Schneider

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# ENGINEERING AND DESIGN

# ICE ENGINEERING

DEPARTMENT OF THE ARMY
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| | | |
|---|---|---|
| E | = | Young's modulus |
| F | = | Fahrenheit |
| $F_R$ | = | Froude number |
| f | = | Friction factor or force |
| g | = | Acceleration of gravity |
| H | = | Depth |
| h | = | Ice thickness |
| $h_t$ | = | Heat transfer coefficient |
| $h_j$ | = | Thickness of ice jam |
| k | = | Empirical coefficient |
| L | = | Length |
| m | = | Meters |
| n | = | Roughness coefficient (Manning's "n") |
| P | = | Pressure |
| p | = | Wetted perimeter |
| Q | = | Discharge |
| R | = | Hydraulic radius |
| $R_n$ | = | Reynold's number |
| S | = | Hydraulic slope |
| s | = | Seconds |
| T | = | Temperature |
| t | = | Time |
| U | = | Wind speed |
| V | = | Velocity or volume |
| Z | = | Accumulated freezing degree-days |
| $\alpha$ | = | Angle |
| $\beta$ | = | Angle |
| $\gamma$ | = | Specific weight |
| $\theta$ | = | Porosity |
| $\lambda$ | = | Latent heat |
| $\rho$ | = | Density |
| $\Sigma, \sigma$ | = | Strength |
| $\tau$ | = | Shear stress |
| $\sigma$ | = | Stress |
| lbf | = | pounds force = (lbm) x (32.2 $ft/s^2$) |
| lbm | = | pounds mass |

# CHAPTER 2
# ICE FORMATION AND CHARACTERISTICS

## Section I. Ice Types

2-1. Introduction. Ice occurs in a number of forms which are not familiar to everyone. The following details about the material should be reviewed before any effort is made toward the study of ice or its effects.

a. Ice grows in hexagonal crystals. There are three "a" axes of symmetry in what is called the basal plane and one "c" axis perpendicular to the basal plane. An ice crystal looks like a pencil, with the "c" axis as the lead. When a calm body of water starts to freeze, the crystals nucleate with axes oriented randomly, but since growth is easiest along the "a" axes, crystals with horizontal "c" axes grow faster and gradually, with increasing ice depth, predominate. However, ice crystals with vertical "c" axes are also common. Crystal growth is a natural refining process that rejects impurities, such as the salts in sea water. Most impurities stay in the unfrozen water, but some are trapped between the individual crystals. Because of the trapped impurities, melting begins at the crystal boundaries and a phenomenon called candle ice often develops. In candle ice, innumerable single crystals are no longer frozen together, but rather are leaning on each other for support. A small wave can collapse the entire mass like a line of dominoes.

b. Much of the ice on a lake or river takes a different form called snow ice. This material is granular, opaque, and white. There are no large crystals so melting is not as spectacular a process; there is no candling. Snow ice is formed when a snow cover is saturated by rain or by submersion in a lake. Compared to crystalline ice, snow ice has more grain boundaries which makes the ice weaker, and it is isotropic. Snow ice and massive, consolidated frazil slush look much the same. Frazil ice, which will be covered in more detail later, results from small particles of ice forming in supercooled, turbulent water.

2-2. Sea Ice. Sea ice is quite different from freshwater ice. While it is growing, plate-like crystals form a mushy layer about 1 inch deep that precedes the ice front downwards. Some seawater is trapped between these platelets, leading to many liquid inclusions or brine pockets in the ice. As the ice gets colder, water freezes to the walls of these inclusions and the brine becomes more concentrated; as the ice warms, the walls of the inclusion melt and dilute the brine. Since these pockets are part of the total ice cross section, the strength of sea ice varies more dramatically with temperature than that of freshwater ice. In passing it should be mentioned that seawater (3.5 percent salts) freezes at 29°F and is most dense at 29°F, unlike fresh water which is most dense at 39°F. As we all know, water expands when it freezes, unlike most other materials. However, once it is ice, it shrinks as it gets colder like any other material. The bottom of an ice cover is always at the freezing point since it is in contact with water. Changes in air temperature, therefore, result in bending and thermal cracks. The effect of these thermal cracks on the engineering properties of ice is not well known.

2-3. Frazil Ice. Frazil ice occurs in two distinctly different states: active and passive. The active state occurs in supercooled water as small ice nuclei form and grow into discoids of limited size. Typical supercooling in natural bodies of water is within several hundredths of a degree below the freezing point. The limit of the discoids' size is dependent upon growing conditions but usually does not exceed about an inch in diameter by a few tenths of an inch in thickness. The active frazil is highly adhesive. As the water temperature rises to the freezing point, discoid growth is curtailed, and the passive state occurs. The discoids then lose their adhesiveness.

a. Frazil ice production requires both supercooling and nucleation. An ice cover inhibits supercooling by insulating the water from radiative and convective heat loss. Any supercooled water passing under an ice cover will freeze to the cover itself instead of forming frazil. Some investigators believe that frazil production takes place in a thin surface layer of supercooled water. An ice cover precludes the existence of such a layer. Surface turbulence, caused by wind, flow patterns, or other factors, will prevent an ice cover from forming and increase frazil production.

b. Any reasonably fast flowing (2.0 feet per second (fps) or more) stream can be considered a frazil producer when air temperatures are below about 20°F. Lakes and reservoirs, where waves provide surface turbulence and mixing, also produce frazil.

c. In addition to boundary growth, active frazil particles may agglomerate. Active frazil will remain in suspension until the buoyant effect of increasing size overcomes the submerging forces of gravity and turbulence. If the frazil surfaces in below freezing weather on open water, it will continue to agglomerate. Field observations indicate that as the stream velocity slows and allows the frazil to surface, the surface turbulence decreases and allows formation of an ice cover. Frazil may then accumulate under the existing ice cover to form an obstruction called a hanging dam.

2-4. Hanging Dams. A hanging dam is a downward projection under an ice cover formed from active frazil. Brash ice brought downstream during the formation of the dam sometimes lodges in the frazil. Frazil particles will continue to accumulate into a rigid structure until some force overcomes the bonding process (Figure 2-1). The bonding process is usually overcome when increasing water velocity (due to the decreasing cross-sectional area of the stream) is sufficient to carry frazil particles under the dam faster than they can attach to the body of the dam.

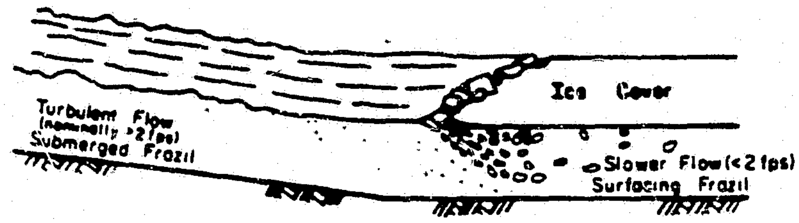


Figure 2-1. Formation of a hanging dam.

a. The growth of a dam may cause dramatic scouring in the river bed as bottom sediment is eroded by the increased water velocities under the dam. As with any restriction to flow, hanging dams tend to cause backup and reduce the water level downstream. In Alaska these dams have broken loose during freezeup and caused some flooding. During breakup, jamming can occur for miles behind a dam, and an excessive head upstream may be required to break through the dam site. Failure of the ice at the site is primarily a function of the watershed runoff. If runoff is gradual and consistent, the dam may "rot" in place. On the other hand, if the diurnal melt is significant, the chance of a head buildup behind the dam increases. If the head is sufficient, a dam may fail dramatically, causing large ice runs and associated flooding. The head buildup may be required simply to dislodge and move the large mass of ice at the dam site. Shear failure often occurs on the sides or bottom because of the different channel dimensions at the site. If the runoff is such that the frazil body of the dam is allowed to gradually rot, the bottom shearing and head buildup are reduced or eliminated. Under heavy spring runoff conditions, it has been reported that dam breaks have run 25 miles of river.

b. Dam formation has been unofficially enhanced at particular sites in order to control downstream levels. This use of dams is marginally effective because of the diversity of freezeup patterns in most rivers and streams.

c. Detection of hanging dams was previously limited to the recognition of characteristic sites. Often dam sites are characterized by a hummocked surface, similar in appearance to that of an ice jam during breakup. This has been determined to be an effect of the buoyancy of a rapidly growing dam under a reasonably thin ice cover. This characteristic will normally be somewhat obscured by the season's snow cover since the surface is formed in early winter. These sites are typically deeper, broader areas in the channel where a significant reduction in flow rate is observed. They must be preceded by a frazil-producing area. Manual sounding has been the only method available for widespread mapping of ice accumulation. During the past few years a radar ice-thickness profilometer has been tested by CRREL under various circumstances to determine its applicability for frazil ice detection and ice thickness measurements in fresh water. The results of the field work were encouraging. Such an instrument used in a remote sensing role was shown to be advantageous for investigating a large or relatively inaccessible area and for searching out areas of ice accumulation. The system evaluated is commercially available (being used for near surface geophysics), but is still in the developmental stage for ice applications.

2-5. Other Frazil Problems. In its active state, frazil will adhere to nearly all submerged objects, clogging channels, trash racks at hydroelectric generating stations, municipal water intakes, and other submerged structures.

a. Submerged objects can be protected from active frazil. Techniques include the use of low thermal conductivity materials and "sacrificial" coatings such as a special silicon grease. The obvious way to eliminate ice adhesion is to heat the submerged object. In some cases, the resources are available within a plant. For example, the heated discharge of an atomic power plant may be circulated through the trash racks of its intake. In other cases, when electrical energy is required, costs may be substantial; so a feedback system which monitors the temperature of the object should be used to minimize the heating expense.

b. Even if the frazil is prevented from adhering to an object, its sheer bulk can often clog intakes. In extreme cases entire generating stations have been forced to shut down for lack of flow. Northern districts have reported lock operation and maintenance problems because of frazil accumulation. Also, frazil accumulation in certain navigable waterways has become so extreme that river tow boats cannot maneuver.

2-6. Engineering Characteristics of Frazil Ice Accumulations. Unless frazil ice has accumulated because of high supercooling and/or high hydraulic forces (such as is the case with anchor ice in a rapids reach), its initial structure is quite weak. Apparently driven by heat transfer from the surface, the weak accumulation ages and attains significant strength. This aging may occur over a few weeks. The in situ forces on the accumulation will also affect the characteristics through deformation and consolidation. Field measurements of the engineering characteristics of such accumulations provide the following parameter ranges: shear strength = 1-8 psi (pounds per square inch), bearing capacity = 15-45 psi, density = 40-70 percent ice by volume, and permeability comparable to a coarse sand or a fine gravel.

## Section II. Ice Growth

2-7. Calculating the Quantity of Frazil Ice Generated in a Water Body. An accurate assessment of the potential problems caused by frazil requires a numerical estimate of the amount of frazil generated in a body of water. While methods are still crude, a comparative estimate can be obtained from the relation

$$V_f = \frac{g_s \, A \, \Delta T}{\rho_i \lambda_f} \quad . \qquad (1)$$

where

| | | |
|---|---|---|
| $V_f$ | = | volume of frazil ice produced per second, $ft^3$ |
| $g_s$ | = | heat transfer coefficient, $BTU/(s \cdot ft^2 \cdot {}^\circ F)$ |
| $A$ | = | open water area producing frazil, $ft^2$ |
| $\rho_i$ | = | mass density of ice = 57.2 $lbm/ft^3$ |
| $\lambda_f$ | = | latent heat = 144 BTU/lbm |
| $\Delta T$ | = | average temperature below 32°F during period of interest, °F |
| $t$ | = | time, seconds(s) |

The volume of frazil ice produced is not the volume that it will occupy when it accumulates. Early field work has shown the porosity of frazil accumulations $\theta_f$ to be between 0.4 and 0.6. The accumulated volume, $V_{f_d}$, will be approximately twice $V_f$. The portion of the total flow lost to ice generation will be $\rho_i/\rho_w \, V_f$, in cubic feet per second (cfs), where $\rho_w$ is the density of water (62.4 $lbm/ft^3$).

a. The heat transfer coefficient is a function of several parameters. For estimating ice generation over several weeks, field experience has shown that a value of $9.8 \times 10^{-4}$ to $1.23 \times 10^{-3}$ $BTU/(s \cdot ft^2 \cdot {}^\circ F)$ is reasonable for most North American rivers and streams. If extreme conditions exist (i.e., sustained high winds) a site specific value of this parameter must be used.

b. The area of open water producing frazil is probably the most error-ridden term in the computation of frazil production. There is an intricate relationship between the amount of ice generated and the extent of the open areas producing ice. The error associated with improper estimates of this relationship is minimal in broad, uninterrupted open reaches. It becomes significant when meandering open reaches are edged with sheet and frazil accumulations and are bridged with sheet ice and snow.

c. The temperature may be varied over small periods of time if short-term variations in ice generation are desired. Over several weeks, however, daily fluctuations tend to cancel each other, and the use of monthly temperature averages provides reliable data.

2-8. Example Problem. A reservoir fed by a 200 to 250 cfs mountain stream can be constructed in a number of ways. The evaluation needed for wintertime operation requires an estimate of frazil generation. The reach of interest is not extreme and may lose $1.0 \times 10^{-3}$ $BTU/(s \cdot ft^2 \cdot {}^\circ F)$. Local temperature records show that the average temperature for the month of January is 26°F. The model describes the stream as being 3 feet wide and open along a meandering course for 15 miles.

a. A normalized value may be calculated that estimates the production of ice in terms of the volume of frazil per unit surface area in square feet per day per °F. By changing the value of variables, one may also establish the sensitivity of the model's parameters.

b. For the present problem the normalized frazil ice generated $V_{f_N}$ is

$$V_{f_N} = \frac{g_s A \ \Delta T}{\rho_i \lambda_f} \tag{2}$$

$$= \frac{(1.0 \times 10^{-3}\ \mathrm{BTU/[s \cdot ft^2 \cdot {}^\circ F]})(8.64 \times 10^4\ \mathrm{s/day})(1\ \mathrm{ft^2})(1^\circ \mathrm{F})}{(57.2\ \mathrm{lbm/ft^3}) \qquad (144\ \mathrm{BTU/lbm})}$$

$= 1.05 \times 10^{-2}\ \mathrm{ft^3/(day \cdot ft^2 \cdot {}^\circ F)}$

i.e., the volume of frazil ice generated per square foot of open surface area, per day, per °F below 32°F is $1.05 \times 10^{-2}$ ft$^3$. For the particular problem,

$$V_f = V_{f_N} \times \Delta T \times \Delta t \times \Delta A \tag{3}$$

where

$\Delta T = 6°F$

$\Delta t = 31$ days

$\Delta A = 3$ ft x 15 miles x 5280 ft/mile $= 2.38 \times 10^5$ ft$^2$

The solution is

$$V_f = (1.05 \times 10^{-2}\ \mathrm{ft^3/[day \cdot {}^\circ F \cdot ft^2]})\ (6^\circ \mathrm{F})\ (31\ \mathrm{days})$$

$$(2.38 \times 10^5\ \mathrm{ft^2}) = 4.65 \times 10^5\ \mathrm{ft^3}$$

To find the volume, $V_{f_D}$, occupied by this quantity of frazil ice when it deposits in the stream, divide by the frazil porosity, $\theta_f$. Recall that the range of frazil porosity is 0.4 to 0.6. On the average then, the deposited frazil volume is

$$V_{f_D} = V_f \ / \ \theta_f \tag{4}$$

$$= 4.65 \times 10^5\ \mathrm{ft^3}/0.5$$

$$= 9.3 \times 10^5\ \mathrm{ft^3}$$

c. Figure 2-2 provides a family of curves based on the amount of open water area during the period of frazil ice generation. The figure plots the volume occupied by the accumulated frazil ice as a function of the freezing degree-days. The family of curves should not be used with smaller open areas (less than $10^4$ square feet). Frazil generation in such small areas is extremely sensitive to the microclimate and cannot be predicted from average parameter values.

d. As an alternative to calculations, one may solve a problem using the previous example. Locate the freezing degree-days ($\Delta T \times t = 6°F \times 31$ days = 186°F days) on the abscissa of Figure 2-2. The ordinate value of the intersection of this line with the corresponding open water curve ($2.38 \times 10^5$ square feet) is $V_{f_D}$. Note that the open water curve is interpolated logarithmically.

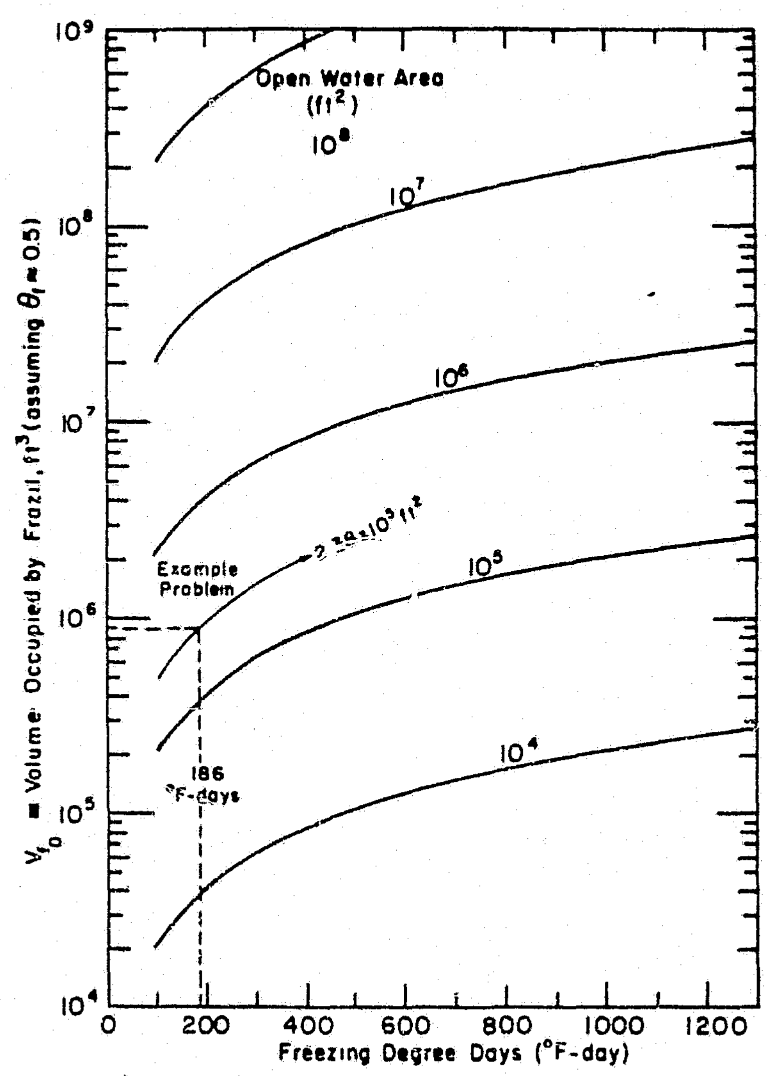


Figure 2-2. Frazil ice accumulation as a function of degree-days.

2-9. Estimation of Ice Formation Dates. A comparison of the long-term freezing degree-days* curve (Table 2-1) and the average ice formation date yields estimates of when ice will form and how long it will remain. The calculations require long-term (30 years) air temperature normals and dates of ice formation in previous years.

*A freezing degree-day is a measure of this departure of the mean daily temperature from a given base (32°F in this case).

TABLE 2-1
Example of freezing degree-day calculations.

| Day | Temperature (°F) Min. | Max. | Avg. | Freezing degree-day | Σ degree-day |
|---|---|---|---|---|---|
| 1 | -10 | 0 | -5 | 37 | 37 |
| 2 | -15 | -5 | -10 | 42 | 79 |
| 3 | -5 | +11 | +3 | 29 | 108 |
| 4 | 0 | +10 | +5 | 27 | 135 |
| 5 | -10 | 0 | -5 | 37 | 172 |

a. These values are plotted through the winter. Each day on the curve represents an accumulated value of freezing. Figure 2-3 shows an example of accumulated freezing degree-days at two sites during the winter of 1976-77 as compared to the normal, along with pertinent notations of dates of ice formation.

b. Lake Champlain, Vermont, for example, is a site that provides sufficient ice and temperature data. Burlington airport, near the lake, has excellent long-term temperature records and a meteorological station has been installed on the lake shore for comparison. Computed freezing degree-day records (Table 2-2) were correlated with data on the ferry's closing and opening dates (because of ice) for 19 years.

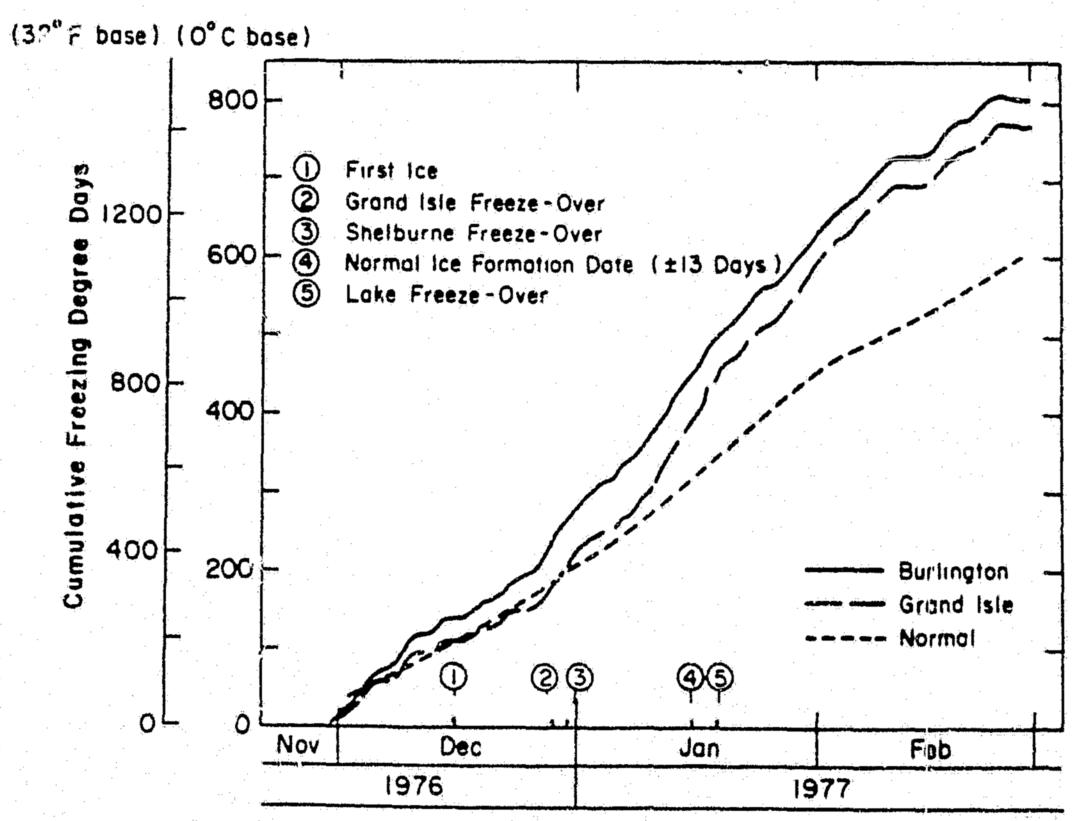


Figure 2-3. Accumulated freezing degree-days at two sites: Winter 1976-77.

c. Table 2-2 shows that on the average, a permanent ice cover forms on Lake Champlain at Grand Isle on 15 January ± 13 days, with normal ice-out occurring on 5 April ± 13 days. The lake normally closes for navigation after 615 freezing degree-days ± 157 degree-days. Table 2-2 also shows that the lake is normally closed for 82 days. To estimate when ice will occur during the current season, we start in November and select either the normal freezing curve or the annual curve (of the 19 available) that best fits the current freezing conditions; we then follow this accumulated plot to the ice formation date.

d. As better air temperature forecasting methods (for 30-60 days) become available, the above method will predict ice formation dates with greater accuracy.

TABLE 2-2
Historical ice data+ for Lake Champlain.

| Date closed (freeze-over at ferry) | Date open (ferry start) | Number days lake closed | Number freezing degree-days to ice cover | Date lake completely frozen | Number freezing degree-days to close of entire lake |
|---|---|---|---|---|---|
| 1/8/60 | 4/2/60 | 85 | 468 | Lake didn't close | |
| 1/10/61 | 4/15/61 | 89 | 594 | 1/27/61 | 1008 |
| 12/31/61 | 4/14/62 | 104 | 324 | 2/16/62 | 1152 |
| 12/30/62 | 4/15/63 | 107 | 396 | 2/8/63 | 1044 |
| 12/31/63 | 3/26/64 | 87 | 522 | Lake didn't close | |
| 1/15/65 | 4/15/65 | 91 | 540 | Lake didn't close | |
| 1/26/66 | 3/25/66 | 59 | 558 | 2/7/66 | 864 |
| 2/6/67 | 4/5/67 | 59 | 720 | 2/13/67 | 909 |
| 1/8/68 | 4/3/68 | 87 | 612 | 2/16/68 | 1386 |
| 1/9/69 | 4/8/69 | 90 | 765 | 3/2/69 | 1404 |
| 1/5/70 | 4/19/70 | 105 | 666 | 1/21/70 | 1173 |
| 1/17/71 | 4/26/71 | 101 | 990 | 2/2/71 | 1368 |
| 1/29/72 | 4/26/72 | 89 | 729 | 2/10/72 | 918 |
| 1/9/73 | 3/16/73 | 67 | 558 | 2/21/73 | 1134 |
| 2/7/74 | 3/26/74 | 48 | 864 | 2/15/74 | 1026 |
| 2/4/75 | 3/29/75 | 54 | 666 | 2/21/75 | 936 |
| 1/13/76 | 3/31/76 | 79 | 666 | Lake didn't close | |
| 12/28/76 | 3/21/77* | 83 | 450 | 1/18/77 | 882 |
| 1/16/78 | 4/8/78* | 82 | 576 | 2/13/78 | 1080 |
| Average: | | | | | |
| Jan 15 (±13 days) | Apr 6 (±13 days) | 82 (±18 days) | 615 (±87 deg. days) | Feb. 11 | 1085 (±99 deg. days) |

* Ferry navigated in ice cover these two winters.
\+ All temperature data are from the Burlington, Vermont, airport.

2-10. Prediction of Ice Growth. The date of ice formation and the initial ice thickness at freeze-over are needed to estimate ice growth for the case cited in this summary.

a. Figure 2-4 is a plot of actual measured ice thickness against computed growth for Shelburne Point, Vermont, on Lake Champlain. The following simplified Stefan equation determined the computed growth of the ice cover:

$$h(t) = kZ^{1/2} \qquad (5)$$

where h is the thickness of the ice in inches at time t, Z is the total number of accumulated Fahrenheit freezing degree-days since time of permanent freeze-over, and k is an empirical coefficient. Figure 2-4 shows an estimated ice growth curve starting on 13 January (first permanent ice) based on observed temperatures and an empirical coefficient of 0.6. The two curves in Figure 2-4 coincide fairly accurately. The predicted curve reaches a maximum thickness of 13.4 inches on 15 February, while the actual maximum thickness was 13.8 inches on 19 February. The two curves are compatible until 8 March when strong northerly winds broke up the ice at Shelburne Point.

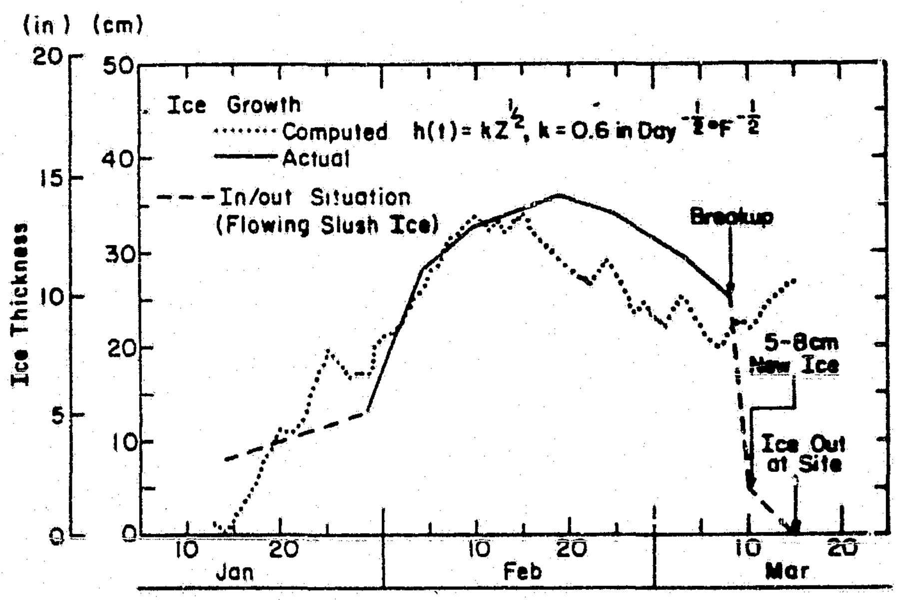


Figure 2-4. Actual measured ice thickness vs. computed growth at Shelburne Point, Vermont: Winter 1975-76.

b. The following year when the measurement site was moved to the Grand Isle, Vermont, location, the empirical coefficient for best fit of the ice growth curve was calculated at 0.3. Caution should be used in stating an empirical coefficient for a large body of water such as Lake Champlain. The empirical coefficient changes with wind exposure and geographical location of measurements on such a lake.

2-11. Thermal Strains in Ice. At 32°F and atmospheric pressure, the specific gravity of water is 1.00 and the specific gravity of pure ice is

0.917; this means that freezing gives a volumetric strain of -8 percent and thawing gives a volumetric strain of +9 percent. As ice is cooled at constant pressure, it contracts. The expansion coefficient varies with temperature, but in ordinary ice engineering this variation can usually be ignored.

a. For a single crystal of pure ice, the coefficient of linear expansion varies slightly with crystallographic direction, but at temperatures near 32°F the difference is only about 2 percent (greater parallel to the c-axis than perpendicular to the c-axis) and can be ignored for most practical purposes. At temperatures between 32°F and -40°F, we can take the coefficient of linear expansion as equal to $2.8 \times 10^{-5}$/°F (±4 percent) at 32°F for freshwater polycrystalline ice, noting that it decreases by approximately 10 percent as temperature drops from 32° to -40°F.

b. In sea ice, or other ice containing significant amounts of dissolved impurities, the situation is very different. At temperatures near the melting point, saline ice consists of solid ice plus liquid inclusions which change in volume and salinity as the temperature changes. Although the ice crystals have a positive expansion coefficient, phase changes in the brine cells create freezing strains in a negative sense, i.e. the volume increases as temperature drops. Above about 23°F, the freezing and thawing of brine inclusions is usually thought to be the dominant effect, implying that sea ice contracts as temperature increases in this range. At very low temperatures, when all the brine is frozen and solid salts are precipitated, the behavior is almost identical to that of pure ice.

# CHAPTER 3
# ICE JAMS

3-1. Introduction. When the ice goes out of the rivers it often jams and causes flooding of fields and homes. The ice floating upstream from a jam can destroy houses, bury roads, and collect on fields, delaying spring plowing and planting. Figure 3-1 shows how massive this ice can be.

3-2. Discussion. There are two processes which either alone or in concert are responsible for breakup. Ice strength gradually deteriorates in the spring when higher sun angles and higher air temperatures melt snow from the ice surface, forming a water layer. This water layer absorbs more solar radiation, causing subsequent melt along the crystal boundaries. If not disturbed by other factors, the ice will melt in place.

a. In rivers, the current flow beneath the ice is a second factor. In fact, water flow is the sole cause of the midwinter breakups that can lead to the most destructive ice jams. Any increase in water flow down the river will raise the ice level and break it loose from the shore. If the river discharge stays high because of rain or snow melt on the upper sections of the watershed, the higher flow will move the ice downstream. As it moves, the ice breaks up; the size of the pieces depends on the distance they move and the degree to which the ice strength has deteriorated. As might be expected, the ice in those reaches with steeper slopes and higher current velocities will go out first. When the moving ice hits the fixed ice in a slow, flat reach, it may break up the stationary ice and carry it along, or form a jam. Ice jams occur in two basic forms, the dry jam and the simple jam. They are essentially identical except that in a dry jam the ice is grounded, restricting water flow to a greater degree than a simple jam.

b. Predicting the time or even the probability of an ice jam occurring is still uncertain. However, there are a number of typical locations where a jam will form. As mentioned earlier, any section of a river where the slope decreases is a possible location. During freezeup the slower moving reaches freeze first, and so will have a thicker ice cover come breakup. Another possible location might be a constriction in the channel, either natural, such as at a bend or at islands, or at man-made features such as bridge abutments and midstream piers. A third typical location is a shallow reach where the ice can freeze to bottom bars or boulders and will not be lifted and moved by the increased water flow.

c. Once the ice is stopped at any location the jam thickens rapidly, primarily by ice blocks turning under existing surface ice. The net result is a very rapid constriction of the channel and subsequent backing up of the upstream flow.

d. Flooding from an ice jam occurs very quickly. The situation is not like a normal open water flood when the channel is not large enough for the flow. Instead the channel is completely blocked. Normal backwater calculations based upon stage level recorders are meaningless. Suddenly there is a new dam in the river, albeit a leaky and temporary one, which is creating a lake and which has no convenient spillway. The best time to try to move a jam is while the water pressure behind it is still high and the flow rates are adequate to carry the ice downstream. If the jam occurs in midwinter and a cold spell reduces the flow before the jam moves on, it can settle on the bottom and remain for the rest of the winter, creating a potential hazard. During the rest of the winter a new ice cover can form upstream, and when the spring breakup comes the new ice cover will be stopped at the old jam; flooding is almost a certainty. The need to free or remove some ice jams is thus obvious, both in cases when flooding is actually present and in cases when the potential for subsequent flooding exists.

Figure 3-1. Stranded frazil ice at Cattaraugus Creek near Buffalo, N.Y.

3-3. Methods of Ice Jam Removal. There are four different methods for removing ice jams or alleviating ice jam problems, and each has its advantages and drawbacks. These are mechanical removal, dusting, blasting, and the use of icebreaking ships. It is important to remember that ice loosened in a stream may jam elsewhere. A decision must be made. Is it best to move the jam and take the possible financial responsibility for downstream damage, or to accept the potential damages caused by the jam as is? Once the decision has been made to try to remove the jam, which approach will be the most effective?

a. Mechanical Removal. Removing the jam mechanically, for lack of a better term, means simply taking the ice out of the stream bed and placing it elsewhere. This, of course, eliminates any downstream problems but it is neither cheap nor fast. In February 1978 it cost approximately $11,500 to make a 2,600-foot channel with one Caterpillar 235 backhoe. The approach is further limited to dry jams in relatively shallow streams. In other words, this approach is used generally for midwinter jams on small streams after the flooding has receded. The idea is to create a small channel within the jam by using mechanical equipment such as bulldozers, backhoes, or draglines. When the ice blocks are small and thin, mechanical clearing does not present too great a problem. When the blocks are around 10 x 10 x 2 feet or larger, small equipment is generally inadequate. Each site is different, so that equipment and methods used are up to the operator. He must be aware of the problems of power lines, poor bottom, and access. An immediate problem is disposing of the ice. Usually it can be pushed to each side, leaving a channel about one-third the normal river width. In reaches where the channel has been severely restricted by man-made works, it may be necessary to remove all the ice.

b. Dusting. A second method for alleviating ice jam problems is the use of dust. By dust we mean any dark substance that can be spread on the ice in a thin layer to absorb solar radiation and thereby hasten the deterioration process. This method is used primarily to alleviate possible jam conditions before the fact. The rough surface of an actual jam creates so many shadows that the dust is not effective. For example, Moor and Watson[7] describe a reach of the Yukon River downstream of Galena, Alaska, which has regularly caused ice jams. Dusting this reach each spring two to three weeks before breakup weakens the ice sufficiently that no jams have occurred there since the practice started. Ideally, the dust should be applied as early as possible but after the last snowfall. In general, any reach with an ice cover that regularly stops the ice run and causes a jam could be weakened in this manner.

(1) Dusting involves spreading (as evenly as possible) a dust or sand layer and letting the sun provide the energy. Thus, time is involved as well as the higher sun angles in the late spring and good luck in avoiding snow storms which would cover the dust. Agricultural aircraft generally apply the dust, which keeps costs fairly low. Moor and Watson[7] give a cost of 34.9 cents (1970 dollars) per lineal foot (100 feet wide) in a remote section of Alaska. The particle size can vary, depending on what is available. Moor and Watson[7] quote 0.5 pounds per square yard for sand and 0.35 pounds per square yard for fly ash. V.I. Sinotin[3] gives similar rates: for 0.04-inch diameter dust he suggests 0.18 pounds per square yard and for 0.2-inch dust, 0.92 pounds per square yard.

(2) A logical offshoot of dusting is to pump water and bottom materials onto the ice surface. This is limited to streams with silt or sand bottoms and, according to Moor and Watson[7], is ten times more expensive than aerial dusting. However, the approach does have application where the stream is too narrow or sinuous for aerial work, or where environmental considerations preclude adding material to the stream.

c. Blasting. The third method is blasting the jam. For immediate flood relief this is probably the most effective. The primary purpose of the blasting is to loosen the ice. However, enough flow must be coming through the jam to float the ice downstream. Thus, a prerequisite to blasting is an ice-free reach downstream where the ice can go, either all the way down the river, or to a spot where it will not jam (or, if it does, where the jam will not cause any appreciable damage). Unfortunately, jams have been blasted without regard to downstream problems. Successful blasting takes time and careful planning.

(1) The ideal time to blast a jam is just after it has formed. In actuality, a jam is never blasted this quickly because a blasting crew and governmental approval cannot be mobilized until the jam is well formed and flooding has begun. If the flow has dropped because of cold weather or has moved into another channel so that after a blast there will not be enough water to carry the loosened ice downstream, the blasting should be canceled.

(2) If the decision has been made to blast, there are a number of procedures learned from experience that can lead to a cheaper and more successful job. Each charge, if placed under the ice, will blow a crater or circle in the ice with a diameter that is related to the weight of the explosive. Figure 3-2 gives this relationship. A handy charge size for most jobs is around 40 pounds, which gives a diameter of close to 40 feet. Experience has shown that two more or less parallel rows of charges, set close enough so the craters intersect, give the best result. If it is possible to locate the thalweg or deepest part of the river the blasting line should be along it. This creates an open channel with good flow depths that is wide enough to preclude most secondary jamming. The charges must be placed in the water below the ice cover. This is extremely impor-

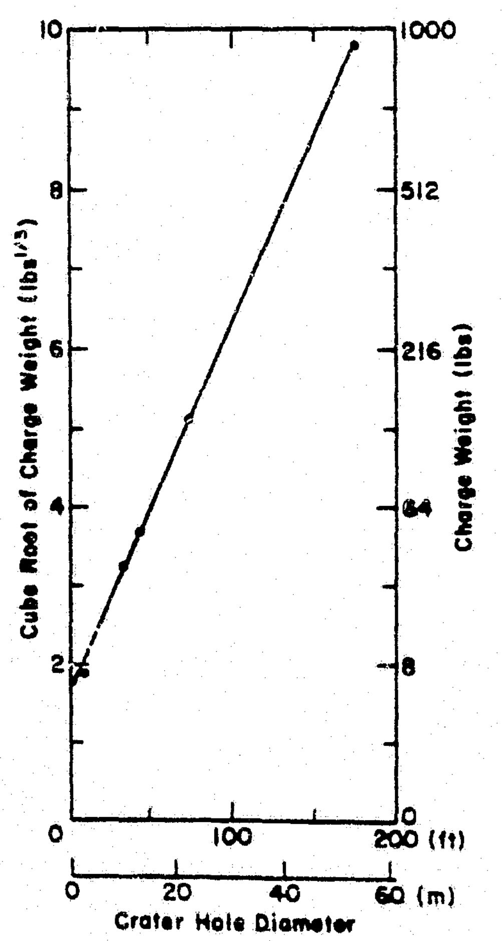


Figure 3-2. Relationship of explosive weight to crater hole (good for ice 1 to 10 feet thick).

tant since the driving force is apparently the large gas bubble resulting from the blast, and not the shock waves. The charges must be weighted to sink but also roped to the surface to keep them from being carried downstream by the current.

(3) Any kind of explosives can be used for this work; however, from experience ANFO is preferred. (The writer has no experience with slurries that may work as well.) ANFO is a mixture of ammonium nitrate fertilizer and fuel oil. The best ratio is 6 percent by weight oil with prilled (in pellet form) nitrate. This ratio works out as 1 gallon of oil per 100 pounds of fertilizer. The mixture must be detonated with a strong booster such as a stick of dynamite, TNT, or the special booster charges sold by the powder companies. Like many other explosives ANFO must be kept relatively dry, so placing the mixture in a plastic bag which can also hold a brick, sand, or whatever weight is necessary to sink the charge is recommended. ANFO is relatively cheap and it will dissolve with time if a misfire takes place, and not leave large, live charges on the river bottom. As a guide, it is preferable to use Primacord for all downhole and hookup lines. This is then set off with one electric cap which is taped to the Primacord at the last moment when the rest of the party is off the ice.

(4) Blasting is not a quick, easy solution. It requires some planning to locate and acquire the explosive, the equipment to make holes to place the charges, and manpower. At all times when the crew is working on the jam, a lookout should be on duty some thousand feet upstream to sound the alarm if the jam lets go by itself. At least two men are required to drill holes, and depending on the roughness of the surface, at least four more to carry the charges to the holes. Add a blaster, a supervisor, and two men to load the charges and you have a crew of 11 people. With good luck this crew can blast two rows of charges along about a half mile of river per day, possibly more when a routine has been established.

(5) A formal safety plan covering all operations is necessary. It should comply with both local and Federal regulations. Such matters as person in charge, communication, transportation, warning personnel, etc. should be fully covered.

d. Icebreakers. The fourth method of removing jams in only usable in a few rivers. When the channel depth is sufficient and the ships available, icebreakers are certainly the easiest, safest and cheapest way to break up a jam. This operation is carried out by the captains, who are responsible for the safety of their ships, so little more needs to be said regarding safe operations. If two ships are available, they work best in echelon (staggered one behind and to the side of the other), starting from the downstream end of the jam. The following ship has to be careful to ensure an equal width channel. If it crosses the path of the leader, the resulting narrow section will inevitably cause a jam and the downstream channel will no longer keep itself clear. Occasionally, if circumstances permit, an icebreaker can work in conjunction with blasting. The propeller wash and wave action of the ship will clear the ice loosened by the blasting faster, and the ship will offer a factor of safety for the people on the ice. A combined operation like this will require extra cooperation as well as good communication. When the jam is very thick, two towboats of essentially equal power have been used together. They mate-up bow to bow, and while the propeller wash of one boat loosens and erodes the ice, the second boat holds the first in position. This operation takes a great deal of skill and coordination between the pilots.

3-4. Summary. Each method of removing ice jams described above has its own advantages and disadvantages. The decision as to which method to use is easy. The difficult problem is to decide if any work is necessary. Will the jam go out by itself? How great a hazard really exists? Experience is helpful for this decision, but ice jams are not that common and few people have the opportunity to observe many jams for logical comparison. Thus, advice from local people familiar with the particular stream and its history is invaluable.