thermit holes about 1500 feet below the railway bridge. The observations noted in the area between the railway bridge and the lower bridge indicated by the settlement of the ice that most of the slush formation had moved out and except in the shallow portion of the river there was a marked stream running underneath the surface ice.

"The effect of the sudden removal of the slush ice supporting the surface ice caused fractures radiating over the whole surface ice field and extending north as far as the foot bridge and even beyond. These fractures, together with the rapid stream movement, produced an effect that permitted blocks of surface ice to move downstream without having to wait for some marked pressure of field ice above. From day to day the action became more pronounced, so that from Monday noon, March 5th, until Sunday noon, March 11th, the whole river from a point 200 feet above the foot bridge to the north side of the railway bridge emptied itself of surface ice. The surface ice itself floated downstream and disappeared under the field ice in the harbor. The whole action of

the removal of the surface ice in the section of the river between the foot bridge and the railway bridge was, in my opinion, the result of the successful treatment by Thermit.

"The flooding of a portion of the city in the years 1918 and 1920 occurred in the period from March 20th to March 23rd in each year, when the river was discharging only 1800 cubic feet of water per second in 1918, and 3000 cubic feet of water in 1920. The peak discharge occurred on the 4th of April, 1918, when 8,590 cubic feet per second was discharged and on March 29th, 1920, when 7,150 cubic feet was discharged. You will note that the peak in 1918 came fifteen days after the flood commenced and in 1920 eight days after the flood commenced. In 1927 on March 12th the condition at the time when the Moira was clear of ice from the railway bridges to the north end of the city limits, showed a stream discharge on only 1,800 cubic feet. This was the same discharge that occurred eight days later in 1918 at the beginning of that tremendous flood and nearly 1,200 cubic feet less than the flow which created the flood in 1920 at a period eight days later. The records from the Dominion Government Guaging Station show a discharge of 8,100 cubic feet on the 19th of March, 1927, which was practically the peak for the year, approximating the 1918 peak, but coming sixteen days earlier. The 1927 peak exceeded the 1920 peak by 1,000 cubic feet per second and came ten days earlier. It is remarkable to note that in the years 1918 and 1920 with the advantage of ten days' more time to destroy and weaken the surface ice, the area of the river from above the lower bridge south was a solid and unbroken field of ice and when the rush of water started to come from the north it brought with it the upper fields of ice, the moving energy of which spent itself in crashing into and breaking up the solid field. This caused the jam and when the waters started to come produced the floods. The 1926 condition, which fortunately did not produce a flood, brought the upper ice into the river on April 11th. At that time the river from the lower bridge to the railway bridges was a solid field of ice and the movement

from upstream filled the river to the top of the revetment walls, but fortunately did not overflow. The 1927 condition after the river was treated with thermit discharged all the ice that came from above Lazier's Dam, Cannifton Dam and Corbyville Dam with no appreciable rise in the river beyond the normal winter elevation. The very heavy snow storms of December 6th and February 20th brought a great menace of slush ice which filled the harbor and river. An extremely early release of flood waters from the north brought the ice fields upon us a week earlier than in the years 1918 and 1920 and yet we find that the channel was so successfully cleared of obstruction of the under slush that there was not the remotest possible danger of a flood by reason of the coming of the upper ice.

"There was a very low stream flow, comparatively speaking, to induce this movement in the breaking up of the ice field and when the first ice came down from Lazier's Dam on Monday morning of the 14th and the Corbyville and Cannifton Dams discharged their ice fields downstream on the morning of the 16th, the movement of the ice was carried into open water, to a point 300 feet south of the railway bridge, and with 8 feet clearance below the railway bridge girders.

"The whole effort of Dr. Barnes, as he explained to me before starting, was to create a channel flow between the third and fourth piers of the railway bridges in the deep portion of the channel and remove the menace of the field of ice north of the railway bridges before the upper ice was released. The results were exactly what he intended they should be; the removal of the large obstructing mass of slush ice where the major portion of the water would flow. In the flood of 1918 and 1920 I find that this was the main point of obstruction and until that was broken down the flooding of the city continued.

"I am fully convinced that the results of the thermit treatment were entirely satisfactory and that this work on the river prevented a most serious flood this present spring.

Ice Jam Relieved on the St. Maurice River.

During the same winter, the writer was called to La Tuque, P.Q., on the St. Maurice River to relieve flood conditions at the foot of the LaTuque Falls. The Power House of the Brown Corporation Plant was flooded by a 10 foot rise of water, due to ice accumulations, forming a solid compact jam about one and a half miles in extent, and a mile wide.

Soundings were taken here in the middle of February, and the jam treated along the main channel of the river which was completely blocked by ice carried over the falls, and produced in the falls.

About a ton of thermit in 100 pound units was used, and the water which had been steadily rising, when the writer commenced operations, began immediately to fall; and in the course of a few days, the river had begun to discharge through its main channel, previously blocked by compact ice. This work demonstrated the really remarkable way in which thermit can open up great areas of ice, and allow the river to be put back into its bed without damage.

This work was harder than otherwise would be for a huge ice accumulation had to be weakened and burnt out as in the Allegheny River the previous winter. This is much more difficult than to prevent the accumulations, and had the work been started immediately, the levels had commenced to rise, the flood might have been prevented.

The writer was not called in until after the flood had reached alarming proportions, unlike the Belleville situation, where it was possible to treat the river before it had gone into flood.

Heat Units Applied to Loosen Frazil Clogging Water Works.

Small thermit heat units of 10 or 15 pounds have been found especially effective in relieving frazil agglomerations at the entrance of pumps for water works. Such

pumps, when closed down, have been put running again in a few minutes through the use of thermit. It is interesting to observe how rapidly the intense heat developed, loosens large masses of the troublesome ice and makes it fluid again.

It should have a useful application for this purpose.

Intakes and Power Canals.

A very valuable study has recently been made by Geo. H. Fenkell, General Manager of the Detroit Water Works, of the Water Works intakes of the Great Lakes Reservoir.

In discussing the ice troubles he says:

"Ice is a source of much anxiety and trouble for those who maintain intakes located in the same latitude as the Great Lakes where severe winter weather must be contended with, and it may reduce greatly the quantity of water coming through the intake and even completely cut off the flow at times."

"Mr. W. J. Barber reported in the "Engineering News," June 19th, 1913, that the Chicago intakes at times of severe storm have experienced heavy ice jams, the ice piling up on the windward side for 10 to 25 feet above the surface and down to the bottom of the lake causing more or less obstruction to the flow. Information at hand does not indicate whether such jams are more serious at the intakes nearer shore than those farther out, and except for work at the crib during such jams there may be no feasible means of preventing trouble from this source.

"In the winter of 1915 trouble from floating ice at the Detroit intake became so serious that the clogging of the ports lowered the water level in the shore basin by 4 feet, reducing the capacity of the intake about 30 per cent. in less than an hour. The crib is so situated at the upper end of the Detroit River that it is exposed to the ice floes and waves of Lake St. Clair. To prevent future trouble, a V-shaped fender of piling and timber sheeting was built upstream from the crib. The sheeting extends

from the river bottom to extreme high water, the wings diverging at 90 degrees and their down stream ends are 25 feet from the nearest point of the crib and 4 feet below its upstream edge. It is braced against the crib, and although it has been necessary to make repairs annually, it has served its purpose well.

"During the winter of 1904-1905, the writer measured the ice formation in Lake Erie opposite Presque Isle, Erie, Pa., and observed that the ice formed a ridge about 18 feet high parallel with the shore line and in about 15 feet of water, and that accumulation of ice grounded in many places in more than 30 feet of water.

"Frazil ice causes trouble chiefly by adhering to the screens, racks and port openings and gradually closing them completely. Under conditions favorable to producing large quantities of frazil ice, it may enter the ports and completely fill the intake well. The most serious trouble with water intakes occurs at night when it is the most difficult to combat.

"Various remedial measures have been tried from time to time, and it has been observed that the depth of port opening below the surface has a marked effect. At Marquette, Michigan, the intake previous to 1912 was in $23\frac{1}{2}$ feet of water, and interference to flow from frazil ice stopping the upturned elbow of the intake was experienced. Since being moved into deeper water, no trouble has occurred, although there is a $\frac{1}{8}$ inch mesh copper screen over the port. It is difficult to fix a minimum depth at which ice trouble will not occur, as this appears to be governed by local conditions and velocities through ports. Monroe, Michigan, reports trouble with 12 feet of water, while Toledo with 11 feet reports none. Erie, Pa., with a depth of 32 feet, and Gary, Indiana, with 33 feet reports trouble, while Windsor, Ontario, with 42 feet, reports trouble, while Oswego, New York, with 80 feet, has experienced difficulty once or twice a winter. The above figures refer to depths of the bottom of lakes and channels. It will be noted that ice troubles for some of the deeper intakes are not confined to those located on rivers.

"Back pressure on the intake port for submerged cribs is used more or less effectively to remove the adhering frazil ice. Steam and compressed air have also been used. At Prescott, Ontario, the water in the pump well is heated and forced back through the intake. Dependence in some cases is placed on sufficient storage to alleviate conditions and tide over the demand until natural causes assist in establishing normal conditions of flow.

"Ice troubles at Chicago occur generally following sub-zero weather, especially *before* sunrise and during periods of maximum demand. The ice is handled by dislodging with pike poles, steam hose and by shocks from explosions of small charges of dynamite. The screens over the inlets to the intake shafts are also removed in winter. Toronto had serious trouble when using stationary screens at the shore well, but since the installation of travelling screens there has been but little trouble on the whole and then only during severe winters.

"For many years Detroit suffered from the accumulations of ice at the intake. New works were built in 1877 at the present site and a large intake box supplying a 5 foot pipe was placed at right angles to the current about 1,000 feet out from shore. The strainer consisted of wood slats on the downstream side. Serious trouble occurred from time to time and in 1884 a second pipe 6 feet in diameter was laid, two strainer boxes of a similar construction to the first were placed at the end, and a self acting relief valve provided. Ice continued to close the supply at times, and in 1890 a third inlet pipe was laid, and the strainer box was placed parallel with stream flow. For a period of ten years there was entire freedom from accumulation of ice, but it was later discovered that this was due to a breakage in two of the lines near shore. On repairing the breaks the troubles were experienced again and every other slat was then removed from the cribs.

"An emergency valve which has been but recently installed was opened in the winter of 1901-1902 and even then ice interference put the city on short supply. Trouble

was also experienced with frazil ice in the settling basin for the first time.

"With the present exposed intake and connecting tunnel, ice trouble has been experienced from time to time. In 1923 traveling screens were installed in a special screen chamber on shore, and these remove the slush ice coming through the tunnel. The behavior of flow is such at times as to indicate a partial temporary stoppage within the intake or tunnel. A supply of steam has been provided in the screen well to reduce the accumulation of slush ice above the screens.

"In an effort to reduce the tendency of frazil ice to be drawn into intake ports, the velocity of flow through the ports has been reduced on various intakes. As low velocities are necessary in order not to overcome the buoyancy of frazil ice, this reduction in velocity has probably not been carried far enough. Chicago designs port openings for a normal velocity of 1 foot per second, though maximum velocities reach 3.63 feet per second. Crib 3 at Cleveland is designed for a maximum of $\frac{1}{2}$ foot per second, the ratio of port area to tunnel being 8 to 1; Toledo has a maximum of $\frac{1}{2}$ foot and a mean of 0.3 foot per second. At Buffalo the ratio of port opening to tunnel area is about 3 to 1. Toronto has a maximum intake velocity of 2.88 feet per second and a mean of 1.48 feet per second. Detroit's intake was designed for a velocity of $\frac{3}{4}$ foot per second for the assumed maximum of 150 m.g.d. This maximum is exceeded now and the port velocity will probably at times in the future equal or exceed 2 feet per second.

"In the design of Detroit's additional water supply the idea of using a fore-bay or lagoon is being considered. It is a matter of common observation that frazil ice does not form when the water is sufficiently quiet to permit the formation of the ice sheet. This has been noted frequently in power plant installation having large fore-bays. The reason for using a lagoon intake is to reduce velocities and wave action so that an ice sheet will form readily at all times, and to locate the inlet so that frazil ice that is formed in the river will be excluded as far as possible. Experience with models indicates that care-

ful consideration must be given to the design of a forebay to prevent stagnation in pockets, and to insure fairly uniform low velocities of entrance to the bay and of approach to the intake.

"There are few troubles other than with ice, although at Sarnia, Ontario, sand and driftwood may enter the intake pipe at any time of the year and at times cause complete stoppage.

Use of Calcium Chloride for Treating Ice.

In March, 1924, the suggestion was made to me by Mr. A. R. Chambers of New Glasgow, N.S., that there might be a new use for lump rock salt in its application to forebays of power plants when the ice was beginning to form, his idea being that the density of the water would be slightly changed and by thus lowering the freezing-point would achieve temporarily the same effect as a slight increase of the freezing-point which accompanies the effect of the sun and relieve the under-cooling in the water. He considered that a ton of heavy rock salt, put in a few lumps at a time, might have some slight effect although he doubted whether it would prove of economic value. The idea was sound in that the presence of the salt would cause the ice to be present in a surrounding medium which from the presence of the salt would normally possess a slightly lower freezing-point and hence the ice would have a tendency to melt and pass into the liquid state. I procured a quantity of crude salt in lump and granulated form, to experiment with, but it occurred to me that probably calcium chloride would be more effective than the salt and more rapid in its action, for two reasons:—

1. That the calcium chloride had a greater power of reducing the temperature of the freezing-point.

2. In process of solution of calcium chloride there is a slight and rapid evolution of heat before the temperature is reduced. This evolution of heat was entirely absent from the action of the sodium chloride.

In considering other chemicals the question of crude sulphuric acid which develops a large amount of heat on mixture with water, was taken up, but owing to the danger and inconvenience of handling sulphuric acid and the undesirable nature of its presence in the river, it was not tried, although it would undoubtedly have an important effect.

The use of common salt in thawing ice is not new. Capt. Bernier of Arctic fame has used it for many years in thawing out his ship from the heavy new ice that forms around it in the winter in the Arctic. He also informed me that he has used coarse sand with much success in thawing ice. This was spread over the ice between the ship and the open water and the effect of the increasing power of the sun was to melt the ice more rapidly and thus in the course of two or three weeks the ship was free to pass out through the opening melted by the sand. He finds that the whole effect is much increased and ice more rapidly melted by adding salt to the sand.

I have authenitc information from the masters of river vessels, that salt has been used to melt the ice around the hull of the ship to prevent squeezing by ice pressure.

Calcium chloride is a by-product of the manufacture of alkali by the Solvay Company. It is used extensively in road maintenance, for relieving dust. It is supplied in flakes in 100 lb. sacks, in iron drums, or car-load lots. It is also supplied as a brine in different strengths.

My experiments consisted in applying common salt, and calcium chloride in the dry state, directly on the ice. The admixture of foreign materials such as sand, etc., to render the salt more effective by absorbing the sun's heat, was carefully tested. The effect of a low temperature was merely to delay the action slightly.

Fifty pounds of calcium chloride were spread on a cleaned ice surface, about 30 inches square, during the morning. A covering was placed over the top. A second plot was made with 50 pounds of crushed rock salt, similiarly deposited. In five hours' time, during a

temperature of approximately 16° below zero, the calcium chloride had penetrated 6 inches into the ice, whereas the salt had penetrated half an inch. On the following day, during a steady temperature of 19° below zero, the calcium chloride had all dissolved, and the ice was honeycombed to a depth of 8 inches. The salt was found not all dissolved but penetrated to a depth of 5 inches. Exactly two days after, the calcium chloride had honeycombed to a depth of 12 inches, and the salt was found to have been all dissolved and had penetrated to a depth of $8\frac{1}{2}$ inches.

Two holes about 2 feet square were cut through the surface ice exposing a mass of hanging slush. Fifty pounds of calcium chloride were emptied into one of the holes and disappeared immediately, cutting through the slush like hot water through sugar. In the second hole 50 pounds of coarse salt produced a similar result, but took much longer to disappear through the ice, but after 24 hours the space was much clearer of ice than the space through which the calcium chloride had been emptied. The reason for this was that the salt had lingered longer in the ice, and had therefore not been washed away so rapidly by the water underneath.

About 2 pounds were applied to a surface 6 x 12 inches, selected on a block of ice 8 inches thick. The calcium chloride passed completely through the block in 40 minutes at a temperature of 16° below zero.

Calcium chloride applied to melt anchor ice attached to shore ice, eats its way through in comparatively small openings going at the rate of about 3 inches in 2 minutes. One of the difficulties in applying calcium chloride or salt is that the higher density of the brine caused by the melting of the salt causes it to sink rapidly by gravity and be washed away by undercurrents. In this respect the effect of salt added to water is entirely opposite to the application of heat.

An 8 inch block of clear hard ice was cut with 3 squares about 6 inches on the side and half an inch deep. Into one was placed calcium chloride, in the second common rock salt and in the third cavity common cattle

salt. Additional amounts were added as each ate its way down. After an interval of 1 hour and 20 minutes the calcium chloride had eaten $3\frac{1}{2}$ inches, the common rock salt $3\frac{1}{4}$ inches and the cattle salt half an inch. The ice cake was 8 inches off the ground thus allowing the full sweep of the wind, and effect of the low air temperature, below zero, underneath. Having demonstrated the effect of calcium chlroide in cutting a cavity in ice, it was decided to try the experiment of running lines or trenches across some ice fields in order that a line of weakness might be established by the honeycombing of the salt. The ice jam at the Pulp Wood Dock was selected (this was two weeks before the experiments with the Heat Units on February 24th, 1925. A line of calcium chloride was put on the ice and run lengthwise for a distance of 600 feet; another line was put on to cross it at right angles on the downstream face. These trenches were made in 4 to 8 inches of ice, and ate a trench approximately two inches before the honeycombing allowed the river water to flood the trench. A few days later this was found frozen but was readily penetrated by a spud. Sometime after this, during which rains occurred, examination showed the trench frozen up solid, but I believe the ice field was much weaker in tensile strength than the original ice field.

The experiments illustrate clearly that where it is desired to fracture field ice along pre-determined lines, either calcium chloride or salt may be used. When the usual process of disintegration takes place it will be broken up along lines of distribution. The same results would be achieved to a lesser extent by other material, such as sand, coal dust or sawdust, which depend entirely on the absorption of the sun's heat. A mixture of calcium chloride and salt with coal dust or limestone chips would be more effective and would preserve the line of weakness after the trench had frozen up. The trench, on examination, was found to consist of a succession of holes after the calcium chloride had eaten a short distance through, and the brine, which formed from the melted ice, had poured through and was lost in the water beneath. In this way a great deal of the

chloride was lost and for that reason experiments were made later, mixing with the chloride a base material to prevent its rapid disappearance. It is interesting to note that the foot of the Pulp Wood Dock jam broke off along the cross lines of calcium chloride. The sheet was heavily underhung with slush ice which was found to be 7 feet at the south edge. The maximum depth of slush was not recorded at this time. Six days after the application of the chloride, the ice field broke away at the lines of the calcium chloride, and the detached portion grounded on a shoal further downstream in 14 feet of water. In doing this it pushed up on the shoal, exposing the covering field ice. When the detached portion moved it carried with it one of the empty drums in which the chloride had been transported.

When applied to this ice field the chloride went through it at the rate of about 4 inches per hour. What it did to the underhanging mass of slush ice was not disclosed and it was assumed that the mass was too great for the quantity of calcium chloride available. However the break in the ice field occurred along the lines of the chloride. On the day that the chloride was applied to the ice the air temperature was 32°. In all about 1,000 pounds of calcium chloride was used on 700 feet of trenches.

Summary of Action of Chloride on Field Ice.

The trials of calcium chloride on hard clear field ice at different temperatures show us that for the lowest temperature the action began slowly but was apparently accelerated after the first inch of ice was penetrated and averaged 4 inches per hour for the first 2 hours, slowing up thereafter. The action continued, however, but the brine which forms always shows a tendency to concentrate in spots and at these spots runs down quickly through holes which it makes in the ice. Around the margins of the holes the ice seems to harden appreciably and the water at its surface again freezes but not apparently to any great depth. The net result was that the ice sheet was penetrated, converted into the cryohydrate and so weakened that with air temperature above the

freezing point or with the rays of the sun striking the point affected, that ice was destroyed for all practical purposes.

Effect of Chloride on Anchor Ice.

Flake chloride was thrown in the water on top of anchor ice beds attached to the bottom of the river but its action was limited, and did not seem to raise any large masses. The high velocity of the stream where the experiments were tried probably carried off the brine so that most of it was lost.

Experiments with Salt on Ice Field below Canada Island.

On the 10th of February, 1925, lines of common salt and calcium chloride were placed on the ice field which formed an extension of the fields usually formed below Canada and Clark Islands. The channel between these islands had been choked with cake and slush ice, uniting both in one great field having an area of over 140 acres, and this was reported to me as being of unprecedented size. At its easterly end the Canada Island field rested upon three shoals which act as buttresses, and from these it continued easterly until the extremity of the field was at rest 300 feet N.W. from the westerly end of Dry Island. The experiment consisted in laying out lines at right angles to one another in a checkerboard pattern with blocks from 50 to 100 feet square, the total length of the lines being over a thousand feet. A total of 2300 pounds of salt and chloride was used. The salt dissolved the ice slowly. Within a few hours after it had been in action a sudden rise of water level fractured the field west of the salt lines where it was anchored to the shore thus liberating the whole mass and no definite conclusions could be obtained as to how far the influence of the salt had contributed to the passing out of the field. About equal quantities of salt and chloride were used but on account of the early termination of the experiments no comparison can be drawn as to their relative effects.

In order to determine the best material for mixing with chloride, four lines of trenches were laid out, 18 inches wide, on McKenzie's Bay, below the boat houses at Morrisburg, Ont.

Line No. 1	With admixture of coal dust.	
2	do	gravel.
3	do	sand.
4	do	sawdust.

Each line was extended with the base material for an additional 15 feet, but omitting the calcium chloride. In this way the relative action of the salt plus basic material against basic material alone could be determined. No. 5 hole was prepared by using coarse salt in place of calcium chloride, the admixture of basic material being coal dust. This experiment was subjected to rainy weather and little sun for several days and was covered by a heavy fall of snow; hence it was considerably interfered with and probably most of the salt washed away. A little difference could be observed between the calcium chloride and the salt. The trench was made practically during the first 24 hours and did not change much after that. The admixture of gravel was the most effective and then in order of effect coal dust, sand and sawdust.

On the 4th of March similar experiments were made with calcium chloride, on trenches 5 feet long and 2 inches wide, adding the following materials:—

Gravel
Bran
Cornmeal
Sawdust
Manure
White flour

After these had settled through the ice, so as to fill the honeycombed portion, more calcium chloride was added and more material as a top dressing in each case. On the next day they were all down about 8 to 16 inches. After several days of cold weather intervening, the basic

materials which remained closely adhering to the sides of the trench were:—

1. Gravel—Fair.
2. Bran—Washed away somewhat by the rain.
3. Oatmeal—Washed a good deal by rain and water fluctuating through openings.
4. Flour—Washed a good deal by the rain.
5. Sawdust—Frozen solid.
6. Manure—Frozen solid but probably stuck well.

It will be seen that the bran and oatmeal and white flour were most effective and about equal in preserving the line of weakness. The weather following these experiments was unsuitable for further tests.

Calcium Chloride to Relieve Ice Pressure.

Two experiments were tried at the pier head, Lock 23, Morrisburg Canal, between the old and the new upper gates, at a point where the sun did not shine on it. The length of the ice that was treated by the calcium chloride was 15 feet. In both cases the ice was melted and opened up and stayed open with light freezing on top. While the salt was distinctly effective in melting the ice from the pier head, the mildness of the weather at that time caused it to clear further down also, so that the tests were not as rigid as could be desired. However, the use of calcium chloride to relieve ice pressure on concrete structures can be relied on. The present practice is to cut a trench between the ice and the structure or else to apply manure after the water has frozen to the pier. Common salt or calcium chloride should prove to be much more effective.

Ice Treatment at Richmond, Que.

In March, 1925, the writer was called to Richmond, P.Q., to report on ice conditions in the St. Francis River. Usually at the time of the Spring breakup the river ice comes down and jams just below the city where the river narrows. It was thought that something might be done

to destroy the ice of the river at this restricted point in order to allow a free flow of the ice and avoid the flood which usually occurs. A store of about 2 tons of calcium chloride was found which the City of Richmond usually used for the roads. The writer decided to trench the ice with the chloride through the narrow part of the river. The ice was about 24 inches thick and quite solid and the trenching could be done very easily. Two lines about a mile long and a foot wide of chloride were laid using about 5 to 6 pounds per square yard. Every 200 feet these lines were crossed by transverse lines about 200 feet long and 6 inches wide.

The chloride immediately cut its way through the hard ice leaving lines of weakness. When the Spring breakup came the ice moved down perfectly well, breaking along the salt lines and offering no resistance. No flood was experienced whether due to this or not, but the important fact was there was no flood.

Ice Problem in Power Canals and Power Houses.

Since the modern turbine has been made of such large dimensions as to pass great masses of ice quite freely the practice of removing rack bars during the ice run, is now widely adopted. The great volume of flow has, however, carried the ice problem back to the Power Canal, or penstock where very little real progress has been made. It is my intention to review very briefly some of the earlier ice troubles, and then to take up the consideration as to the best means to overcome ice in various forms of penstocks.

When possible, the water at the intake of a power-house should be covered by a layer of surface ice. The ideal condition for this is when works are supplied by water from a river completely frozen over. The most effective prevention to the formation of both frazil and anchor ice is the protection afforded by a surface-sheet, and under these conditions no trouble need be expected. This condition may not always hold, however, if there are stretches of open water situated in the river above the

surface ice. In all open waterways large quantities of frazil and, during mild weather, anchor ice are carried down by the currents under the surface sheet, and deposited along the under side of the ice. An excessive accumulation of this undergrowth may result in either the stoppage of the channel, or a very serious reduction of the volume of water conveyed. Ice shoves or flooding, may temporarily cause inconvenience or loss. This contingency must be carefully considered in the location of any power plant, where a temporary shutting-down of the works means delay to others depending on them.

When located with a stretch of open water above, means should be taken to construct a power canal of sufficient magnitude and depth, to serve as a settling-basin for the ice drawn in. Even in this case, the head-race may become blocked at the mouth by frazil. In such cases, a channel has to be cut through the surface sheet to allow of sufficient water for the turbines in severe weather. Large groups of men are kept at work during such times in clearing out the frazil from the channel.

The construction of a skimmer boom of cribwork at the intake of such a channel will help to deflect much of the ice.

It will take only a single cold night to cover completely a surface with floating ice before the surface permanently freezes and when the water has dropped to 32° and a sudden cold dip, with high wind, produces a choppy surface. This condition may not occur every year, and yet means must be taken to handle the ice should such a contingency arise. The only way to treat such a state of affairs is to handle the ice at the power house, and pass the frazil through, if possible, rendering it harmless by artificial heat, either in the racks, or directly in the turbines, or both. This expedient, although at first sight seeming impossible, on account of the large amount of energy required to warm water, is a practical one, in many cases. When we remember that a thousandth of a degree is sufficient to stop the formation of ice and prevent its adherence to surrounding objects, a simple calculation will show that an artificial heating plant is quite within the realms of possibility. We do not need

to warm the entire volume of water which passes through the wheel house. That would be an absurd notion. Nor could we cope with nature in such a way; but we can apply the heat where it is needed, and by so doing prevent the first ice crystals from gaining a foothold. It does not take long for the crystals to build up an impenetrable barrier when once the first layer of ice has adhered to the gates, racks, or metal surfaces of the wheels.

We can place the most vulnerable spots in a power house at the gates, the rack used for removing logs or wood from the water, the wheel itself, and the power canal.

A long narrow canal, which is fed from a stretch of open water or rapids, is one of the most troublesome of all forms of construction. We cannot hope to draw in water separated from frazil under such circumstances, and every means should be provided to pass it on as quickly as possible. A surface covering is only useful for preventing the ice forming. If it has formed, then the addition of a little more can do no further harm, and the ice sheet is not only useless but detrimental in forming a means for the massing of the crystals into lumps. It is much better not to have a covering at all than one which will act as a filter for the ice-laden water.

Although a power house may be most conveniently located at the base of a river normally frozen over, there are times when the ice problem may become serious. This occurs sometimes in the best regulated work, and I have in mind a power company who recently lost a unit, on the refusal of the gates to close. Enough damage was then done to pay many times over the cost of a heating plant. Salt is applied in large quantities to the frozen parts, or they are left alone until they remedy themselves, as is usually the case when the conditions change. The greatest agent in thawing out a frozen gate is the direct action of the sun on the affected part.

The racks are a continual source of trouble, and men are usually kept busy cleaning them off with long rakes. During the severest weather this is sometimes not effective, and a complete block of the waterway results.

In old fashioned plants the racks are metal bars passing into the water, and freely exposed to the cold air. Such a construction is to be avoided under all circumstances, unless the ends of the rack can be made to protrude under cover in a warm atmosphere, or be artificially heated.

When the frazil is in the agglomerating state, and ready to adhere to everything in its path which is also cooled below the freezing-point, the long iron bars of the rack act as a magnet to iron filings, and the frazil crystals soon mass about them. So firm do they freeze that they cannot be dislodged while the cold weather lasts without temporarily shutting down, and cleaning off with salt.

A method of preventing the accumulation of agglomerated ice in the wheel pits has been applied with much success. During the winter the iron racks are removed, and the housing completely closed around the wheel pits, and free access of heat allowed from the generator rooms. The result is that no ice forms there, and ice drawn in may be passed directly through without agglomerating.

At the Ottawa Power Company's works the water is open, and large quantities of frazil are made in the rapids above the Chaudiere Falls, which have to be passed through the turbines. It has been demonstrated by Mr. Murphy that this may be successfully accomplished in the severest weather, by his system of steam heating. *Supra*.

It is reported that on occasions a power user builds a fire out of oily waste and wood around the wheel cases, in order to get them running again, otherwise the usual thing is to wait until the sun relieves the aggolmerating masses.

The original object is the correct one of keeping the surface of the metal sufficiently warm to prevent the ice from attaching, and permitting it to pass straight through. During the time when the water is producing frazil, which is when it is slightly supercooled, there is tendency for ice to adhere to all bodies immersed

in proportion to their thermal conductivity and surface. Thus hemp rope will grow ice on it much sooner than a metal rope. This first layer of ice is like a slim precipitate which is very tenacious. As time goes on, the ice builds up a thicker layer, more or less compact in proportion to the current of water flowing. In quiet water long needles gather and grow out until the whole rope is encased in a mantle of ice crystals and plates. In fast running water, a solid layer of clear ice is usually found, which resembles surface ice, and is thickest on the upstream side. One of the most interesting methods of determining the ice forming power of the water, is used at Holtwood, Penn., where it is the custom to hang a frayed rope in the intake of the power house. Long before other evidences of ice are present in the wheels, it is seen growing from this rope. It is stated that this simple test is much more sensitive than a thermometer, and thoroughly reliable, as a warning of approaching ice troubles.

Ice coating takes place in the runners of a turbine, to such an extent as to cut off the water supply, and seriously curtail the output. Only heat can prevent such a state of affairs. *Supra.*

A system of powerful flood lighting is being developed by the writer for relieving the ice forming power of the water, and preliminary experiments with lamps designed for this work, seem to produce very helpful results.

Turning our attention over to the Power Canal, one of the best rules to be followed in designing a penstock or canal, is to make as much of the water flow under the surface as possible. Thus a pipe line is of much less trouble, than a ditch canal. The 13 mile long canal constructed by the Hydro-Electric Power Commission in their Queenston Plant is about ideal for an open water course. This is a narrow, deep, and smooth wall trough, and has given very little ice trouble. The worst form of canal may be found in a number of the larger power developments where the design has been for a wide shallow water way. Such a construction is bound to be troublesome and becomes in itself a serious ice manufacturing plant.

It is my contention that this matter does not receive the attention and study it deserves, the result being that a great many plants throughout the north country are greatly handicapped during several months of the year, either by being entirely shut down at times, or by a great reduction of power, and increased expense in wages also being incurred.

Mr. A. W. Dawson discussed this problem fully in 1913. He says in part:—

"As water powers in this country are usually designed to have a water velocity of from 2 to 4 feet per second, the ice is not frozen to the banks or walls of the canal, but moves along the current in large sheets of thin skim ice from 1-32 to ¼ inch in thickness, varying with the temperature and velocity of the water.

"The moving sheet of skim ice floats down the canal and breaks up into small pieces by coming into contact with the forebay boom, racking, or penstock walls. In passing under the boom or through the racking, these small pieces are turned over and churned up, and, provided sufficient time is occupied in getting from that point to the wheels, the nature of the ice will sometimes change from that of a thin flint-like crystal to a more spongy substance, which gathers together possibly in bunches, causing a loss of power as it passes through the wheels. This ice does not adhere to the wheels as readily as anchor ice or frazil, but when coming down in large quantities will, in time, cause considerable loss of power. Anchor ice or frazil mixing with it will, in a few hours, put the average low-head plant out of service.

"Cake ice usually comes from ice forming to considerable thickness along the shore or edge of structures and then breaking off into large cakes which drift down the canal. These cakes are usually kept from the wheels either by booms shunting them past the penstock entrance or through spillways into the tailrace. If allowed to get to the wheels the ice cakes jam up against the turbine entrances, causing a reduction of power until worn away by the current or broken by ice chisels into

small pieces to allow them to pass through the wheels or discharge outlets.

"Slush ice, is usually caused by a heavy snowfall, especially where the canal supply is taken from a large body of open water. This slush or wet snow has no life and if agitated by being turned over in a current before reaching the penstock will break up into very small particles, which pass through the wheel and give no great trouble. If anchor ice or frazil happen to be coming down at the same time, either of these will cling to and build up on the bunches of slush as it floats along, the lower temperature of the anchor ice or frazil causing the slush to thicken up and hold together. This makes a tough, doughy formation, the adhesion properties of which increase as the temperature lowers, the mass freezing around the grating, gate rigging, and wheels.

"The mixture of frazil, anchor ice, and slush holds on much longer than anchor ice or frazil would alone at the same temperature, due, no doubt, to its greater body of volume. If the slush is coming in very large quantities and packs about the iron gratings and turbine cases, the lower temperature of the iron will at times cause the mass to freeze and harden up. This formation once frozen will hold on for several days unless broken off with ice chisels, thereby allowing it to rise to the surface or pass through the wheels or discharge openings.

"Anchor ice and frazil very frequently visit the plant at the same time and unless the power house is fortunately situated or the canal structures particularly well designed, so as to keep the greater portion of this formation away from the wheels, operation must be suspended until the mass is ready to let go. In the majority of cases the trouble sets in toward midnight; relief may be expected between 6 and 11 a.m., depending on how bright the sun shines or how quickly the temperature rises. The writer has noticed that on a clear, bright morning, things loosen up several hours sooner than if the weather is dull and cloudy.

"No fixed rule can be given regarding the velocity of water, temperature of air and water, at which anchor

ice or frazil will form, as it is obvious that the results will vary, depending on the depth of streams, nature of banks and bottoms, velocity of water, and temperature at different depths, all of which more or less influence the results. Although every plant will have to be dealt with separately, the writer is satisfied that an observant superintendent can, after a few winters' experience in the same locality, usually tell when he may expect trouble from anchor ice or frazil, provided he has established a system of records relating to the above-mentioned points.

"Forebay racking is quite generally spoken of as ice racking or ice racks in describing hydro-electric plants. The writer has often wondered why this term should be used, his experience having satisfied him that the so-called ice rack in most cases is more or less of a detriment than anything else to the average low-head plant when anchor ice or frazil come down the canal. Very few ice racks are so designed that the total openings through the racking is much in excess of the penstock entrance, the result being that the velocity of the water is increased in passing through the grating, causing the formation of frazil as mentioned above. The only usefulness of the racking during the winter months consists of stopping any cake or bordage ice which may get past the head gates or break away from the canal banks.

"The main usefulness of the forebay rack is really during the summer season, and especially in the spring and fall in preventing drift logs, sticks, bark, and other debris from getting into the wheels and causing low power, broken wheels, and gate riggings. In order to do this work efficiently and stop small sticks, the opening between the gratings should be small, not over $1\frac{1}{2}$ inches near the surface and 4 inches at the bottom. A forebay rack of this description is an expensive structure during the winter months, because the openings are so small that they close up very quickly with either frazil, anchor ice, or slush. As the openings near the surface clog up, the water becomes more agitated, being turned over in getting through the gratings and thus causing the formation of frazil, which will, in time, entirely close up the openings and make a very good dam in place of an ice

rack or screen. It is a common occurrence in some northern plants for a large crew of men to be kept working night and day in the month of January and February with rakes, pike poles, and the like, keeping the so-called ice rack clear. Many power companies spend hundreds of dollars in this way."

Traveling Screens.

Racks which can be moved continually upwards and cleaned of ice adhering to them by a stream of water, have been used with considerable success. These are called traveling screens and have been used for several years in the Detroit Water Works intake.

There are times, however, when the ice run is so large as to block even these. Much of the ice carried to the screens is in the form of flat plates probably true anchor ice. These plates are too large to pass through the mesh of the screen and effectually block the openings. As this is a purely mechanical obstruction, heat has little effect on the metal screen and other remedies must be sought. Usually the trouble can be corrected at the river entrance to the penstocks.

Various Kinds of Ice Jams.

There are two typical forms of ice jams in a river. The one represents the blocking of the channel by a large ice field which wedges securely in between heavy batture ice, like a cork in a bottle. Into this plug, ice is carried and lodged until the water way is restricted, and a high head produced sufficient to cause a shove. The jams which form in the St. Lawrence are like this, and are often many miles long in a succession of ridges or shoves. The Waddington jam and Chimney Island jam, loosened by the thermit treatment, are good examples. To relieve such a jam it is necessary to find the key point and destroy it just as a log jam is relieved by loosening the key log.

The second form of ice jam is the dry jam which consists of a great mass of ice which has packed in by shoves for many miles and is solid to the bottom of the stream.

The natural flow of a river, so obstructed, flows around both sides of the pack causing flood conditions above. There is no key point, but the whole mass is like a glacier solidly resting on the bottom. Such a jam is represented by the Allegheny ice gorge, and ice jam at the mouth of the Moira river at Belleville, Ontario.

To treat such a jam it is necessary first of all to open up channels through the pack by burning out the ice with thermit through the main river channel, and gradually bringing the natural flow of the river back into its bed. The method of doing this is typically described in my account of relieving the ice jams at Oil City, Pa., at Belleville, Ont., and at LaTuque Falls. The function of the thermit is not to melt the ice away as so many uninformed people think when associating heat with ice, but rather to destroy and crack the ice to allow an entrance for the pent up waters. Once started the river flow continues to eat out and open up channels by itself and wash away immense areas of the under mass.

CHAPTER VII.

ICE PRESSURE.

On account of the great importance of this subject, we shall devote a full chapter to a discussion of it. Much confusion exists in regard to what ice pressure means. That there is a real difference in the conclusions arrived at by various experimenters is true, because of the peculiar nature of the solid characteristics of ice. No substance appears to offer such a wide variety of effects, and all we can hope to achieve is to correlate the best of previous measurements and observations, and to arrive at some general idea of what may be expected under natural conditions.

Complications arise, due to the peculiar plastic properties of ice, and to the regelation effects under pressure. Elasticity and viscosity have a new meaning, when studied in relation to ice. What we measure under ordinary conditions is something like a combination of effects, more or less proportioned according to the temperature.

Thus at a few degrees near the freezing-point, we are dealing with a substance, which is akin to a very viscous fluid, the properties of which rapidly merge into a true solid, as the temperature is reduced. Opinions seem to differ among Engineers as to the importance to be attached to ice pressure. It is held by not a few, that ice exerts no pressure, while others as sturdily maintain that such exists.

There seems little doubt of the baneful effects of ice pressure in many cases, but so much depends on the general character of the ice in relation to structures on

which it abuts. Despite opinions to the contrary, the expansive force of ice is a matter of great importance, in engineering work.

In the design of concrete dams the amount of allowance for the thrust of the ice sheet, is as yet a somewhat uncertain factor. Engineers are divided as to the amount to be allowed.

C. A. Mees gives some of the values which are assumed by various authorities in the design of dams. He gives the following:

G. P. Stearns (Wachusett Dam)—47,000 lbs., per linear foot.

Board of Experts (Quaker Bridge Dam)—43,000 lbs. linear foot.

J. D. Van Buren (Tran. Am. So. C. E.)—40,000 lbs. per linear foot.

S. M. Gray (Columbus, Ohio)—34,000 lbs. per linear foot.

He works out, from data on the modulus of elasticity of ice by taking the crushing strength of ice as 400 lbs. per square inch, values similar to these. He admits that according to his references, the case of a failure of a dam, which he studied, was caused not by pure temperature expansion, but more probably by a change in water level.

A paper by Walter H. Sawyer (Proceedings Maine Society of Civil Engineers, Vol. I, p. 27, 1911) gives a clear and satisfactory account of his observations of the ice thrust on several large lakes. He gives also some very valuable measurements of the expansion coefficient of ice at different temperatures. He cites authorities as follows:—

Wegmann (Croton Dam) . . . . . 43,000 lbs.

Morrison and Brodie. . . . . 47,000 "

In his own work on the construction of the Azicohos Dam on the Magalloway River he was obliged to select a value for the ice thrust, but owing as he says, "to the meagre information on this subject," it was difficult to

arrive at any definite conclusion. Experiments were therefore undertaken by Mr. Sawyer to determine the thermal expansion and contraction of ice at different temperatures, the crushing strength of ice, and the tensile strength.

Mr. Sawyer's first observations were made of the expansion ridges or "wrinkles" on some of the Maine lakes which were observed to form during the winter season. He describes his observations as follows:—

"Early in the winter of 1910 the Superintendent in charge of one of the Rangeley Dams was instructed to be on the watch for the formation of reefs, and about the first of January, 1911, information was received of the formation of reefs on Lake Mooselucmeguntic, and a party was immediately sent to study the formation and to gather information from residents in that section.

"Following are the conclusions reached after investigation, making observations, and sifting the evidence.

"The ice first cracked at the site of the reef during a cold period about December 22nd, 1910.

"On January 2nd there was a rise in temperature from 3 below zero to 41 above.

"A large reef was formed about 10.00 a.m. on January 2nd, 1911.

"When reefs form they do so near the same location each year.

"Reefs form in a warm period preceded by a very cold one, and may form at night if the temperature is rising.

"Reefs generally form when the ice is free from snow, or at least with very little upon it.

"Reefs do not always occur where there is a crack in the ice, neither do they always rise, as occasionally one sheet may slide under another.

"Reefs act for a time as expansion joints,—that is the peak of the reef may rise and fall with expansion and contraction of the ice sheet.

"They seldom occur when the ice is over a foot thick, but instances are known where they have been formed with ice twenty inches thick.

"They are generally higher at the middle of the lake than at the shores.

"No pushing up of rocks or soil is noticed in bays or inlets."

After making his observations on reefs, Mr. Sawyer devoted himself to a careful study of the expansion of ice. In this he constructed a trough the total length of which was 100 feet. This was made in 5-ft. sections connected together with a bellow-like construction to allow for expansion and to maintain the whole apparatus water-tight. The sections were constructed with a 2-inch by 8-inch plank bottom with 1-inch by 10-inch sides. Rollers were placed under the plank bottom, so that the sections would be free to move. The trough was filled with water, and after it was frozen the sides of the box were removed, so that the air would be in contact with as much of the ice as possible. An indicator was made by fastening one end of a swinging arm to one end of the ice box, the free end of the arm moving in the arc of a circle which was divided into one-hundredths of a foot. The arm was 16 inches long and at a distance of $1\frac{7}{8}$ inches from the pivoted end was attached to one end of a pine rod 1 inch square; the opposite end of the pine rod being attached to the opposite end of the ice column. As the column of ice varied in length, the pine rod remained at nearly a constant length. The temperature of the ice was found by reading a thermometer placed in the hole near the middle of the column. The true expansion of the ice between any two temperatures equaled the difference in scale reading at these two temperatures $\times 17/8 \div 16$, plus the linear coefficient of expansion of the pine rod $\times 100 \times 14\frac{1}{8} \div 16$. The coefficient of expansion of the ice equals the total expansion divided by the variation in temperature, multiplied by 100. In order to ascertain the coefficient of expansion of the ice per degree Fahrenheit, the total expansion between any two temperatures was divided by the total change in temperature

assuming that the variation of expansion was uniform, which is not strictly true, as we find that the coefficient of expansion varies at different temperatures. The coefficient at the higher temperatures is much greater than at the lower temperatures. In computing the length of the pine rod its temperature was taken as that of the air. The thermometers were only calibrated for even degrees, so that small variations in temperature gave but little information, six to eight degrees being the smallest change in temperature which did give consistent results.

During the first part of the experiments, Mr. Sawyer found that the ice would expand during the warm hours of the day, and contract during the cooler hours of the night, and that cracks were formed in the column which did not close during expansion due to rising temperature. To counteract this tendency to form cracks, weights were attached to the end of the ice column, and this device worked perfectly, the column remaining intact during the subsequent observations.

"The results obtained were uniformly less than those obtained by Andrews, Chapter 2, vraying from eighty-five to ninety per cent. of his results. There are two reasons which may account for this difference.

1. The ice in his experiment probably adhered to the plank forming the bottom, and free expansion was partly prevented. 2. The cross section of the column was large enough to prevent it assuming the temperature of the air in a short time, the observed lag in the thermometer placed in the ice being very noticeable. Then too as the column was protected on the bottom by the plank, the temperature was not uniform throughout its mass, and the temperature in the ice probably registered a greater variation than actually occurred in the ice as a whole.

"A study of the curves shows that the coefficient of expansion is a maximum at the freezing-point, decreasing rapidly at first, the rate of decrease becoming less as the temperature approaches zero, while below zero the coefficient appears to decrease very slowly.

"Having demonstrated that ice expands or contracts as the temperature rises or falls let us consider the effect of variations of temperature of the ice covering the surface of a lake, assuming the ice to be free from snow.

If the temperature of the air is —20° F. and that of the water 32° F. the temperature of the top surface of the ice will be nearly the same as the air when below the freezing point, while the bottom surface of the ice being in contact with the water will be at a little below the freezing point. As the ice in contact with the water remains at nearly the same temperature, and consequently expands and contracts but little, and as the ice in contact with the air is exposed to the greatest variations in temperature, and consequently the greatest amount of expansion and contraction, the actual expansion of the whole mass will be one-half of the maximum computed expansion of the range of temperature. The average coefficient of expansion of ice between —20° F. and 32° is .0000284, so that the total expansion of a sheet of ice a mile long for a rise in temperature of 50 degrees Fahrenheit would be = 3.75 feet.

"This corresponds closely with a statement by E. R. Beardsley in his pamphlet on the "Gravity Dam," that ice will expand ninetenths of an inch per hundred feet for the maximum range in the temperature of the ice that we are likely to have in the Northern States. This is equivalent to an expansion of about 4 ft. per mile."

Mr. Sawyer's experience with this problem is so large that his conclusions should be of the greatest value and consequently we give them as follows:—

"The problem of the amount of force applied to dams by reason of ice expansion is not solved. There are many experiments and observations yet to be made, and in the end we cannot lay down a 'hard and fast rule' for the intensity of the ice pressure. As in all engineering problems the engineer will have to take into consideration the local conditions.

"For the purpose of aiding in the study of the problem, I give a few of the conditions which may be found at different places.

"A dam may be built at the upper end of a valley, the opposite shore of the lake or pond consisting of soft mud or slit, in which case it would be expected that the ice thrust would force up the mud into ridges, rather than act to over-turn the dam. If, however, the opposite shore is formed of ledge or of a very hard soil, precautions must be taken to meet the thrust on the dam.

"The width of the shore above the dam will have a great influence on the amount of thrust exerted. If the distance between the dam and the opposite shore is comparatively short, we may reasonably expect that the thrust will be a great deal more than it would be if the distance between the dam and the opposite shore is considerable. The ice, in the latter case, will act more like a long column; that is, it will have a greater tendency to buckle than in the first case, the movement of the ice, however, if such occurs, will be greater, the longer the sheet.

"If the dam is situated in a narrow valley, even a short distance below the reservoir, we would expect that the shore at the upper end of the valley would receive the greater part of the ice thrust, but if these shores would happen to be of a soft or yielding nature, some of the thrust might be passed on to the dam. If the dam is situated below a reservoir, the elevation of which is being constantly changed, as in a mill pond from which water is being drawn for manufacturing purposes, the ice will be broken at the dam and on the shores, and the liability of the occurrence of a dangerous thrust will be reduced. Slanting up-stream faces of dams do not add an element of safety against ice thrusts, unless the water level is constantly varying,—that is, the tendency to slop on the slanting surface is more than offset by the greater adhesion to the surface by reason of the large area of ice in contact. We will admit, however, that a vertical upstream face will leave the dam open to receive blows from floating ice which would not be dangerous to the dam with a slanting up-stream face."

Observations Made Upon the Ice in the Montreal Filtration Chambers, 1914.

In order to obtain some information on the expansion and contraction of a restricted field of ice, some observations were undertaken, of the behaviour of the ice sheet which had formed in the North East chamber or bay of the Montreal Filtration Beds when being constructed in 1914. This chamber is fifty feet wide and three hundred and fifty feet long. It is completely roofed with the exception of a few man-holes, the roof being carried on concrete pillars, thirty feet square, spaced nineteen feet apart. The North and East sides are banked up outside with earth. The West side is the division wall between this and the adjoining bay, and the South end is open and faces a wide passage crossing the whole plant. The whole floor of the chambers had been flooded to a depth of about four feet. The ice which formed on the surface was quite clear enabling observations to be made of the condition of the under side of the ice. Direct observations were commenced on Feb. 17th of the system of cracks which had developed over the surface. In order to avoid any serious effect of ice expansion, a long channel had been cut through the ice. Over this channel a cover of ice blocks had been placed, which subsequently became cemented by freezing to the general surface.

When the temperature rose above the freezing point the cracks closed and disappeared, except where the upper edges had become chipped or rounded. A succeeding hard frost opened a new system of cracks similar to them. On Feb. 17th, and at the times when the temperature was well below the freezing point, the cracks started and opened as a rule from the pillars, and intersected, like the meshes of a net. Where blocks of ice had been removed from the channel and placed on the surface and became frozen to it, the cracks were observed to run directly through them without being deflected. This showed us that the tensile force of the ice which was exerted by the contraction of the general surface, acted in such a way as to split a thick block of ice, not contributing to the contraction.

All these cracks were observed to be wedge shaped, ending before the under surface of the ice was reached. This showed us that there was unequal contraction from the surface downwards. The breadth of the cracks seems to bear a close relation to the temperature.

Size of Cracks in Relation to Air Temperature.

In examples measured there was only one crack in the 19 ft. between the pillars.

			Opening of Crack.
Feb. 17th	Temperature	8° F.	.130 inch
" 26th	"	21° F.	.079 "
Mar. 12th	"	22° F.	.063 "

In a curve of the linear contraction of the ice from Andrew's measurements the range of breadth of some of the cracks measured at various temperatures shows us conclusively that the opening and closing of the cracks is occasioned by the temperature changes.

Besides the cracks on the upper surface of the ice we observed distinct marks of cracks which had been produced on the underside and which extended roughly only half the thickness of the ice. We could see these cracks through the clear ice on account of the entrance of water into them, with subsequent freezing. From the restricted nature of the freezing, air bubbles were shown eliminated from the water in freezing. Each crack was marked by a thin vertical layer of whitish ice, which showed in contrast to the perfect clearness of the surface sheet.

Temperature of Water Under the Ice.

On Feb. 17th, an attempt was made to measure the temperature of the water under the ice. A special mercury thermometer was obtained, reading to hundredths of a degree, which was enclosed in a brass protective case with a valve in the bottom. An ice auger was used to drill the ice sheet. This made a clear hole about $1\frac{3}{4}$ inches in diameter, through which the brass case of the thermometer could be readily lowered. The act of lowering the thermometer caused the inrush of water through the valve of the case, and around the bulb of the ther-

mometer. When held steady, or when raised the valve at once closed, thus trapping the water around the bulb. The thermometer could be then raised and the reading taken through a window in the case. The temperatures near the bottom ranged from 3°.4 C. to 1.8° C. It is doubtful if they would have yielded anything of importance for this investigation. We may say that the temperature at the underside of the ice was at 0° C. and increased rapidly to a probable maximum of 3°.4 C. at the bottom. This is entirely as we should expect from a body of still water upon which ice has formed.

The disturbance of the water by cutting the hole and lowering the brass case was considerable and owing to this, the readings were variable.

Thickness of the Ice.

A series of measurements were made of the thickness of the ice sheet from Feb. 17th to March 14th. This period included some days of mild weather and rain previous to March 5th as well as some periods of intense cold. The mean results we show in the Table.

They all show a gradual increase in thickness. The difference in the initial thickness is due to the position of the ice with respect to the openings through which the cold air gained admittance. This illustrates very well the protective action of a cover under which the heat of the water is more easily conserved.

TABLE OF ICE THICKNESS-FILTER BED NO. 16.

FEBRUARY AND MARCH, 1914.

Date	Ice Thickness in Inches.						Temp. of Air Chamber
	A	B	C	D	E	F	F
Feb. 17.....	21	..	20	22	13	9	8
" 24.....	..	24	..	..	..	..	..
" 26.....	25	24	23	..	..	..	21
Mar. 5.....	1 Ice water 24 ice	..	3 Ice water 22 ice	28	20	8	36
Mar. 12.....	27	25	25	27	20	7	22
" 24.....	29	27	26	30	24	6	28

A.—Thickness near south or open end of chamber.

B.—Thickness near centre of chamber.

C.—Thickness near north or closed end of chamber.

D.—A channel in the ice was made down the centre of the chamber and covered with blocks of ice early in the winter. Measurements were taken near the north end through these blocks where it was found that ice had formed downwards on these blocks, into the channel giving a greater thickness as indicated.

D.—Total thickness.

E.—Depth of ice extending below general surface.

F.—Height of block above general surface.

Melting of the Ice.

The melting of the ice with the advent of warm weather was a problem of some difficulty. The roof prevented the rotting action of the sun which is the most powerful agent in nature for getting rid of ice. Some water was pumped out of the beds under the ice and soon after the ice thawed along the concrete walls and pillars, and settled down on the water again without breaking or getting jammed. A steam boiler was erected and live steam blown into the water under the ice. This proved very effective locally, but not enough circulation could be set up to melt a wide area.

Theory of Ice Cracks.

The forces set up in a large sheet of ice when the changes of temperature occur are very great. They are also unequally distributed throughout the ice thickness, and thereby cause the ice to bend readily. It has been concluded by many observers that a large ice sheet will buckle and bend before the ultimate crushing strength of the ice is reached. This we believe to be true, for the strains set up in the ice sheet all tend to assist this bending. Let us consider the contraction and expansion of an ice sheet represented in Fig. 38. In the upper block we suppose the upper surface subject to a cooling atmosphere below the freezing point. The under surface of the ice being in constant contact with the water cannot ever differ by more than a very small fraction of a degree, from the freezing point. Hence we cannot have changes of length taking place at this surface by pure expansion or contraction. The temperature decreases upwards

through the ice to the surface, the gradient depending on the thickness of the ice and the period of the cold or warm wave affecting the upper surface. Contraction

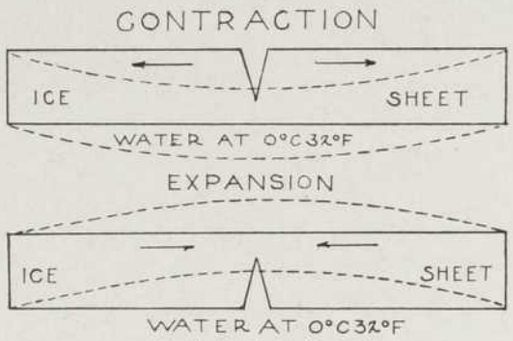


Fig. 38.

takes place in the upper surface, which causes the sheet to bend downwards as we have represented by the dotted contour. Under the tension the ice cracks, as represented in the diagram. No force of a harmful nature can be exerted at the edges of the ice sheet, under these circumstances. As long as these cracks remain open, they act as pressure cracks, to take up the thrust of the ice, when the temperature rises. In general we may assume, however, that these cracks will become filled up either by snow or by water coming over the ice surface. The ice being cold will cause the cracks to freeze solid and cement the whole sheet into a firm mass.

When a rise of temperature results, the top surface of the ice will expand while the under face will remain as before, free from strain. This will cause the ice sheet to bend upwards as represented by the dotted figure. Relief cracks will start on the underside, and the ice sheet will remain as before, level on the surface of the water. There is no question but that the under surface cracks will at once fill with water and freeze, so that a permanent increase in the length of the sheet will result.

There seems every reason to believe that an ice sheet may gradually expand by small increments, where the cracks are filled and frozen and hence a permanent thrust will result.

Pressure ridges on large lakes are seldom seen to disappear again, but we believe these are permanently formed by this gradual increase in length of the ice.

Working back and forth in these ridges will take place to some extent as was observed by Mr. Sawyer, but we believe these ridges are gradually increased with every great change of air temperature.

Crushing and Tensile Strength of Ice.

Crushing Strength.

In 1914, with Prof. H. M. Mackay, of McGill University, I found the crushing strength of clear blocks of St. Lawrence river ice at or near the freezing point to be very nearly 363 pounds per square inch. This agrees very well with the values assumed by many Engineers, which is in round numbers 400 lbs. per square inch. It was found, however, that the ice block first yielded at approximately half the crushing strength, and that what we have called the crushing strength was the pressure per square inch which caused the ice block to burst.

If we take in round numbers the crushing strength to be 400 pounds, as C. A. Mees has done in his paper on design of dams, then we find with him, that the thrust for various thicknesses of ice can be taken as follows:—

Ice Thickness	Thrust in pounds per linear foot.
6 inches	28,800
8 "	38,400
10 "	48,000
12 "	57,600

Tensile Strength.

The American Civil Engineers' Pocket Hand Book gives a range of 142 to 223 pounds per square inch.

The best tests which we have seen on the tensile strength of ice have been made by Mr. George G. Bell (Maine Society of Civil Engineers, Vol. I, page 41, 1911).

Mr. Bell employed a cement testing machine. The samples of ice were prepared in two different ways. The first lot by filling cement moulds with water which were allowed to freeze. In these samples the air bubbles arranged themselves perpendicular to the surface of the ice in contact with brass, forming a core in each end, and

when tested, failure occurred along the line containing the points of contact, and the core. The second set of samples was prepared by cutting the ice to nearly the proper size. These pieces were set in the moulds and the remaining space filled with water and frozen.

Mr. Bell in describing the effect of ice thrust writes as follows:—

"Although the ice forms in our northern rivers and lakes up to three feet thick, it seems probable that the greatest ice pressures occur when the ice is from a foot and a half thick,—that being the greatest thickness at which ice reefs are formed. The thrust for a sheet of ice 18 inches thick is $2,400 \times 18 = 43,200$ pounds per linear foot, for a twenty-inch sheet $2,400 \times 20 = 48,000$ pounds.

"There are only two references that give actual values of ice thrust. The first is in the discussion of the New Croton Dam by Professor Cain. He states that 'The ice between two bridge abutments 90 feet apart, expanded during a rise in temperature and arched so that the center was three feet above its original level.' He gives the thrust for a 12-inch sheet of ice as 21,000 lbs.

"The second reference is given in Volume 5, Part II., of the Canadian Society of Civil Engineers by Duncan MacPherson, of a bridge pier subjected to ice on one side only, which was shoved out of line two inches, and held there under passing trains until a channel was cut in the ice, when the pier settled back into its original position.

"The thrust of the ice to tip the pier only was given as 14,600 pounds per linear foot for ice 12 inches thick. Taking the train load at 3,000 pounds per linear foot, would bring the thrust up to 18,000 pounds for ice 12 inches thick.

"Probably all that prevented rupture in the first case was that there was not sufficient expansion. However, the thrust of the ice would probably be much greater when the arch was flatter.

"In the second case, the ice had not reached the point of failure, and there is no information given from which to estimate it."

The results are of interest as representing forces actually exerted by the ice, although they do not give the theoretical maximum thrust, which according to accepted notions, would equal 28,800 pounds per linear foot for ice only half as thick. This bears out the fact of the yielding of ice below the crushing strength.

Mr. Bell states: "The crushing strength of floating ice may be taken at about 10 tons per square foot.

"A bridge pier was shifted by a blow from a large field of ice, and the crushing strength of the ice was figured from the force necessary to replace the pier. This was 11 tons per square foot.

"A careful study of ice reefs and the maximum thickness of the ice at which they form in any locality, together with experiments on long columns of floating ice in the water, would furnish much valuable data. From the present limited data, I believe that a dam exposed to the full pressure of ice should be designed to resist from 43,000 to 48,000 pounds per linear foot, and that structures subject to blows from floating ice should be capable of resisting from 10 to 12 tons per square foot, on the area exposed to the greatest thickness of floating ice."

Experiments made by Mr. Bell on the adhesion of ice frozen to concrete surfaces is of much interest and importance. He states:—

"These tests indicate that if ice is firmly frozen to the concrete, it will develop its full crushing strength, irrespective of the inclination of the line of ice to the surface of the concrete, as long as the temperature of the ice is below the freezing point.

"William M. Patton, in his treatise on foundations, says that the adhesion of ice to a pier, even to the sloping surface, may be so great as to develop the full crushing strength of the ice.

"When the natural upper surface of the ice was perpendicular to the line of thrust, the samples fractured horizontally and vertically, when the natural upper surface was parallel to the line of thrust, the samples fractured in parallel vertical planes only.

"In the latter case, if the ice had reached a temperature of thirty-two degrees, it was often impossible to obtain further signs of failure, as the ice under the pressure of five or six hundred pounds per square inch, would spread or flow without further fracture."

Recently some valuable measurements were made by John N. Finlayson at Winnipeg.
Can. Engineer 53 101 (1927).

Tests on the Shearing Strength of Ice.

The average value of shearing strength in the direction parallel to the basal planes is shown to be 114 lbs. per sq. in. and in direction parallel to the crystal walls 98 lbs. per sq. in. The average of many tests extending over a range of temperature from −10 F. to 30 F., and the results would seem to indicate that temperature has very little if any effect on the strength of ice in shear. As might be expected in such a material as ice, there was considerable variation from the mean values, and oddly enough the maximum value obtained was 353 lbs. per sq. in. parallel to the walls of the crystals at temperature 30° F., and the minimum value 68 lbs. per sq. in. parallel to the basal planes at temperature −12° F. It was observed that at temperatures below zero greater values were obtained when the load was applied rapidly; consequently care had to be taken to apply the loads uniformly throughout the series of tests. No marked elastic limit was noticeable before the specimens sheared off; but there was evidence of a slow realignment of crystals under pressure, as the load was found to fall off if the head of the testing machine were brought to rest during the test.

The fact that ice will resist greater stresses on planes parallel to the basal or freezing plane of the crystals than on planes parallel to the optical axes or side walls of the crystals had been established by Professor Matsuyama as a result of his investigations on the rigidity of ice in torsion; but the values of the shearing strength are much greater than those deduced from his data.

River Ice Stronger than Artificial Ice.

A few tests were made to determine the strength of artificial ice in shear. It was found to be about 80 per cent. of the strength of river ice.

The strength of river ice in compression was found to be about 1,800 lbs. per sq. in. in a direction parallel to the walls of the crystals and about 1,050 lbs. per sq. in. in a direction parallel to the basal planes, shorter rectangular columns being tested in the usual manner. The temperature at which these results were obtained was 11° F. There is reason to believe that the compressive strength will be greater at lower temperatures.

A few experiments were made by Finlayson to secure some information concerning the strength of ice in tension. Briquettes were made by allowing water to freeze in molds such as are used in cement testing, and a few briquettes by placing in the molds a mixture of snow and water. The latter froze with fewer cracks than the former, but by allowing the molds to remain unclamped during the freezing, and coating the edges and joints with melted heavy asphalt, very satisfactory briquettes were obtained, the few cracks which did appear running lengthwise in the briquette. They were tested in a small shot weighted testing machine, the grips having been cooled by coatings of snow. The load was applied slowly and uniformly and the breaks usually occurred at or near the plane of minimum section. The average tensile value of water ice was found to be 103 lbs. per sq. in. There was no very great variation from the average in any of the briquettes tested, which may add weight to the value of results of the tests. In both the tension and compression tests failure was sudden accompanied by sharp reports. The remains of the compression blocks had conical projections in which the walls of the crystals were easily discernible.

Compression tests of St. Lawrence River Ice.

In order to determine the crushing strength, perfectly clear river ice was cut in larger blocks, and a number of

measurements using a hydraulic press were made in 1914. The blocks were cut from ice which was specially selected for me through the kindness of the City Ice Co. of Montreal.

One large piece 6″ x 28″ x 40″ furnished the largest number of individual blocks. The direction of the

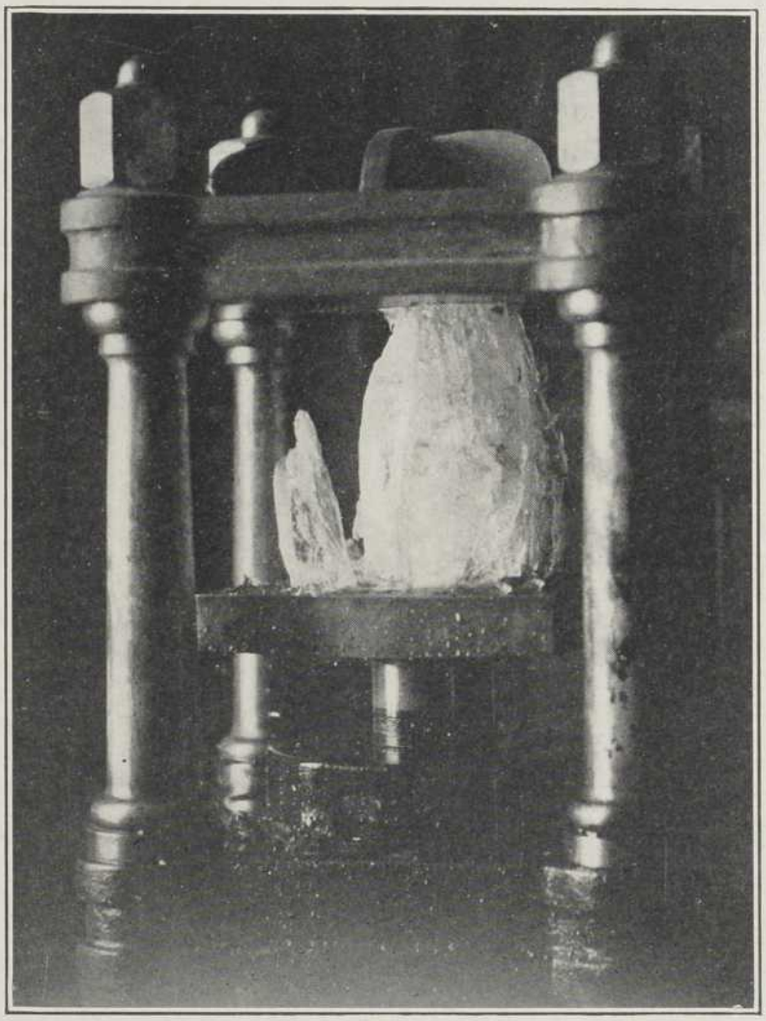


Fig. 39.—Ice Crushed with pressure applied along the main crystal axis.

crystalline axis was determined by knowing the plane of freezing, and the various blocks were cut by a hand saw accordingly. The ends of the blocks were melted

smooth on a hot plate to fit the plates of the press. When the pressure was applied, considerable melting resulted on the ends. The blocks were kept outside at a temperature ranging from −8° C. to 0° C. and were brought into the laboratory for the tests. One interesting fact was noted, that the blocks were heard to crack

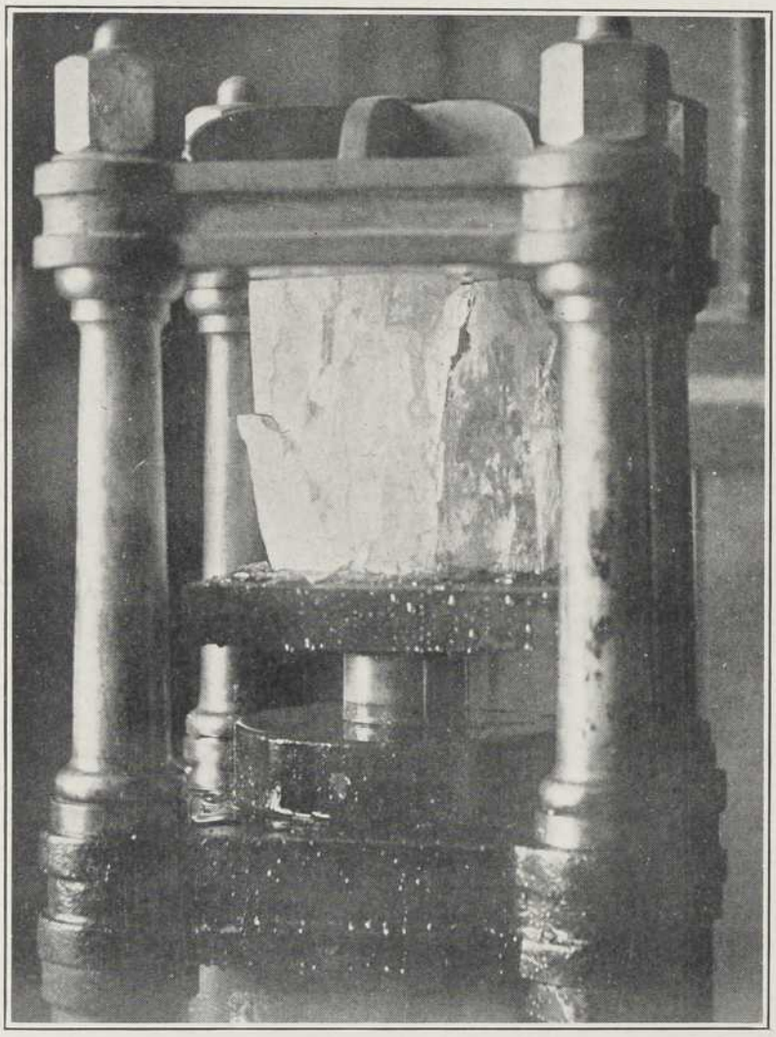


Fig. 40.—Ice crushed with pressure applied at right angles to main crystal axis.

at a pressure, approximately one half the ultimate crushing force. It was repeatedly observed that as soon as the pressure was increased sufficiently to cause the

first audible crack, the block appeared to stiffen, and the pressure ran up much quicker, with much less melting. In some cases the melting appeared to cease altogether. I calculated that the giving way of the ice under pressure allowed the melted ice to run into the cracks, where it must have frozen and cemented the block more firmly. I was unable to see any of the cracks which we could distinctly hear at half the crushing pressure.

The only effect of varying the position of the axis of the ice with respect to the direction of the pressure, appeared to be the way the block burst. When the axis was parallel to the applied pressure, the ice burst sideways into innumerable long needles, resembling a cake of ice which has all but fallen to pieces in the sun. The cake fell to pieces on being removed from the press. When the axis was at right angles to the applied force, the block cracked lengthwise and transversely without shattering.

Fig. 39 shows a cake crushed in the direction of the axis, while Fig. 40 shows the reverse effect.

The mean value for all the tests for parallel axis is a little higher than the mean for perpendicular axis, but the difference is too small to make it possible to draw any definite conclusions.

The results show considerable variation, which may be purely accidental or may have some bearing on the character of the initial distribution of the strain.

The question of the relation of temperature to the crushing strength is one of importance. It has been assumed that ice becomes stronger at low temperature. The hardness of ice increases considerably as the temperature falls to O° F. but I am inclined to think that the ice also becomes more brittle. In the neighborhood of the freezing point, ice is much more plastic than it is at lower temperatures. The plastic effect is, however, masked by the regelation effect, and it is a question whether the ice mass is not different near the freezing point than when cooled much below. This can, however, only be settled by further experiment.

TABLE II.

Date	No.	Size of block.	Direction of axis with respect to direction of applied pressure.	Pressure when first crack was heard.	Pressure when block crushed.
				Lbs. per sq. inch.	Lbs. per sq. inch.
Mar. 21 1914	3	3 x 6 x 4	Parallel.	87	289
"	4	6 x 5 x 4	Perpendicular	123	247
"	5	4 x 4 x 5	"	183	251
"	6	5 x 4 x 6	Parallel	166	335
Mar. 26	7	7 x 6 x 6	Perpendicular	183	424
"	8	7 x 6 x 6	"	183	364
"	9	6 x 6 x 6	Parallel	....	485
"	10	7 x 7 x 5	Perpendicular	....	238
"	11	7 x 7 x 6	"	200	400
"	12	7 x 6 x 6	Parallel	121	304
"	13	7 x 6 x 5	"	159	398
"	14	7 x 6 x 5	Perpendicular	140	292
"	15	7 x 6 x 5	"	234	422
"	16	7 x 7 x 5	"	227	568
"	17	7 x 6 x 6	Parallel	....	224
"	18	6 x 6 x 5	"	248	557

Mean 370 lbs. per sq. inch, axis parallel
Mean 356 lbs. per sq. inch, axis perpendicular
Mean of both 363 lbs. per sq. inch.
or 3885 kilos per sq. cm.

RESULTS OF COMPRESSION TESTS (BELL)

No. of tests	Size of cube	Crushing Strength	Lbs. per sq. inch.	Temp's ice.	Air	Remarks
1	2 x 2	1926 lbs.	481.5	18	27	1 height after crushing.
2	2 x 2	2059 "	516	18	27	" "
3	1 x 1	3430 "	1128	13	25	
4	1 x 2	2074 "	535	32	40	Grain perpendicular to force.
5	1 x 2	2224 "	636	32	38	Grain parallel to line of force.
6	1 x 2	1884 "	539	32	39	" "
7	2 x 2	3400 "	753	32	40	
8	2 x 2	2474 "	488	32	40	These were 4 in. long and had grain parallel to line of force
9	2 x 2	1811 "	358	32	40	
10	1 x 2	3214 "	783	32	40	
11	2 x 2	3449 "	765	32	40	Perpendicular to line of force Parallel to line of force.

RESULTS OF ADHESION TESTS (BELL).

No. of Tests	Size ice	Bevel	Load at failure	Unit compression at failure	Unit adhesion to concrete	Method of failure	Temp. Fah.
1	2 x 3	12 8	4200	370 lbs.	195	Crushing	30
2	2 x 2	12 8	3800	504 "	228	"	30
3	3 x 3	8 12	3856	395 "	158	Crushed & sheared.	32
4	3 x 3	8 12	2960	250 "	116	Adhesion	32
5	3 x 3	1 1	4100	420 "	185	compression.	30

In 1915 O. W. Von Engeln determined the crushing strength of ice at comparatively low temperatures, 8, 10, and 12 degrees Fah. below 32°. These for small blocks, 2 inch x $\frac{1}{2}$ an inch, gave results up to 1000 lbs. per sq. inch.

Undoubtedly this high value which agrees with Finlayson for very cold ice is due to the lower temperature. Further work is required on the effect of temperature on the crushing strength.

Measurements of the Strength of Ice.

Some valuable measurements have been made by Prof. E. Brown of McGill University, which have recently been published in the Report of the Joint Board of Engineers for the St. Lawrence River. He says in part:

"The primary object of the tests was to determine the behavior of ice at different temperatures when compressed normally to the crystals, as it is under natural conditions in an ice field. The deformation of the ice was measured by the use of mirror extensometers, and its elastic properties and strength determined. Tests were to be made also on beams, to find the modulus of rupture and the modulus of elasticity, "E", by observation of the deflection under load.

"The tests were carried out during the months of February and March, 1926, in the Cold Storage Warehouse of the Harbor Commissioners of Montreal, where rooms which could be kept at uniform temperatures

ranging from O° F. to 32° F., were available. A supply of river ice of excellent quality was obtained through the City Ice Co. of Montreal from their ice cutting field in the Laprairie Basin of the St. Lawrence River, off Verdun. It was noticeably free from flaws, cracks, air bubbles or foreign material, and the upper layer of white ice was only about one inch thick. The blocks were cut under special supervision and handled with the greatest care during transportation to the warehouse so as to avoid risk of damage, and were stored in a room at a temperature of about 30° F. where the necessary specimens were prepared for test. It was proposed to carry out tests at different temperatures, and as the work of cutting specimens could be carried out more conveniently at a temperature near the freezing-point than at a temperature near zero, it was decided to cut and store all specimens at about 30° F., removing them to other rooms at lower temperatures as required for testing. It was found later that ice splinters considerably when sawn at temperatures near to O° F. but at 30° F. the sawing was accomplished with comparatively little difficulty. A series of special mitre boxes was made by which compression specimens 5″ x 5″ x 5″ and 5″ x 5″ x 10″, and beams 3″ x 2″ x 50″ long were prepared, using ordinary carpenters saws and planes, on the rough specimens cut with ice saws from the larger blocks. All specimens were marked to denote the direction of the crystals.

Bending Tests—Modulus of Elasticity and Modulus of Rupture.

"A number of bending tests were made at different loading rates. In all cases the beams were approximately 3″ wide by 2″ deep, and the span was 41″. Glass or brass bearing plates were placed between the beam and the supports to distribute the pressure, and the load was applied in increments of 1 lb. at each of two loading sections 14″ from the supports. Half-round wooden-bearing blocks were placed across the beam, and cords were passed over the top and notched ends of these, being kept vertical and close to the faces of the beam by wooden spacing bars at a convenient distance below the

beam. A cord attached to the centre of the spacer bars carried a circular piece of wood on which the slot weights were placed, to load the beams. The supports were carried on a heavy lathe bed, on which was set a telescope by which the central deflections were read on a small steel scale attached to the face of the beam by freezing in place under a small pressure. The deflections were estimated to 0.0001."

"Preliminary tests showed that the recovery was not complete even for very small loads, and that the deflection increased continuously over long periods under sustained load. It was decided to make the tests at different loading rates, the procedure being as follows:—

"After the zero reading of the scale had been taken, each of two operators added 1 lb. load at his stirrup, and the deflection was read say 5 secs. later. Similar loads were added and deflections read every 5 secs. until the beam broke. Tests were made in the same way with loading intervals of 10, 20 and 40 secs. at temperatures approximately 14° F. and 28° F. Time did not permit making tests at 3° F.

"In all cases the deflections for 1 lb. increment of load increased as the loading proceeded, so that values of the modulus of elasticity computed for successive stages of loading would show continuously decreasing values. Approximations to the form of the load-deflection curves were made by drawing two straight lines, representing the first and second stages of loading, the latter extending to the point of fracture. This was deemed to be sufficient, as the results cannot be compared as simply as those for the compression tests. In the latter the blocks were all approximately 5" x 5" so that deformations due to a given load were comparable. But in the case of the beams, the specimens could not be prepared so easily to a definite size, and variations in breadth and depth, praticularly the latter, affect the stress due to any given load. All the beams broke suddenly and fracture occurred at or near the loading point. The modulus of rupture and values of "E" corresponding to the two stages of loading defined above were computed for all beams. Tests were made with crystals horizontal and vertical,

the average of three tests being given, except in cases where only two tests were made.

Examination of the results shows in general:—

(1) That values of "E" are somewhat greater when the crystals are vertical than when they are horizontal.

(2) That values of "E" are greater at 14° F. than at 28° F. under similar conditions.

(3) That values of "E" decrease as the load increases under all conditions, and generally as the length of the loading time interval increases for both stages of loading.

(4) That the modulus of rupture is about the same value for crystals horizontal and crystals vertical, but is much greater at 14° F. than at 28° F. The average of all tests at these temperatures being 226 lb/sq. in. and 171 lb/sq. in. respectively.

(5) That the modulus of rupture does not vary much at the different loading rates.

"Other comparisons may appear from a study of the results, but it is worth suggesting that there may be a connection between the modulus of rupture and the load intensity at which certain peculiarities were noted, particularly at 14° F., during the compression tests. These have also been referred to in describing the results of tests at 14° F. under sustained loads, and the evidence suggests that a critical condition, possibly related to intercrystalline displacements, exists at a load intensity of about 200 lb/sq. in. The average modulus of rupture for 24 beams at this temperature was 226 lb/sq. in.

"In the compression tests at 28° F. to 30° F. the deformation increased continuously for successive load increments of 1000 lbs. There were no cases similar to those at 14° F., in which the actual deformations for certain of the later increments of load were less than those for earlier increments. The average of 21 beams was 171 lb/sq. in. which corresponds to a load of about 4250 lbs. on a 5″ x 5″ cube.

"Distinct lagging in the deformations at higher loads was noted also in some of the compression tests at 3° F., and occurred at higher loads, than those at which it was noted at 14° F. No beam tests were made at 3° F., so that modulus of rupture values are not available, but the evidence so far as it goes is consistent and interesting. Tests on the compressive or crushing strength of ice showed that it becomes greater as the temperature is lowered.

Crushing Strength of Ice.

"Most of the tests were made with the load normal to the crystals, but a few were included with the load parallel to the crystals. In the former, the typical failure was tent-like, the horizontal crystals forming a ridge parallel to the loaded faces, while in the latter distinctly conical fractures resulted. There appears to be little difference between the strengths at failure under these two conditions; and there was considerable variation in results at each temperature.

"At 28° F. the average ultimate strength of nine specimens which failed under the standard rate of loading was 300 lb/sq. in. Three others which had not failed under the standard rate of loading were broken immediately afterwards by suddenly applied loads, the average strength being 417 lb/sq. in. The load in two cases was of less intensity than had been sustained previously.

"At 14° F. the loads carried were higher than at 28° F. none of the specimens measuring approximately 5″ x 5″ failing at a load of 10,000 lbs. even when this was applied suddenly. One specimen withstood this sudden load seven times after being loaded previously to 10,000 lbs. at the standard rate. Of three specimens which failed at the standard rate of loading, one failed unaccountably at a much lower load than the other two. All were cut from the same block. The mean of the two higher results is 693 lb/sq. in. which compares rationally with 600 lb/sq. in. and 625 lb/sq. in. for two others, these being loads which did not cause failure. Of six blocks tested under suddenly applied loads, only two failed, at approximately 500 lb/sq. in.

"At 2° F. eight out of nine blocks tested failed under the standard loading rate, and the average ultimate strength was 811 lb/sq. in. The other block, with crystals vertical, carried over 1,165 lb/sq. in. applied at the standard rate without failure. The strengths were approximately the same for both conditions of loading.

"The tests show that the crushing strengths of the given blocks loaded at the rate of 1,000 lbs. in 2 secs. were as follows:—

Temp. Fahr.	Crushing Strength, lb/sq. in.
28°	300
14°	693
2°	811

"For other loading rates different figures would be obtained. It has been shown that the time element is probably the greatest factor in determining the pressure of ice against a structure. Conclusions drawn from the crushing strength alone are of no value. The crushing strength itself at any given temperature depends on the rate of loading.

CHAPTER VIII.

ICE NAVIGATION AND ICE BREAKING.

In 1908, through the kind assistance of the Department of Marine and Fisheries of Canada, it was possible to extend my studies of ice phenomena to an investigation of the conditions governing the formation and disintegration of river ice on a large scale. It is a pleasure to record the interest shown by the late Hon. L. P. Brodeur, Minister of Marine, and to the former Deputy Minister, G. J. Desbarats, and the present Deputy Mr. A. Johnston. Observers were supplied by the Government who devoted two years to the work.

Two months were spent on board the Canadian Government Icebreaker Stanley doing duty in the Northumberland Straits, and two months were spent on the ice-breaker Montcalm, by Mr. J. B. Woodyatt, now President and General Manager, Canada Power Corporation.

The next year studies were made on C.G.S. "Lady Grey" by Dr. L. V. King. Nearly every winter since, the writer has spent some time on the icebreakers observing their work. The result of this study has shown where improvements can be made when it is found economically desirable to lengthen the navigable season to the port of Montreal.

In treating the ice problem even those with the oldest experience are inclined to regard the task of ice breaking from the wrong end. Anyone who views the ice accumulation in the river towards the end of the winter thinks rightly of the impossibility of coping with such masses. Where ice is prevented from accumulating and usually the task of prevention is not an insurmountable one,

these large masses cannot form. It is the work of but a few days or less for the formation of the famous ice bridge at Cap Rouge, and yet it is the work of two months to break it down again, whereas the presence of an ice-breaker during the first few days and after will prevent the bridge from forming altogether, and make the task of keeping the river clear at that point a simple one.

Work at the Northumberland Straits.

Observations on the formation and action of salt-water ice are of great interest. It is quite unlike fresh-water ice, being so very variable in composition and different in appearance.

Prof. Otto Petterson of Stockholm, President of the International Commission for the Study of the Sea, has made an extended study of saltwater ice. As a result of his enquiry he finds that ocean water is divided on freezing, not into pure ice and a more or less concentrated solution of ordinary sea salt, but into two saliniferous parts, one liquid and one solid, which are of different chemical composition. It is found that the formation of sea ice is chemically a selective process. Some of the elements of the salt water are more fit than others to enter into the solid state by freezing; those that are rejected by the ice will preponderate in the brine, and vice versa. As a rule the ice is richer in sulphate, the brine in chlorides. With time the ice appears to give up more and more of its chlorides and to retain its sulphates. The general opinion has been that pure ice was formed at the freezing of sea water. The small impurities always present in sea ice were accounted for by adherent sea water but it has been conclusively shown that the freezing of sea water envolves a separation of its chemical constituents of which one part enters into the composition of the solid, another into that of the liquid water. The actual salinity of the ice is of course small and was found to diminish with the age of the ice. Immediately after its formation sea ice contains a noticeable quantity of salt, chlorides as well as sulphates, carbonates and other salts. Such ice is very different from fresh water ice in its physical properties. It melts below zero, and begins

to show signs of melting by contraction of volume at temperatures far below O° C. Thus ice which contained as much chlorine as 2.73 parts per thousand commenced to contract at −14° C. (6.8° F.) and continued to do so up to the melting point. Ice formed by freezing at low temperatures of arctic sea water which contained 6.49 parts per thousand of chlorine began to contract its volume already at −18 C°. (O° F.). This phenomenon is, however, a relative one so far as any ice is concerned. Even fresh water ice contains small traces of impurities which cause a contraction of volume before the actual melting occurs. The purer the ice, the sharper is the change from solid to liquid differentiated. E. V. Drygalski has found in his study of polar ice for the Berlin Geographical Society that the salinity of newly formed sea ice is from 4 to 5 parts of salt per thousand. He found what is very important, that the salt is not confined to the uppermost layer of the ice. The salt was found to be almost equally distributed in every layer of the sea ice from the surface to 68.4 cms. depth, where the salinity was 4 parts per thousand. But after two months the salinity in all layers decreased from 4 to 5 parts per thousand to 1 or 2 parts per thousand.

A very interesting characteristic of the thin layers of salt-water ice is their great mobility. It is entirely different in appearance to fresh-water ice being white, and the top layers seemingly full of mechanically suspended salt. Extreme brittleness which characterizes the fresh-water ice is entirely wanting. A small wave set up in the water travels through it without breaking it, the thin layers rising and falling and exhibiting great plasticity.

The observations made by Mr. Woodyatt were, accurate temperatures of the water and air, the humidity, barometric pressure and the determination of the strength of the various forms of ice met with in the straits. A close watch was kept of any relation between air and water temperature, and the effect of other meteorological conditions including the tides, on the ice conditions. It was clear that the chief factors in the ice conditions in the Straits were wind and tide. The temperature of the water remained very constant everywhere at 30° F.

The severity of the air temperature had an influence on the quantity of ice formed, but the greatest difficulties in ice-breaking were always experienced in the milder weather especially after a period of great cold. The intense frost appeared to hold the ice which was afterwards let free to be carried from immense distances by wind and tide. The notes from Mr. Woodyatt's report are interesting and some are given here.

On Satuday, January 16th, 1909, a strong gale from the west had been blowing all night, and increased in strength in the morning. The temperature dropped rapidly to 40° F. Georgetown Harbor was clear of ice. Sea a little choppy along Island (Prince Edward Island) until we struck ice about six miles south of Cape Bear. The ice was in large flat cakes, not yet frozen together. The boat pushed these apart or split them, there being plenty of room for the pieces to move in. Some of the cakes were about 8″ thick but the general run was 4″. These pieces were fairly firm but not at all like fresh water ice. The ice is not clear nor elastic, but is of a lump sugar formation and crushes into a slush. There was no tendency of the ice to stick to the sides this morning, it passed by easily. After passing the solid ice the sea was quiet, and in different parts the whole process was visible. At first there appears a sort of thin slush on the surface. Its appearance resembles oil on water, when some distance away. It has a surface tension, however, as shown from the fact that the sea from the ship does not break it up as it does the solid ice. This slush forms into little discs about 4″ in diameter, which gradually grow in diameter. These discs have no power of cohesion, and the wind and movements of the water push them all around until several are piled half on top of each other, making pieces about 2 feet in diameter, the intervening spaces between them being filled with the slush. The water lapping up against these deposits of slush along the sides makes little ridges on top and along the borders. With these slushy edges the little clumpets seem to cohere. They are continually on the move more, and more pieces come together and stick, but a small wave will pull them apart, or slide them on

top of each other. The intervening slush hardens, and cements the surface, giving the ice a chance to grow, which it apparently does very rapidly, once this stage is reached. The tide is very strong in the straits, and the ice is moved about continually, which keeps the cakes broken up into small areas, which it is no trouble to the boat to split, acting as a wedge. We have not yet struck any pans of ice, that the boat has had to crush. The splitting of course causes a reduction in speed, but so far the reduction has been in proportion to the area of the pan rather than to its thickness.

On Tuesday, January 19th, 1909, the wind was very cold, and though most of the trip was through open water, we had to break through several large pans. The ice was clearer and more brittle. It appears to be of the lightest green in color, and cleaves perpendicularly to the surface. This ice is evidently not joined in the method described before, as it is more glassy and less powdery, but is the result of very cold weather on still water. We got jammed twice in "pans" of hard ice, there was apparently no give at all, the ship pushed in and forced the ice down, but gradually lost headway and stopped, a second trial after going astern a hundred yards or so, was all that was necessary in each case. This was the first real ice crushing that has been done so far. The pans were large enough to resist splitting, that is the ship could not start a crack that would extend to the borders and thus divide the pan, so the boat had to crowd through. The stern tanks were filled lowering the stern deck below the wave set up by the wheel, the bow thus elevated rode up onto the ice and cracked it. It would crack off a piece on either side about twenty feet back. The edge of this piece under the ship was turned down, and the other edge turned up to the deck, showing a thickness of from one to three feet of stratified ice. The piece in this position took up much less horizontal space leaving an amount of open water for the boat to float on, while the main body of the pan remained intact. This and the splitting, are the only two natural ways of the ship's obtaining a free surface of water. After the ship passes, the pieces right themselves, and

50 yards astern the path is completely blocked. Once we ran far enough in to be squeezed so tight, that it took some little time to loosen.

On Wednesday, January 20th, 1909, the wind had blown the ice off the Nova Scotia shore, and we ran along the edge of this ice due east, almost to Cape St. George, we then turned on a northerly course straight into Georgetown, arriving there an hour and a quarter late due to the length of the course only, as we avoided the ice, though in cutting a corner of it once, we ran right into a considerable depth of lolly that stuck tightly and gradually compressed until we were stopped. We went astern and on going ahead again avoided the spot, and had an uninterrupted course. The "Minto" tried the usual course, but became blocked, and did not dock in Pictou until half past twelve.

On Monday, January 24th, 1909, the winds of the last couple of days had jammed the ice in between Pictou Island and Pictou Harbor, and yesterday's cold weather cemented it. We ran about two miles out of the Harbor and then came up solid. The ice was piled high, big cakes on top of each other, and these were impassable. There were large pans of ice of diameters varying from a few feet to a quarter of a mile, these were flat, but at their edges where they had been grinding each other, big pieces were broken off and turned up, giving the pack the appearance of a lot of fields divided by rough fences. The pans themselves though sometimes two and three feet thick were not so hard to negotiate, but the barriers, consisting of ice "rafted" high above water and very deep below were simply impossible. The air was very cold, and the ice brittle, but it was too solidly jammed by the rising tide for a crack to extend very far. The tide on the rise was making the ice run, and carrying us with the ice. The ice at the edge of the fields could be seen "rafting" over and under the surface and piling up, the process being accompanied by very loud groans and grinding, the movements and sound having a very wierd effect. Sometimes the ship would get caught in between two of the fields, then the ice would slip up against the side and jam her so that she could not move either ahead

or astern, until the ice shifted again. Finally the fires were burned down to wait for the tide to change. Until 1 o'clock this rafting and groaning kept on, and the ship wedged tightly in the packed ice was moved around with it. Then the tide commenced to ebb, as if by magic, big stretches of clear water opened within the solid ice, and by skillfully taking advantage of these "leads," we rounded Pictou Island and were past the worst part. See Fig. 41. The rest of the run was through surface ice of thick-



Fig. 41.—A "lead" opening up through an ice pack. Northumberland Strait.

nesses varying from 2″ to 1 ft., but as it was not rafted into barriers we went through it, at a slightly reduced speed. Some of this ice was clear sheet ice, and some of it consisted of the discs with the lapped up edges described before, frozen solid with a five or six inch background of a rather cloudy ice. These two kinds of new ice are evidently the results of cold air and quiet and rough water. The ice under the discs was slightly easier to get through than the clearer ice of the same thickness.

The manouvring adopted in breaking through very heavy ice is as follows: First the ship is driven full speed in the direction in which we want to go. The engines are reversed just before she comes to a stop, so as to avoid

getting stuck, and she is run back a couple of hundred yards. The next drive is made a few feet to the right of the first, and the intervening ice having nothing to hold it on that side is split off and crowded into the centre. The next drive is similar and to the left of the first. This leaves a fairly large area of broken ice which can always be turned over so as to accommodate more ice in the space, and is so much "gained ground", the process is then repeated until the ship breaks through to easier going.

The wonderful effect of the tide upon the ice was the most interesting part of the day's experiences. It was hard to believe, after observing the ship make so little effect on the ice, that the ice would suddenly and silently disappear from sight, and disclose big stretches of clear water. The tide runs very fast at this point, and the ice is carried three or four hundred yards in a very short time. The silent disappearance or rather opening up of the ice with the tide in the ebb stands out in contrast with the roaring and jostling of the ice when the tide is coming in. We arrived in Georgetown at 4.20, making the longest run of the season.

On Wednesday, January 27th, 1909, the snow storm ceased, and the day became clear. The wind was still strong from the N.W., which was very unfavorable for us. We got under way on the beginning of a favorable tide. A favorable tide is one which tries to drive the ice against the wind, the result being a loosening of the pack. The Stanley did splendid work. Through 8″ of hard, clear pan ice, she could make from four to five miles an hour. This ice was turned under to make way. In the softer lolly, there was more trouble. Great areas of lolly would cling to the sides and greatly impede progress. Sometimes as much as two feet of the ice on her side would be coming along with us. This clinging is not as if the lolly were frozen to the sides, but is more like the adhesion of "packing" snow. The snow that had fallen made the going bad, especially in the looser parts, where the water had washed it, and turned it into slush. In the afternoon we were fighting westward about two miles north of Pictou Island, trying to make the east

end of it. We struck a big pan of ice extending right up to the Island shore. This ice was about 10″ thick. After driving through it for a quarter of a mile, we started a crack that ran ahead as far as could be seen (three quarters of a mile at least). We steamed along this until it was thought we were far enough west so as not to drift past the Island, and then on the change of tide in the morning we hoped to get through the lead at the east end of the Island, which is almost sure to be there under the existing conditions. In this position we burned down for the night.

On Thursday, January 27th, 1909, at daybreak this morning, we found that we had drifted with the ice a good 12 miles to the S.E., and were lying about five miles off Malignant Cove on the Nova Scotia coast. There had apparently been open water along the shore, and the wind had blown the ice we were in, into it. The work of yesterday was thus all lost, and we started again, heading for the east end of Pictou Island, as there was no possibility of getting through along the Nova Scotia shore. The ice was rafted into high barriers that needed a lot of ramming before they would divide. The ice was clear and hard, but as before the ship made far better progress in the clear hard pans than in the broken lolly covered debris. This of course does not refer to the barriers of hard ice, which were sometimes impassable. After getting to about four miles east of the Island we received a message from the "Minto" (which had been lying at the Pictou Dock waiting for more favorable conditions until this morning) that she had run up on a barrier at the mouth of the harbor, and was stuck, and that to all appearances the ice in the channel was grounded. With this in prospect, and with supplies and water for the boilers running low, the Captain decided to turn back. We turned towards Georgetown and in a short while struck the open water and arrived in Georgetown at noon. They cut the Minto out with slice bars, and she tried again. This time she was more successful. She came through the ice between Pictou and Pictou Island, at the time when the tide and wind had opened it right up and before it closed, she had rounded the Island,

and then came on straight to Georgetown, arriving there about 4.00 p.m.

On Friday, January 29th, 1909, we left Georgetown at 7.00 a.m. and steamed easily past Cape Bear. The wind was still from the N.W. but was veering around westward. By five o'clock in the afternoon by constant fighting, we had rounded Pictou Island and had reached a point about six miles from Pictou and north west of it. The Stanley has never done better work. With no open water in sight she battered along, through pans, barriers, and lolly, backing, turning and manouvring, but always getting on. She turned down three feet of solid, hard ice from the big pans and went rapidly through anything under a foot at a good five miles an hour. We were smashing through an 18″ pan (extending for about two miles) when the tide started to move the ice. The pan we were in came together and nipped us, so that we could not move an inch either ahead or astern. This jamming is wonderful. The ice lifts the ship and presses until you can feel the plates springing. We were in a very bad place, and after we burned down a very careful lookout was kept for any chance to get out of it. About midnight the tide changed and for a few minutes during the slack water the ice fell away, and we pounded on for a mile or so, when the tide caught us again, but this time we were in broken ice which protected us from the full pressure of the pack. At 2.00 a.m. we burned down to wait for daylight.

On Thursday, February 4th, 1909, the wind veered around through W. into S.W. by W. and was blowing quite strong when we left Georgetown. The wind had blown the ice up along the Prince Edward Island shore. We struck it farther north than we have done before, so we were in ice practically from the start, but it was pretty well opened up until we passed Cape Bear. From there on the ice was very solid, the leads being short and far between. The tide was also causing the ice to run so that we not only had to crush it, but also squeeze through it, as it came together, as soon as we opened it. Once a field closed in on us, so that we could not move a fraction of an inch. Two big points of the

field pressing against the sides of the ship localized the pressure causing indentations in the steel plates. There was no relief, and we had to fight all the way, except for about two miles off the Nova Scotia coast from which the S.W. wind had blown the ice. The lolly between fields was cemented together and very hard to get through, so the flat pans were generally taken in preference. A hard clear pan up to 30″ in thickness is much easier to go through than the lolly, for two reasons. In the first place the friction between the hard ice and the steel is a good deal less than between the softer ice and the steel, and secondly it is comparatively easy to sink the edges of the heavy pan, and so make displacement for the ship, while the lolly and broken stuff will not sink, but bobs up from under the bow and chokes the path, making progress almost impossible.

The ice at the barrier at Pictou was practically in the same position as we left it, so we tried the path again. The path was full of lumps of ice, the result of the battering. This was a new form of trouble. The ice was in pieces up to three feet across but mostly smaller. It is not at all like lolly as the pieces are solid. It is known by the most expressive term of "slob" ice and the expression "bogged in the slob" accurately describes its effect on the ship. It crowds ahead (and will not sink) until enough of it is wedged together to bring the ship to a standstill. The screw churning up the water gradually passes the ice back and out into the path behind, and until it does that there is no progress. We docked at 6.00 p.m.

On Wednesday, February 10th, 1909, the wind was from the S.S.E. and the sky was clear when we started out. As usual we did not have much trouble with ice until we passed Cape Bear. We could see the Minto had drifted to a point about half way between Cape Bear and Cape St. George, and was stuck solid. We passed along through leads until we passed the East end of Pictou Island and were working west, about a mile off the south shore of the Island. We were in open water, running at full speed, and were making for a narrow bridge of ice (about 150 feet through) which separated us from more open water, when the bow ran up on

the ice, but did not break it, nor could she back off. From where we were to shore was solid ice, and the bridge we were on was holding back another big field which was being pressed in by the wind; consequently it was very solid. After several attempts to move we "burned down". About 12.00 o'clock there was a slight slackening in the ice, and the men started to "cut her down" with slice-bars or chisel-bars. (See Fig. 42.)



Fig. 42.—Cutting out the "Stanley" from an ice pack

This operation consists of cutting away the ice for about six feet along one side of her, starting at the stern and shoving the ice, as cut back into the pond of open water created by the screw. The ice was opening up ahead so that now her bow was in open water. The instant enough ice was cut away to clear her, she moved for the open water, but the ice started to run, and before she could cover the 100 feet or so, the ice on the east side came in to fill in where it had been cut away, and nipped us tight. It would seem as if the ice gained considerable momentum in traveling the six feet that it did, for when it nipped us, it nipped hard, started plates, twisted bulkheads, broke ports, and sheared bolts. And it

didn't stop there. The ice coming on behind started to climb over the ice on our side, and piled up until it was coming in over the decks. See Fig. 43. With great



Fig. 43.—C.G.S. "Stanley" nipped between two ice floes.

groaning it piled and squeezed, and the ship shook under the strain. We were not quite broadside to it, however, and it was gradually passing to our stern, so that after about an hour of the squeezing we got another chance, to cut down the ice and got under way before it closed in again. From there to Pictou was easy sailing, as there was lots of open water. The Minto is drifting around and has not turned a wheel since yesterday at 10.00 a.m.

The ice troubles experienced by the Stanley were found to occur invariably on days of higher temperature following a period of colder weather. Prolonged cold weather had little or no influence when compared to the effect of a rise of temperature. This is what might be expected, for it is during the cold weather that the ice is formed, extending out from the shores and remaining securely frozen so long as the temperature is low. When, however, mild weather followed this ice became loosened and was carried about by wind and tide. Prolonged

mild weather cleared away the ice by rotting and melting it until no ice was found. The lolly which is an accompaniment of the hard ice is formed by spray and wind agitation on the surface in the proximity of the large fields of ice when the presence of the ice keeps the water at or near the freezing-point. During very cold weather, with no sun, the lolly is formed everywhere on the surface and, mixed with snow, is blown together in large masses. From the thermograph records obtained by Mr. Woodyatt it is found that after the mild weather of January 10th, 11th and 12th, when the temperature was almost constantly entirely above the freezing-point, the colder weather of January 13th and 14th found no ice at all in the Straits. On the 14th a sudden rise of temperature from a minimum of 15° F. the day previous to 42° F. brought out masses of lolly and field ice. A second cold dip to 0° F. on the 17th followed by a rise to 43° F. on the 18th produced large pans of ice on the 19th when the temperature fell again. Cold weather with a strong wind from the North on the 19th made the "pan" ice very brittle and difficult to split and produced lolly in such quantities as to stop the ship entirely on the 20th during a rise of temperature to the freezing-point. The North wind is always accompanied by great dryness, which produces a marked influence on the strength of the ice.

Open water was experienced on January 23rd, although the temperature was 10° F. owing to the effect of two days of mild weather, when the temperature reached as high as 48° F. on the 22nd. Increasing cold weather followed from the 23rd to the 25th but no trouble was experienced until milder weather which commenced at noon on the 25th and remained just below freezing until February 6th. During this time a small rise and fall in temperature formed and again loosened the ice until the conditions became so bad, accompanied by adverse wind and tides, that the Stanley was very irregular in the trips.

On the 8th of February, after two days of mild weather above freezing no ice was found in the Straits. A cold dip on the 8th, 9th and 10th followed by a rapid rise at noon on the 10th caused much trouble. Very mild

weather on the 11th found no ice at all. On the 17th of February a rapid rise of temperature after cold weather caused a great deal of trouble again from masses of lolly so great as to stop the ship. On the 20th of February, mild weather following a cold dip again caused much trouble from lolly.

Ice Breaking on the St. Lawrence.

I shall now briefly review our first experience in clearing out the ice jam at Cap Rouge which always forms and grows rapidly to great thickness. This famous ice bridge in the old days usually remained long after the river had cleared and delayed the first ships to Montreal. It was also responsible for the winter floods along the shore between Lake St. Peter and Quebec. Since 1908 with the exception of one or two years when the ice-



Fig. 44.—The first ice breakers built by the Canadian Government to prevent the destruction of farm buildings along the shores of the St. Lawrence by ice fields carried inland on flood waters, were rock filled cribs. These are now obsolete.

breakers were out of commission, this ice barrier has been broken up and flooding of farm lands avoided. The in-

creased value of these farms has more than compensated for the expense of using the ships.

Before the icebreakers were used many farms were in danger every year from flood water carrying great ice fields. Wooden ice breaking piers are seen at many points along the river, now going to ruin from disuse. See Fig. 44.

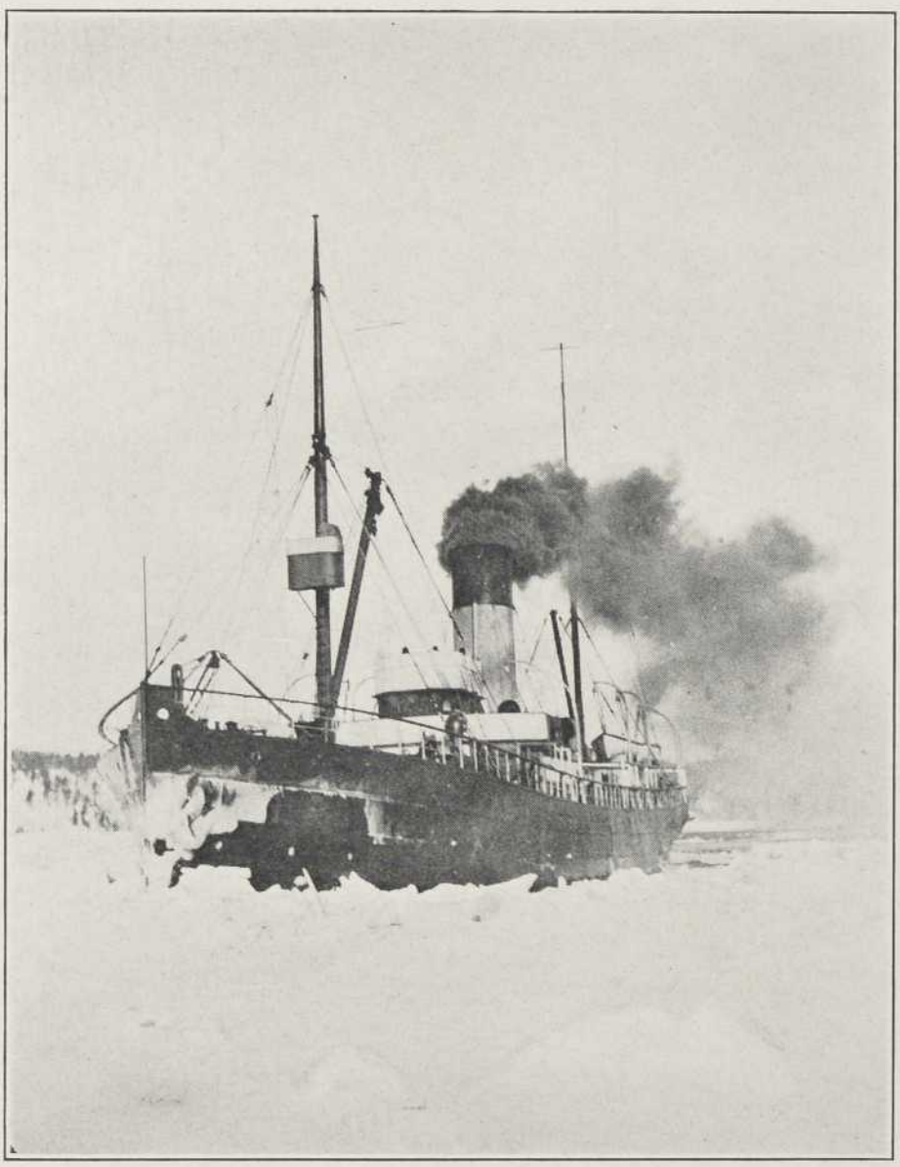


Fig. 45.—C. G. S. Montcalm working through the ice pack at Cap Rouge, Que. in 1909.

Mr. Woodyatt's observations are very interesting and I again quote from his report:—On Friday, February 26th, the Montcalm left dock at 11.00, just at high

water, and proceeded up the river to the ice-bridge. When she started work at the beginning of the season the bridge extended down as far as the piers of the Quebec Bridge. The Montcalm has been cutting a channel about 1,200 feet wide through the centre of it. The ice we were working in this morning was about three feet above the surface, and from 15 to 20 feet below. See Fig. 45. It consists of a tightly jammed mass of broken ice and snow. The ice is a great deal glassier than the salt water ice, and much more brittle. It parts or cracks with a report, and the thin shell ice, as it is broken by our sea sets up a rattle which is entirely missing from the salt water ice of the same kind. The Montcalms bangs at the ice and on hitting fresh unbroken stuff goes into it for about 30 feet. If no large crack appears, another drive is taken in the same place, but if a crack appears, the next drive is taken so as to shake the piece off. The size of the pieces separated vary up to about 30 feet across. The ice floats away with the ebb tide and does not bother us any more. At the first pier of the bridge the ice was about 15 feet out of water in a great many places, and progress was slow, at the rate of about 50 feet per day (1,200 feet wide), but now we are doing between 200 and 300 feet per day. The fore tanks are all filled and the bow well down, in contrast with the fighting trim of the Stanley. They are afraid to run up on the ice as it might be too thick to crush, in which case she would stick until they could shift the water ballast. She does not turn the ice under, but rather crushes it sideways, the ice crumbling into snow and piling up on each side of the bow. On reversing she slides away without any sticking, other than a slight mechanical one when she runs up a little too far.

It is sufficiently evident that the performance of the Montcalm was very satisfactory, and that she succeeded in enabling the ice to move out of the river much earlier than usual. No trouble to speak of was experienced at any point below where the ship was working. The only trouble was from the large pieces of ice cut off being blown back by wind and carried by the tides. This condition need not have occurred had the Montcalm

been put at work earlier in the winter, before the ice jam at the narrow part of the river below Cap Rouge had formed. It was but the work of a few days for this jam to form and during that time the ship was not at work. No form of ice gives the ice breakers so much trouble as frazil or lolly ice. The ship is practically helpless when surrounded by masses of this material, chiefly from the

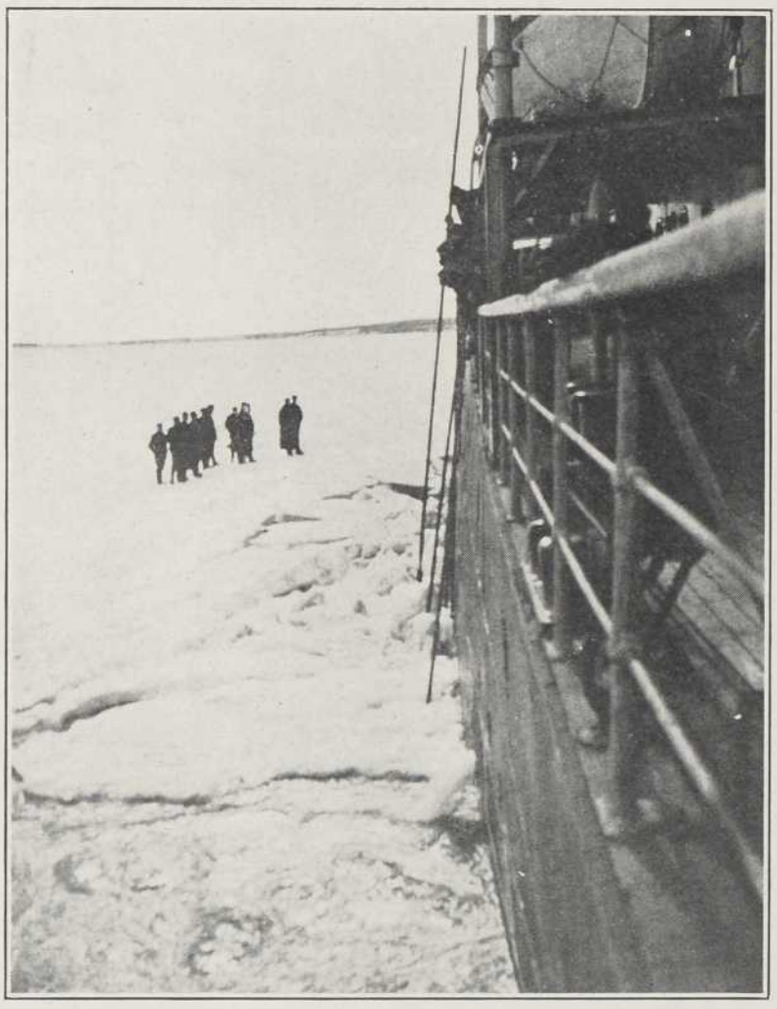


Fig. 46.—C. G. S. "Montcalm" stuck for ten hours in an ice pack on the St. Lawrence river at Cap Rouge. Note the removal of all ice by the discharge of the circulating water.

difficulty of gaining sufficient water to float. It masses under the ship and by its buoyancy, and in cold weather its adhesiveness, pushes up and sticks to the plates. In the Northumberland Straits the Stanley was time and again completely stopped from the clinging of this ice. An observation made by Mr. Woodyatt on April 10th

when stuck in the frazil may help to indicate a way in which a ship may get free of this ice. The presence of the frazil is always observed to lift up the surface ice. As soon as the surface sheet was carried off by the blow of the ship, the frazil rapidly floated up and filled the opening. In so doing it surrounds the ship and squeezes out the water necessary for the ship to float. When in this condition it was observed that the frazil became rapidly melted and loosened on each side just at the point where the circulating water was discharged. Frazil is easily disintegrated by a very minute temperature elevation in the water, which is so small as to have absolutely no effect on any ordinary thermometer. With the discharge water at 60° F. it was evident that this was sufficient to raise the temperature of the water enough to disintegrate the frazil at and below the point of discharge. Fig. 46. Had the circulating water been carried up to the bow of the ship, and discharged there, it is evident that the frazil from the bow aft would have been rapidly loosened and sufficient water available to float the ship away. Ice breakers equipped with steam injectors at the bow would always be in a position to loosen the lolly or frazil, and never be seriously impeded by it. Such an equipment would be even more important in the Northumberland Straits, than elsewhere, but it is believed that it would form a most important addition to a modern ice breaker.

The hygrograph records made by Mr. Woodyatt, indicated on a day of low relative humidity when the evaporation of the ice and water is rapid, the ice is more resistant. A very large amount of heat is absorbed in the evaporation of a pound of ice or water at the freezing-point, considerably more than the evaporation of a pound of water at the boiling-point. Hence when evaporation is rapid as we know it to be over the surface of ice and water, the ice is more easily cemented together, and the water is more rapidly congealed.

Again through the kind assistance of the Department of Marine and Fisheries, I was able to extend these studies of ice phenomena, and to examine in more detail certain interesting questions which arose during the work of

the previous year. As in the previous work the Department generously provided an assistant, and Dr. L. V. King devoted four months to a close study of ice conditions from the deck of the C.G.S. Lady Grey and Montcalm.

Ice conditions were studied at Cap Rouge during the winter, and an excellent opportunity was afforded for studying the disintegration of ice at Lake St. Peter. A trip to the Northumberland Straits enabled observations to be made on the new ice breaker Earl Grey, which did such excellent service before the war between Pictou and Charlottetown, P.E.I. Three weeks in April spent on the Lady Grey at Crane Island completed the winter's work.

The use of two ice breakers at Cap Rouge resulted in an entire absence of any ice jam permanently setting in there. At no time were the icebreakers severely taxed. It was an easy task for the boats to keep the channel clear with the result that the tide and currents had their full effect on the river, above giving open water all the way to Three Rivers.

No more marked demonstration of the efficiency and ease of preventative measures in dealing with ice conditions could be cited than the work of the icebreakers. The two ice breakers had no difficulty in keeping the river clear to Three Rivers by merely working at Cap Rouge. One of the most important discoveries made, was the effect of open water on the water temperature in winter. At no time was frazil troublesome, and for the entire winter the temperature of the water at Quebec was higher than freezing owing to the effect of the sun on the open water above. The whole effect of surface ice on the temperature of large masses of water is presented in a new light when considered with reference to the absorption of the sun's heat. I am convinced that the task at Quebec is rendered much easier owing to the presence of open water above. Much study was given the effect of the sun on the temperature of the water and many important meteorological results came from these observations.

General meteorological conditions, and extracts from reports submitted by Dr. King on the ice conditions existing during the winter are here given:

The winter of 1909-10 was a mild one, so far as the meteorological records show, all the months except February being above the average. February was, however, below the average. The temperature during the month of March departed to the greatest extent from the mean, being some eight degrees warmer. A strong sun with fine mild weather assisted very much the early disintegration of the river ice. In some respects extremes of temperature following one another make the ice problem harder to cope with. The cold weather forms the ice, which always grows faster in its initial stages, and the warm weather brings it down the river in large quantities making the danger of a jam at Cap Rouge more likely. When the cold weather persists the battures remain in their places, and merely increase in thickness. The total growth of ice under such circumstances is, I believe, actually less than when the mild weather dislodges the battures and the next cold snap forms them again.

On Dec. 21, 1909, (Tuesday). Moderate snowfall during the day. Wind N.W. The Lady Grey left her dock about 1 p.m. with the high tide. Light open ice, somewhat heavier than on the preceding day was met with. The ice was for the most part in large sheets about eight inches thick and often several hundred feet across. This ice was very brittle and gave way before the Lady Grey with a sharp crackling sound. The waves caused by the steamer were sufficient to break up the ice for about 60 feet on either side of the steamer. There was, especially below and above the Quebec bridge, large spaces of open water; these were often partially covered over with thin "lolly-ice", soft, flakey and easily disintegrated. This ice forms very rapidly, especially on windy days, a piece as large as a man's fist growing to a couple of feet in diameter in the space of two or three hours. This kind of ice was observed to form and extend out from the windward side of the fine cakes, and is no doubt responsible for cementing these together. In

the narrow portion of the river opposite the Quebec bridge, the open spaces of water had disappeared; the ice was very rough and presented the appearance of small cakes piled up, on one another and frozen together. This was no doubt due to the crumpling up of the ice floes in the narrow gorge. Above this point as far as St. Nicholas the ice became more open. The crucial time is at a period of high tides. If up to this time cold weather has prevailed the large ice fields of from two to three feet in thickness form in the wide and shallow bays in the river near Pte. aux Trembles, about 10 miles above Cap Rouge. Here the river widens to four miles and is often not more than six feet deep. A very high tide and a N. to N.E. wind will dislodge enormous floes which come down the river with the ebb tide in very large solid pans. Some of these pans are large enough to reach right across the river at Cap Rouge, and if the ice is strong enough to resist being broken up it remains jammed from shore to shore, and starts the ice bridge. Ice coming from above is caught by this bridge, some is carried underneath the floe, some piled on top, the whole is cemented together with frazil and snow, and very soon the bridge becomes a solid mass of ice, 15 to 20 feet thick.

It is not likely that any bridge would form were it not for the initial bridge formed by the large, solid pans coming from the shallows of Pte. aux Trembles. The water is too shallow for the Montcalm or the Lady Grey to break up those large pans as they form over the shallow water; a fleet of small tugs escorted by one of the large boats might do good work in keeping the ice broken up here. Three or four large piers sunk in the bay at this point would probable suffice to keep the large pans in place through periods of high tides, and so throughout the whole winter. There would be no difficulty arising from large pans coming down from points higher up the river.

On Dec. 22nd, 1909 (Wednesday). Snow during the night; sky overcast during the day. Air temp. max. 26° F., min. 22° F. Humidity, max. 90%, min. 81%. The Lady Grey left her dock about 1 p.m., one hour before the turning of the tide. The increase in the humidity

since yesterday was at once noticeable in the character of the ice; to-day the ice which was encountered in large pans covered with snow, was very soft and gave way before the icebreaker with a dull grating sound; often long cracks would open out in front of the steamer. Although the pans were for the most part no thicker than yesterday, the ice was much stickier, and in consequence offered considerably greater resistance to the ship. A number of large floes presented the appearance of broken ice loosely cemented together. Ice of this character is formed by the breaking up of the large pans in passing through the gorge at Cap Rouge either with the inward or ebbing tide. Several large masses of this type reached a thickness of three or four feet with loose ice underneath, and proved difficult to break. A great deal of the ice formed in large pans showed mud and gravel on the underside, indicating that these had formed on shoals and were left stranded at low tide.

A sample of water in an open space was examined, but no frazil crystals could be detected in it.

On Dec. 23rd, 1909, the Lady Grey left dock at 1 p.m., about two hours before high tide. The ice was much lighter than yesterday, much more open, and owing to a N.W. wind was thickest on the south shore, the north shore being practically open water. The ice was somewhat more brittle than yesterday, and as far as the Quebec bridge presented much the same appearance. Above this point, the ice was for the most part very thin (1 to $\frac{1}{2}$ in.) and showed evidence of having formed in the quiet open spaces between the thicker floating pieces. Adhering to the underside of the pieces of heavier ice, especially such ice as was covered with snow, large spongy masses of frazil ice could be noticed; in fact several samples of water showed a number of frazil crystals (about 5 per cubic centimeter on the average). Above St. Nicholas there seemed to be no heavy ice, most of the ice at this point being the thin recently formed ice already described. Water temperature was 1/100th of a degree above 0° C.

On Dec. 24th, 1909, The Lady Grey left dock with the last of the ebb tide at 7.15 a.m. The weather was per-

fectly bright and clear. The river was open as regards ice, which was more brittle than on the preceding day, and was still inclined to accumulate on the South shore. The effect of the sharp frost during the night could be seen by the quantity of new, thin ice formed between the heavier cakes. Often the water in the open spaces was covered with a thin scum of ice-crystals on the point of forming thin surface ice. Several large areas of thin "conglomerate ice" were met with. These are made up of round cakes of ice, a couple of feet in diameter, formed by the action of a moderate wind in breaking up and rounding up into ridges around the edges of the cakes. In many cases these fields were not frozen together rigidly, so that the waves caused by the ship could be seen traveling along them. In general such areas presented the appearance of the surface of a honeycomb.

On Dec. 28th, 1909, The Lady Grey left dock with the high tide at 8 a.m. Up to Cap Rouge, the ice was light and open, the larger pans being four to five inches thick. The morning was misty and the water steaming. Following the valley of the river, and hanging almost down to the water, a line of cloud could be seen. At Cap Rouge the ice showed signs of congestion, and above that point several large masses of "batture-ice" were encountered, one of these bore a small fishing cabin. The spring tides prevailing at present were responsible for dislodging the "battures" from the shoals between Pte. aux Trembles and Les Ecureuils. Several of these, had they been heavier after a prolonged spell of severe weather, would have been large enough to start the blockade at Cap Rouge. One of these "battures" was estimated at $1\frac{1}{2}$ miles in width and 2 miles long. In places the "batture ice" was as much as six feet thick, and conglomerate in composition, although not very solid nor difficult to break up.

On Dec. 31st, 1909. Night fine and clear; morning and afternoon partly overcast: very slight snow flurry—calm, with no frazil.

Later about 30 crystals per c.c. were found.

The Lady Grey left dock at 12 noon: although the ice proved light and open below Cap Rouge, at this point it seemed to be massed in large quantities. A great deal of it was very rough, and was made up of blocks piled up on each other to a thickness of 4 or 5 feet with frazil slush underneath. This type of ice, although not solid, is very hard to get through and offers great resistance to the ship. Nevertheless the Lady Grey was able to get through it at a rate of about 3 miles an hour. Above the Quebec bridge and as far as St. Nicholas numerous large fields of sheet ice (about 4 to 6 inches thick) were encountered. These often reached from shore to shore, and there was little open water visible. Large numbers of frazil crystals were found in the water.

On Jan. 1st, 1910. Night and day overcast; light snow falling. Slight E. breeze. Frazil fairly plentiful, 15 crystals per c.c. The Lady Grey left dock at 1 p.m. Very light ice was everywhere encountered, one or two battures were seen, one bearing down three fishing cabins. These battures were very thin, and had been dislodged by the mild weather prevailing at present. A large number of globular sponge-like masses of ice were met with. These floated very low in the water, and were brown in color due to the quantities of mud contained in them. These masses constitute a type of "anchor ice" and are said to form over mud flats by the action of cold weather, and wind at low tide. Above the Quebec bridge, the ice was met with in large pans, but was very thin (2 to 3 inches).

On Jan. 3rd, 1910. Night fair and clear, becoming overcast towards morning with considerable snow falling in the afternoon: slight E. breeze. Frazil crystals 15 per c.c. Water temperature in dock 32 °F. Air temp. max. 12° F., min. 8° F.

The Lady Grey left dock at 1 p.m. Open ice was everywhere encountered with a few pieces of batture ice. The open spaces of water were everywhere covered by a thin scum of ice, caused by the falling snow. Above the Quebec bridge, the ice was very open and thin. The effect of a day of mild weather is at once noticeable in

the quality of the ice met with during the next two or three days. Ice then forms very slowly, and that coming down in consequence very thin. Samples of water, besides containing a great deal of slush due to the falling snow showed frazil crystals in considerable number. The Lady Grey turned at St. Nicholas and arrived at Quebec at 3.45. Just opposite the Beauport shoal and extending almost from shore to shore, a large field of "batture-ice" was noticed. This was broken up before proceeding into dock.

On Jan. 4th, 1910. Night overcast with E. wind. Sudden fall of temperature towards morning with a N.W. wind. Fine and clear during the day. Air temp. max. 0° F., min. −13° F. Frazil plentiful, 40 crystals per c.c.

The Lady Grey left dock at 1 p.m. The sudden fall in temperature was responsible for the formation of large areas of thin ice. Comparatively few open spaces of water could be seen. Over these a strong W. wind was blowing and frazil was forming very rapidly. (Samples showed about 40 large crystals per c.c.) The wind caused these to collect on the windward side of the ice sheets where it first forms a thin scum and finally solidifies to the thin sheet ice. Most of the ice met with varied from 2 to 5 inches in thickness, and no heavy ice was encountered.

The rapidity with which ice forms when the temperature is in the neighborhood of −10° F. could be seen when on several occasions we crossed our original track on the return journey. Although not more than $\frac{1}{2}$ to $\frac{3}{4}$ of an hour had elapsed, the broken ice in the ship's wake had been cemented together by ice about $\frac{1}{2}$ inch thick. On returning to dock about 3.30 an inch of ice had formed over the quiet water where the ship had been.

On Jan. 12th, 1910. Night over-cast; light snow flurry during the morning: afternoon clear and calm.

Traces of frazil. Air temp. max. 18° F., min. 5° F.

The Lady Grey left dock at 7.45 a.m. with the high tide. As far as the Quebec bridge and in the open river beyond the ice was light and open. An hour was spent

cutting away the "batture-ice" which forms between the north pier of the bridge and the Cap Rouge river. As soon as this batture has grown to a certain width, it increases very rapidly owing to the fact that the channel is considerably narrowed, and the floating ice is crowded up against the "batture" with great force by the set of the current at this part of the river. Since Jan. 10th the batture has grown out about two hundred feet so that fifty feet may be added during a single tide. The addition of each tide is marked off from that of the preceding tide by a well marked ridge running along the batture parallel to its edge. The ice between these ridges consists of piled-up blocks, which have the characteristic thickness of the ice prevailing at the time this part of the batture was formed, and so the whole "batture" gives an indication of the severity of the weather which has prevailed day by day during its formation. In order to cut away the "batture" it was necessary to resort to "bucking", *i.e.*, to charge into the ice at full speed. Best results are obtained by working in the direction of the tide. The "batture" cracks most easily along the tide-ridges already mentioned: as soon as a crack opens out large quantities of small broken ice and slush rise to the surface. Progress is at first slow, but very soon the whole batture becomes rapidly weakened by the repeated charges, by the wash of the ship, and by the suction of the propellers, with the result that before very long large pieces can be easily disengaged from the main mass. As the result of an hour's work, a long strip of batture about a mile long, and five or six hundred feet wide was cut away without difficulty. See Fig. 47.

The Lady Grey then proceeded as far as St. Nicholas Church: the ice was everywhere thin and no "battures" could be seen coming down the river from above. After stopping to take on a supply of fresh water at the Government wharf, the Lady Grey arrived in dock about noon.

Distinction has several times been made between "small" and "large" frazil crystals. The small crystals (about $\frac{1}{2}$ inch long) seem to occur only when the weather is very cold (below zero) and even then none may sometimes be found when the weather is clear. The small

crystals are needle-shaped, have small buoyancy, and seem to be uniformly distributed throughout the water of the river. The large crystals usually occur in loose

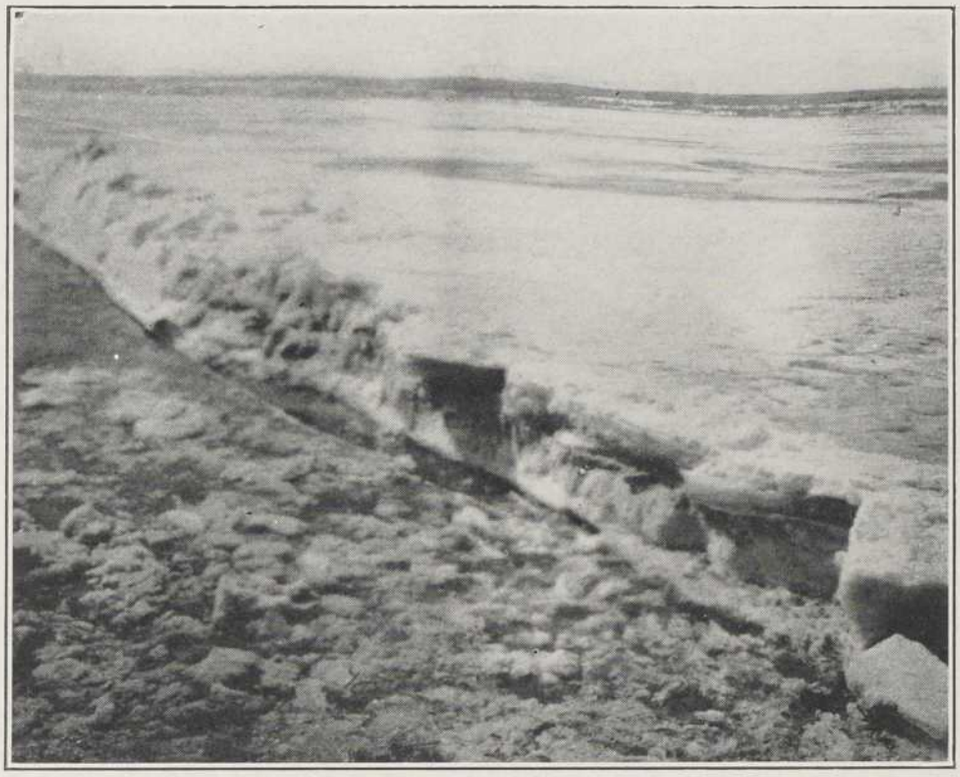


Fig. 47.—Edge of the ice pack cut by an ice breaker. Surface ice is lifted by the slush accumulation underneath.

aggregates. They may either be needle-shaped or in the form of irregularly shaped flat disks. In most cases several crystals seem to be loosely stuck together. These aggregates have greater buoyancy than the small frazil crystals, and tend to collect together in open spaces of water. The effect of ripples would perhaps tend to make these aggregates collect. When the water is rippled by a light breeze the areas over which the crystalline aggregates have collected are marked out as calm spots or streaks. Surface tension is altered by the presence of the crystals, and the formation of thin surface ice is facilitated. These areas quietly merge into one another, and the formation of surface ice begins rapidly especially if the water is covered with floating cakes of ice with small interspaces of water.

During the morning news was received that the ice bridge had formed at Cap Rouge about 8 p.m. the previous evening. At 11.30 a.m. the Montcalm left dock, followed by the Lady Grey at noon. On arriving at the Quebec bridge, it was seen that two immense battures had met, and locked together so as to block the gorge. From the piers of the bridge upwards for a distance of two miles the river was covered by successive sheets of heavy batture ice, showing several long pressure ridges, in many cases formed of piled-up blocks six or seven feet high. At this time, the tide was still rising; at the edge of the ice, the current was very strong, and the ice carried by the rising tide was often seen to be sucked underneath the surface ice. It was impossible to work under these conditions, for the strong current kept packing the ice in as fast as the ice breakers cut away large pieces. It was decided to wait until the turn of the tide, about 3 p.m. The steamers began to work at slack water, and as soon as a perceptible ebb had set in, progress became rapid. The boats worked so as to cut a channel about 200 yards wide and both made about the same rate of progress through the batture. Several times the ice was so thick that the steamers lifted up on to it and were unable to back away. On these occasions, it was only necessary for the disengaged ship to take a diagonal cut toward the ship that had become fixed; the ice cracked across and the imprisoned ice breaker was soon free. Working in this way rapid progress was made toward the free water above. Greatest difficulty was experienced when only two hundred and fifty feet of ice remained to be cut through. The ice here was very heavy (15 to 20 feet) and here the steamers showed the greatest tendency to become stranded. Finally about 5.10 p.m. the bridge gave way, and the two boats retreated rapidly to Quebec where they arrived about 6 p.m. At 10 p.m. news was received from Cap Rouge that the entire mass of ice had passed down. See Fig. 48.

During the afternoon of February 7th a series of measurements were made on the rate of growth of surface-ice. (Chapter 3.) A little of the ice which formed in an open space near the ship in dock (the Lady Grey) was

broken away from time to time, and the pieces taken on board and measured. The results are tabulated in

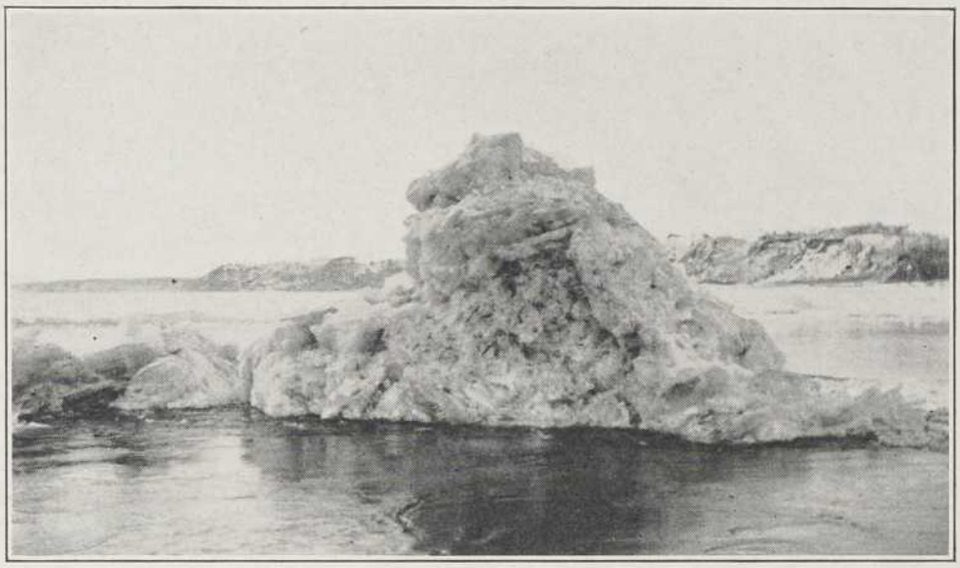


Fig. 48.—Under ice exposed by overturning of a pan out by an ice breaker.

Chap. 3. It was impossible to continue the measurements during the night. The next morning snow had set in and the tides had broken up the surface sheet.

Note on the Formation of Ice Over Lake St. Peter.

The thin ice which forms in the fall over Lake St. Peter becomes jammed in the narrow channel opposite Point St. Francis at the outlet of the lake where the river is crossed by shoals. In this way the river between Point St. Francis and Three Rivers is frozen over solid before the lake itself. In the spring, the reverse happens, the river above Lake St. Peter is often clear of ice before the Lake, which generally begins to give way at the head before the ice moves at the outlet. The broken ice from the river above the lake is carried under the still solid lake ice, and is apparently melted away at the head of the lake by the comparatively warm water which has become somewhat heated by the sun's action on the open water in the upper reaches of the river. By the time the

water reaches the foot of the lake it is cooled down so near to zero that it has little or no effect in melting and weakening the ice at the foot of the lake.

The Lady Grey left dock at 6.30 a.m., and attacked the ice about 1 mile above Three Rivers at 7.00. The ice was found to be very much harder and tougher than on the preceding day. The weather had turned cold (near zero) during the night, and a W. wind had made the air very dry (Relative humidity between 50% and 70%). Headway through the ice was made very slowly but slightly better progress was made during the afternoon. In thickness the ice varied between 15 and 20 inches of clear blue ice with about 6 inches of snow on the surface. Advance could be made only by repeated "bucking". The Lady Grey would back down about 200 feet and advance between 60 and 100 feet into the ice. By working in this way a channel was cut about 200 to 300 feet wide and three miles long during the day's work of 10 hours. The difficulty in cutting through the ice was due to the fact that there was no give to the ice on either side. On the return journey to Three Rivers at 5.15 p.m., the Lady Grey was able to widen the channel by slicing off a strip 200 feet wide on the N. side of the channel. She was able to cut through this ice without stopping at a speed of about 6 miles per hour (with the current of about 3 miles per hour). This gives one an idea of the necessity of specifying the boundary conditions (whether free or fixed) of a sheet of ice in speaking of the rate of progress through it. By having two boats to "buck" alternately into the ice in parallel directions, the ice gives more rapidly and progress can be made about three times more rapidly.

The ice which was cut through presented several very remarkable features. Most of it was the clear, blue, snow-covered ice already mentioned, and some of it showed distinct strictions. In several spots there appeared considerable quantities of frazil ice when ice blocks split away. In a large number of cases the entire thickness was seen to be made up of a succession of plates of thin ice (about 1 inch) cemented together, many of them carrying mud and silt. In many cases the

muddy ice was directly on the underside of the conglomerate mass. The occurrence of ice of this kind confirms the statement already made that the thin surface ice of the lake is carried under the ice already formed at Port St. Francis in the fall. The interesting point to note is that this muddy ice must have been deposited before the Lake became frozen over solid, so that the conglomerate ice had apparently not thickened after that time (two months at least). This gives some support to the view that a limiting thickness is formed fairly early in the winter, and that the ice does not thicken much beyond that amount.

A water temperature was taken at the edge of the ice at 6.55 a.m. Both the readings indicate a lower temperature than was ever recorded at Quebec even during the severest weather. This gives an indication of the power of the sun in keeping the water slightly above zero when the surface is free of ice as it was during the winter between Three Rivers and Quebec. The current in the channel cut out by the Lady Grey was about 3 miles per hour. On returning to dock about 5.50 p.m. thin surface ice was already forming over the water opposite Three Rivers in spite of a light breeze. This gives an idea of the rapidity with which surface ice forms when the air is dry (about 60% rel. hum.) and the water near 32° even if the air temperature is moderately cold (about 15° F.).

On March 19th, 1910, the Lady Grey left dock at 6.30 a.m. A water temperature was taken just opposite Three Rivers. (+.09° C.) On the way to the head of the cutting, a little above the wharf at Port St. Francis the steamer was run at full speed along the channel. The ship-wave thus created, did considerable service in widening the cut. The waves had little effect so long as the wave-fronts were at right angles to the edges of the channel. Whenever the waves cut the edge of the ice at a small angle they had considerable effect in breaking up the ice. See Fig. 49.

Work was begun at the head of the cutting about 7.15 a.m. At first the ice proved to be fairly heavy and the rate of progress was about the same as on the pre-

ceding day. Some distance ahead could be descried a line of "air-holes" in the ice. The ice proved to be considerably thinner as these holes were approached



Fig. 49.—Ship waves created by the "Lady Grey" for breaking bordage ice.

(about 15 inches). Here the most efficacious method of making progress was to back three or four hundred yards to let the ship waves travel into the ice. It was, then, only necessary to keep to one side of the channel. The ship's waves followed the icebreaker, and broke up the ice two or three hundred feet to one side. Whenever the ice exceeded 15 inches or so in thickness, this method was not so advantageous, the effect of the waves being then very much less. The Lady Grey made her way into one of the air-holes mentioned at 10.05 a.m. Although the ice was thinner here than elsewhere (about 15 inches) it ended abruptly at the edge of the hole with a thickness of about 12 inches. A water temperature taken here gave a very steady reading at +.118° C. The open space was one of a chain extending across the outlet of the lake and just over a shoal almost (excepting in the ship-channel) crossing the entire river. This would seem to indicate that the warmer water of the bottom of the lake is here thrown upwards, to the surface. The

fact that these air-holes have remained open all winter is a striking point in support of the conclusion made in connection with the "Rate of Growth of Surface Ice," in which results are given to show that when the temperature of running water is slightly above 32°, ice will not form unless the mean air temperature is below a certain limit (the approximate figures are for water temperature +.118° C. ice will not form unless the mean air temperature is below 8° F.).

By 4.50 p.m. a channel was cut along the ship channel about 1000 feet beyond the sunken wharf, giving a total of $4\frac{1}{2}$ miles or an average of about $\frac{1}{2}$ mile per hour. The lake ice is mostly about 15 inches of clear blue ice with about 6 inches of frozen snow on top. In certain places there were frazil accumulations—in others the ice showed a rotted appearance (a columnar structure at right angles to the surface). The clear hard ice was always deeply pitted on the under surface. A water temperature was taken at the end of the cut just before turning back (at 4.50 p.m.) (somewhat unsteady) giving T = + .066° C. This temperature although taken later in the day was much colder than that of the air-hole. The Lady Grey returned along channel already cut out, and went into dock at 5.40 p.m.

On March 20th, 1910, the Lady Grey left dock at 8 a.m. On the way some time was spent widening the cut near Nicolet Traverse. Work was begun at 9.30 a.m. at the head of the cut 1,500 feet above No. 8 Lightship. Progress was made at the rate of $\frac{1}{2}$ mile per hour. The rain had softened the ice which was honey-combed in several places. The effect of the rain was seen in the high water temperatures observed during the day.

9.30 a.m. near No. 8 Lightship. T = +.115° C.

4.50 a.m. at end of cut 7,500 feet above No. 35. T = +.165° C.

By 4.50 p.m. the cut had advanced 7,500 feet above No. 35 light giving a total of 18,600 feet during the day or a little more than $3\frac{1}{2}$ miles.

The Lady Grey continued to cut along the channel and made an average rate of progress of $\frac{1}{2}$ mile per hour. By 4.50 p.m. the total made was a little less than 5 miles. The ice showed a much more rotten appearance than on the preceding day.

A water temperature taken at the end of the cut before turning gave T = +.050° C.

On March 27th the Lady Grey left dock about 8.30 a.m. and proceeded up the river. The entire day was passed at anchor about $\frac{1}{2}$ mile above the Nicolet light. An interesting series of measurements showing the heating effect of the sun on the water was taken,—the current was about $1\frac{1}{2}$ miles per hour, and the edge of the ice-field about $1\frac{1}{2}$ miles upstream.

On March 29th, towards 2 p.m., the Lady Grey proceeded dead slow against the current up to the edge of the ice, a distance of 12,200 ft. Temperatures were taken at intervals of a minute to the edge of the ice. In this way it was possible to show the temperature gradient towards the edge of the ice.

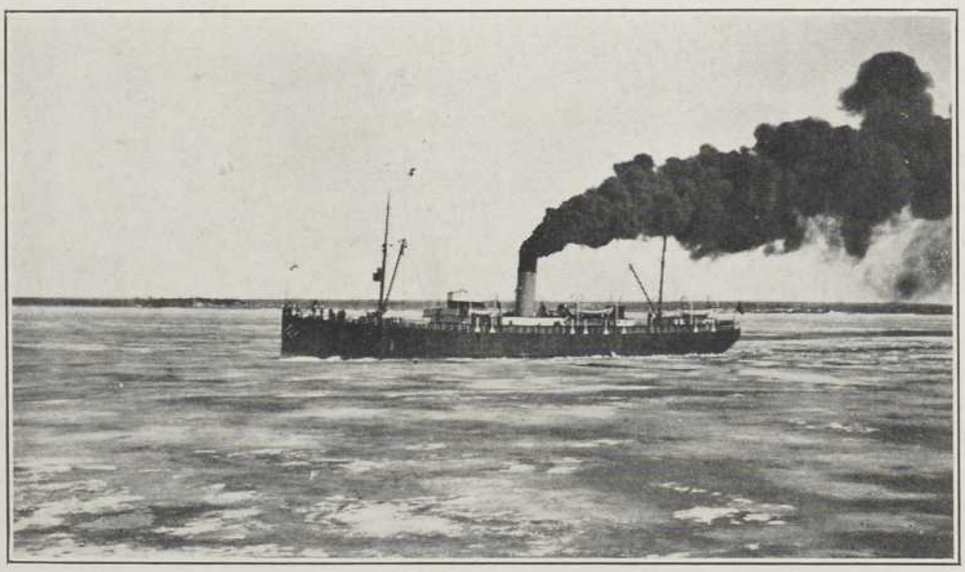


Fig. 50.—C. G. S. Montcalm steaming though the ice in Lake St. Peter in April to clear a channel.

WATER TEMPERATURES APPROACHING AN ICE FIELD

Time of day	Time	Sc. R.	Temp.	Time of day	Time	Sc. R.	Temp.
2.16	80	26.8	+.210° C.	2.41	55	30.5	+.182 °C.
2.18	78	.9	.208	2.42	54	.4	.183
2.19	77	29.0	.206	2.43	53	.6	.180
2.20	76	.1	.205	2.44	52	.2	.186
2.22	74	28.7	.211	2.45	51	29.8	.193
2.23	73	29.1	.205	2.46	50	.6	.197
2.24	72	29.2	.203	2.48	48	28.0	.222
2.25	71	.1	.205	2.49	47	27.7	.227
2.27	69	.5	.198	2.50	46	.5	.236
2.29	67	30.1	.188	2.51	45	.6	.229
2.30	66	.2	.186	2.52	44	28.2	.220
2.31	65	.3	.185	2.54	42	.0	.222
2.32	64	.3	.185	2.55	41	27.8	.226
2.33	63	.6	.180	2.56	40	.9	.224
2.34	62	.2	.186	2.57	39	.6	.229
2.35	61	.5	.182	2.58	38	.9	.224
2.36	60	.8	.177	2.59	37	.7	.227
2.37	59	31.0	.173	3.00	36	.8	.226
2.38	58	30.8	.177	3.01	35	.5	.231
2.39	57	.5	.182	3.02	34	.1	.237
2.40	56	.7	.178	3.03	33	.2	.236
3.04	32	.4	.232 C.	3.30	6	31.7	.162 C.
3.05	31	.3	.234	3.31	5	32.4	.150
2.06	30	.8	.226	3.32	4	33.0	.140
3.07	29	28.0	.222	3.33	3	32.8	.143
3.08	28	.4	.216	3.34	2	33.0	.140
3.10	26	.3	.218	3.35	1	33.5	.131
3.11	25	29.0	.206	3.35.5	0.5	34.0	.123
3.12	24	28.8	.210	3.36	0	....	.107
3.13	23	.5	.215				
3.14	22	.9	.208				
3.15	21	.9	.208				
3.16	20	.9	.208				
3.18	18	29.3	.201				
3.19	17	30.2	.187				
3.20	16	.2	.187				
3.21	15	29.8	.193				
3.22	14	31.2	.170				
3.23	13	.1	.172				
3.24	12	.0	.173				
3.26	10	.5	.165				
3.27	9	32.0	.157				
3.28	8	.0	.157				

The Lady Grey left dock at 6.30 a.m. and proceeded up the Lake to the head of the cut, slicing away the ice along the channel wherever possible. The ice was very rotten. The cut was continued for a distance of $3\frac{1}{2}$ miles. Considerable quantities of conglomerate frazil ice were met with along this cut; this ice was still fairly firm and was by no means as badly honeycombed as the uniform ice elsewhere. See Fig. 50. This is due

to the fact that the axes of greatest conduction are pointing in all directions and besides layers of frozen snow, etc., prevent the conduction of heat from the water, and air into the ice. Beyond this frazil accumulation the clear ice was very rotten. The Lady Grey cut through 2,000 feet of this ice without stopping.

The water temperature was rising owing to breaking up of the ice and exposure of surface.

The weakening of the river ice in the spring is due in great part to a very small increase in the temperature of the water. The "debacle" begins on the land. The sun's heat melts the snow with the result that heated water drains into the small brooks, etc., where this heat is absorbed melting away the ice. As soon as the ice has disappeared in these small tributaries the larger creeks and streams are the next to feel the effect of the warmed

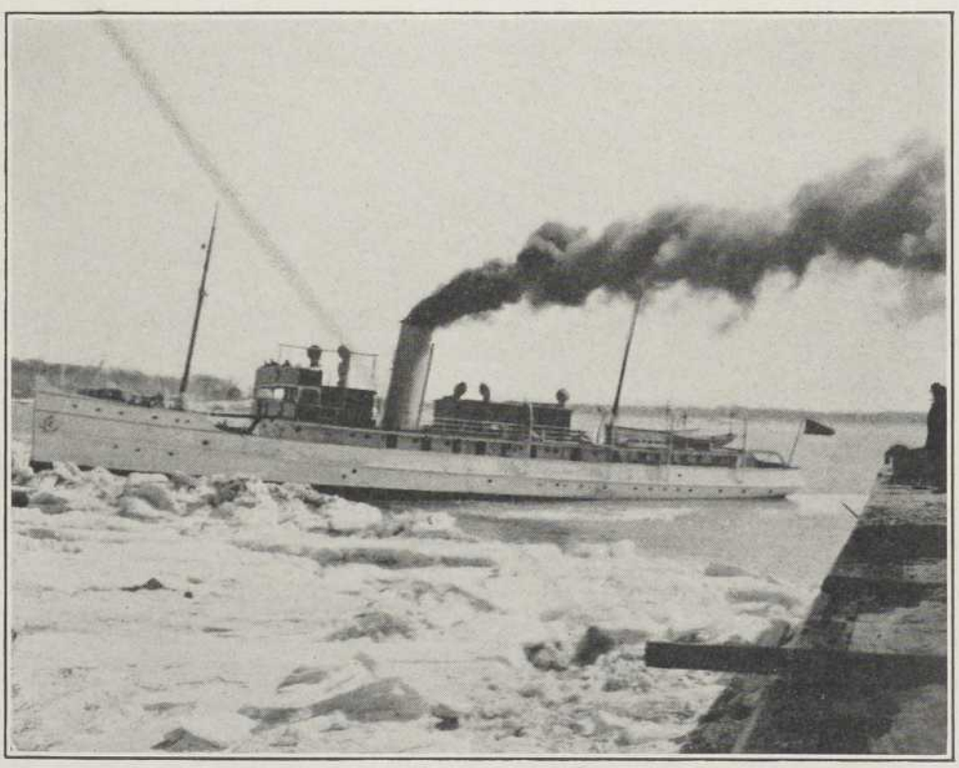


Fig. 51.—C. G. S. "Lady Grey" cleaning the ice from Montreal Harbour in the spring.

water whose heat is absorbed in clearing them of ice. This accounts for the rule stated by the river pilots and

captains, that the Lake St. Peter ice begins to move a stated number of days after the Richelieu is free of ice.

This means that the Richelieu once clear of ice is able to supply heat at a definite rate to the colder St. Lawrence. Since there is approximately the same quantity of ice to be melted every year before the lake ice becomes weak enough to start, the process will require an interval of time which is not very different year by year.

On April 3rd, 1910, the Lady Grey left Sorel for Montreal at 5.30 a.m. The whole river was practically free from ice—here and there large piles of ice on the banks showed where a "shove" had taken place. The Lady Grey arrived in Montreal at 9 a.m., the first steamer of the season to come up the St. Lawrence to Montreal. Montcalm arrived in Montreal on April 3rd, also. See Fig. 51.

Measurement of Water Temperatures by the Microthermometer.

One of the most important developments resulting from the study of ice conditions under the assistance of the Department has been the perfection of a new type of marine thermometer, which was specially designed for obtaining small variations in water temperature from the ship going at full speed.

In 1896 I first drew attention to the important influence which the minute variations of water temperature had on the formation and disintegration of ice. An electrical thermometer of special design was employed at that time, but this instrument proved to be much too delicate for work on board ship.

After several trials and failures an instrument was evolved which has proved to be very satisfactory for our work. Our thermometer, a description of which follows, was arranged to be supported over the side of the ship about 5 feet under the surface of the water. Wires led from this instrument to the chart room, where a simple

wire bridge and Weston portable galvanometer made it possible for us to accurately record temperatures to 1/1000th of a degree centigrade. This could be done while the ship steamed at full speed, with the greatest ease. This gave us a measure of the average temperature of the water over a wide area, a measurement of great importance as we shall show in a later work.

Hitherto marine temperatures have been made entirely by the "drop bucket" method at stated intervals. This gives, however, by no means an accurate idea of the true water temperature. The influence of local surface currents are completely averaged out by the electrical method and much new and uesful information could be obtained by a temperature survey of the ocean with this instrument. The thermometer is of the electrical resistance type in which the variations of the resistance of a metal wire serve to give a measure of the changes of temperature of the medium in which the instrument is immersed.

The resistance of the wire is made so high that small variations in temperature produce comparatively large increments of resistance. The problem of suitably arranging the measuring instruments, and galvanometer is a mathematical one to be worked out for each particular resistance.

It was decided to make the coil of 125 ohms consisting of 250 feet of pure iron wire silk covered, and wound on a copper cylinder about 4 inches in diameter, and 6 inches wide. This cylinder fitted accurately inside a second copper cylinder. The ends of the cylinders were carefully soldered and rendered water tight, while the connecting wires passed out through the middle of the outer cylinder. A stout copper tube was riveted on to the outer cylinder to which other copper tubes could be fastened. The wires passed through a lead cable to the chart house, where they were connected to the bridge for obtaining a measure of the thermometer resistance. Thus the absolute temperature as well as the small variations could be accurately measured. More recent development has shown that it is possible to record automatically the temperature to 1/100th of a degree by

means of a suitable modification and combination of a Calendar recorder, and our wire bridge. Although these additions were not made in time, to include in our ice studies, they have since been employed in an investigation of the influence of icebergs on the temperature of the sea-water by the kind permission of the Department on the trip of the C.G.S. Stanley to Hudson Straits. Much valuable information was made possible with the use of this instrument. Readings could be taken as often as every half minute, and hence curves could be plotted showing the variations of water temperatures. So sensitive was this thermometer to the changes in temperature of the water that the influence of the sun shining for one minute on the open water was easily measured. A temperature gradient of 1/10th of one degree per mile was accurately recorded, as the ship steamed at half speed from open water up towards an ice field.

The final form of concentric ring thermometer was not obtained without many trails and alterations, before the best form was devised.

Many discouragements and failures through faulty insulations were overcome but it may be said that the final from is free from fault in that it is of great strength combinde with the maximum sensitiveness necessary.

I am deeply indebted to the Department for the necessary assistance in perfecting this instrument which I hope may be of practical assistance in marine work.

Effect of the Sun on General Ice Conditions.

Absorption of the Sun's Heat in the Water.

It is evident from Dr. King's report on the ice conditions throughout the winter, and more especially in the spring that the sun is the chief factor in rotting the newly formed ice, and preventing the formation of ice in open water.

It has been known for a long time to power house operators using water, that no bad effects from frazil or anchor ice are ever noticed when the sun is shining.

Even though a "shut down" has occurred, as a rule, a few hours of sunshine the next day relieves the situation. Not until the present work was completed did I fully realize the great influence of the sun, as a means for reducing the formation of ice.

As soon as the whole body of water is brought to the freezing-point in the autumn, the formation of surface ice preceeds at a rapid rate at all points, where the current is not flowing too swiftly, for ripples and eddies to form. Once the surface has solidified, the wind has no further influence on it. Coarse-grained ice such as is usually formed at first, and especially ice on the surface on which snow has accumulated scatters the sun's heat, and prevents its absorption by the water. Thus the surface ice becomes a means of keeping the water at the freezing-point during the winter, and long into the spring, Without the surface ice the sun's heat is absorbed completely, and the temperature is elevated sufficiently above the freezing-point to prevent the formation of ice.

Surface ice can form only at such times when the air is below the freezing-point, the wind is not blowing, and the current is not sufficiently rapid to produce eddies. The problem of preventing surface ice from forming is not so difficult when these various factors are taken into account. The problem of artificial wave production is one which we are considering as a practical means of preventing surface ice.

The effect of keeping the river open at Cap Rouge was felt all the way up to Three Rivers. This was mostly due to the free rise and fall of the tide not being interfered with by the ice bridge. The open water also served as a great absorption chamber for the sun's heat. Our water temperature measurements in the channel at Quebec were surprisingly high, and had a great influence in weakening the ice.

Some important preliminary conclusions were arrived at by Dr. King from a study of the curves taken at Three Rivers, of the absorption of the sun's heat in the open water. These curves were repeated several times, and by the kind courtesy of the Department, the measure-

ments were continued at Crane Island, during the latter part of the month of April.

The accompanying curve (Fig. 52) taken from the observations made on March 27th, from the deck of the

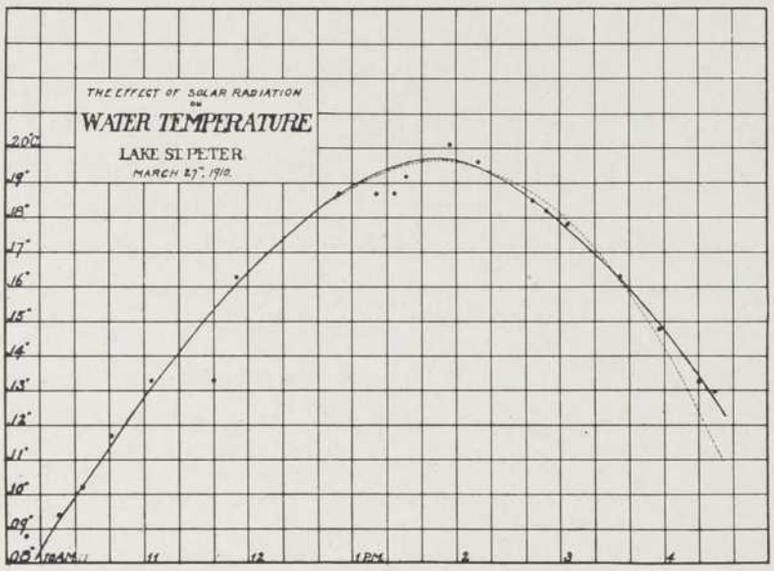


Fig. 52.—Absorption of sun's heat by water.

Lady Gray at anchor shows the remarkable accuracy with which small measurements can be obtained.

The diurnam variation is represented, not by a simple sine harmonic curve, but more accurately by a quasi-periodic function of the type.

$$\theta - \theta_0 = A\, e^{\alpha t} + \beta \left\{ \text{Sin}\, \frac{2\pi}{T}(t+\epsilon) - \text{Sin}\, \frac{2\pi}{T}\, \epsilon \right\}$$

where θ is temperature at time t

θ, is the temperature at noon (t = 0)

T is the length of a day (24 hours)

α, β, ϵ, are constants which can be expressed in terms of the solar and radiation constants, sun's declination, latitude, etc.

A remarkable result was shown by the high value of the solar constant even though the sky was clouded. The clouds act as a blanket in cutting down the radiation constant from the earth.

An interesting feature of the Crane Island work was the difference in the character of the rise of temperature in the water below and above 4° C. the point of maximum density. As soon as the water was warmed by the sun it sank, giving rise to a fairly uniform temperature throughout the water. As soon as 4° was passed the warm water tended to remain on top, thereby giving greater extremes of temperature at the surface. Nearly the whole of the solar heat is absorbed in the first 5 feet of water. The action of the sun in dislodging anchor ice makes it appear probable that some heat may penetrate as far as 30 feet below the surface in a comparatively clear river water. See Figs. 53 and 54.



Fig. 53.—Making Microthermometer readings of the open water of the Lachine Rapids.

It was interesting to observe the effect of scattered clouds on the temperature of the open river. Thus temperature streaks were observed in the water during such times, denoting the effect of a strong sun contrasted with the weaker radiation through the clouds.

There appears to be some source of radiant heat other than the direct rays of the sun. This is probably a scattering effect from the upper layers of the atmosphere before the sun actually rises.



Fig. 54.—Observation cabin placed by the Harbour Commission of Montreal in the Lachine Rapids for temperature studies of the river in 1896.

Influence of Ice on the Temperature of Water.

Some observations were made by Dt. King, and detailed under date of March 29th, pages 46 and 47, in his report which in a remarkable way illustrates the effect of ice in lowering the temperature of the water.

From anchor at Port Francis, the ship steamed at half speed up towards the field of ice on Lake St. Peter from which the water was running. A map in the form of a diagram will show how the curve falls at first, indicating the nearer approach to the ice, then rises again as the distance

between the ice field and the ship becomes greater (measured along the direction of the current) from a distance of 1 mile the temperature drops at the rate of 1/10th of a degree per mile until within 500 feet, when it drops more rapidly. These results suggest a possible means of telling the proximity of large masses of ice in the open water of the sea.

Other facts make it appear probable that delicate recording thermometers would be of use to a ship navigating the ice track. Thus the temperature of the Arctic current is influenced by the proximity of masses of ice, and some useful information has been obtained from our observations.

The main factor in ice formation is the loss of heat due to conduction through the ice into the air, but the growth of ice will be affected by loss or gain of heat due to convection currents in the water. There will be a cooling effect due to evaporation from the surface of the ice, which will be governed by the relative humidity of the atmosphere, and by the velocity of air currents over the surface of the ice. There will also be a loss or gain of heat due to radiation. This will include the effect of radiation to the ice, from the atmosphere, and the reverse effect of radiation from the ice. The effect of conduction is the largest, and the others may be considered small in comparison. It makes the problem simpler to consider the equations for the first and largest condition, and then see what effect each one of the others has on it, rather than try to deduce an expression involving them all, which would prove to be too complicated. In the first case, that of ice losing heat by conduction, we consider a slab of ice kept at the freezing-point on one side, and losing heat to the air on the other. The boundary condition between the ice and air is specified by Newton's law of cooling, which states that at the boundary the rate of loss of heat is proportional to the difference of temperature between the surface of the conductor, and the air temperature. These conditions are discussed in detail in Chapter 3.

Effect of Convection.

Precise measurements to 1/1000th of a degree have shown variations of the order of 1/100th of a degree, about zero in the temperature of the St. Lawrence River during winter. Sometimes this is above and sometimes below the freezing-point. If the water under the ice is in motion, as is usually the case in the St. Lawrence, then convection currents play an important part in adding to or melting the under side of the ice. Usually the water under the ice is slightly warmer than the freezing-point, and hence the introduction of a term in the equation may be shown to indicate that a limiting thickness exists, to which ice will grow.

This idea of a limiting thickness is a very important one and the limits depend on the mean air temperature over a given period, and the mean water temperature measured from the freezing-point in 1/1000ths of a degree. The appearance of open holes in a lake or river otherwise frozen over, thus becomes easily explained. Some point such as a shoal where the warmer under water is deflected up to the surface, or where a warm spring of water rises from the bottom of a lake.

Atmospheric Humidity.

The effect of evaporation from the surface of the ice is one which has been hitherto almost entirely overlooked. The effect was noticed on the ice-breaking operations of the Montcalm. The effect of humidity on the growth of surface ice is surprisingly great, in the initial stages but as we might surmise, becomes smaller as the ice grows in thickness. On dry days surface ice forms much more readily than on damp days with no evaporation. (Chapter 3.)

It is possible to arrive at some important conclusions in considering the effect of humidity on the rate of growth of ice. The temperature at the surface of ice is higher than the air temperature, especially when the ice is thin. The relative humidity of the air at the surface of the ice will be diminished, that is, evaporation will take place

with greater rapidity, so that the cooling effect will be greater than the depression of the wet and dry bulb hygrometer. This is supported by the fact that dense clouds of hoar frost emanate from the surface of open water, and thin ice in cold weather (below 10° F.). The air in contact with the water and thin ice is warmed to some extent and so is able to take up more water vapor than it can contain, when it is carried by convection into the colder portions of the atmosphere. Thus even when the relative humidity of the air is 100% evaporation may still go on over water and over ice, which is thin enough to transmit sufficient heat and sensibly warm the air in immediate contact with it.

Since the latent heat of evaporation is very large, the effect is very great in the early stages of ice formation, increasing the rate of growth at least 50% up to nearly 1 inch thickness.

Effect of Radiation.

The layer of ice is capable of losing or gaining heat from the atmosphere by direct radiation. Owing to lack of experimental data on the diathermancy of ice, and how the transmission is affected by its thickness, it is difficult to estimate the effect on ice-formation arising from this cause, but it is probably small.

Ice-Breakers and Their Services.

In the Northern Hemisphere of the world, there are many ports which during winter become closed to navigation, and chocked with ice owing to climatic conditions. To free these ports, and render navigation possible throughout the winter, resort has been to a class of steamer called "ice breakers."

The best descriptive account of icebreaking ships has been given in a paper by A. Gulston in the Jour. Society of Arts, 52,215 (1904). This article I quote from here:

"These are of many forms and dimensions, varying from a steam launch 40 feet long, spoon-shaped at the bow like a Norwegian "pram", to the enormous Ermack,

of 8,000 tons displacement and 10,000 horse power. These icebreakers are placed on their various stations to assist steamers of the commercial fleets, which become fast in the ice, and which, without assistance, are unable to free themselves, owing in most cases to insufficient horse power, and the light scantlings of their propellers. These vessels also run considerable risk of sinking, owing to the ice pressure.

There are in Canada and in the Baltic, many merchant steamers which can cope with ice of considerable thickness, and the ice-breaking mail boats of Helsingfors are fine examples of this type; but without the aid of "icebreakers" proper, the work of the commercial fleets in winter would indeed be sadly crippled.

Railway ferry ice-breaking steamers are another type, and they play an important part in keeping open railway communications where bridges or viaducts are an impossibility.

The first recognized "icebreaker" was a tug called the Pilot, of Cronstadt, belonging to a Russian gentleman named Britneff, who wished to keep the ice from fastening inside and outside the breakwater at Cronstadt, and to prolong the trade with lighters to St. Petersburg at the setting in of the winter for a longer period than had previously been possible.

With this in view, a new bow was built on the vessel, and in 1870 she was set to work. She was also used to keep a canal open through the ice between Cronstadt and Oranienbaum, the present railway terminus on the coast, during the time of the formation of the ice. Before this vessel began to work communication to and from Cronstadt and the mainland was impossible for some time during the formation and breaking-up of the ice. This boat had a single engine of 85 horse-power, and was about 65 feet long.

The Pilot was superseded in 1889 by two small icebreakers, the Zarja, and the Luna, which act as ordinary tugs during the open season, and have a horse-power of 150 each, are 98 feet long, and draw six feet of water.

When working in ice, these two icebreakers work together, each vessel running alternately upon the ice, and returning. This system of ice-breaking is necessary, as the mainland shore water is so shallow, that a large icebreaker cannot be employed on this station. Hamburg and Copenhagen followed the lead of Cronstadt, and at Hamburg there are now several icebreakers, which have proved themselves capable of dealing with the heavy traffic in the ice between Hamburg and Cuxhaven during most of the winters that they have been at work. Though these vessels are not large, they are well designed and suitably arranged for the work they have to perform.

The first boat (Eisbrecher No. 1) built in 1871 is 130 feet, draws 13 feet, has 300 I.H.P., and has a spoon shaped bow. The succeeding boats have increased in size and power, the last new one (Eisbrecher No. 3) being 140 feet long, with a draught of 12 feet forward and 16 feet aft in working trim. Her engines are of the triple expansion screw type of 950 I.H.P.

As a result of experience the form of Eisbrecher No. 3 differs considerably from that of No. 1.

At Copenhagen, the ice in the sound is during the hard frost very dense and much under-shot. In strong winds, it packs tightly, and under some climatic conditions becomes spongy and difficult to negotiate.

The first icebreaker at Copenhagen was the Staekodder, 150 feet long, having only 10 feet 6 inches draught. She was 800 I.H.P. which was too little for her dimensions to negociate successfully the ice at this station, and her propellers were too near the load line, and suffered many accidents.

The fine icebreaker, Slejpner, belonging to the Harbor authorities, controls the winter traffic in Copenhagen. She is a vessel of 2,000 I.H.P. and 1,450 tons displacement; is 161 feet 6 inches long, and her speed on trial was 12.75 knots. This vessel is fitted with compound machinery on the assumption that less damage was likely to occur to low pressure boilers, than would be the case with higher pressure owing to the constantly

changing steam pressures consequent in an icebreaker when at work. She is fitted with a lowering tube in the stern, to enable the propeller blades to be changed whilst afloat; The frames at the bow are close-spaced, and in fact the framing throughout the structure is of a strong character.

There is also another icebreaker here, the Bryderen, belonging to the United Steamship Company. This vessel is 131 feet long, has great towing power, and is of immense assistance to the large fleet of steamers belonging to her owners. She is used a great deal during the winter in Danish water, to keep the communication open for the company's steamers between the ports, where they run. The services of these icebreakers have often to be supplemented by the Copenhagen salvage steamers, owing to the large winter traffic in the Belts and Sound, where the ordinary cargo boat is at the mercy of the ice. Before the Slejpner and the salvage boats were put to work, considerable delay occurred to steamers passing the Belts in winter and using Copenhagen during times of hard frost. The salvage boats are strengthened to resist ice.

At Korsoer, in the south of Denmark, three ice-breakers are used during the winter to break the ice in the Storr Belt, to keep the passages open for the important railway service between Korsoer and Nyborg, and when the ice is too heavy for the railway ferry boats to pass through; these ice-breakers transport the mails, and passengers between these ports. They are the Tyr, the Mjolmer, and the Staerkodder, the latter was originally at Copenhagen. The Tyr is 138 feet long, has compound engines, and is most efficient as an icebreaker.

The Mjolmer is 143 feet long, has compound engines, of 500 horse power, and is an able boat amongst ice.

In the davits of these vessels are stowed what are termed "ice-boats" which are used for mail and passenger transport, when the ice is too heavy for these vessels to work. These boats have runners under them, and are pulled over the ice by fishermen; the passengers walk, their luggage being in the boats, and when they come to

an opening in the ice, all embark and cross the water, and resume walking on the other side. This method of traveling is very slow and fatiguing, but it was quite customary at one time, especially before the Danish State Railway in 1894 obtained a powerful ice-breaking railway ferry steamer.

There are also icebreakers at Kiel, Riga, Rostoff, Stettin, Libau, Amsterdam, Kalmar, Stockholm and Nicholaisk, but they are all more or less vessels similar in type to the Sampo and Ledokol III, built on the River Tyne.

There are many small icebreakers used as post boats, and pilot boats, in the Baltic, the German coast, and the Black Sea. At Amsterdam, the ice in the sea Canal is kept in movement principally by small steamers, and, as it is not very thick, this arrangement answers well in ordinary winters.

Nearly all the canals in Holland, when frozen, become the principal means of communication by skating and sledging from one town or village to another. Ice-breaking as an assistance to commerce is brought to a high state of perfection at the ports of Hango, and Helsingfors, in Finland, though the latter port is not kept open all the winter, the whole power of the Finnish ice-breakers, Murtaja and Sampo being, about January, concentrated entirely on Hango. The latter vessel was built on the river Tyne. She has a propeller at each end, the bow engine being 1,200 I.H.P. and the stern engine 1,350 I.H.P. She is 202 feet long, and 2,000 tons displacement; has a draught of water 18 ft. with all coal and stores on board, and her sides are angled considerably. She was put to work at the commencement of the winter of 1898, and has been most successful during her career. The actual performance of the Sampo, in the Gulf of Finland, shows that she has a very efficient form for ice-breaking; she passes through field ice of 12 inches, to 16 inches in thickness at eight knots an hour. The thickness of the drift ice, she has generally been at work in, is some eight to ten feet, through which she can pass at from two to three knots an hour. She also breaks down larger packs, without much trouble. It is found in prac-

tice with this vessel, that charging in drift ice is more effective than cutting it down with the bow propeller, as is advocated in America. The Martaja and the Sampo, proceed out into the Gulf of Finland, the harbours of Hango and Reval are much affected by the wind, as the outer drift ice during a southerly wind makes Hango difficult of approach, and a westerly or northerly wind has the same effect at Reval.

During gales, the icebreakers of these parts suspend operations as the pressure of the ice becomes so enormous, that even if the icebreaker can force her way, the canal behind closes up almost at once, so that to the ordinary tramp steamer it becomes a problem as to whether it is safer to proceed or to rest in the ice, in which latter circumstances she will be drifted with the ice, or squeezed if the ice packs.

There are two icebreakers at Gotheberg, and two at Drammen, in Norway; these vessels are well able to keep these ports open. At Christiania, there is a fine icebreaker, the Isbjern, built at that port. She cuts a canal down the lovely fiord from the harbor to the sea, and keeps a channel free, under all the conditions of ice at this place. Ordinary merchant steamers trading during the winter in ice should have the plating at the bows doubled, and the side plating for some width about the water line should be of a much heavier scantling than usual. The propeller blades should be of very strong design and fitted to the boss to facilitate repairs; when this is done, steamers can take care of themselves to a very large extent. Without strengthening of this nature, vessels dare not "charge" the ice, or the plating would be holed, and it is impossible to drive the engines, or the blades of the propeller would be knocked off. On the other hand, if the ship is allowed to rest in the ice, the sea inlets become frozen up, and the risk of being squeezed and holed, is ever present.

Many German, Finnish, Norwegian and Danish steamers, comply more or less with these requirements, and are therefore able to give a good account of themselves in ice. At Reval, there are four icebreakers, of

varying dimensions, and the efforts of these vessels are supplemented by a well arranged system of telegraphing all ships, approaching the coast. The larger icebreaker, attends to vessels to and from the harbor, to the entrance of Reval Gulf, a distance of 15 miles, and occasionally goes as far as the open water beyond. The three smaller boats keep the ice broken inside the mole and harbor, and tow, and move the vessels in the harbor. The large boat is a fine vessel, but somewhat out of trim, as when she was put to work it was found that she pushed the broken ice in front of her, owing to her bow lines being too full.

To meet this difficulty she is trimmed a good deal by the stern, but this prevents her having the valuable advantage of "tipping" herself more by the stern, when she sticks on, or in the ice. An icebreaker should be capable of altering her trim quickly, by moving water from her forward end to the after end, or by filling up the after compartment rapidly, as should she stick forward, her engines might be unable to release her.

At Odessa, there are three powerful icebreakers, the latest one, Ledokol III., having been built at Walker. She is 148 feet long, 2,200 I.H.P., and has a speed of 13 knots. This vessel is well able to break the ice three feet thick and has, therefore, been most successful on her station, never having been jammed, and being always able to free others in distress, or fast in the ice. The ice at Odessa, is principally pack ice, of a broken-up description, which at times, owing to wind and tide packs very tightly, and occasionally freezes together, in a hard compact mass.

At Vladivostock, in Eastern Siberia, there is a fine icebreaker, the Nadeshny, which is of vast importance and assistance to the port, as the Russian fleet, stationed at Port Arthur, is now able to patrol this harbor which is the naval base, during the whole winter. The ice at Vladivostock attains a thickness in hard winters of 36 inches, but the packs only occur at the outer edges of the field ice, when the wind blows in the direction of the entrance to the harbor. The harbor is an ideal one,

surrounded by hills, is quite land-locked, and has a curved entrance, from which the town cannot be seen.

The Nadeshny was built at Copenhagen, is 183 feet long, has twin screws of 2,800 I.H.P., and is fitted with powerful pumping appliances that can be used for salvage purposes. The vessel has a speed on trial of 14 knots, in open water.

Coming now to the design of icebreakers, and vessels suitable for working in ice, they should have the bow angles and lines so arranged that when they have mounted the ice, and the ice is giving way under the vessel's weight, they must not jam when returning to be water-borne forward, always remembering that they are advancing and should remount the ice. When the ice is broken down, it should pass along below the vessel or under the field ice, otherwise it lies on the water, and has a tendency to jam the vessel sideways; this results in the icebreaker having to smash a larger proportion of ice than necessary, to give side clearance, thus absorbing more power, coal and time, and probably resulting in having to back and charge the ice. An icebreaker should also be able to turn out of the channel she has cut, and the form of the bow lines has much effect on this manoeuvre.

The designs of icebreakers vary so much, that there are no certain data to guide builders; but practice has shown that the full forward form of spoon-shaped bow is not successful in hard and packed ice, as the vessel pushes the ice in front of herself, instead of cutting and dispersing it. It should be borne in mind that ice-breakers when "charging" in heavy ice, are in collision, so to speak, during the whole time that they are at work; this, therefore, entails much more strengthening at the bow and sides, as the ice to be dealt with, becomes more formidable. The shell plating must be considerably increased in small boats, and still more so as the vessels increase in size; additional stringers, stronger decks, and a liberal addition to the number of bulkheads, transverse and longitudinal, as well as many pillars, become a necessity to prevent constant recurrence of repairs.

In the days before icebreakers came into use at Amsterdam, Stockholm, and other ports, the custom was to have from 50 to 200 or more men to liberate a vessel. These men formed two parties, making holes through the ice at a sufficient distance apart to clear the beam of the ship, then from hole to hole a groove was cut, and the ship would charge to the best of her ability to break the ice, or saws were used to cut from hole to hole, but the operation was very slow and tedious. From a fortnight to six weeks to go fifteen miles to the open water from the ports of Reval and Amsterdam, was a fair time for a vessel, with success to clear the ice. In arranging the accommodation of icebreakers, it is desirable to have all this under the weather-deck, for the sake of warmth and comfort, with covered over companions forward and aft for access below. All piping should be kept under the deck, and the fire pipes should be fitted with hydrants below and above this deck. The boiler rooms must be well closed up, and consideration has to be given to the disposal of the ashes, and special arrangements have to be made inside the vessel on which the sea inlets are fitted.

Steaming arrangements and circulating water should be delivered at will to the sea inlets, to warm the circulating water, and prevent ice forming in very severe frost. Care has to be given to the lining of the cabins at the ship's sides, and it has been found that air spaces are the best non-conductors of cold. Condensation is always a difficult problem, and dried heated air pumped in, lends itself better to overcoming this trouble than the ordinary system of steam heating. Ventilation has also to be carefully considered, though it is not so complex a question as that of heating. The rudder should be arranged for easy unshipment afloat, and should be of large area, and immensely strong. The moving parts of the machinery and the shafts must be extra strong, and largely in excess of ordinary practice. Large surface in the stern tubes is also required to support the shafts, when the blades are striking the ice and smashing it up, and the boss and blades must be of the most liberal dimensions.

The vessel should be so designed that, if possible, she can be "tipped" to replace a propeller blade whilst afloat. On the engines, it is preferable to have steam reversing gear, as the "all-round" type is a very heavy tax on the engineers when the ship is ice-breaking. In fact all the controlling gear of the engines, if they are large, should be mechanically worked so as to reduce to minimum the labor entailed by the almost continuous handling of the engines, when the ship is at work. The safety-valves should have silent blow-offs to the condenser, so that at sudden stoppages, commands on deck can be given to the crew, or to another vessel alongside of which the icebreaker may be at the moment. Noise occasioned by escaping steam is most annoying, and makes it nearly impossible to transmit orders on deck. Most icebreakers are fitted with large pumping arrangements for salvage purposes, as cargo steamers often get damaged in the ice, and require assistance to keep afloat. Navigating in ice, although hazardous, is most fascinating work; it is always changing, difficulties to be overcome at a moment's notice are ever present. Think of the position of an ice master in a breaker, with say one or two steamers following in his track. Down comes the fog; no astronomical observations can be made; all lights are blotted out; he cannot take a sounding on account of the ice; if he stops, the boat behind, (if the master is not on the alert) will run into him, and this in turn applies to the second following boat. Add to this, that the ice is "on the move" but its direction is not certainly known, and the snow comes to help the complex problem? Only an iron nerve, and quick decisions by those in charge of the icebreaker can meet such a position, and if the vessel is amongst rocks or shoals, and in most places these dangers to navigation are present, the difficulties are indeed increased.

Ice pressures are far reaching and serious in their results; as showing the distance they reach, one case came under Mr. Gueton's observation at Reval. A north-west gale had blown the drift ice at the mouth of the Gulf of Finland into Reval Bay, against the field ice at rest in the Bay, thus forming an enormous pack

at the mouth of the Bay, fifteen miles from the mouth of the harbor. The result of this great pressure was shown on the outside of the stone mole, or breakwater of the outer harbor, where the ice was pressed 32 feet in height, destroying a wooden pier used for steamboats; the amount of ice pressed up represented many thousands of tons in weight.

The Captain or ice-master has to exercise considerable care in cutting out vessels fast in the ice, and the procedure is to pass across the bow and then the stern of the fastened vessel. Endeavor should be made to crack the ice in some direction towards the ends of the vessel, before passing her in a parallel direction, in order to obviate as far as possible all chances of crushing the steamer's sides. In passing alongside, the ice may "bend" between the vessels, with the result that the ships fall together, and the "drag" of the icebreaker is sure to fetch the other vessel alongside, unless the speed of the breaker is great enough to clear the other vessel. This has actually occurred in the Gulf of Finland, when a train of eight steamers were following the Ermack to Cronstadt, and but for the timely assistance of the Ermack, life would have been lost. Another type of steamer used in the ice, is the ice-breaking passenger and mail steamer. There are not many of these vessels at work, and of course they are not able to force the packs as readily as an icebreaker can. They are fitted with every requisite for winter service, including electric projectors, as a rule they propel themselves through the ice, at night well as by day. Three vessels of this type, the Express and the Abo, running between Stockholm and Hango, and the Bore running between Stockholm and Abo, keep up a steady time-table.

Three of the mail boats running between Kiel and Korsoer are also examples of this type, and are well known to many English travelers. The latest, the Prinz Sigismund, is 205 feel long, and has twin screws of 1,200 I.H.P.

The Arcturus and Polarius, of Helsingfors, are splendid types of these vessels. They were built in Dundee, are 281 feet long and 3,500 I.H.P. They are first class pas-

senger vessels, are magnificently found in all respects, and have a speed in open water of $14\frac{1}{2}$ knots.

I have seen the Arcturus make a splendid entry to Reval through the canal cut in the ice by the Ermack, although passing through the great pack at the entrance of the Gulf, she had too much speed on, and damaged her sides below the waterline—in fact, she squeezed herself badly. These boats run from Hull to Helsingfors, and are, therefore, ocean going steamers.

The Oihonna and Wellamo are also handsome boats of the same class, but small in their dimensions.

The Aegir and Linnear, of Helsingfors, are typical cases of ice-breaking cargo steamers. They trade regularly all the winter between Hango and Lubeck; are 172 feet long, 15 feet draught, and 500 I.H.P., and are much strengthened over the requirements of the Registration Societies, and well arranged for winter navigation in open water and amongst ice.

The Britannia, the first steamer of the Cunard Company, in 1844, became fastened in the ice in Boston Harbor; the townspeople arranged to help to cut her out; this was accomplished by sawing and breaking the ice, and by the aid of the vessel's paddle-wheels, she reached the open water, as the townspeople of Boston made up their minds that the vessel should keep her sailing date. The distance that the Britannia had to be cut out, was seven miles, and at that date, this was a remarkable undertaking, and meant a great deal to the mail service between England and America.

The old time whalers of Dundee and other ports, some of which are now engaged in Polar work, either on Polar expeditions, or whaling, are essentially icebreakers of a type; they are built entirely of wood, the bows sheathed with iron, and many daring deeds have been done with some of these vessels in the Polar seas. We must not except from case, Dr. Nasen's Fram; she is well designed to withstand shocks and ice pressures, and this she has proved in her long endurance in Polar ice on two expeditions.

Nor must we over look the Discovery of the National Antarctic Expedition, at work in the immense ice of the Southern Polar Ocean, especially built for service in the ice; and the Scotia of the Scottish National Expedition, known for long as the whaler Heckla, built of wood, having sides 24 inches thick, and nine feet of solid timber at the bow, wherewith to attack the ice. There is a large field for winter service steamers, and their number and power will probably increase in the future, especially as more information regarding them is obtained from winter to winter, and the method of dealing with ice navigation becomes known. Another type of vessel for use in winter is the railway ferry ice-breaking steamer. This useful type of steamer represents many problems, and is by far the most difficult to design and arrange. Some of the vessels are of great size, and those best known to us are used by the Danish State Railways, between the islands of the great Belt and the mainlands. The State possesses no fewer than fifteen or sixteen of these steam ferries; of these only the five largest have two lines of rails, the remainder one line, and only three have screws—two being twin screws, the remainder having paddle-wheels.

The Zyeland, built at Copenhagen, is 170 feet long and has a draught of 11 feet 6 inches. Her indicated horse-power is 1,200, and she is a very useful ship. She crosses between Korsoer and Nyborg, on the main route of railway between Denmark and Germany, a ferry of about twenty miles. Another fine railway ice-breaking steamer is the Malmo, built at Malmo, running across the Sound between Copenhagen and Malmo, a distance of 16 miles. She is a powerful vessel, 268 feet long. She draws 10 feet 6 inches of water, and has a speed in open water of 25 knots. Her engines are triple expansion, she has a space on deck for eighteen railway cars, and successfully copes with the peculiar conditions of the ice at this station. On the main route of railway between Denmark and Sweden at Elsinore, there is a railway ferry steamer, the Heslingborg, built at Elsinore. She is 177 feet long, has one line of rails, and is fitted with a screw propeller at either end. The distance across is 11 miles. She has

compound engines of 800 horse power, has attained a speed, in open water, of 10 knots, and has to attack heavy packed ice during the winter.

The Danish State Railways have established a railway ferry between Gjedser in Denmark, and Warnemunde, in Mecklenberg; the distance across is 24 miles. There are four steamers on this route, two twin screw and two paddle, 285 feet long. They have two sets of rails. Their speed will be 14 knots an hour and the intention is to keep up an express railway service between Germany and Denmark all the year, without the passengers having to leave the carriages, and at times during the winter the ice sets heavily on the land.

Following these vessels comes the famous railway ferry icebreakers at Saratoff on the river Volga, which are used for keeping up the services of the Riazan Ouralsk Railway across this mighty river. The river is ice bound for several months during the winter. The fleet consists of two steamers, one being an icebreaker, whose duties consist of taking across the passengers, mails, and luggage. The distance across is less than a mile, and she is generally able to accomplish the journey in twenty minutes to half-an-hour when the ice is fast.

The other steamer is a railway ferry icebreaker, 243 feet long, 55 feet 6 inches broad. She is capable of taking twenty-four of the railways company's large goods waggons at once, the loading and unloading of which is very expeditiously carried out. She has four lines of rails, and two very powerful hydraulic lifts at the fore end of the vessel to raise the trucks from the deck to the railway level. As the Volga changes its level all the year round, and the difference of levels at this points is about 45 feet, it is necessary to introduce the hydraulic system on the boat, otherwise four large double lifts would have had to be fitted at the four railway piers, two of which are high levels, and two low level. These low level piers are submerged during the period of high water which occurs in spring during the melting of the snow and ice.

The ferry steamer is assisted by the icebreaker before referred to when the ice gets difficult to negotiate,

as occasionally the canal cut in going one way is closed before the return journey is begun. These steamers are entirely fired by oil fuel, the icebreaker going through her trials on the Tyne and steaming out to St. Petersburg under this system, which has given entire satisfaction. As these two vessels had to pass through the system of locks on the Marinsky Canal from Lake Ladoga to the River Swer, and so to the mighty River Volga, it was necessary to build them so that they could be parted to enter the locks. The Scotia, a most interesting boat, was built for service across the Strait of Canso, between Cape Breton Island and Nova Scotia. She is a typical icebreaker. Either end of the vessel is intended to be bow or stern at will, so that in working she does not require to turn round in entering or leaving her landings, the gangways resting on either end of the ship when lowered for loading or discharging the trains. As her ends are alike, both propelling engines are on the center line of the vessel, and can be coupled to each other, if so desired. The ice in which the vessel has to work is blown into the Straits from the Atlantic or the Gulf of St. Lawrence, and at times it becomes very tightly packed. The vessel is 269 feet long, draws loaded 14 feet and has a speed in open water of eleven knots. Her framing is exceptionally strong, and her shell-plating in way of the belt is very heavy, as she has to withstand severe local shocks.

The vessel has three sets of rails and is designed to carry nine Pulman sleeping cars, 80 feet long, each weighing 52 tons unloaded. The decks of the steamer are enormously strengthened by deep girders and pillars throughout, so that she can, when necessary, take over a locomotive or tender. The vessel has four boilers, and the disposition of the four funnels and the Captain's bridge gave rise to considerable ingenuity. The ship is entirely controlled from the bridge, as the centre of the deck must be kept clear for the coaches. In this steamer the descent of the rolling stock on to the deck of the steamer is somewhat steep, and consequently very large buffers are provided to catch the coaches should the brakes fail. As time is an all-important factor when the

train is being put on board, three coaches are run on and taken off at one time, the taking off being done by a small shunting engine.

The next railroad ferry ice-breaking steamers before us are the St. Marie and the St. Ignace working across the Straits of Mackinaw, between Lakes Huron and Michigan, a distance of seven miles. Both these boats are built of oak, and are sheathed with iron in way of the water-line. The St. Marie is 304 feet long, has 4,000 I.H.P. She has a propeller at either end, fitted with the idea that it helped her immensely to clear the landings. This vessel takes her trains on at the bow, has three lines of rails, and is, with her sister vessel, designed to work in ice up to 24 inches thick. The power of the engines of the St. Marie is nearly equally divided on the propellers. She commences work as soon as the ice begins to form at the setting in of the winter, and crosses in the same channel. As the ice seldom moves at Mackinaw, she has not much trouble in keeping the ferry going. She is splendidly handled, and the manner in which the trains are put on board and taken off is remarkable.

One of the finest railway ice-breaking ferry steamers afloat—the Pere Marquette—built by Messrs. Wheeler, of Michigan, has to cross the centre of Lake Michigan, between Ludington and Manitowoc, a distance of some 56 miles, in all weathers, and encounter open water, heavy, solid, and packed ice, and steam through strong gales and high seas. She is 350 feet long, 56 feet beam, and when fully loaded has a displacement of 4,950 tons on 12 feet 3 inches draught. She is strongly constructed, and her shell plating is very heavy. She has a splendid arrangement of cabins in the deck-house and every accommodation for first class express service where the passengers may be on board all night. Her engines are twin screw compounds, 135 lbs. pressure, and 4,000 I.H.P. The rolling stock enters at the after end, and as there are four lines of rails, she can take on fourteen 80 foot cars, weighing about 56 tons each, loaded, or thirty freight cars. This steamer is really a palatial floating hotel. All the rolling stock on board is secured and blocked by mechanical means, to prevent movement in

a sea-way, or when striking ice at high speeds. On the great lakes of America, there are no fewer than fourteen car ferry routes.

From these vessels we come to the famous icebreaker Baikal, on Lake Baikal, in the center of Siberia. This splendid vessel was built to connect the western and eastern ends of the Siberian railroad, which, as you know, makes a continuous railway from Ostend to Vladivostock, in Eastern Siberia, and Port Arthur, in Manchuria, some seven thousand miles long. Now Lake Baikal lies N.E. to S.W., and all round the S.W. corner of the lake, the Tartar mountains impinge on the lake itself; and to make this railway round the corner of the lake meant some 500 tunnels and bridges, more or less, and the valleys are very steep. Work can only be carried on during the open months, and the engineering difficulties are apparent. Also, landing from the lake is out of the question, as the debris from the mountains and valleys prevent this; and as very strong gales blow without warning on this stretch of water (principally from the north east), the lake being 500 miles long, and nearly 4,000 feet deep, very dangerous seas get up, making it impossible for vessels to lie at the south-west corner. The field ice on Lake Bailkal forms 36 inches deep, and owing to the gales it packs heavily, particularly towards the Tartar coast, even grounding in some cases, and, owing to the extreme cold coming at times quite suddenly, and the ice being land-locked, it contracts and cracks leaving dangerous crevices across the lake. This lasts for well over four months every year. Until lately all crossing Lake Bailkal in winter was by sledges over the ice, and severe blizzards and fogs are common, it sometimes happened that an unfortunate traveller, driver, horses, and sledge would go down one of these cracks. The distance of the ferry across the lake is 52 miles. The vessel is 290 feet long, and 4.200 tons displacement, and her draught, under ordinary working conditions, is about 19 feet. She has three sets of triple expansion engines, one at the bow, and two at the stern. The principal of subdivision is carried out in the highest degree and a large number of compartments would have to be pierced before

she would sink. The vessel has luxurious accommodation, and a promenade deck for the use of passengers whilst they are making the passage across. During the winters that this enormous steamer has been at work, she proved herself to be most successful in keeping the service open under difficulties of ice-navigation that were unknown, and therefore ever unthought of, during her construction. Of course there was no knowledge of the ice as regards navigating purposes in Lake Bailkal until this vessel went to work.

The hull was completely erected, marked, taken down, and shipped inside of six months, and 2,700 tons weight, in 6,900 packages, had to be transshipped for some 1,500 miles across Siberia by boat to the place of re-erection.

The boilers (of which there were fifteen) had to keep under 20 tons in weight, for transhipment purposes, and even these great pieces were moved in sledges by the aid of hand and pony power from the railway trucks to the ship. The vessel has three lines of rails, entered from the forward end; the centre back is very strong to carry locomotives, which, on this railway, weigh, loaded with tender, from 94 to 104 tons. Her consort, the Angara, is a fine icebreaker, having one screw of 1,500 I.H.P. triple expansion engines and loco boilers. She is a most successful icebreaker, making her passages with the utmost regularity with mails and passengers.

The Ermack, a most magnificent piece of naval architecture, is 335 feet long, 71 feet beam, and has a displacement (with coals on board) of 8,000 tons on a draught of 22 feet. As the Ermack was built for polar enterprise, as well as for ice-breaking in the Baltic, she was designed to receive the very severe blows that locally strike her when amongst the enormous ice of the Polar ocean, and ice pressures that may lift her clean out of the water, leaving her ice-borne. Her bow engine, though successful in one year old ice, has been removed, as the shape at the bow to admit the propeller was not suited to the requirements of the Polar ice. Her speed through 24 inches of solid ice, with six to twelve inches of snow on the top of it, is nine knots an hour, and she can

charge and demolish packs of ice twenty to thirty-five feet in thickness. In Polar ice the speed has to be kept at about $2\frac{1}{2}$ knots to $3\frac{1}{2}$ knots an hour, as one is apt to lose control of the vessel in this enormous ice, and the local shocks become very severe when she is charging about at her own "sweet will" amongst the Palaeocrystic ice. She has proved herself to be of enormous use on her station on the Baltic coast of Russia, where she can negotiate any ice, and can safely bring out of danger, all steamers that she goes to assist. In one short season she rescued and assisted shipping of over two millions sterling value, and, in another winter, she salved the Russian battleship, General Admiral Apraxine, of £750,000 value. With the Ermack in the Baltic, there is no difficulty in Russia putting to sea her fleet, which usually winters at Cronstadt, as the Ermack could easily guide them to open water should necessity arise; and there is nothing to prevent this vessel herself being made an armed cruiser."

In 1910 W. G. Armstrong Whitworth, the builders of the Ermack, constructed the Tarmo for the Gulf of Finland. Size 200 feet long, 50 ft. beam, and 1,000 H.P. Displacement, 2,800 tons. This ship is provided with bow propeller, and has proved very efficient in taking ships in and out of Helsingfor during the winter.

In 1925 one of the latest and best icebreakers was launched, for use in the Gulf of Riga, by Messrs. William Beardmore & Co., of Dalmuir. Length, 186 feet; breadth, 54 ft. Normal draft 22 ft. and displacement 2,800 tons.

The vessel has a specially designed stem, with considerable rake under the water-line and a stern of cruiser type, both stem and sternpost being of cast steel reinforced as necessary for ice-breaking purposes. The framing, which is on the deep frame principle, is except tionally strong, the spacing of the frames being 18 in. apart amidships and reduced to 12 in. apart at ends. The shell plating is also much in excess of the usual requirements of the Bureau Veritas, with whom the vessel is to be specially classed, and the ice belt from about 6 ft. above the water-line to about 9 ft. below is 1 in. in thick-

ness all fore and aft. the end plating down to the keel-line being practically of the same thickness.

In addition to the heavy closely-spaced watertight bulkheads there are on each side of the vessel for about three-quarters of the length amidships longitudinal watertight bulkheads forming coal bunkers and water ballast tanks, and the whole system of sub-division is



Fig. 55.—Ice breaking tug James Whalen.

so arranged as to enable the vessel to obtain the special mark assigned by the Bureau Veritas to vessels which are capable of remaining afloat with any two compartments open to the sea. By rapidly transferring water from the end tanks forward to the end tanks aft, or vice versa, the vessel may be quickly trimmed either way, similarly by transferring water from tanks on one side of the vessel to tanks on the other side, she may be quickly heeled, and by these means she is able to free herself in the event of her being locked in ice.

Special arrangements are made for taking a vessel in tow, a recess being provided in the stern so that the stem of the following vessel may be drawn into it and held in that position by means of a large towing winch of exceptionally powerful type fitted on top of the aft deck-house.

From the general study which I have made of ice-breaking ships, and from information of those skilled in their operation, it is clear that quite a small boat is most easily handled in an ice pack. Such a boat must be sturdily built to resist ice pressure, powerfully engined, and provided with a means of rocking from side to side, during her performance. In addition some steam and hot water ejectors provided for very cold weather, will assist very much from freeing the ship when working in soft masses of ice. See Fig. 55.

Ice-Breaking Tugs.

The "James Whalen", named after its owner, is the most highly efficient of three tugs, the duty of which is to keep a channel open from Port Arthur and Fort William to the open water of Lake Superior.

The steel hull of this boat has a lining of about 4′ of concrete, and it has been known to break clear ice 40″ thick.

This ice breaking contract is worth $50,000 per season (paid by the Canadian Government). This system advances the spring handling of grain and is a great assistance to the transportation companies, and to Western Canada in general.

From a paper by F. M. & F. P. Williams read before the Int. Congress of Navigation at Cairo in 1926, we learn that typical icebreakers built in the nineties have a displacement of about 800 tons. Boats built in recent years have been of about 2,000 tons burden.

"An exception to the above is the "Ermak" of 8,000 tons displacement, built in Russia in 1899; the largest icebreaker ever built. It has been demonstrated that the performance of this large boat is not materially greater than that of much smaller icebreakers. The difficulty in manoeuvring large vessels, like the Ermak in ice is quite evident. The fact that additional boats of its size have been constructed indicates that the smaller boat is the most valuable for economic and practical reasons.

Lines.

The ratio of breadth to length may be somewhat influenced by the desire to secure as great a width of channel through the ice as possible. In the earlier boats a ratio of 1 to 4 is the rule. The width is made somewhat less than indicated by this ratio in some of the later boats. The great breadth aids in securing stability and ease in manoeuvring.

The lines of a breaker are designed so as to avoid all flat surfaces, the effect of which would be to increase the difficulty of freeing the boat when caught in ice. A convex surface is favored from stem to stern. Modern icebreakers are provided with wing ballast tanks with pipe line connections so that the boat may be listed by pumping water from one side of the boat to the other to free the vessel when frozen in.

The principle followed in the early construction of breakers was to provide for crushing the ice by having the boat "ride" it rather than to attempt plowing the ice to the sides. The stem was given an angle of 30 to 40 degrees which resulted in creating a large downward component of the horizontal force of the boat. This angle has been made somewhat less, or about 20 degrees on later boats.

The earlier boats had a full or spoon-shaped bow. This type proved ineffective in ice covered with snow for the resaon that the snow packed around the bow to such an extent that it was difficult to drive the bow on the ice. The knife cutting bow of the more recently constructed boats does away with this difficulty.

Bow Propeller.

The utility of the bow propeller was discoverd as early as 1890. The "Ermak" the large Russian ice breaker, originally installed a bow propeller. In 1909, the bow of the boat was remodelled and the forward propeller removed. However, there is no reason for doubting the utility of the bow propeller when its per-

formance is taken into account. In 1890, when the ferry at Port Huron was stopped by ice, Capt. Houghton found that by turning the ferry around and backing it into the ice, the screw broke the ice and sucked it down out of the way. The weight of the boat in crushing the ice is made more effective by the drawing away of the water from under the ice by the propeller. It has also been found that when an icebreaker is used to clear ice, at full speed with the propeller working, the water is sufficiently disturbed to cause six inch ice to break before the stem actually reaches the edge of the solid ice."

In pack ice, the bow propeller serves the useful purpose of drawing the blocks of ice and slush towards the stern of the vessel and out of the way. It is advocated by some designers of icebreakers that the boat should be so constructed that the throw of the forward and stern propellers should meet.

The "Tarmo" used in the Gulf of Finland, having a knife cutting prow and a bow propeller, combines the qualities of an ice crusher with the advantage of sucking the ice away. The principal dimensions of the Tarmo, which was built in 1907, by Armstrong Whitworth & Co., at New Castle-on-the-Tyne, are as follows: Length, 220 ft., beam, 47.1 ft., draft, 18.25 ft.; displacement, 2,300 tons; indicated H.P., forward, 1,300, aft., 1,700, forced H.P., forward, 1,450, aft, 2,400; stem attack 20%.

The American ferries generally have the bow propeller. This form of bow, however, has been omitted from Canadian boats.

Although from the above it is shown that it has not been universally adopted, it appears that the installation of the bow propeller, which is of undoubted utility but somewhat complex, is gaining in favor.

The extent and thickness of ice successfully broken indicates the character of machinery that is necessary for the work. Ice up to 3 ft. in thickness has been successfully broken in the St. Lawrence River, although the ice in this river seldom exceeds 27 inches in thickness. Ice crushing ferries operate for a distance of 50 to 60

miles through 3 or 4 feet of ice at the Straits of Mackinac and City of Duluth on the Great Lakes. Clear ice, four feet thick, in the Gulf of Finland is readily broken by the "Tarmo".

It will readily be seen that for such work boats of heavy construction with powerful machinery are necessary. Operations that frequently require sending the boat at full speed into ice so hard that at times the propeller is stopped, require a very heavy engine and a propellor constructed to withstand the shock and the constant vibration caused by crushing heavy ice. Rugged construction is the most important characteristic of all ice breakers. A contribution to such construction is the specially treated steel and the heavy shop machinery available at the present time. See Fig. 56 of the C.G.S. "Mikula".



Fig. 56.—Canadian Government icebreaker "Mikula" largest and most powerful boat of its kind in America. This boat does ice patrol service after the winter operation of breaking ice in the lower river is completed.

More recent advancements in auxiliary equipment include electrically operated deck machinery to avoid the possibility of frozen steam pipes. Also the intro-

duction of high pressure steam or hot water lines are installed for the purpose of freeing the ship from frazil when stuck.

Although the remarks on ice breaking above refer more especially to work on large rivers and harbors, the underlying principles apply generally. The particular difficulty in adapting ice breaking to the channels is the disposal of the ice.

In England, where the winters are not severe enough to close such waterways as the Manchester Ship Canal, less formidable means of breaking ice are employed. On the Bridgewater Canal, for example, boats 41 ft. long, 4′ 5″ beam, with square punt ends, are employed. Each boat is hauled by 9-horse team. The crew of 12 to 16 men produce an oscillating motion when the boat is passing through ice, thus facilitating the breaking of it. This oscillation or roll in all ice-breaking steamers is a distinct advantage.

CHAPTER IX.

CONSERVATION OF HEAT IN LAKES AND RIVERS FOR ICE PREVENTION, POWER HOUSES AND CANALS.

It has been pointed out repeatedly in these pages, how small a temperature difference in water will inhibit the growth of ice. In this chapter there will be given some account of studies which have been made to show how the ice forming period is controlled under natural conditions and suggestions will be made based on these studies whereby in certain cases, heat may be conserved in running streams and stored in lake areas.

On account of the high heat capacity, both sensibly and latent of water, there is required a much longer time for a water body to fall or rise in temperature, than air or land masses. Thus every autumn the temperature of a lake or river lags behind the atmospheric change, and in the spring remains much cooler far into the summer. Water like all material things immersed in the ocean of air, shares in the heat exchange between earth and sun.

Through countless ages, this heat exchange has remained almost constant. The climate of various parts of the earth varies from the strength and obliquity of the sun. In a general sense it is the sun which controls the average temperature in any locality, but in particular cases local conditions produce small variations which like the weather, influence our surroundings temporarily. It is necessary to determine separately, what these conditions are in order to understand the problem of heat conservation.

Without doubt, the presence of large quantities of water fundamentally influence the local climate. Thus, throughout the region surrounding the Great Lakes the

climate is much milder than further inland, or over the prairies. Periods of frost are much later near open water and the air temperature all along the open stretches of the St. Lawrence river are from 5 to 6 degrees warmer, even in the coldest weather, than several miles inland.

The larger the volume of water, the greater influence will be exerted in tempering the atmospheric conditions. This has recently come up in a striking way in the Lake St. John region. The large power developments there of the Duke-Price interests, have raised the lake level some 17 feet, impounding a very large area of water with a consequent great increase of heat storage. In consequence the lake has frozen over later in the season, and the ice has not grown to such a thickness during the winter. Also on the St. Maurice river the influence of the great storage reservoir has made itself felt for miles by diminished ice formation and more open water with consequent tempering of the climate of that region.

Heat Exchange in the St. Lawrence River.

In the application of this method of study, the St. Lawrence river was treated as a heat machine or calorimeter, and the heat exchange of the various reaches were studied. The river was divided into four main sections and these main sections subdivided into single units.

We shall now describe this method of study from the purely physical standpoint, and the results which have so far been achieved. There is a great deal more to be learned and the conclusions which have been arrived at are to be regarded as a starting point for further investigation. They have enabled us to form a close estimate of the total amount of ice that can be produced in any given season.

Ice maxima are valuable in estimates for ice control works. On the other hand the value of the minimum estimate is useful in pointing the way towards a proper understanding of the conditions which nature brings into play for ice prevention, and which may be to advantage copied in an intelligent treatment of the entire river. All previous estimates of ice maxima have been based on

measurements of ice accumulations, but the figures which have been given are so variable that it is difficult to get any correct idea as to their accuracy.

The most notable are those given in the report of the Montreal Flood Commission in 1887, and they have been copied by nearly all ice investigators on the St. Lawrence. These diagrams are interesting and are of help in an attempt to modify the character of the river or estimate the minimum ice formation which can be expected under new conditions. It has not been necessary to devote much time to estimates of backwater effects during the winter, due to ice, and to the determination of ice accumulation, except where these measurements have been useful in indicating a method for getting rid of them entirely. Long experience with river ice study has convinced me that much time spent on measuring and charting existing conditions, is essential for results of permanent value since these change from year to year. In the first place the physical characteristics are never quite the same, and in the second place there are so many different factors entering, of a fortuitous nature, that there are as many different maps to be prepared for the river as there are years.

We have prepared maps of general ice conditions as they existed during the years 1911 and 1925, showing conditions which existed during those winters. There have been other maps prepared and they show one main fact, that the International Section maintains, throughout its course an open channel, and that the ice packs which have been observed and described in previous years are caused by artificial obstructions to the channel and not by normal freezing.

The study herein described has disclosed an interesting fact, in that there are really two rivers existing in the St. Lawrence. One of these rivers carries 75 to 80 per cent of the flow, following the deep channel, with a current of from one and a half to ten feet per second, and the other flowing irregularly through the islands and bays and shallows reaches and joins the main stream at different points. It is to this second river that we have to ascribe all of the serious and undesirable effects of ice.

It has long been recognized that the main river of the St. Lawrence would maintain itself free of ice entirely, from Prescott to tidewater, if it were not for the expansion occasioned by the lake areas and wide shallow bays. It was pointed out many years ago, if the lakes could be canalized and the bays anchored in by suitable piers the river would never freeze over. As a result of this study we can now go further than that, and say with confidence that a very little work done on the upper river, between Prescott and Lake Ontario, would enable the water of the lake to be brought down through the main channel at a greater speed and at such an elevated temperature that it might keep the ice out of the river altogether, except that which would form in the second river and which could be held in place to rot in the spring. At the present time the temperature measurements have shown that Lake Ontario influences the entire river more than any other factor.

Permanent Automatic Recorders.

In a study of the heat exchange in the river it is essential to have automatic recorders. Disconnected observations are of little value except for local study.

The temperature of the river is influenced primarily by Lake Ontario water and in a secondary way by local winds and weather conditions. Continuous curves show at a glance how the conditions vary from place to place, and an inspection of the micro-temperatures show how variable the temperature is at different hours of the day during the coldest weather. It is only through the automatic recorders that any reliable information can be obtained and therefore a number, suitably chosen and calibrated, were installed in the water works intakes at points along the river. Two types of thermometers were used, one made by the Taylor Instrument Company of Rochester, having the round dial of the usual type. The other form of instrument was made by Negretti & Zambra of London, and was of the horizontal type, giving a scale of from 30° to 80° Fahr. Three of these latter instruments were placed in the open portions of the river not conveniently situated to any of the water

works. The object in using the intake pipes of the water works was to get out as far into the current as possible and draw the water from a considerable depth. All of these locations were amply suited for this purpose, and the water came from such a depth as to be practically unaffected by the diurnal variations of temperature near the surface. The three locations other than the water works were along the shore and give indications of the surface changes in a very interesting and remarkable way. These instruments were all of the seven day type and were visited once a week for the purpose of changing the records and at less frequent intervals of setting the scale. These instruments are not as delicate as the more detailed study of the river demands, but were sufficiently so for the purpose of this preliminary investigation. The three Negretti & Zambra instruments could be read easily to one-tenth of a degree but the Taylor instruments were only equal to an accuracy of about one-half of a degree on account of the coarseness of the scale. The changes of temperature which take place from week to week on the advent of cold weather and on the arrival of spring were what was desired and the automatic recorders could be used to give these. On account of the difficulty of procuring the necessary number of instruments at once, they were not all installed at the same time, the one at Cornwall was first put in early in October, followed by the ones at Morrisburg and Prescott and at Locks No. 27 and No. 21, Brockville, and finally, early in December, at Kingston.

As a matter of interest a recorder was placed in the water works at St. Lambert, opposite Montreal. This site was chosen as giving some indication of the effect of the lake areas, St. Francis and St. Louis, as well as the influence of the shallow region in Laprairie Basin. The water works intake at St. Lambert runs out to the seventh pier of Victoria Bridge and gives a fair representation of the average temperature of the water in this region.

The duration of the records is from the first of October until June thirtieth. The air temperatures were taken from the records at Kingston, being the readings, as given by the Meteorological Office, at 8 a.m. The reason for

choosing this time was the fact that the 8 o'clock reading is a very good representation of the average for the 24 hours and furthermore gives the closest value for the period of principal ice formation during the previous 24 hours. The minimum temperature for the 24 hours could have been plotted but would not differ to any appreciable extent, for the purposes of this study, from the value which was read direct from the Meteorological Office records. It is true that the air temperatures will be different at the different stations, but on the whole the change will be, from day to day, approximately the same. It is to this change, more than to the absolute value of the reading, that the purposes of this study are directed towards the final estimate of the heat values of the river. By consulting a diagram of Lake Ontario and the river it will be seen at a glance what an important influence the immense body of water in Lake Ontario must have on the general characteristics of the river. The curves of the different stations sometimes cross one another due entirely to local influences. In the main, however, the lower down the station is situated, the lower the temperature is at any given date in the Autumn, when the heat loss from the river exceeds the heat gain, and the converse for the Spring of the year after the ice goes out, when the lower sections of the river are at a higher temperature. It is interesting to observe the approximate dates when the temperature of the river at the various stations arrived at freezing-point. These dates are in order of the distance from Lake Ontario, taking St. Lambert as the start, they follow in order, Cornwall, Morrisburg, Prescott, Brockville and Kingston.

This is set forth very clearly in Fig. 57 where the dates of the arrival of the water at 32° Fahr. is indicated with the distance from Kingston. The greatest amount of cooling is to be found between Kingston and Prescott, after which there is less effect and the curve falls off more regularly from Prescott to St. Lambert. The exceedingly cold weather which came in the early part of the winter during January had its effect on the entire river reach and the milder weather in the middle of February, followed by a colder interval towards the end,

is illustrated by the changes of temperature at Kingston and Brockville. The disappearance of the ice in the upper river at the end of February and the first part of March is well shown in the effect on the curves. At no

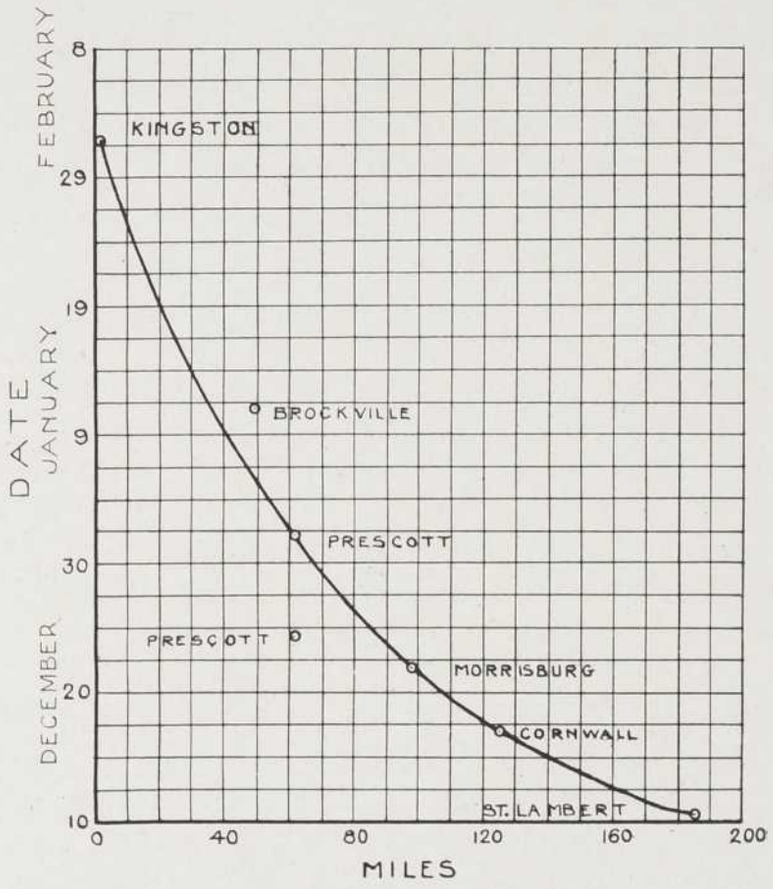


Fig. 57.—Curve showing date of arrival of water temperature at freezing-point.

time is the water at Kingston, for more than a short interval, at the freezing-point and even when the curves on the recorder indicate the freezing-point, the micro-temperature readings show a considerable elevation above 32°. The effect of the melting ice in the river is shown in the lagging behind of the various curves for the stations below Brockville. It was not until the 5th of April that the ice was cleared above St. Lambert sufficiently to allow the sun's heat to influence the water. Then it was seen how rapidly the temperature curve of St. Lambert rose, due to the large shallow areas above, and it soon crossed the curves for all the other stations. The curve for Kingston is particularly interesting in the spring, being entirely below the other curves, and during

the interval from June 20th to July 1st, when a remarkable train of circumstances brought about an almost continued uniform air temperature, the curves for all the stations with the exception of Kingston, are approximately the same. It was particularly noticed how the temperature for Kingston came below the others, as this affords one of the strongest evidences of the effect of what we have called the second river exerting it's influence on the main channel, and is the strongest possible argument in favor of the proposals, for remedial works in the upper river to prevent the influence of air temperatures over the immense areas of the 1000-Islands from influencing the main river, which flows into the International channel at Cape Vincent.

A general analysis of the temperature curves enables us to calculate the heat loss or heat gain of the river in it's various reaches. The factors influencing the heat exchange in the water, common to both the periods of loss and gain are heat absorbed from the sun, which is always positive; and heat supplied from Lake Ontario, which also, is always positive. The factors which differ during the two period are:—

(1) The heat loss due to low air temperatures including normal convection currents, which are modified by fog and humidity, and strength of, direction and velocity of the wind. This factor is very complicated and is positive during the Spring of the year and negative during the Fall.

(2) The radiation from the earth, known as nocturnal or terrestrial radiation, which is negative during both periods of the year and is directly opposite to the solar radiation.

(3) The evaporation from the surface of the water. The latent heat of evaporation of water is so large that it exerts a tremendous influence on the temperature and a dry wind will cause an immense amount of ice formation.

In our study of the rate of growth of surface ice an attempt has been made to separate these different factors. In the present study it is sufficient to include them all in

one term, which may be positive or negative, and which are all embraced in the temperature curves. We have analyzed the curves, with the object of estimating the ice maxima and minima. By the ice maxima I refer to the total quantity of ice that it is possible to produce under the existing conditions of any particular season, as illustrated by the conditions of 1924-25. No greater amount of ice can possible be formed than will correspond to the greatest loss of heat that can occur. Any calculation which gives a greater quantity than this must be wrong. The ice formation is solely a product of heat loss, and when we have accurately estimated the maximum of heat loss, then we can form an estimate of the maximum ice formation. An estimate of the ice minimum will give figures of a variable character, but in spite of this they will be helpful as we can observe them from year to year. We know that the main river itself is continually exerting it's influence towards the production the ice minimum, and in this respect the future developments must, of necessity, follow nature's own plan of channel improvement, and only by so doing can we rely on the forces of the river to exert their influence toward the accomplishment of this desired state. The whole matter is so beautifully and simply illustrated from year to year during the past ages up to the present date, and is so completely borne out by the present study that instead of the ice in the river becoming a serious obstacle and handicap to the development of the full power of the river, it will become a vanishing factor. The main river is writing it's own record and it is a simple matter to plan the various developments to facilitate the ready elimination of a large quantity of the ice. This is also true to a less extent in other rivers.

Calculation of Heat Loss.

For the purpose of calculating the heat loss of the river, the time is taken from October 15th to December 15th, during which period the river was falling in temperature regularly due to the falling air temperature. During the entire time of this interval, heat was escaping at a regular rate from the open river surface. This rate was uniform

at the various stations, as one would expect, over the entire period, although differing at short intervals at the local stations. This period is one in which the sun's effect on the water is rapidly decreasing, when it passes through a minimum about the end of December. If we take an average over the period of time we have selected, during which the automatic recorders make it possible for us to calculate, we can assume that this average is the same as the average which we shall use for the cooling factor for the winter months. A determination will also be made of the cooling factor for the minimum sun period, which explains very clearly why December and January are the months in which the greatest quantity of ice is produced and that during February and March, the rapid increase in the strength of the sun reduces the loss of heat enormously. At some future time it will be possible, with more observation, to separate the various effects involved in the cooling factor which we give here, and which include a number of the most important physical constants. Time does not permit at the present moment to do this, and it is especially important that further observations be taken extending over a number of years.

The period during which the cooling factor becomes reversed is quite apparent, although the radiation constant remains the same throughout. I have not attempted to evaluate the radiation constant separately here, although this is of the greatest importance for the calculation of anchor ice formation. Had it been possible to complete the experiments planned for the use of electrically heated plates for anchor ice formation, it would have been possible to obtain an accurate value through water and ice, as well as through air, but it is hoped that this work will be continued at some future time.

The main fall of temperature in which we are interested, from October 15th to December 15th, was practically the same at all the stations, disregarding purely local effects, such as changes in the meteorological conditions. These changes tend to average out over a period as long as the one we have chosen. While the rate of fall at

Cornwall is slightly greater than the rate of fall at Prescott or Brockville and these are greater than the rate of fall at Kingston, yet in our estimates we will take the average rate of fall between Prescott and Cornwall. It will be seen that the drop of temperature in the water follows very closely the fall of temperature in the air. This is not so much due to the fact that the air temperatures is the dominating influence on the water as to the fact that the air temperature is the direct result of the changing strength of the sun. The water, with so high a specific heat, changes more slowly than other objects on the earth in the same latitude and longitude. The sun is then the ultimate source of the heat exchange for all objects on the earth, and slight variations in the sun's strength produces enormous effects. Nowhere is this exemplified more than in the behavior of the river ice.

As soon as the water reaches the freezing-point no further drop of temperature takes place, but continued cooling results in the production of ice. The ice period in the river shifts from place to place in a westerly direction, with the advent of cold weather, principally due to the heat reserve of Lake Ontario. Thus, as we have seen in Fig. 56, the 32° point is reached at St. Lambert first and takes an appreciable time to extend up the river. Ice formation can occur only below the points where the water has reached 32°. On December 17th, ice formation commenced below Cornwall, resulting in the freezing of Lake St. Francis at Lancaster on the 21st. Hence we see that even after the temperature has arrived at the freezing-point, an appreciable period is required for the ice to stop. From December 17th to December 20th the river was gradually dropping in temperature from Cornwall to Morrisburg. From the latter date to December 31st the freezing temperature had reached Prescott, from that date to January 20th, the water, as it left Kingston, was about 32°. In order to calculate the ice-forming period in the International Section, it will therefore be necessary to take from the time the water leaves Prescott at 32°, correcting for the period from December 17th to December 31st by estimating the rate at which the freezing-point travels upstream.

The period from December 31st to March 15th will be taken as the time for the calculation of the ice production period, and the cooling factor over this time will be equal to the period from October 15th to December 15th, in which the rate of drop of temperature down to 32° has been observed. Hence the reason will be apparent why it was important that the period from summer to winter should be obtained, for during this period we have the average cooling effect quite similar to that existing later during the winter. In the first case the cooling factor is increasing regularly up to the point of maximum cooling and in the second place the cooling factor is decreasing at the same rate after the maximum has been passed. I am speaking here of average values, which eliminate local disturbances, such as periods of intense cold or periods of thaw, cloudiness or bright sunshine. As previously mentioned disconnected observations may be worse than useless and that is why there should be automatic instruments placed whereever possible and that records be taken over the peak of the summer conditions in August and extend throughout the year.

Calculation of Cooling Factor.

In order to calculate the cooling factor, we will take an analysis of the curves and determine the total fall in temperature from October 15th to December 15th, a period of 60 days. The average water temperature fell from 58° Fahr., down to the freezing-point or 32°, showing a change of 26° Fahr. The average air temperature fell from 45° Fahr., to 18°, showing a change of 27°. An almost steady difference of temperature was maintained between the water and air amounting to 13.5° Fahr. The total cooling for a period of 60 days, or 5,184,000 seconds, gives for the rate of fall of temperature during this period .00000512° Fahr. per second. This represents the average rate of fall of temperature for a total difference of temperature between the water and the air of 13.°5. Since the rate is, by Newton's Law of Cooling, proportional to the difference of temperature, the cooling factor becomes .000000379° F. per second per degree

difference of temperature between the water and the air. The significance of this factor is very great, and will enable us to form some very valuable deductions. The maximum value for the short interval of time from December 1st to 15th will be deduced later. The value of this cooling factor for the period around April 1st, when the influence of the ice is retarding the rise of temperature, has become vanishingly small.

Ice Formation.

Let us now apply the value which we have just deduced to the winter period and make an estimate of the maximum amount of ice that could be produced. We will select a period from the time that Prescott reaches 32°, until the middle of March, i.e., from Decemger 31st, to March 15th, a period of 75 days. During this average period the minimum temperature of the water is maintained at 32° and the average temperature of the air is found to be, from the meteorological tables for that period, 18.°9 Fahr. This gives a difference of temperature, between the air and the water, of 13.°1, which is very close to the average difference which was maintained during the Autumn, when the cooling factor was estimated. Considering the stretch of river between Prescott and Cornwall and that the total superficial area between Prescott and Cornwall is 701,695,000 square feet, of an average depth of 20 feet, we find that the total number of pounds of water existing at any instant of time between Prescott and Cornwall is approximately 880,000,000,000. This is cooling at the rate of .000000-379° Fahr. per second per degree difference of temperature between water and air or losing 333,500 B.T.Us. per degree difference of temperature between water and air. As, however, the difference was maintained on an average of 13.°1, it will be seen that there is being lost during this period, 4,370,000 B.T.Us. per second or being produced, 531 cu. feet of ice per second over the whole surface, which represents, for a period of 75 days, 3,440,-000,000 cu. feet of ice. It makes no difference whether the water is running or stationary, because the cooling effect which we have calculated is independent of the

velocity of flow. If the area was stationary we should have the ice forming at the same rate, slightly diminished by the fact that it would collect on the surface, forming a surface sheet and reducing the cooling factor. The exposed surface being the same whether the water is flowing or stationary, does not alter the amount of ice that will be formed. If the water does not flow there will be no ice accumulated at Cornwall except the normal growth there. The entire ice accumulation of the surface cannot amount to more than this. We know that the bays and shallow places freeze first, and the ice is retained in place. What collects at Cornwall is the run from the flowing river in the open channel less the storage in the bordage ice. Hence this estimate is entirely too great. We know that the open water surface, when there are no jams or packs above Cornwall, is close to 300,000,000 sq. feet, which gives the ice at Cornwall, not deducting the ice caught by the bordage, as 1,420,000,000 cu. feet, which is the maximum possible from the open water during the time from December 31st to March 15th, instead of 3,440,000,000 previously found.

Calculation Under Existing Conditions by the Flow Method.

We can arrive at another estimate of the ice from consideration of the flow. Taking the normal rate of flow for winter as 200,000 second feet, or 12,500,000 pounds, subject to the same cooling factor there would be lost 4.74 B.T.Us. per second per degree difference of temperature between water and air. Where the difference is 13.°1, the heat loss would be 62.06 B.T.Us. per second or .00755 cu. foot of ice produced per second. The amount of ice that is deposited at Cornwall during the time that the water takes to flow from Prescott down, which we have estimated at 14 hours or 50,300 seconds, gives us 378.0 cu. feet of ice per second, when the steady state of flow is reached. If this is maintained unabated for 75 days or 6,470,000 seconds, it gives us a maximum ice accumulation of 2,450,000,000 cu. feet. This estimate is also too high, but it represents a figure beyond which it is impossible to go with conditions as they existed in

1924-25. This method of calculation differs from the other but the value deduced appears very well when we remember it involves the time factor from Prescott to Cornwall. The elimination of the bays and quiet water areas brings down the estimate, as before, to a reasonable figure. Taking 43 per cent as representing the amount of open surface left after the first freezing, then we find the maximum amount of ice formed is reduced to 1,053,-000,000 cu. feet. The difference between this and the first estimate of 1,420,000,000 cu. feet is to be found, probably, in the time factor between Prescott and Cornwall, which we have taken as 14 hours, but which may vary. For instance, if this time interval should be increased from 14 hours to 18 hours, it would bring the amount by this method up to the estimate by the surface method exactly.

The Cooling Factor During Time of Sun Minimum.

For the purpose of local calculations of short duration during the greatest intensity of ice production it is of importance to give an estimate of the increased cooling factor. It must be borne in mind that this is only operative during a very short interval of time and therefore, in estimating the total pack, which might be formed from open water conditions during the entire winter, it would be entirely too high. It is for this reason that I have purposely delayed the calculation of it till after I have utilized the previous average factor for the purpose of estimating maximum ice production. I hope before long to be able to produce a curve of cooling factors to be selected for each period of the year.

In order to accurately calculate the cooling period over the short period from December 1st to 15th, it has been done by getting the average difference of temperature as it exists between Prescott and Cornwall, as shown by the difference in the temperature curves. The average difference between December 1st and 15th, is recorded as 1.7° Fahr., and the average air temperature,

14° Fahr., giving a difference between water and air of 16°. Hence the cooling rate is .106° per second per degree difference of temperature between water and air, that is the result of the time limit of exposure of the entire flow between Prescott and Cornwall of roughly 14 hours, which gives a rate of cooling of .00000211° Fahr. per second per degree difference of temperature between water and air. The amount of ice that would be formed between December 17th and 31st under this cooling factor, may be added to the total amount which we have estimated and will be found in the ice pack, will depend on the time in which the freezing-point travels from Cornwall to Prescott. If we assume that it travels at a uniform rate, then one half the ice formation during this period will be a sufficient approximation. The rate of heat loss will be 421 B.T.Us. for a difference of temperature of 16°.

The factor which was previously calculated for the Autumn period is, as before given, .000000379°; hence the cooling factor during the minimum is considerably greater than the average over the whole ice period. I believe it is far too high, judged by the rate of fall of temperature during the same time at Cornwall, which gives a factor just double the rate during the Autumn. However, as we wish to get the maximum figures, we will use the factor .00000211, when we find the ice formed per second as 0.512 cu. foot. The time interval of flow from Prescott to Cornwall, taken as before as 14 hours or 1,210,000 seconds gives 2,562 cu. feet of ice. But we must take only half of this amount because the average time interval with water at 32° is only 7 days. Hence for the period from December 17th to 31st there is produced an amount of ice not greater than 1,550,000,000 cu. feet. Neglecting bays and fixed ice, from the open channel we will get only 666,000,000 cu. feet. This added to the amount from December 31st to March 15th gives 1,719,000,000 cu. feet as the total possible formation.

For short intervals of time around the minimum or ice producing months, December and January, this

factor may be used and probably represents the greatest ice formation because it is exceedingly unlikely that after February the ice production does any more than balance the ice disintegration.

This is proved very effectively in the curve which we give in Chap. 3, Fig. 15, illustrating the maximum thickness which ice attains towards the end of February and showing that the growth during February is quite small. Further investigation will be required in this subject.

Snow Precipitation.

On account of the important influence which infiltration of snow has on open water conditions, it is important to make an estimate of the total amount which would fall into the river over an area as great as that represented getween Prescott and Cornwall and which in an extreme case would be found to augment the ice pack at Cornwall. This is a simple matter for calculation, by taking the records of precipitation at Kingston, as given by the Meteorological Office, in lieu of any local determination in the International Section. However, the average cannot be very different and it is to this average that we are now devoting our attention. We find by consulting the meteorological charts that the total precipitation over the period of 90 days, December 15th to March 15th, is 5.19 inches. This gives 5.66 cu. inches of snow or .47 cu. foot of ice per square foot of area. Taking the total open channel area between Prescott and Cornwall, which we used before for calculating, we get the total cubic feet of all the snow: 141,000,000, representing the maximum possible amount for the winter of 1925 and which would be added to the pack at Cornwall, except the proportion which would be detained and stored under the bordage ice.

The storing capacity of the bordage ice is a considerable factor in eliminating the amount of ice which reaches Cornwall, as a large percentage is retained and rots in position. Hence we see that as far as estimating the ice pack at Cornwall it cannot be greater than two billion

cubic feet if the entire ice flow for the three months, snow and all, was concentrated there, undiminished by storage along the sides and evaporation when traveling its tortuous path towards its resting place.

An estimate of two billion cubic feet of ice which might finally find itself lodged in the ice pack at the end of the winter, is an outside, conservative estimate of what nature can possibly produce in an average winter. Any estimates of this pack from open water conditions, which are higher than this involve a cooling factor which is very much greater than we have observed or implies an average air temperature very much lower than anything which our records are able to discover. It can be shown by other methods that estimates of the ice accumulated at Cornwall made by a third and quite different method, yield a value almost identical with this.

Influence of Lake Ontario Water on Ice Formation.

It has been already pointed out that the immense heat reserve in Lake Ontario has a controlling influence in the ice formation of the entire river. Long before the St. Lawrence has frozen over the various tributaries have assumed their ice surface. It is a striking feature of the river to notice how the channel maintains itself clear of ice until late in December. Lake Ontario is so large and deep, and is such a great storage reservoir that the duration of the cold weather is not sufficient to lower it to the freezing-point. Ice is made in the shallow bays and along the shores but the main body of the lake never freezes. The mixture of the water by the changing of levels and by convection currents always keeps the surface at a temperature higher than the freezing-point. The deeper parts of the lake are never cooled below the point of maximum density and the entire surface does not reach the freezing-point until long after this point has been reached in the river. In our temperature study we placed an automatic recorder at Kingston, and as a

WATER TEMPERATURES 20TH JUNE, 1925.

No	Depth	Temp.	Location	Time
1	Surface	62.2 °F.	Cape Vincent	5.5 p.m.
2	do	62.2° F.	do	
3	30 ft.	61.0° F.	do	
4	50 ft.	62.0° F.	do	
5	Surface	60.1° F.	Foot of Wolfe Island, U.S. Channel.	6 p.m.
6	40 ft.	59.7° F.	do do	
7	60 ft.	58.8° F.	do do	
8	Surface	60.0° F.	do do	
9	Surface	61.4° F.	Round Island Park, U.S. Channel.	6.30 p.m.
10	50 ft.	61.2° F.	do do	
11	50 ft.	61.2° F.	do do	
12	Surface	61.1° F.	2,500 ft. W. of T.I. Park, U.S.Channel	6.40 p.m.
13	70 ft.	61.0° F.	do do	
14	85 ft.	60.9° F.	do do	
15	Surface	62.2° F.	2,000 ft. E. of Whiskey Shoal, U.S. Channel	7.30 p.m.
16	40 ft.	61.7° F.	do do	
17	70 ft.	61.9° F.	do do	
18	75 ft.	61.9° F.	do do	
19	85 ft.	71.9° F.	do do	

MEMO.

Wind S.W. about 15 miles per hour.

Cloudy until 4 p.m.

Air temperature in cabin 72°, probably lower than that outside.

Note the lowest temperature of 58.°8 in the deep channel in the main line of flow from Cape Vincent.

Note the higher temperature of 62.°2 at Cape Vincent when a south-west wind was banking the warm surface water of the lake in the Cape Vincent Channel.

Note the lower temperature further down stream indicative of the influence of the deep waters of Lake Ontario.

Temperature at Kingston this day, 59°.

check, measurements were made of the temperature of the water at Cape Vincent, which is the deep channel through which the main body of the flow of the St. Lawrence River comes. These temperatures are indicative of a profound influence of the deeper waters of the lake on the water flowing into the river through that channel and in the autumn are higher and in the spring are lower than the temperatures at Kingston, where the great area of shallower water in Kingston Bay makes the temperature fluctuate more quickly. In the accompanying table

is given a list of the temperatures which were made on June 20th at Cape Vincent and vicinity, and localities shown in Fig. 58. We can form some estimate, under

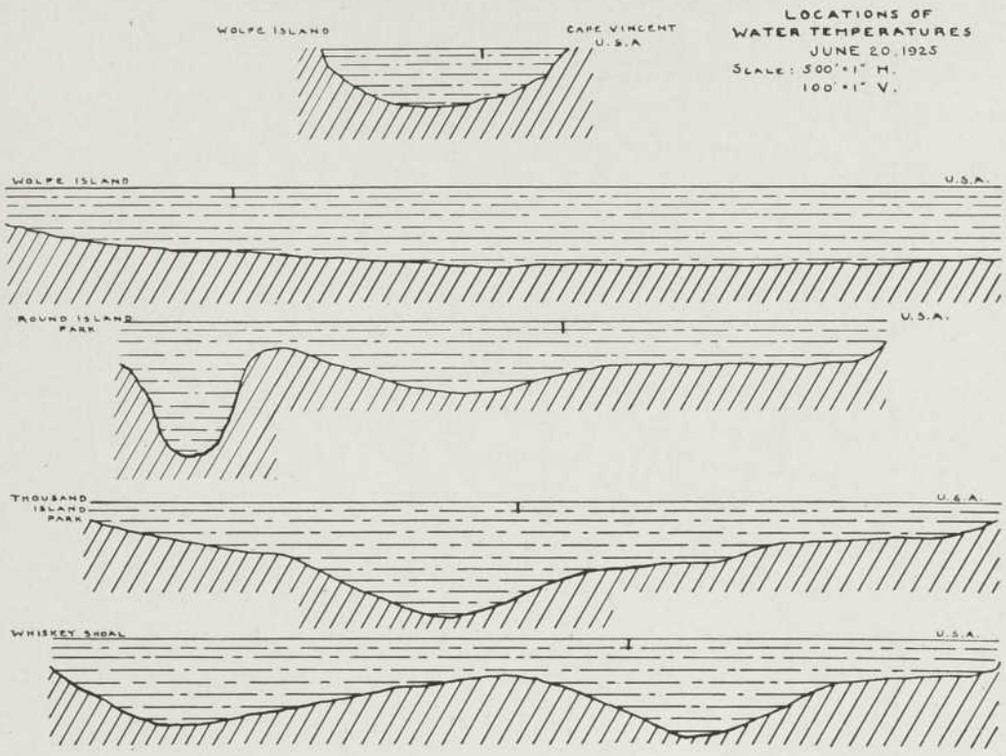


Fig. 58.

present conditions, of what the temperature of Lake Ontario would have to be in order to keep the ice away until the end of January. According to the present rate of cooling it will be necessary to maintain a temperature of 40° at Kingston, in order to keep the river temperature from reaching freezing-point at Cornwall for a period of 33 days. It cannot be more accurately estimated at the present time until more data is available, what the improved conditions would be in the event of Cape Vincent channel being used entirely for the main flow of the river, but it is certain that a greater benefit than it is possible for us to estimate would result by the improved conditions and that it should be possible, by utilizing the deep channel at Cape Vincent, to draw continually on the under water of the lake. No one can possibly foretell the immense benefits to the river channel, which will result from the cutting off of the large areas of the Thousand Islands. All our estimates of ice formation would be

enormously too high and in fact it is not too much to expect, with the improved conditions and the regulating dams whereby the Lake Ontario waters could be controlled, that the ice would be kept out of the river as far as Morrisburg, for the entire winter. As it is now, the river freezes over late in the season above Prescott, but is never known to produce very thick ice, except in exceptionally severe seasons. This area opens up early in the spring and the ice which forms over the main river is so thin as to be unsafe for the greatest part of the time. For the purposes of winter navigation, the effect of this elevated temperature from Lake Ontario, would be felt all the way down to Quebec and it is quite within the realms of possibility, by treating the river at certain strategic points, to have the main river open for its entire length from Lake Ontario to tidewater. The wonderful benefits resulting from this would outweight the cost of its carrying out for the river would be entirely clear of ice early in the spring. Even if it should freeze temporarily at a few points, the areas of open water would be so vastly increased that the returning power of the sun would make itself immediately felt.

Conservation of the Heat of Lake Ontario for Ice Prevention.

It has been already pointed out that the temperature of Lake Ontario is the most important factor in modifying and controlling the temperature of the river water. In turning to the records which are available of the hydrography of Lake Ontario it is impossible to find very much which can be put in a connected way with a study of this kind. The study of the temperature of the Lake from day to day, season to season and year to year, has been entirely neglected. There are records available at the Toronto Water Works and these should prove an important contribution, but this is an isolated station, one locality out of many which should be selected, and it is entirely wrong to base final conclusions on such results.

A temperature survey of Lake Ontario, both surface and depth, is urgently needed. The influence of Niagara River should be studied and the progress of the ice

formation at that point should be carefully noted. The importance of this is very great when we realize that the ice gorges in the Niagara River have their start at the entrance of that river into Lake Ontario.

The exit of the water into the St. Lawrence River is in two channels. The main flow by Cape Vincent on the American shore and the lesser by Kingston Bay and the Thousand Islands. Already a very brief and insufficient attempt has been made to obtain some temperatures in the Cape Vincent channel and these have been referred to already. These were taken on the 20th of June, 1925, and were made with an ordinary thermometer enclosed in a brass case, at the localities selected. The object was to trace the influence of Lake Ontario water during the time that the temperature was rising rapidly in the river, in the surface waters of the Lake and in the main channel passing Cape Vincent. This comes from the deepest sections of the lake and was expected to show a temperature lower than the surface during this period of rising air temperatures. This was verified by readings taken at the foot of Wolfe Island, where the surface was lower than the surface at Cape Vincent, and lower than the surface at other points. The readings taken at a depth of 60 feet were the lowest recorded. The temperatures at Cape Vincent were higher than elsewhere owing to the westerly wind which was blowing the surface waters of the lake down the channel causing the heaping up of the water, with a consequent backwash underneath. This was shown at a depth of 50 feet, where the temperature was practically that of the surface. This backwater effect was not noticeable at the second location at the foot of Wolfe Island. It would be expected that an easterly wind would blow the surface water of the lake away and the drop in level would cause an out flow of cooler underwater down the channel during the spring, and warmer water during the autumn and winter.

Hydrography of Lake Ontario.

Surface Area:

The most recent surveys give the area as 7,243 sq. miles. The U.S. Engineers take 7,260.

Shore Lines:

As a rule the shore lines are regular, with few indentations except at the eastern end where the character of the lake changes. From Prince Edward County, Ont., westerly to Burlington along the north shore, and from thence easterly to a point about 30 miles N.E. of Oswego, N.Y., there is not an island in the total distance of approximately 400 miles. A few sand bars exist which have been formed either as estuaries by small rivers discharging into the lake, or by material eroded at certain points and transported by lake currents.

The N.E. end of the lake is totally different in character having numerous islands, deep bays, and shoals with sand bars. Various theories have been advanced to account for this, but whatever the reason is it is of no practical consequence, as any changes which may now be in progress are not noticeable. The fact that the N.E. end is as it is, would not be of special interest were it not that the physical features have a bearing on the temperature of the water drained off by the St. Lawrence River and this has an appreciable effect on ice formation during the winter months.

Water Supply:

The main water supply, which is also the most regular, comes from the Niagara River, and constitutes about 90% of the total supply.

The drainage basin of the lake provides the remainder, but this supply is irregular, varying from 150,000 C.F.S., down to relatively small quantity.

Water Temperatures.

Intensive studies of this subject do not appear to have been made, nor is the relative effect of the lake's tributaries on the mean temperature known. The discharge received from the Niagara River is colder in winter and warmer in summer than the lake water, which probably accounts for the quantity of ice which sometimes accumulates at the mouth of the Niagara.

As the axis of the lake lies in the direction of the prevailing winds the surface temperatures at the easterly and westerly ends are much influenced by wind. When westerly winds blow, the surface currents carry immense quantities of water into the restricted discharge of the St. Lawrence River at the Kingston and Cape Vincent channels, causing a rise on the guages. Easterly winds of equal velocity do not cause an equal effect on the guages at the west end of the lake owing to the fact that the westerly end is both wide and deep. Temperature readings taken at the west end, near Burlington, disclose that the cooler deep water a long way out from shore is displaced by the warmer surface water. The same undoubtedly occurs at the east end when westerly winds are blowing, and it would be interesting to get velocity readings at the greater depths in the cross section between Prince Edward County and Galop Island.

Sub-aqueous Contours.

Sub-aqueous contours run parallel with the shores and with each other. Along the south shore equal depths are found at about one-half the distance from shore as compared with the north shore, although this is not true of the 60 ft. line which is generally about a mile off shore on the north side of the Lake and a somewhat greater distance from the south shore. The bed of the Lake has a decided tilt toward the southeast, and the south half of the Lake is generally deeper than the other side. On the other hand the 120, 180, 240, and 300 ft., contours approach the south shore much more closely than they do the north shore.

Studies of Heat Conservation for the St. Lawrence.

The great area and average depth of Lake Ontario provides a reservoir of heat which is evidenced by the fact that there is relatively little ice formation along the shores except in shallow and protected localities, and no ice fields whatever in the body of the lake itself.

Under the present undeveloped conditions, the lake water flowing down is at such a temperature that it keeps

the River entirely free of ice during the first of the two ice-forming months of the winter. As the lake water lowers in temperature the chilling of the water in the river proceeds until finally the ice is produced, first at the lower end, gradually working back upstream as the influence of the ice free water of the lake is reduced.

By putting the river under control so as to draw the water down from the lake at a higher velocity during the second of the ice-forming months, the temperature can be kept sufficiently high to prevent the formation of ice during this period, thereby tiding over the critical period until the increasing power of the sun exerts its influence in preventing ice formation.

The summary of our proposals, is to restrict the flow to Cape Vincent down to the main navigation channel, and prevent the chilling of the stream by the admixture of water which now filters through the channels of the 1000-Islands. Preliminary studies show that this can be done comparatively easily and inexpensively, and the effect would be to simplify greatly the ice control works throughout the International Section of the river.

General Description.

The upper St. Lawrence River discharges the water of Lake Ontario through two well defined channels which apparently have not been formed by erosion, but by the elevation of a considerable area of land, of which Wolfe, Grindstone and Wells Islands form the major part. This formation gives broken and irregular lines to the shores and river bed, causing more or less deflection to the line of flow in the channels. On the north and south sides of Wolfe and Wells Islands are restricted sections of nearly equal area. The channel south of Wells Island is about 3 miles in length and fairly straight. The one north of the island is generally wider and more broken in outline than the south channel, and of greater average area except at a point known as the "Fiddler's Elbow." West of Brockville another elevation of the bottom has taken place with channels north and south of the Brock group of Islands. The north channel is

similar to the channel south of Wells Island, but the south channel is mostly shallow, and broken up by islands and shoals.

Physical Characteristics of River with Relation to Ice.

Studies being made of the physical characteristics of the river indicate that it may be practicable to divert a higher percentage of the total flow of the river through the south channel from Cape Vincent to the foot of Wells Island by means of relatively inexpensive fills in the vicinity of the "Elbow" in the north channel without interfering with navigation, or casuing undue velocities in either channel, or obstruction of the deep channel in the "Elbow".

This is important in relation to ice control, for the increased percentage of flow and consequent higher velocities in the south channel would reduce the time factor in transferring the lake water to the Galops reach east of Prescott. Another beneficial effect would be due to the higher channel velocities in the line of main flow east of Wells Island, and to the well known tendency of water to keep going in a straight line instead of spreading out. In fact this is illustrated from Prescott to the head of the North Channel cut, and throughout the river reaches down to Lake St. Francis.

Fills placed in shallow water east of Wells and Grenadier Islands would help to straighten the line of main flow, and would also prevent the undercooled water in those large areas from mixing with the main flow coming from the lake.

At the western end of the Brock group a fill could be placed which would obstruct the discharge through the shallow channel between the Islands and the U.S. shore, confining the total flow of the river to the deep navigation channel north of the Islands where most of it now goes.

Taken in conjunction with the proposed regulated maximum discharge of about 280,000 C.F.S., under im-

proved conditions during the early winter and open channel of considerable width would result throughout the greater part of the south channel of the river from Cape Vincent to the Brock group, and from thence down to Maitland. The undercooled water between Oak Point and the McNair group of Islands east of Brockville would also be rendered more or less stagnant and would have less tendency to mix with the main flow than at present.

Soundings should be taken across the line of main flow and plotted. These will indicate the extent to which it is influenced by changes in the cross sectional area of the channel. With the higher winter flows under improved conditions, it is almost certain that the main flow will tend to concentrate in the centre of the general line of flow, with consequent higher velocities than at present.

Observations should be made with respect to the tendency of the main flow to follow the deeper channels.

A general chart should be prepared as a result of these studies showing:

A. The deep channels along the present line of main flow.
B. The line of main flow, with existing velocities at intervals where change is noticed.
C. The cross sectional area of the main flow.
D. The expected area and direction of the main flow under improved conditions with fills in place, and regulated discharge of 280,000 C.F.S.
E. Anticipated maximum velocities under improved conditions with open water areas.
F. Fills, or other recommended works.

The above work programme is less extensive than might appear at first sight, as the cross section soundings can be proceeded with simultaneously with the float measurements. In any event the soundings can be made irrespective of ordinary weather conditions, the float sections staked out, and general observations carried on in the more protected channels.

Storage of Sun's Heat in Open Water.

The great influence of the storage capacity for heat of open water areas is remarkable. Both in my study of the International Section of the St. Lawrence river, and in the work on the ice-breaking operations on the lower river, everywhere and at all times, the average temperature of the water has been higher throughout the winter in open water.

Water is an almost perfect absorber of solar heat, and an ice surface covered by frost or snow scatters it almost as efficiently. It is true, the sun's heat is very weak during the two ice-forming months of the year, December and January, when atmospheric temperatures are at their minimum, but all effects are made much worse by the covering over of the absorbing areas, and the loss of immense quantities of solar energy.

It is safe to predict that were it found possible to prevent surface ice formation over our water areas during the night, that these areas would absorb enough scattered radiation during the day to help very materially in reducing the amount of ice formed, if not prevent it altogether. Thus a great scheme of heat conservation might be worked out whereby a large amount of the valuable solar energy could be held and stored during the winter, instead of as at present scattered and lost.

It may be a dream for the future, and at present entirely impractical but it is my opinion, some day it may be necessary to work out a method of storage in order to temper the climate of the northern parts of the world.

General Notes on Heat Conservation.

Ice maps which we have prepared of the St. Lawrence have shown that the 18 foot contour is very accurately the limit of extension of the bordage ice over the open water section.

Ice appears to form very readily along the shores and in the bays up to this limit of depth. This is probably connected with the average velocity of flow, for in shallow

reaches of lower velocity the flow is in stream lines with little eddy motion to bring up the under water to mix with the surface. In the deeper parts of the channel the flow exceeds the critical velocity, and eddy motion helps to mix and expose a greater volume of water.

Depth and consequent volume is a large factor in preventing and delaying ice formation. Lake Erie, which is a shallow lake, forms much more ice than Lake Ontario, or the other lakes. This should be kept in mind in designing a power canal for a reduction of exposed surface and an increased depth will contribute very much to a small ice formation. As was pointed out in Chapter 8 it is essential to make as much of the water flow under the surface as possible. The turning up of under water always results in less ice and often ice can be entirely prevented by this means. This is illustrated very frequently in a canal lock when the water flows from low ports and boils up to the surface. Stream line flow will always produce greater surface ice in deep water. In rapids, stream line flow is of little effect since the shallow bed is influenced very considerably more by changes of atmospheric radiation.

In general a power house should be placed parallel with the current in order to allow of a free passage of floating ice. A great deal of trouble from frazil pockets are then avoided. Whenever possible the water should be passed along the intake with an accelerating velocity, because ice will show little tendency to form or stick, when there is less pressure ahead of it. With a retardation of flow, ice rapidly forms and adheres, owing to pressure on the down stream side.

The ideal ice deflector is a skimmer boom along which the water is graded to flow with a gradually accelerating velocity. This not only tends to prevent ice from sticking, but by the well known tendency for water to flow in stream lines under such circumstances, surface ice cannot be drawn down into the entrance so easily.

The greatest ice troubles come where the whole flow of the stream has to be used in the wheels. For such

cases ice troubles are sure to arise at certain times of the year, and can only be cured by a sufficiently long stretch of ice-covered channel above. The cooling factor of evaporation is an important matter to consider at times during open water conditions. Next to radiation it is the greatest ice forming agent. In the Great Lakes it sometimes results in fine surface ice formation even with the under water well above freezing.

John R. Freeman has given us the best discussion of evaporation in his Report on the Regulation of the Great Lakes, 1926. He says in part:—

"It is high time that further research be made with the aid of present-day laboratory resources, of delicate thermometry, of electric heaters, electric fans, electric stirrers, vapor absorbents, air conditioners, refrigerating coils, etc., by which the effect of a change in one cause at a time can be measured, and the confusion of causes plainly evident in data now on record, could be eliminated. It would cost relatively little to provide the necessary outfit and to conduct first a series of laboratory experiments, and to supplement these by further experiments on large tanks, either on a floating raft or on a rigid base on an island, pier or crib, provided with a stirring device to simulate waves and a small heater to keep the tank from freezing over in air at 30° below zero, and by further comparative observations made on ships and ferry boats navigating these waters, which would include the simpler ordinary Weather Bureau station instruments and an improved Piche evaporimeter. Care must be taken that water in the tank represents that in the lake in content of ice and temperature, or to allow for total heat content in Btu.'s per cubic foot.

"The data that are being accumulated at many reservoirs in the semi-arid parts of this country, of depth evaporated per week, or per month, from floating tanks, commonly about 3 feet in diameter, with no accompanying records of wind near water level and no temperatures of air, of water and of dew-point recorded, are of little more than local value, and tell little about the general laws.

"Various algebraic formules of greater or less elaboration, have been written for estimating evaporation from temperatures, humidity, wind movement and barometric pressures, but those so far published do not present any advantage over the original simple methods of Dalton, who made use of no algebraic formula, but simply had recourse to the four fundamentals of:

(1) Temperature of water surface,

(2) Dew-point temperature of the air,

(3) Velocity of wind,

(4) A table of saturated vapor pressures, in inches head of mercury, corresponding to temperatures by the Fahrenheit scale.

"The future formulas may perhaps contain a heat supply factor and a better vapor diffusion factor, but until some short comings are shown by precise experiments, covering a wide range, the Dalton formula promises the best results.

The Dalton law has an advantage that it can be expressed very simply. It may be written:

$E=C\ (V-v)\ (I+KW)$ or $(V-v\ )(C+CKW)$

In which

E is the evaporation in inches depth per 24 hours.

V is the saturated vapor pressure corresponding to the temperature of the water.

v is the vapor pressure corresponding to the dew-point temperature of the air.

C is a coefficient of evaporation determined from experiment for winds less than 3 miles per hour.

K is a coefficient for wind effect.

W velocity of wind in miles per hour.

A formula is given by Dr. Freeman, who states that he finds the simple expression

$$E=(V-v)\ (0.5+0.05W)$$

expresses the results of all of the experimental data that he has found applicable to these conditions around the Great Lakes. Elaborations of the simple Dalton formula thus far rest on extremely insecure, unproved foundations.

CHAPTER X.

GLACIER ICE AND ICEBERGS.

The subject to be taken up in this chapter is one of very wide interest. The literature on Glaciers and Glaciation is so voluminous, that it is hardly possible, or necessary, to review it all in a book of this kind, which has to do more with ice control, and ice prevention. Ranking with the Earth's greatest geological formation, the polar ice is conspicuous. Its interest centers on the remarkable property of distribution over the earth, both in the past in the glacial periods, and present day in the casting off of the accumulations at the two poles.

Icebergs come from accumulated snow and frost as a result of the tremendous pressure over the interior of Greenland, where the great ice plateau reaches a depth of a mile or more. The weight of ice causes a plastic flow towards the edges of the continent resulting in the glaciers, which divide and pass through the fyords along the coast. Some of these glaciers move with great speed towards the sea. A speed of 120 feet a day in summer and 30 feet a day in winter has been recorded.

Vast tongues of ice protrude out into the sea, and are broken off by the buoyancy of the salt water. These broken masses form the icebergs, which are carried southward. The Arctic current moves with a velocity varying from 10 to 30 miles a day, and it therefore takes several months for a berg to reach the southern shipping lanes. Icebergs born in the Winter are held up in the pack ice until liberated the following summer, and do not reach the navigation tracks until the following spring and summer together with those born during the previous

summer. The period free from icebergs, from August to February, represents the period when they are held back in the North during the previous Winter.

Icebergs are composed of fresh water ice and hence when melting rapidly form streams which do not mix readily with the salt water.

Icebergs set up local currents, but do not influence to any extent the main ocean circulation as has been claimed. They affect the ocean current in so far as they form a source of added weight of displacement which causes the arctic waters to rise and flow Southward turning the heated surface waters of the Gulf Stream Eastward. This effect is also aided by the rotation of the earth which causes a massing of the Atlantic sub-waters along the coast of Labrador and Newfoundland.

While a drop of temperature in the sea indicates the presence of colder currents carrying bergs, a rise of temperature frequently follows as a result of the immediate proximity of a berg. This makes it difficult to detect them by the ordinary thermometer especially in the region south of the Grand Banks, where tongues of water from the gulf stream extend for a considerable distance into the colder Arctic current. Icebergs also act as a large pump by sinking the cooled sea water and attracting the warm surface layer.

Various methods of detecting bergs have been tried such as the reflection of sound waves under water, and the focussing of the cold radiation from an iceberg into delicate thermo-elements on a ship, but all of these remain to be proved effective.

Masters of vessels who are used to ice rely on visual signs such as whiteness, echo from the steam whistle, nearness of birds, or small floating pieces of ice. As a matter of shipboard routine sea temperatures are taken every hour in the ice track by dropping a bucket over the side, withdrawing to the deck and inserting a mercury thermometer. This is often misleading, for while the ship is moving the temperature recorded on the bridge may be miles away from the exact spot in which the ship was at the moment of observation.

Proper instruction in ice navigation should form a part of the training of all sea captains using the North Atlantic. It is a fact that the northern routes offer a shorter ice track than further south where the icebergs rapidly break up into smaller pieces, and are carried further afield. A large solid berg can be seen and located easier than the small growler floating low in the water, and offering no surface for detection.

The air which has been pressed into the ice under the great pressure from the masses of snow, comes out when the berg melts and often causes explosions and loud disruption. This air is of great interest since it must have been stored for thousands of years.

Ice water prepared from pieces of iceberg ice will effervesce very much like soda water.

The theory of glacier flow is much disputed, but it has never appeared difficult to understand once the physical characteristics of ice are known. Any substance at or near its melting point on the earth exhibits similar properties, ice, being so much more widely distributed, has come to be regarded as exceptional. All substances show plastic properties when subjected to high enough pressures, and the hardest rock can be made to flow by pressure.

Icebergs are of special human interest, and the physics of them is a special study, which up until the Titanic disaster in April, 1912, was left to navigators and Arctic explorers.

My interest was aroused in these huge masses in 1893, but it was not until 1908, after 15 years time spent in studying the behavior of river ice, that requisite assistance to make actual measurements was obtained. The Canadian Dept. of Marine under the Ministry of the late Hon. L. P. Brodeur gave what assistance they could to these studies. The first expeditions (eight in all) were directed to determining the effect of such large masses of ice on sea water temperatures. This formed the subject of a report to the Government in 1912. The main result of this study was to show how an iceberg in melting, sinks water cooled against its icy sides, and by

acting as a great pump, drains the warmer surface water towards it. Of course the wind and tide influence this, but in no case can a berg exert a surface cooling effect, due to itself alone, except from a copious outflow of cold surface water, which as fresh water tends to flow over the sea.

Even this becomes rapidly warmed by the surface effect of solar absorption, since the vertical convection currents which in normal salt water serve to distribute solar heat do not influence these layers. As warm surface layers are present in the sea, those of highest temperature are forced over first by the hydraulic head towards the ice. Thus the dominant or average effect of an iceberg is to cause the temperature in its vicinity to be higher than elsewhere.

The following chart (Fig. 59) shows this in the temperature survey made outside the Strait of Belle Isle in

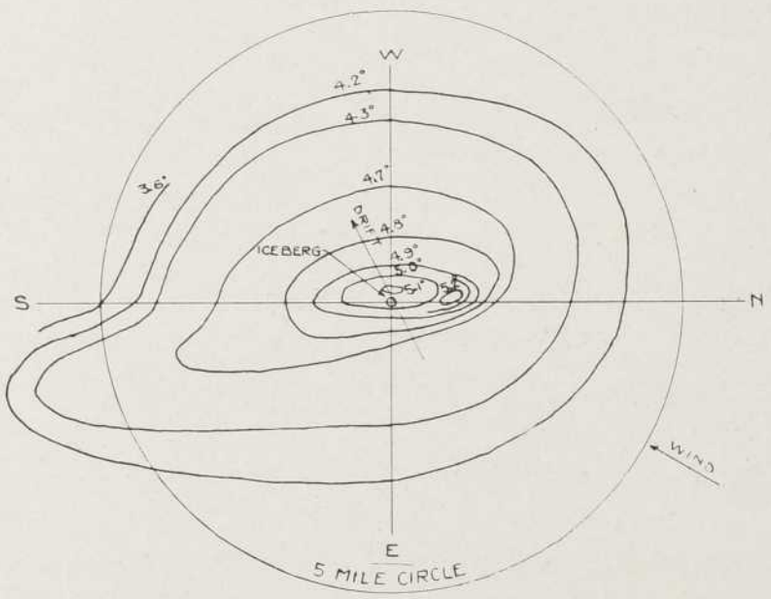


Fig. 59.—Isothermal map of an iceberg floating freely.

1912. Isothermal lines were drawn around a large berg floating freely in the Arctic current and plotted to show their zonal distribution.

Several iceberg expeditions were sent out up to 1913. Not until 1924, however, was the writer able to make further progress with these iceberg studies, when it was

made possible through the kindness of the U.S. Coast Guard to make observations of iceberg melting During this cruise on theU.S. C.G.C. Modoc the idea of using the intense heat of thermit for assisting the disruption of an iceberg first occurred.

The reasons for the anticipated disrupting action of intense heat will now be set forth as briefly as possible. While watching an iceberg break up in 1924 the writer repeatedly observed the sound of cracks much more abundantly in the early morning just at sunrise. It was thought that the sun's rays shining on one side of the ice mass created a state of expansive strain. The heat of the sun was able to penetrate the ice at this hour because the ice surface was dry. The night's radiation having cooled the surface, the water dried up from the natural tendency of a large mass of ice to maintain its inherent cold and freeze. During the day when the sun was high the whole ice surface was running with water and all the heat of the sun was continually washed away. At night the water stopped running, and by midnight the surface was dry and frozen again. It was apparent that the cracking was in some way caused by the sun light on the dry surface and strains set up from the penetrating of the radiant energy. It may be thought absurd to ascribe any potency to rays so weak as those from the rising sun, but the immense influence of the very weak rays in the sky, even before sun-up, on the anchor ice of the St. Lawrence, where hundreds of tons of ice are brought up every morning in the winter, makes it no longer a matter of surprise to find an influence in this case of the sun on the dry iceberg surface. It seemed then quite reasonable to look for results from a quick application of powerful heat to an iceberg, and by this means set up a heat wave in the mass to cause thermal strains. In the spring of 1926 we at last succeeded in arranging a party for a trip to the east coast of Newfoundland for the purpose of applying the thermit heat units to some icebergs. This work was organized as a private venture and, apart from the courtesy of the Government of Newfoundland kindly admitting equipment and materials free of duty, received no aid from any government.

Iceberg Experiments.

In all, three icebergs were treated with thermit. These were selected from 45 large bergs off the coast of Newfoundland at the twin islands of Twillingate in Notre Dame Bay. (Fig. 60) The first one was a large



Fig. 60.—Twillingate Harbour with icebergs in the distance.

berg 500 feet long and as many wide, floating freely out at sea with cliffs rising 75 feet in the air. A long plateau enabled the writer to climb on easily with the aid of a scaling ladder and the equipment to be hoisted up with ropes. (Fig. 61.) Calked shoes and life belts served to make the sojourn on the bergs safe. A dory was used to land while a motor cruiser carried the party out to sea and remained at a short distance away to watch the berg and give warning of any instability. The icebergs are of such enormous mass that they turn over very slowly and ample time is always available to get off even if one should start to turn without first giving warning by the falling off of a cliff or overhanging mass. The cruiser's whistle was the signal to retreat.

The thermit was placed in a galvanized iron container made for the purpose with lined walls. The can was sunk into the ice three feet and filled in place with thermit.



Fig. 61.—Method of landing on an iceberg.

It was very uncomfortably hot working on the bergs, which made it difficult to work fast. The cans were fused and when started, the party removed to the dory and then to the cruiser to watch the result of the shot. Only one charge of 100 pounds was placed in the first berg, but this reacted perfectly, causing a very powerful explosion of the ice, which disintegrated a great part of the large plateau. (Figs. 62 and 63.) Immediately after cracks were heard which continued all during the evening, and towards morning, about 2 o'clock, a very loud cracking awoke many people in the village. On visiting the berg the next day a great part of the inside had come out between the thermit hole and the main cliffs and most of the plateau, 400 feet long, was gone. In two days the disruption thus started went on and the iceberg once so grand and firm became a poor shadow of its



Fig. 62.—Ice exploding under a charge of 100 lbs. of thermit.



Fig. 63.—Masses of iceberg broken off by the explosion.

former self, breaking up rapidly and turning nearly completely over. No other charge was put in to complete



Fig. 64.—Same iceberg as Fig. 62 two days after use of thermit.

the disruption, for the writer did not like the look of the ice and thought it more prudent to try other bergs. (Fig. 64.)

The second iceberg treated was one grounded in Jenkin's Cove in Twillingate harbor. (Fig. 65.) This was selected in order to give the people of the village a chance to see the beautiful sight of a burning iceberg. A natural ampitheatre was provided by the high cliffs all around the cove. During the day a large charge of thermit, 500 pounds, was sunk into the ice and in the early evening just at sundown it was fired. Those who saw the spectacle will never forget the wonderful sight as the charge roared and flamed hundreds of feet into the air with the exploding ice scattering fire and sparks for hundreds of feet on either side. (Fig. 66.)

Vesuvius in eruption was the nearest approach to this unique sight. The effect on the ice was the same as

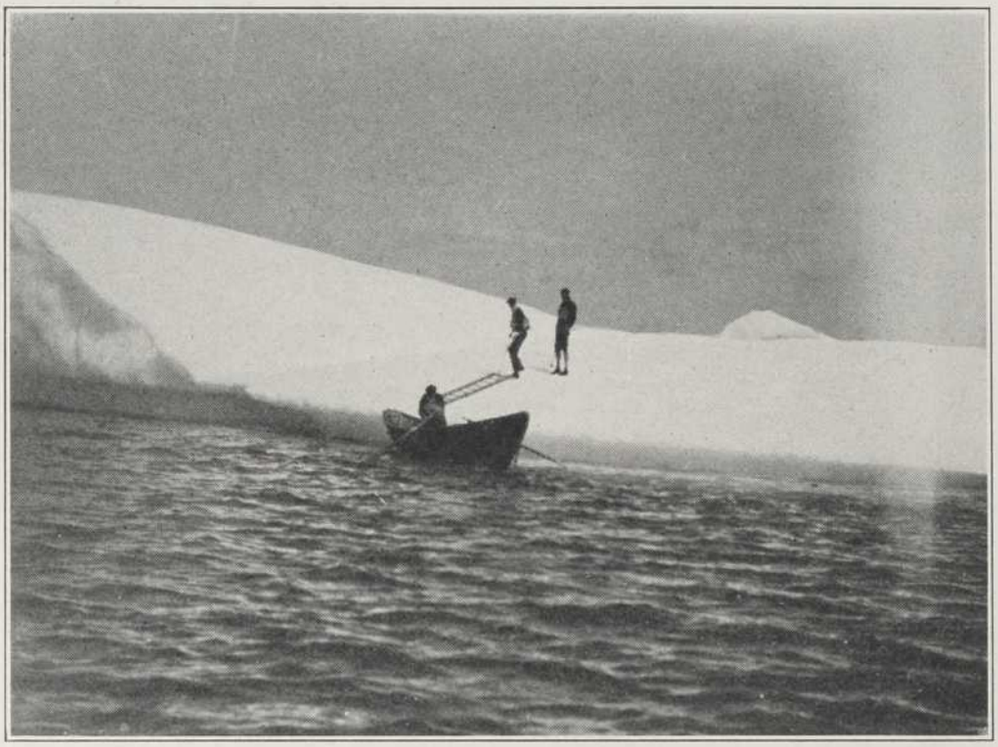


Fig. 65.—The second iceberg being prepared for a charge of 500 lbs. of thermit.



Fig. 66.—Iceberg exploding and burning under the fierce heat of a thermit charge.

before. The explosion disrupted a great deal of ice, but the intense heat wave cracked and honeycombed the mass and during the night and all of the next day the berg continued to fall to pieces, rolling to one side and the other as the mass was lightened by the falling pieces. (Fig. 67.) An attempt was made the next day to put



Fig. 67.—Same iceberg as in Fig. 65 next morning after the treatment.

a charge of high explosive on the ice to see what a sudden shock would do to the rotten ice, but a large mass fell into the sea directly in front of the dory and it was considered far from safe to venture on.

The third experiment was made on a medium-sized berg off the North Island. (Fig. 68.) This was grounded alongside of three icebergs and from its massiveness and shape served our purpose very well. It had the appearance of an inverted tea-cup. The ice was very hard and firm and showed no sign of disintegrating. Two charges were put off on the very peak of this berg, one of 60 pounds and the other of 100 pounds of thermit. Both charges exploded the ice (Figs. 69 and 70) but no

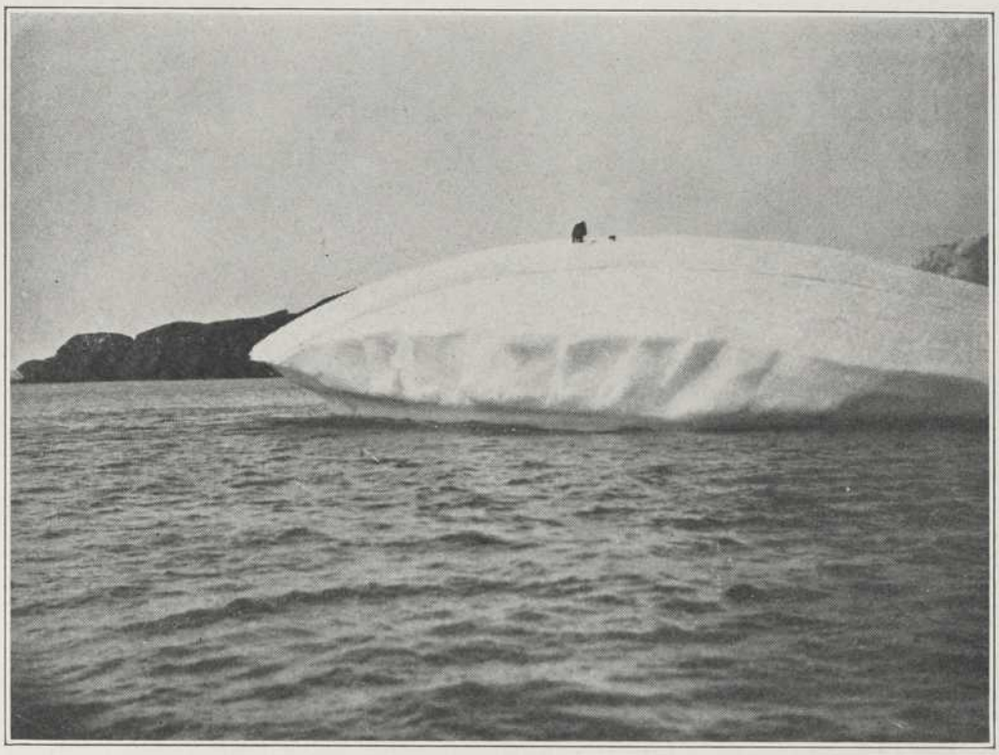


Fig. 68.—Third iceberg to be treated with thermit. Lighting the fuse for the first charge.

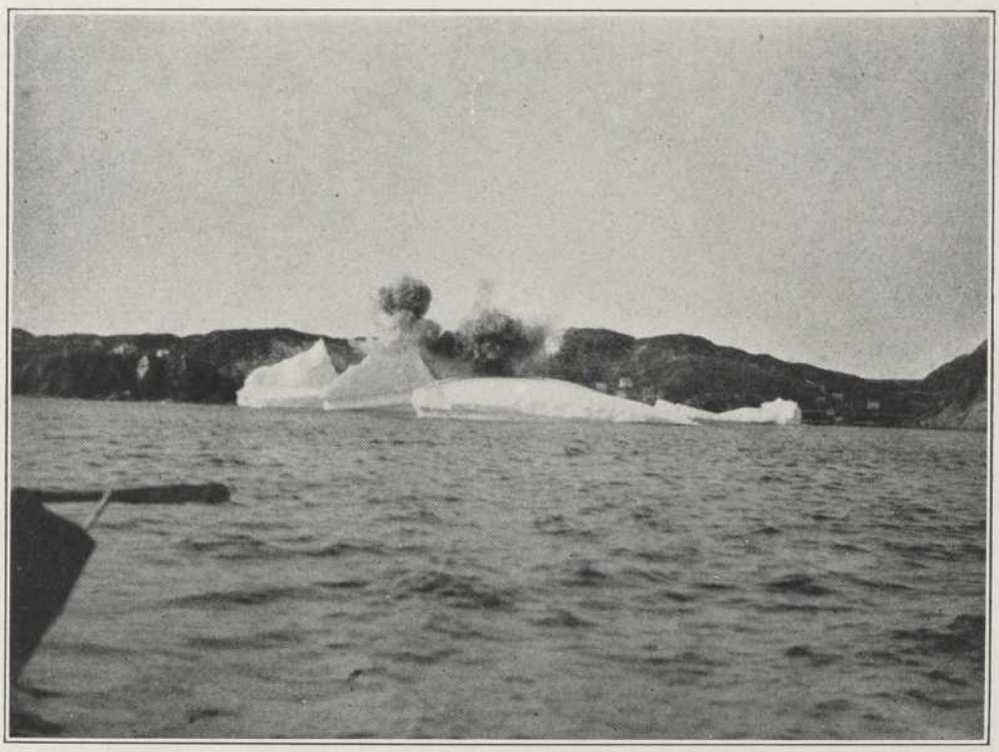


Fig. 69.—Iceberg exploding under the first charge of 60 lbs. of thermit.

ice was knocked off by the force of the explosion. This occurred about six o'clock in the evening. In the morning the writer with his party visited the spot to inspect the result of the treatment, but the iceberg had disap-

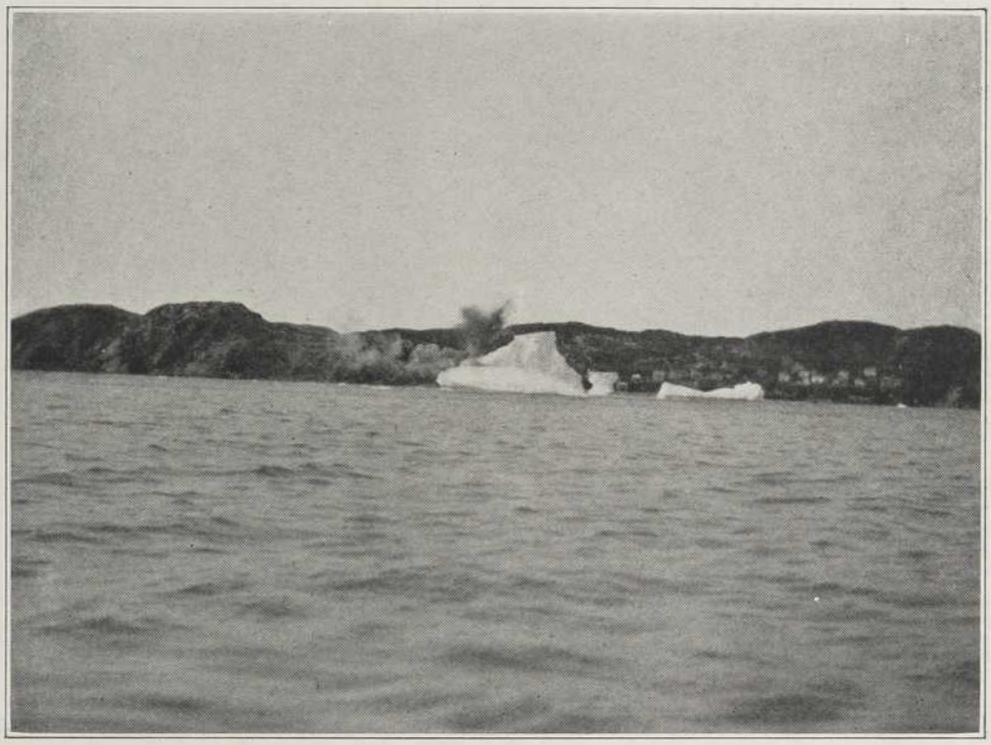


Fig. 70.—Iceberg exploding under the second charge of thermit.

peared and could not be found for a long time, until sufficient evidence was found that it had not floated away from the spot because a fragment was located floating in the vicinity, which contained marks of the thermit slag together with a part of the hole made for the thermit can half submerged under the water line. (Fig. 71.) This hole had been cut on the top of the berg 30 feet above the water line and been blown out funnel shaped by the explosion, easily located by this peculiar shape. The three other icebergs in this place were still in position and had not broken up. No better evidence of the peculiar nature of the heat action could be found. The writer's party left for home that night well satisfied with the results of the experiments.

There is no question of the wonderful effectiveness of the heat treatment to control the iceberg menace, for the action of the thermit heat units are most effective

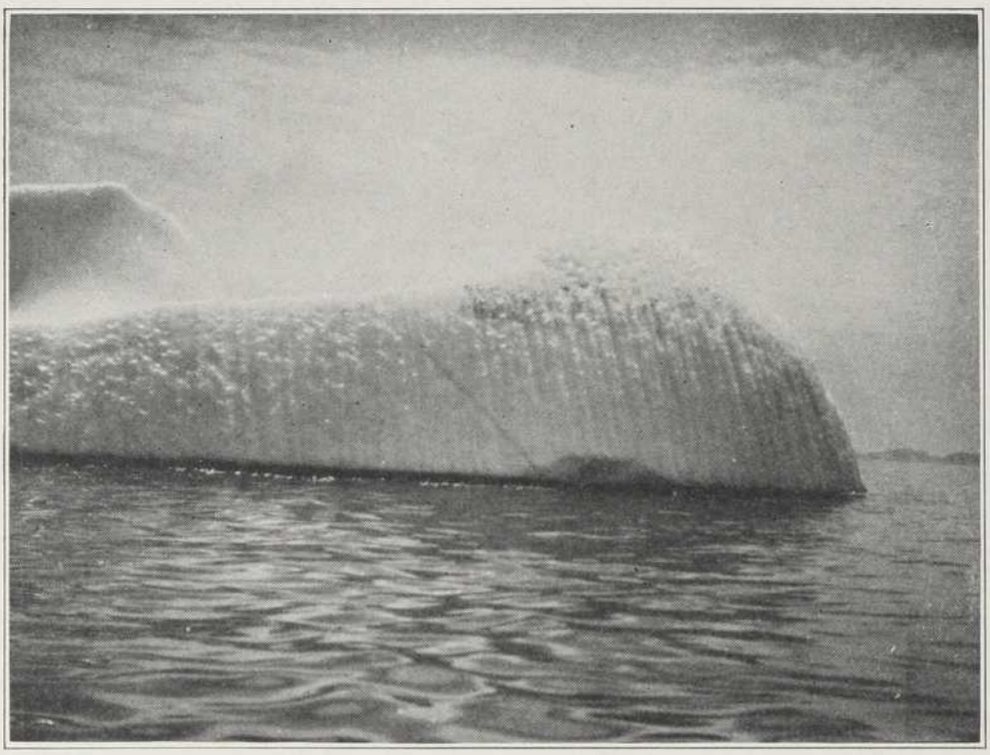


Fig. 71.—Fragment of disrupted iceberg shown in Fig. 68.

in the hardest and most resistant ice masses. Our experiments with high explosives verified the results obtained by the U.S. Coast Guard that they have little or no effect on these solid masses of ice. The action of the heat is quite different; it sets up the thermal expansion strain which causes innumerable cracks and fissures through which the sun and melted ice water gain access, causing the falling apart of the ice wherever the heat has been applied.

Physical and Chemical Properties of Icebergs.

We have gathered information on the purity of the iceberg ice, and the amount and quality of the air compressed in the berg. By inference the density of the co-volume of ice and air which composes the bulk of the iceberg was obtained.

This chemical work has been done entirely by my son, Dr. W. H. Barnes, Demonstrator of Chemistry in McGill University, now Ramsay Memorial Fellow Royal Institution, London.

Comfortable quarters were given us in the Notre Dame Bay Memorial Hospital situated at Twillingate, which was the headquarters during the stay in Newfoundland. The director, Dr. Charles E. Parsons, was most kind in giving us a room for a laboratory. The photographic rooms connected with the X-ray department of the hospital gave us an opportunity for developing the color plates which were made to show the wonderful deep blue and green of the ice masses. The Agfa color process plates were found very satisfactory.

Result of the Chemical Tests.

Total Solids—About one litre of water was evaporated to dryness in a weighed platinum dish, and the dish and residue was re-weighed. The following results were obtained:—

Nature of Water.	Volume Evaporated.	Residue.	Total Solids. Parts per (100000)
Melted iceberg ice.....	1079 c.c.	0.0045 gms.	0.41
Distilled Water.....	1044 c.c.	0.0055 gms.	0.52

The residue, which in each case was black and insoluble in water, was probably made up of dust particles from the air accumulated during the evaporations.

Relative Volume of Air in Iceberg Ice.

A large test tube having a thin paper strip down one side was partially filled with toluene and placed in an ice-salt freezing mixture. When the temperature of the toluene had become constant its level in the tube was marked on the paper strip. A piece of iceberg ice was then quickly dried with filter paper and placed in the toluene, the new level of the toluene being marked on the paper strip as before. The piece of ice was then rapidly transferred by means of a long forceps to a bath of melted

ice water at room temperature, where it was allowed to melt under an inverted funnel.

The air on escaping passed into an eudiometer tube, where it collected by displacing the melted ice water with which the tube was filled. Care was taken that no bubbles adhered to the stem of the funnel, or the walls of the eudiometer tube. The volume of air collected was read at atmospheric pressure from the graduations on the eudiometer tube.

The volume of the ice was obtained by replacing the toluene in the large test tube by water run in from a burette, the volume between the two marks on the paper strip being carefully noted.

The following results were obtained with two samples of ice:—

Temperature of Toluene.	Volume of Air (reduced to temperature of Toluene.)	Volume of Ice and Air.	Per cent. Volume of Air.
—0.8 C.	0.28 c.c.	1.85 c.c.	15.1
—2.1 C.	0.55 c.c.	7.4 c.c.	7.4

The calculations involved in the above results assume that the air in the samples of iceberg ice is at atmospheric pressure. Observations of the behavior of the ice on melting, and the sizes of the bubbles in the ice, and after being released from the ice, support this assumption.

Analysis of Air Enclosed in Iceberg Ice.

Ground-glass stoppered bottles of about 500 c.c. capacity were filled with melted ice-water and inverted in a bath of melted iceberg ice. The iceberg ice was allowed to melt under a funnel, the stem of which passed through a rubber cork into the neck of the bottle to be filled. Two of the bottles were completely filled with the air, whereas three others were sealed up with water. The ground-glass stoppers were wired to the bottles and sealing was completed with paraffin.

At a later date the bottles were opened under water which had previously been aerated for 10 hours. A long

bent glass tube filled with water was inserted through the neck of the bottle into the gas, the other end being connected to a gas burette. A sample of the air was taken and analysed for carbon dioxide and oxygen in the usual manner, using the Hempel apparatus; potassium hydroxide and alkaline pyrogallate were employed for absorption of carbon dioxide and oxygen respectively.

The following are the results obtained, together with particulars of each sample:—

Sample 1.—Air from growler shortly after it broke away from berg, collected over sea water at 46.°5 F. Sealed up with sea water in bottle.

Analysis:—

CO_2	0.0 per cent.
O	20.0 "

Sample 2.—Air from growler collected over melted iceberg ice without regard to temperature of bath. Sealed up with water through which bubbles passed.

Analysis:—

	CO_2	O
1	0.2 per cent.	17.7 per cent.
2	0.0 "	17.9 "
Mean	0.1 "	17.8 "

Sample 3.—Air from growler collected over melted iceberg ice. Temperature of bath, 40°-45° C. Bottle completely filled with air.

Analysis:—

Mean of six analyses agreeing with one another to 0.6 per cent. oxygen.

CO_2	−0.1 per cent.
O	19.0 "

Sample 4.—Air from 2 feet below surface of berg collected over melted iceberg ice. Temperature of bath, 45°-50° C. Only a very small sample (23 c.c.) of air was collected. Bottle sealed up containing water from the bath.

Analysis:—

CO_2	0.4 per cent.
O	13.8 "

Sample 5.—Air from growler collected over melted iceberg ice at temperature of 40°-45° C. Bottle filled completely with air.

Analysis:—

Mean of six analyses agreeing with one another to 0.6 per cent. oxygen.

CO_2	−0.1 per cent.
O	18.8 "

With regard to the determination of total solids, it will be seen that melted iceberg ice is at least as pure as distilled water. At some future date it is planned to make conductivity measurements on this water.

The two determinations of the relative amount of air contained in iceberg ice are only approximate because of the difficulty in reading such small volumes of gas in the eudiometer tube, which was only graduated to tenths of a cubic centimetre. The next determinations will be made with a specially constructed tube of small bore, with which readings can be taken to a further number of decimal places. The values already found, however, are probably a minimum because the ice on melting undoubtedly dissolved a small fraction of the air liberated. There was probably very little loss of air from the bubbles passing through the water in the eudiometer tube, because it was obtained by melting iceberg ice and allowing it to stand in an open pail for some length of time before use as a bath.

It is also planned to make tests at some future time on the relative amount of air at different depths through the bergs.

The air analyses indicate that the air contained in the iceberg ice has probably the same composition as the atmosphere at the present day.

The peculiar values for carbon dioxide obtained are due to experimental error. The carbon dioxide found was zero after the first few analyses due probably to the fact that the air sample was allowed to remain in the gas burette for 15 to 20 minutes before passing into KOH. This enabled it to come to the temperature of the room before the first volume was read. A very slight change in temperature would have a marked effect on the volume of the gas, since in most cases from 50 to 100 c.c. were used for each analyses.

That the composition of the air is probably the same as that of the atmosphere of the present day is shown by the following rough calculation.

Taking the results of Sample 3, namely 19.0 per cent. oxygen and neglecting the value for carbon dioxide recorded and assuming that the relative volume of air is, say, 10 per cent., then the relative amounts of oxygen and nitrogen in the original air are given by $(0.19 \times 100) + (0.0045 \times 1000)$, for oxygen at 40°-45° C. from air is equal to $\frac{1}{5} \times 0.0225$ vol. of O_2 per vol. of water and $(0.81 \times 100) + (0.0092 \times 1000)$ for nitrogen, since the solubility of the nitrogen at 40°-45° C. from air is equal to $\frac{4}{5} \times 0.0116$ vol. of N_2 per vol. of water.

The amount of oxygen in the original air is then equal to

$$\frac{(0.19 \times 100) + (0.0045 \times 1000)}{[(0.81 \times 100) + (0.0092 \times 1000)] + [(0.19 \times 100) + (0.0045 \times 1000)]} = \frac{23.6}{113.7} = 20.7 \text{ per cent.}$$

assuming saturation of the iceberg ice with oxygen and nitrogen as it melts.

The slightly larger value of 20.0 per cent. oxygen obtained for sample 1 is probably due to the lesser solubility of air in sea water. The lower value obtained for sample 2 can be accounted for by the fact that no attention was paid to the temperature of the bath, and consequently it was usually at a much lower value than for samples 3 and 5.

Samples 3 and 5, although from growlers from different bergs, were collected in exactly the same manner with the temperature of the bath maintained 40° and 45° C.

The results obtained for the two samples agree closely with one another.

The peculiarly low result obtained for sample 4 may be due to experimental error because the sample obtained was only 23 c.c. Unfortunately, no check could be made on this sample. The result, however, remains interesting, although not necessarily of special significance. It is hoped that at the next opportunity of obtaining iceberg ice a chamber capable of being evacuated will be available. The ice will be broken up by a magnetic crusher in vacum and the air collected and analysed very carefully over mercury. It is also planned to collect samples of the air from different depths in the berg in this way.

The Microthermometer.

The advantage of the microthermometer, which makes it different to all other temperature recorders, used by other observers in marine work, is freedom from lag. The main principle of the Electrical Microthermometer is a high resistance iron wire coil, in which the changes of resistance with temperatures are recorded on a special recorder made quick acting in its mechanical parts. The relay, or galvanometer system, is made from a Weston portable galvanometer, and the contacts are revolving wheels of chromium plated metal. The needle also is chromium plated. The extreme sensitiveness of the chromium contact is worthy of note here. It is vastly superior to platinum, and better than gold. No other metal which the writer has used shows so small a contact resistance.

The bulb of the thermometer is made as free of temperature lag as possible and this has been found to a thousandth of a degree to be not more than 10 seconds for a change of 10 degrees. This feature is essential in Marine work, since a moving ship equipped with the ordinary means of temperature measurement, is many miles away from the indicated temperature. Not only

that, but a record of sea temperature made by an ordinary recorder is only an average over any given range, and is no criterion of the exact temperature at any one locality, at any instant of time. For iceberg detection the instantaneous reading is essential. Then the recorder must be very light in its moving parts so that no lagging behind of the recording pen is noticed. In other words the pen must at each instant give the true reading. This the writer found was wanting in all the usual temperature recorders which he tried. While this lag is of no account on a steadily changing temperature, it is fatal for conditions which prevail in the ice where a ship passes rapidly from a high to a low temperature many times a minute.

A mercury microthermometer has recently been made for the writer by Messrs. Negretti & Zambra, of London, which depends merely on the expansion of mercury in an extra large bulb. This instrument is a marvel of workmanship and should prove to be of great help in ice navigation.

The International Ice Patrol.

In 1913 the International Ice Patrol was established by the Maritime Nations to study and report on the ice in the North Atlantic steamer lanes. This has been under the direction of the U.S. Coast Guard, Admiral F. C. Billard, Commandant. The very fine work done by the U.S. C.G.C. Tampa and Modoc is described in the yearly reports of the Ice Patrol. As a result of this study some interesting conclusions are arrived at as to the forecasting of the number of icebergs, which may be expected each year from the relationship between the varying amounts of Arctic ice from year to year since 1913 and meteorological events occurring in the North some months previously. In Bulletin No. 16, Lieut. Commander E. H. Smith describes the results as follows:

"It appears logical to believe that the prevailing direction of winds over the Labrador-Greenland region, when expressed in terms of departures from normal, and considered in monthly periods, would be reflected sometime later in the variations from normal in the amounts

of ice. It has been found best throughout the investigation to work with differences from means, and this fact should be kept in mind by the reader.

"The first factor, consisting of the atmospheric pressure differences between two points taken across the line of drift of the ice on its journey to the southward, is being furnished by the United States Weather Bureau in the form of monthly mean pressure records from meteorological stations scattered around the shores of the North Atlantic. Observations points even in Greenland are now connected with the outside world by radio, a fact of great importance to the success of this particular ice forecasting problem.

Maps showing the anomaly isobars, one map for each of the months, October, 1926, to March, 1927, give a pretty fair picture of events leading up to the ice season of 1927. It is plain, for example, that during October, 1926, meteorological conditions were less favorable than they usually are for Arctic ice to drift southward into the Atlantic. December, 1926, the winds were more or less neutral, but November, January, February, and March were more favorable than ordinarily to a greater abundance of ice appearing in the spring of 1927 than is normal.

"A more accurate method of measuring the value of the meteorologicla factor was found by our investigation to be an equation.

$$\text{Bergs} = 4.8 - 0.08\ (c) - 0.12\ (d)$$

where the number of bergs is expressed as a value $0 - 10$; c represents the pressure difference in millibars between Belle Isle and Ivigtu; d represents the pressure difference between Stykkisholm and Bergen. (For details of the values see Bull. No. 15, p. 48.)

"A forecast was made in a letter, March 11, 1927, to the chairman of ice patrol board, that about 396 bergs would drift south of Newfoundland during 1927, or field ice and bergs somewhat in excess of that during a normal year. As a matter of fact we now know after a careful check that the number of bergs for the danger season, March to July, was 367, and about 390 for the entire

year, and thus the forecast was quite accurate. The number of bergs may vary within wide limits; for example, in 1912 there were 1,200 and in 1924 only 11.

THE END

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