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ICE FORMATION - A REVIEW OF THE LITERATURE AND BUREAU OF RECLAMATION EXPERIENCE

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A review of published literature and Bureau of Reclamation experiences related to ice formation on rivers, reservoirs, and hydraulic structures is presented. The review is directed toward ice problems associated with Bureau of Reclamation projects where flooding or inefficient operation results from ice formation.

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ICE FORMATION - A REVIEW OF THE LITERATURE AND BUREAU OF RECLAMATION EXPERIENCE

by

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September 1971

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Denver, Colorado

UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION
Rogers C. B. Morton, Secretary
Ellis L. Armstrong, Commissioner

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PURPOSE

The purpose of this investigation was threefold. The primary purpose was to present a state of the art review of published work related to ice effect on rivers, reservoirs, and the operation of hydraulic structures. A second purpose was to review the major icing conditions that have occurred in recent years on Bureau of Reclamation projects. The third purpose was to furnish recommendations as to the potential for research to determine possible means of alleviating or preventing adverse operating conditions caused by ice.

CONCLUSIONS

This report has disclosed and summarized the major icing problems which have occurred on Bureau of Reclamation projects. Various remedial measures are discussed in both the literature review and the survey of Bureau of Reclamation experiences. There appears to be sufficient need for further research in this area. The past successes of the limited ice-related research mentioned in the literature review and the multiplicity of the problems experienced by the Bureau of Reclamation indicate a need for further study by the Engineering and Research Center.

RECOMMENDATIONS

Because of the involvement of various disciplines within the Bureau, it is recommended that a Research Study Team be formed to consider ice-related problems. The objectives of the team will be to review the major icing problems on Reclamation Projects and to furnish recommendations as to further research needs with regard to methods of alleviating ice problems on existing facilities, and possible design changes on future facilities.

LITERATURE REVIEW
STATE OF THE ART

I. Introduction

The purpose of this phase of the report is to present a state of the art review of published work related to ice effect on riverflow and on the operation of hydraulic structures. The report is not inclusive with regard to all published material on the subject matter. However, sufficient work has been included to indicate the status, to date, of the subject knowledge.

II. Formation of River Ice

A. Frazil ice

Frazil ice is defined by the ASCE[1] * as:

> "Fine spicules of ice found in water too turbulent for the formation of sheet ice. Frazil (derived from the French word for cinders, which it resembles) forms in supercooled water when the air temperature is far below freezing."

Michel[2, 3], discusses the formation of frazil ice (Figure 1):

> "In cold temperatures, the water of a river reaches 32° F on a reach up to a point, shifting with time, where there is a state of supercooling. In this supercooled zone, there appear throughout the entire cross section of the flow little individual particles of frazil ice which, as they are displaced, agglomerate to form extremely porous flakes. These flakes successively come to occupy the surface, and without perceptible augmenting in volume, become thickened with new crystals of ice in an exchange with the exterior."

Williams[4] indicates the many variables that might affect the rate of cooling of a section of river water (Figure 2):

> "The rate of cooling of a section of river water can be considered as a complex heat exchange problem which, from a practical viewpoint, will not have an exact solution."

B. Ice covers

Michel and Triquet[5] describe the formation of an ice cover from frazil crystals:

> "Frazil crystals . . . agglomerate into flocks which after a while flow up to the water's sufrace. Water imprisoned between the crystals freezes at the surface, and soon the upper parts of the flocks form solid ice crusts (cakes). These ice cakes by hitting each other and the banks while moving with the current, have a tendency to adopt a more or less circular shape and develop an edge which stands higher than the center part; in other words they evolve into the well known form of pancake ice. Pancake ice floes, if they are transported long enough in fluvial stretches, may further develop into ice plates consisting of individual floes frozen one to another. When the concentration gets heavy enough, flocks or plates will cover the whole width of the section and, being held up by the banks, constitute an ice bridge from which the ice cover progresses upstream."

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*Numbers refer to references in the Bibliography.

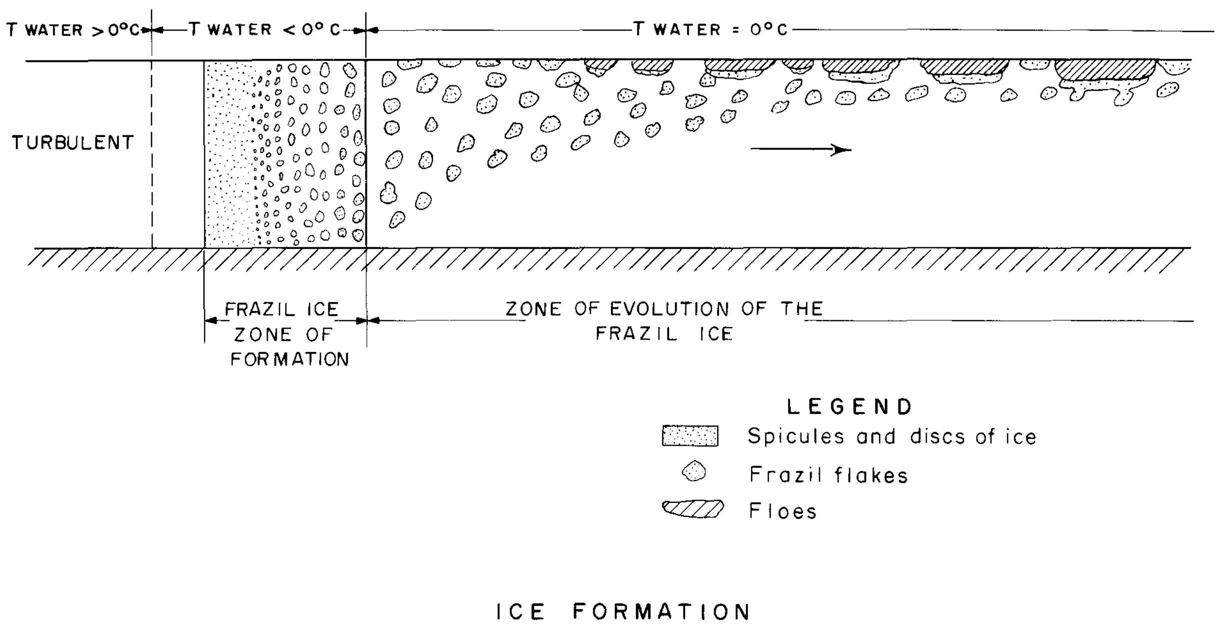

Figure 1. Development of river frazil ice.

From Michel.[2]

The authors also mention a second type of ice cover formation, namely; border ice. This ice covers forms along the banks of a river in areas of laminar flow:

> "The top layer adjacent to the bank will go through undercooling considerably while the average temperature of water in the middle of the river will still be much above freezing point. Ice will be nucelated starting right in contact with the colder (because more conductive) material of the banks and this nucleation will propogate on the surface towards the middle of the flow, forming a clear and solid ice sheet."

Cousineau[6] defines ideal ice formation conditions as those prevailing when:

> "the temperature of the water must be at the freezing point and the atmospheric temperature down to at least zero degree Farenheit or better still subzero weather prevailing.

> "Although ice forms more rapidly under ideal conditions, it must be realized that once a cover is formed, the latter acts as an insulator in preventing further formation of ice save for the growth of the cover itself. The result is that less ice will form and the slopes will be smoother if the freeze-up occurs under ideal conditions."

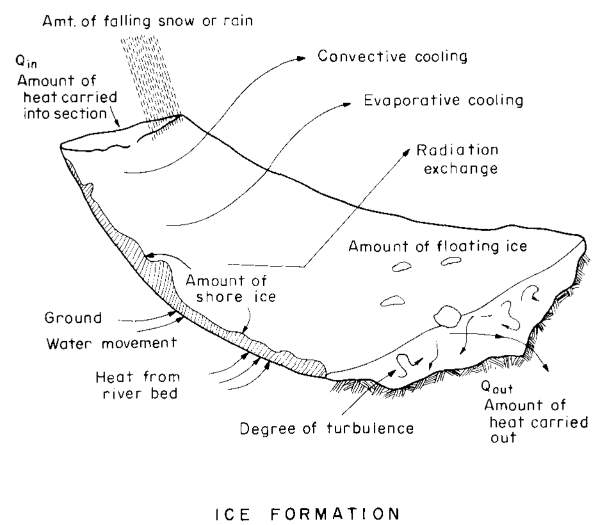

Figure 2. Factors that affect the rate of cooling of a section of river water.

From Williams.[4]

Cousineau[7] in work on the St. Lawrence River found that there was no growth or decline in the ice cover thickness for an air temperature of 20° F.

a. Ice cover stability

Pariset, Hausser, Gagnon[8] analyzed the equilibrium of an ice cover considering an ideal rectangular channel of constant shape and roughness as shown in Figure 3:

$$f = \frac{B}{2K_1 tg\phi}(f_2 + f_3) - \frac{\tau t}{K_1 tg\phi} - \alpha e^{\frac{-2K_1 tg\phi L}{B}} \quad (1)$$

where

$$\alpha = \left[\frac{B}{2K_1 tg\phi}(f_2 + f_3) - \frac{\tau t}{K_1 tg\phi} - f_1\right]$$

and K_1 = f_t/f
f_t = transversal stress pushing the cover against the bank
f_2 = shearing stresses of flowing water under the cover per unit area
f_3 = component of the weight of the cover in the direction of the slope of the ice water interface per unit area
f_1 = hydrodynamic force of the current against the upstream limit of the cover per unit width
$tg\phi$ = friction coefficient of the ice
τ = the cohesion of the ice on the banks
t = cover thickness
L = distance between the upstream edge of the cover and the section under study

Equation (1) indicates how the external resultant force, f, varies with distance from the upstream edge of the cover, L.

The authors consider two cases for Equation (1). The first case being for $\alpha < 0$ which they define as the "narrow river" case. For $\alpha < 0$, f will be a maximum at L = 0 (upstream edge of ice cover) where $f = f_1$.

By applying the energy equation to the upstream edge of the ice cover and the requirement for equilibrium of the ice at the water level, the authors derived the following equation, which relates the thickness of the upstream edge of the cover to a modified Froude number:

$$\frac{V}{\sqrt{2gH}} = \sqrt{\frac{\rho - \rho'}{\rho}\,\frac{t}{H}\left[1 - \frac{t}{H}\right]} \quad (2)$$

where

ρ = specified mass of water
ρ' = specified mass of ice
H = river depth upstream of ice cover

Equation (2) is plotted in Figure 4:

> ". . . the thickening at the upstream edge does increase with increasing flow velocity or decreasing depth, but that a maximum exist at t/H = 1/3 beyond which the added thrust from the shallower water passage is no longer compensated for by the added buoyancy resulting from the thickening of the cover. Therefore, this condition is unstable; all ice floes sink beneath the cover and pile up."

The second case studied was for $\alpha > 0$. In this case the thrust in a section of the ice cover will increase with distance from the upstream edge, L. It will approach the limit:

$$\lim. f = \frac{B}{2K_1 tg\phi}(f_2 + f_3) - \frac{\tau t}{K_1 tg\phi} \quad (3)$$

> "The thickness of the cover in wide rivers is given by

$$\frac{BV_u^2}{\mu C^2 H^2}\left(1 + \frac{\rho' t}{\rho R_H}\right) = \frac{2\tau t}{g\rho\mu H^2} + \frac{\rho'}{\rho}\left(1 - \frac{\rho'}{\rho}\right)\frac{t^2}{H^2} \quad (4)$$

where

V_u = velocity under the ice cover
μ = a constant, function of the angle ϕ
C = Chezy coefficient
R_H = hydraulic radius of the water passage

Figure 5 shows the application of Equation (4) to a rectilinear channel having a 4,000-foot width, a 30-foot depth, and a Chezy coefficient of 60:

> "Curve B gives the thickness of the upstream edge of the cover [Equation (2)] as a function of the flow velocity. Curve A gives the final thickness of the cover to support the ice thrust after the progression of the cover [Equation (4)]. Curve A' applies the same conditions but when the influence of the ice cohesion is negligible. The curves indicate that considerable supplementary thickening occurs as a result of the increase of resultant forces, as soon as the flow velocity surpasses 2 fps."

> "Point C corresponds to the transition from a 'narrow' to a 'wide' river, clearly showing how a

particular river can be 'narrow' for low velocities, and 'wide' for faster velocities."

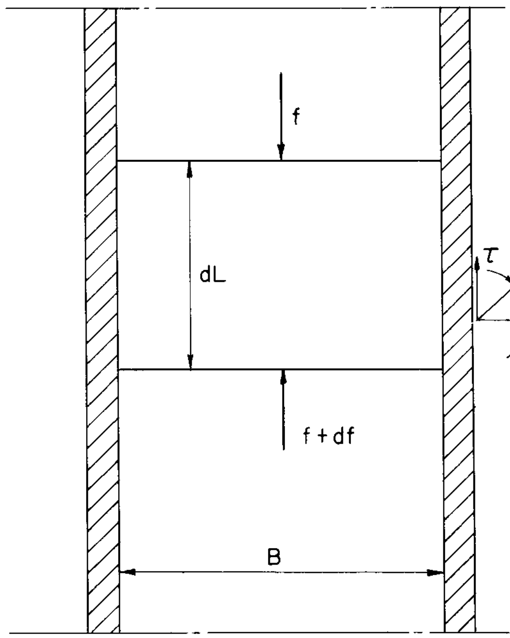

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Figure 3. Definition Sketch.

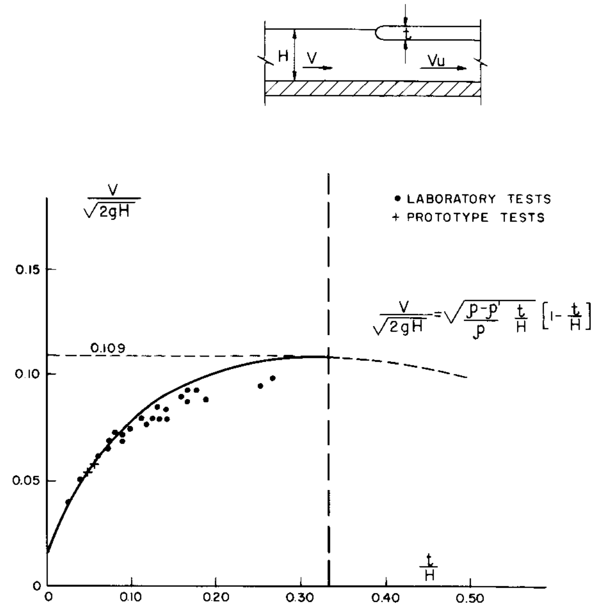

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Figure 4. Thickness at upstream edge of cover.

From Pariset, Hausser, Gagnon.[8]

The author assumed the cohesive term in Equation (4) negligible thus yielding:

$$X = \frac{Q^2}{BC^2H^4} = \frac{BV^2}{C^2H^2} = \frac{\mu\left(1-\frac{\rho'}{\rho}\right)\frac{\rho'}{\rho}\left(\frac{t}{H}\right)^2\left(1-\frac{\rho' t}{\rho H}\right)}{1+\frac{\rho' t}{\rho H}} \quad (5)$$

Substituting valves of $\mu = 1.28$ and $\rho' = 0.92$, Equation (5) was plotted in Figure 6.

"Regardless of its relative thickness, a stable cover can exist only if:

$$\frac{Q^2}{BC^2H^4} \leq 2.8 \times 10^{-3},$$

or

$$Q \leq 0.053\, H^2 C\, \sqrt{B} \quad (6)$$

Equation (6) shows the value of having a deep and narrow channel or as the authors suggest, dividing an existing channel by a longitudinal dike.

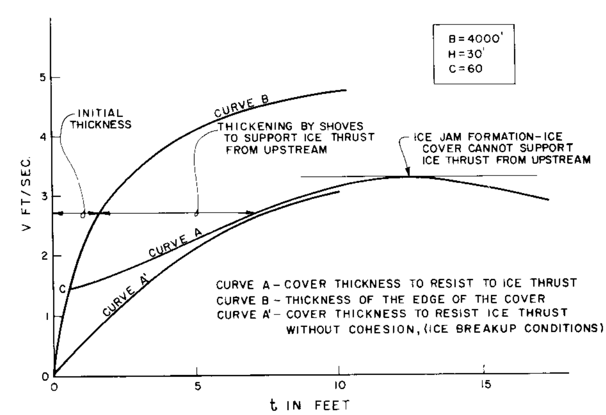

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Figure 5. Thickening of cover following ice thrust.

From Pariset, Hausser, Gagnon.[8]

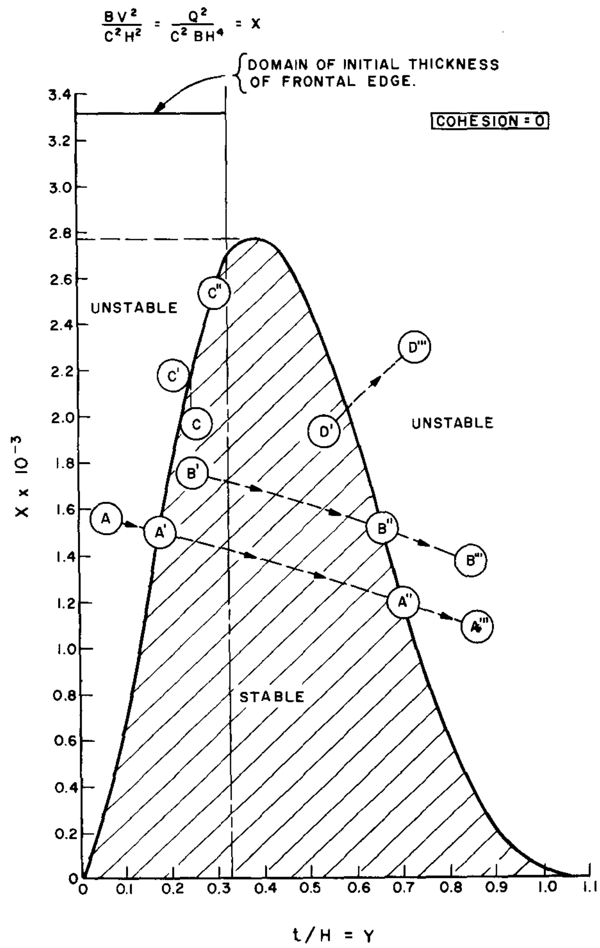

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Figure 6. Dimensionless stability diagram.

From Pariset, Hausser, Gagnon.[8]

Let us follow through an example given by the authors:

> "Channels where depth, H, does not vary with discharge. This is a typical case of rivers or power canals upstream of a dam. It can be seen on Figure 6 that starting from an initially stable cover, C, the discharge can be increased to a point corresponding to C′ without any instability, i.e., Y = t/h remains constant. At C′, the limit of stability is reached and any further increase of discharge will force the cover to thicken, C′ to C." If the discharge exceeds the critical value mentioned previously, it will no longer be possible to attain a stable equilibrium."

In most natural channels a decrease in discharge will cause an increase in both t/H and $Q^2/(C^2\,BH^4)$ since $Q \approx (B,H)$. This could produce an instability if the initial condition is near the descending part of the curve.

Michel[9] also analyzed the stability of an ice cover. He studied its equilibrium at various sections and under various forces and then compared their relative values.

The equilibrium of an ice cover under pressure can be represented by Figure 7 or,

$$2R \sin\phi = Bp \qquad (7)$$

where ϕ = angle of internal friction of ice at rupture

$$p = \frac{\rho f}{8}\,\frac{h + t\,(1 - 2\epsilon)}{(h - t)^3}\,\frac{Q^2}{B^2} \qquad (8)$$

where

h	= depth of water in front of ice cover
ϵ	= porosity
t	= ice thickness
f	= coefficient of Darcey
n	= coefficient of Manning
f	$= \dfrac{4.56\, gn^2}{(h - t)^{1/3}}$

$$R = \frac{1}{2}\, tg^2\left(45^{o} - \frac{\phi}{2}\right)\left(1 - \epsilon\right)\frac{\rho(\rho - \rho')}{\rho'}\, t^2 \qquad (9)$$

Equation (7) can be satisfied by:

$$(h' - t')^3\,(t')^2 - h' - t'\,(1 - 2\epsilon) = 0 \qquad (10)$$

where

$$h' = \frac{h\sqrt[4]{B}}{\mu\sqrt{Q}} \text{ and } t' = \frac{t\sqrt[4]{B}}{\mu\sqrt{Q}}$$

$$\mu = [g\rho'\,\frac{f}{8}\,(1 - \epsilon)\,\sin\phi tg^2\left(45^{o} - \frac{\phi}{2}\right)(\rho - \rho')]^{1/4}$$

Equation (10) is shown in Figure 8 for $\epsilon = 0.40$. The points indicate data obtained by Mathiew[10] using polyethylene to represent ice with specific gravity of 0.92, $\epsilon = 0.40$ and $\phi = 30^{o}$. Equation (10) passes through a minimum that can be obtained by derivation:

$$\frac{h\sqrt[4]{B}}{\mu\sqrt{Q}} = 2.36 \text{ at } \frac{t}{h} = 0.4$$

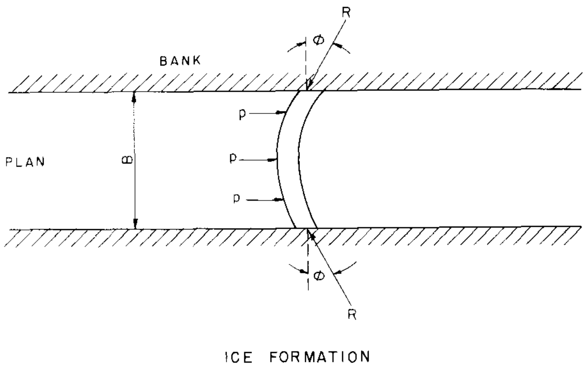

Figure 7. Definition sketch.

Therefore

$$h \geq 2.36 \frac{\mu \sqrt{Q}}{\sqrt[4]{B}} \qquad (11)$$

in order for the ice cover to be stable under pressure. Michel states that for a value of the internal friction 0.1 to 0.5, μ varies from 0.51 to 0.26. From experiments in the laboratory he fixes the value of μ at 0.26. Therefore, Equation (11) can be written:

$$q \leq \frac{2.67h^2}{\sqrt{B}} \qquad (12)$$

Equation (12) is very similar to Equation (6) developed by Pariset. They both give a maximum value of discharge above which an ice cover cannot form.

Michel states that the hydrodynamic equilibrium of the frontal rim of an accumulation of floes can be represented by:

$$F_r = \frac{V}{\sqrt{gh}} = \sqrt{2 \frac{\rho - \rho'}{\rho} (1 - \epsilon) \frac{t}{h} \left(1 - \frac{t}{h}\right)} \qquad (13)$$

where

- V = velocity
- h = depth of water in front of cover
- ρ, ρ' = specific weight of water and solid ice
- ϵ = porosity
- t = thickness of frontal rim

For $t/h = 1/3$, a maximum F_r occurs yielding:

$$F_r = 0.154 \sqrt{1 - \epsilon} \qquad (14)$$

or for $\epsilon = 0.40$

$$q \leq 0.68h^{3/2} \qquad (15)$$

Equation (13) is very similar to Equation (2). The big difference being the porosity term, ϵ. Michel stresses the importance of the porosity.

Michel also discusses the equilibrium of an ice cover with drag.

Where the limiting velocity, V_c is:

$$V_c \leq 10 \sqrt{D} \quad \text{or } q \leq 10 \sqrt{D}\,(h - t) \qquad (16)$$

where

- t = thickness of ice accumulation below the water in feet
- D = thickness of ice floes in feet

Equations (12), (15), and (16) are shown in Figure 9. It appears that in most cases the equilibrium under

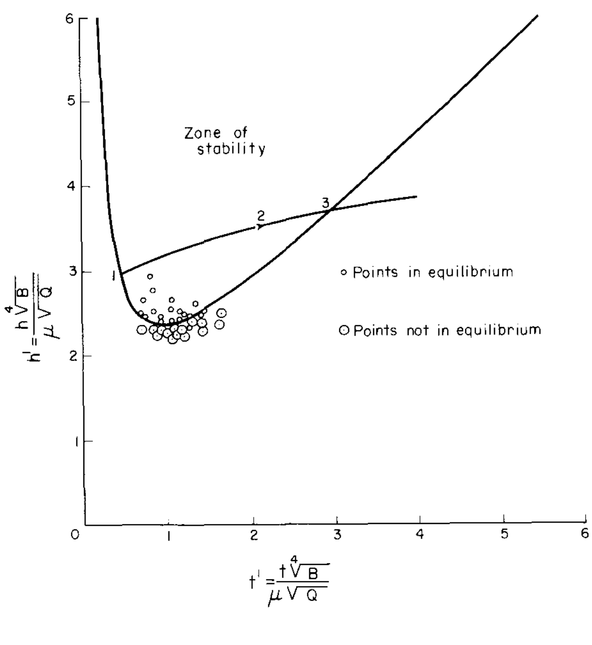

Figure 8. Equilibrium of locks under effect of pressure.

From Michel.[9]

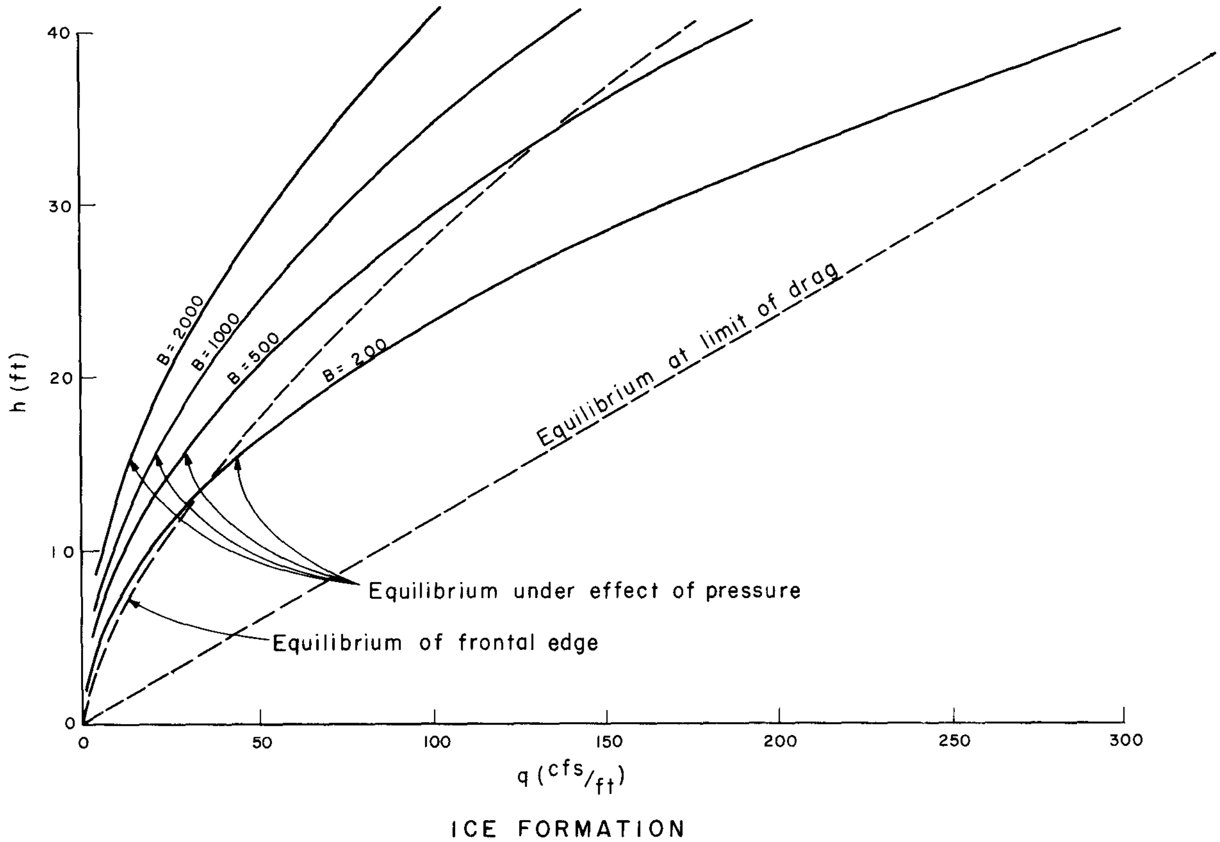

Figure 9. Predominant criterion of equilibrium of locks.

From Michel.[9]

effect of pressure will be the limiting curve. This would seem especially true in the Western States where the width to depth ratio is relatively large.

Kivisild[11] shows in Figure 10 an upper limit for the Froude number of 0.08:

> "When the Froude number is lower than 0.08, ice is accumulating at the upstream end and the pack grows upstream. As the Froude number approaches this value, the pack tends to become more massive. At higher Froude numbers, ice is carried under the ice cover and is deposited at the nearest section where the shear stress against the ice cover is below a certain critical value. When the deposits have narrowed the section and velocities are increased so that the critical shear stress has been reached, additional ice is carried further downstream to deposit at the next section with the shear stress below the critical value.
>
> "Ice deposits in hanging dams* under the ice cover narrow the free area for water and increase the slopes to critical values over a progressively increasing length of the ice dam. This process continues until the water surface at the upstream end rises to levels which make the hydraulic conditions favorable for ice accumulation there. Then ice starts packing and the pack grows upstream until the next upstream lying critical section for packing is reached."

Michel[2] used Kivisild's graph and added another ordinate, ϵ (Figure 11). He used the relationship

*Author's note: Hanging dams occur in high-velocity flows where floating ice is carried under the upstream edge of an ice cover and deposits on the underside of the cover. The "hanging" ice accumulates more ice and progressively grows larger.

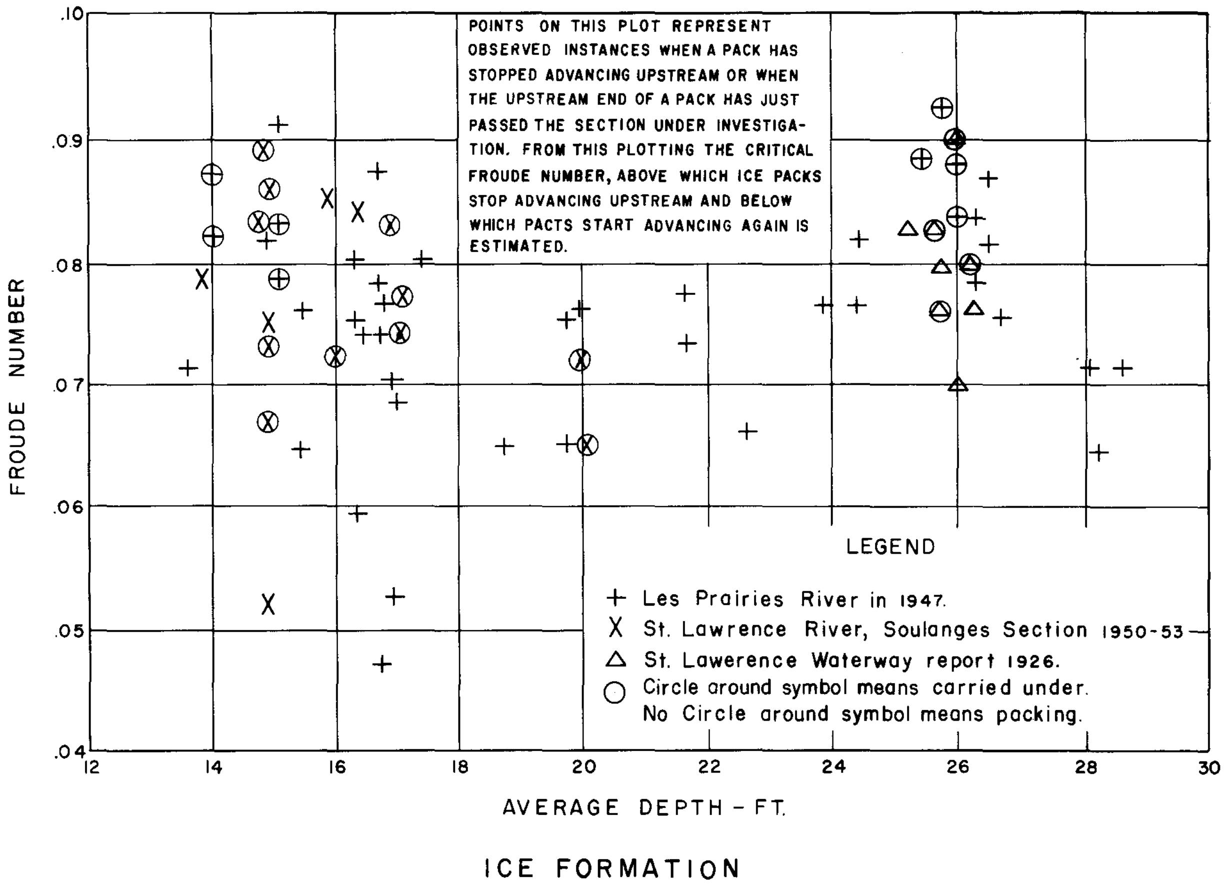

Figure 10. Critical velocities at the head of pack.

From Kivisild.[11]

expressed in Equation (14) to aline the two ordinates on the graph. Michel added four points taken from data on the Beauharnois Canal:[12]

"The testing points of the Beauharnois Canal are particularly useful, for the two upper points correspond to the limit of formation of the cover fed by large floes, while the lower points were obtained from covers fed by frazil ice and by very thin pellicular ice.

"Despite the imprecision of these facts, we will take, preliminarily, floes of a porosity of 0.73 to correspond to ideal conditions of progression, and flakes of frazil ice of a porosity of 0.90 for difficult conditions of progression. We will be on the safe side in both cases, and we will have the limit of the progression velocities given in the following table:

Table 1

APPROXIMATE LIMIT OF THE PROGRESSION VELOCITY OF AN ICE COVER

Depth in feet	Velocity, linear feet/second	
	$\epsilon = 0.73$	$\epsilon = 0.90$
40	2.9	1.8
30	2.5	1.5
20	2.0	1.3
10	1.4	0.9
5	1.0	0.6

Michel[2] states that there is an upper limit of velocity at which an ice cover can form in nature:

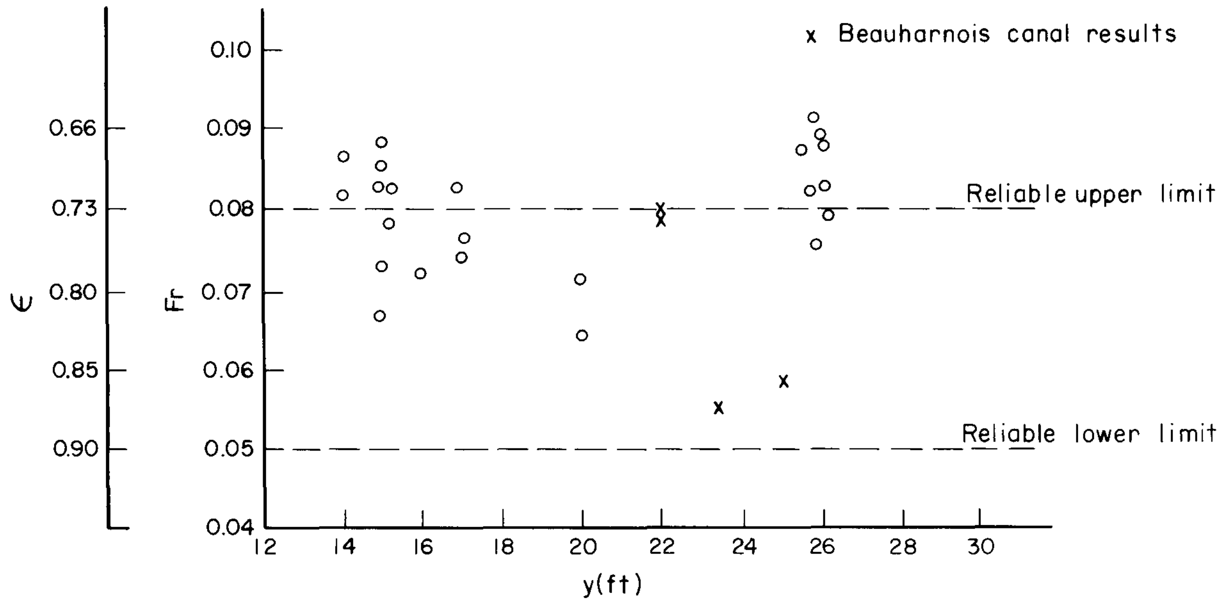

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Figure 11. Equilibrium limit of a cover in the grip of the ice.

From Michel.[2]

"All the measurements taken in the field over nearly 40 years on the limit of formation of ice covers, have shown that it was not possible to make an ice cover form if the flow velocity upstream exceeded a maximum limit of about 2.6 ft/sec."

Apollov[13] and Jarocki[14] discuss the effect of temperature on ice accumulation. Apollov derives the equation:

$$h^2 = \frac{2K}{\delta L} (\theta - t) T \qquad (17)$$

where

- h = thickness of ice cover
- K = coefficient of thermal conductivity
- δ = density of ice
- L = latent heat of ice formation
- θ = temperature of water
- t = temperature of air
- T = period of time

Bydin's equation is also mentioned:

$$h = 2\sqrt{\Sigma t} \qquad (18)$$

where

Σt = sum of mean negative daily temperature in degrees Centigrade from beginning of the formation of the ice cover up to the date of computing the thickness of the ice

Under ideal conditions ice covers can progress upstream very rapidly. Cousineau[7] observed an ice cover progression on the St. Lawrence River at 25 miles per day. Laszloffy[15] speaks of one on the Danube which progressed 100 kilometers per day.

b. Roughness coefficient for under surface of ice cover

Accepted values for the roughness coefficient of the under surface of an ice cover have eluded investigators for years. Some investigators assume the coefficient of the under surface to be the same as that of the channel bottom.

Nezhikhovskiy[16] presents a thorough literature review on this subject giving existing formulas of the adjusted coefficient of roughness used by Russian investigators. He states:

> "... in the overwhelming majority of cases the coefficient n_2 gradually diminishes during the winter period. This is explained by the smoothening of the bottom surface under the influence of flowing water and of heat derived by the stream from the bed and from ground water. The maximum value of n_2 is observed during the first days of freeze-up (1-3 days)."

Using the hydraulic characteristics obtained from almost 400 winter measurements, Nezhikhovskiy introduces the following equation for the value of the coefficient of roughness of the under side of the ice cover, n_2:

$$n_2 = n_{2,\,end} + (n_{2,\,init.} - n_{2,\,end})e^{-kt} \qquad (19)$$

> "In this equation $n_{2,\,init.}$ is the coefficient of roughness at the beginning of freeze-up; $n_{2,\,end}$ coefficient of roughness at the end of freeze-up before the rise in spring waters, or at the moment when all of the slush* has disappeared and the coefficient of roughness during the remaining part of the winter remained almost constant and equal to 0.008-0.012 (smooth ice); T – number of days after freeze-up. The parameter k was selected for the condition of best agreement with observed points; mainly during the first half of the winter period."

Table 2 can be used to determine $n_{2,\,init.}$ if the initial thickness of the ice cover and the type of ice making up the cover are known. The value of k can be estimated from Table 3. A winter is considered severe if the average temperature of the two coldest months is less than -12° to -15° C, moderate when the temperature ranges from -7° to -11° C, mild is the temperature is above -5° to -6° C.

Table 2

COEFFICIENTS OF ROUGHNESS OF THE BOTTOM LAYER OF THE SLUSH-ICE AT THE BEGINNING OF FREEZE-UP, n_2

Initial thickness of slush-ice cover, meters	The slush-ice cover was formed (principally): From loose slush	From dense (frozen) slush	From ice
0.10	–	–	0.015
0.30	0.010	0.013	0.04
0.50	0.01	0.02	0.05
0.70	0.02	0.03	0.06
1.00	0.03	0.04	0.07
1.50	0.04	0.06	0.08
2.00	0.04	0.07	0.09
3.00	0.05	0.08	0.10
5.00	0.06	0.09	–

Table 3

VALUES OF PARAMETER k

Description of meteorological conditions of the winter	Characteristics of the ice cover: Many polyn'yas*	Few polyn'yas	No polyn'yas
Severe	0.005	0.010	0.020
Moderate	0.023	0.024	0.025
Mild	0.050	0.040	0.030

*Polyn'yas—an open water surface surrounded by an ice cover.

> "For the most part at the moment of disappearance of slush in the middle of the winter $n_2 = n_{2,\,end} =$ 0.008 to 0.010 and before spring rise of water (if the slush remains all winter) $n_2 = n_{2,\,end} = 0.010$ to 0.012."

Equation (19) is presented in a series of nomograms for $n = f\,(n_{2,\,init.}\,T)$ and for the condition $n_{2,\,end} =$ 0.010 (Figure 12).

*Author's note: Slush-ice in this quote means solid ice underlain with slush.

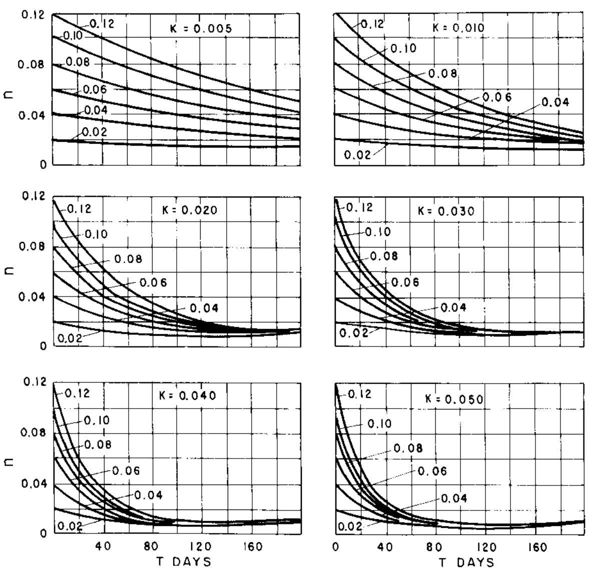

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Figure 12. Nomograms for the computation of coefficient n_2.

From Nezhikhovskiy[16]

In a study based on the St. Clair River flowing between Lake Huron and Lake Erie, Graf[17] developed an equation of the form:

$$n = cn_1^d \tag{20}$$

where

- c, d = constants found from least square analysis
- n = roughness coefficient of channels with ice cover
- n_1 = roughness coefficient of open channels

In analyzing the data from the St. Clair River he developed the following empirical equation:

$$n = (0.63)^{(n_2/n_1)^{1/6}} n_1 [1 + (n_2/n_1)^{1.5}]^{2/3} \tag{21}$$

where

- n = roughness coefficient of frozen river
- n_1 = roughness coefficient of channel bed
- n_2 = roughness coefficient of ice cover

Beccat and Michel[18] gave the following relation for the friction coefficient under an ice cover:

$$k_1 = \frac{k\ k_o}{(2k_o^{3/2} - k^{3/2})^{2/3}}$$

where

- k_o = friction coefficient of riverbed
- k = friction coefficient of the ice sheet and riverbed
- k_1 = friction coefficient of ice cover used in Strickler-Manning formula $v = kR^{2/3}S^{1/2}$

They give values of k_1 = 50 for solid ice cover made only of ice floes.

k_1 = 90 for same ice cover and frazil ice deposited underneath

Frazil ice actually makes the surface smooth.

De Bellmond[19] found that the head loss was increased by the friction of the surface ice cover to 1.36 times the head loss without ice cover in a uniform cross-section earth channel carrying 2,260 ft^3/sec.

Larsen[20] also investigated the head loss caused by an ice cover on open channels. He derives an equivalent roughness factor.

c. Forecasting ice formation and jams

Bolsenga[21] in a very thorough literature review of river ice jams lists several references related to forecasting ice formation and ice jams.

Williams[4] discusses the work of several investigators who have attempted to forecast the formation of frazil ice from water-air temperature measurements.

A report by the United States Bureau of Reclamation[51] describes a method used to forecast ice growth on the upper Arkansas River in Colorado.

Shulyokovskii[22] in directing his remarks to forecasting ice breakups on rivers states:

> "Ice cover drift and ice breakups on a river (the beginning of ice drift) are usually the result of two processes: (1) melting of the ice cover—reduction of its thickness and strength and, (2) increase in the water discharge and accordingly in the flow velocities and rise of the water stage as a result of snow melting in the particular river basin.

> "Irrespective of how the ice breakup takes place, with or without a flood, it begins when the flow velocity of the water under the ice for a given state of the ice cover is sufficient to overcome the

resistance of the shore or of the shore ice, and to cause the breakup and drift of the ice cover downstream."

Hausser and Beauchemin[23] in discussing the rate of ice production on an open water surface, compare the MacLachlan formula based on measurements of ice jams and cover volumes with some results they have obtained at La Salle Hydraulic Laboratory in Quebec.

III. Problems Resulting From The Formation of River and Reservoir Ice

There are myriad problems resulting from ice formation in rivers and reservoirs. In areas of periodic subfreezing temperatures such as parts of Eurasia, Canada, and the United States there has been a history of flooding, damage to hydraulic structures and even loss of life due to ice formation.

A. Ice cover and ice jams

Pariset, Hausser, and Gagnon[8] discuss the formation of an ice cover on the St. Lawrence River starting at the outlet of Lake St. Peter and extending 60 miles up the river through Montreal Harbor. As a result of this ice cover the water level in Montreal Harbor has risen as much as 22 feet above the normal water level for the same discharge:

> "During these maximum levels, some flooding occurs in the harbor, and water levels are dangerously high in Laprairie Basin where flooding has occurred in the past, and where the dikes protecting the cities of Verdum and La Salle are only a few feet above maximum high water level."

As ice cover or ice jams form in a natural river the ice cover produces an added head loss and results in a rise in upstream water level. Laszloffy[15] lists two possibilities that will occur due to this unstable condition:

> "The water level continues to rise until:
>
> (1) There is sufficient pressure to expel the water beneath the ice,
>
> (2) or else until the water finds another channel bypassing the obstruction to flow. The more deeply the bed of the river is incised, the more probable it is that situation (1) will be produced."

In describing the potential danger in an ice breakup he states:

> "(1) The lower the water level at the time the river freezes (hence, the narrower the flow section beneath the ice sheet),
>
> (2) the colder and more prolonged the winter (hence, the thicker the ice),
>
> (3) the more violent the thaw (hence, the greater the discharge),
>
> (4) the flatter the slope of the river (hence, the lower the velocity),
>
> (5) the less deeply the river channel is incised,
>
> (6) the more deteriorated the channel,
>
> the more dangerous is the breakup."

Vadot[24] discusses the effect of ice cover on water level and backwater curve changes.

Cousineau[6] stated that in one section of the St. Lawrence River he found that the largest hanging dams and the highest water elevations were associated with the milder winters and not with the colder ones:

> "The departure from ideal conditions may be brought about chiefly by a rise in atmospheric temperature or by a rise in water temperature or by both at the same time. The more remote the departure is from ideal conditions, the lower the average velocity will be that the pack can overcome and the larger the hanging dam required to provide the lower velocity."

B. Reduction in flow due to ice storage

Erskine[25] by using data from gaging stations, shows a loss of several thousand acre-feet per season in the Heart River resulting from storage of water in the form of ice. Figure 13 illustrates the losses recorded for several seasons at various air temperatures and discharges. He stated that conclusions drawn from Figure 13 were complicated by differences in temperature and discharges:

> "However, we might say that generally the rate of loss is relatively low for the small discharges, particularly if the rate of release is decreased somewhat as the winter progresses. Higher losses are usually indicated for higher rates of releases as is to be expected of a stream of this type which widens rapidly as the discharge increases in the range of flow being considered. Decreases in the rate of flow during a given period tend to decrease the rate of loss in all ranges of flow experienced. Increases in the rate of release add substantially to the rate of loss probably owing to water breaking through the existing ice cover and flowing on top where it is readily frozen."

Hunt[26] in discussing the St. Lawrence River Power Project, lists reduction of riverflow as one of the ice problems on the St. Lawrence:

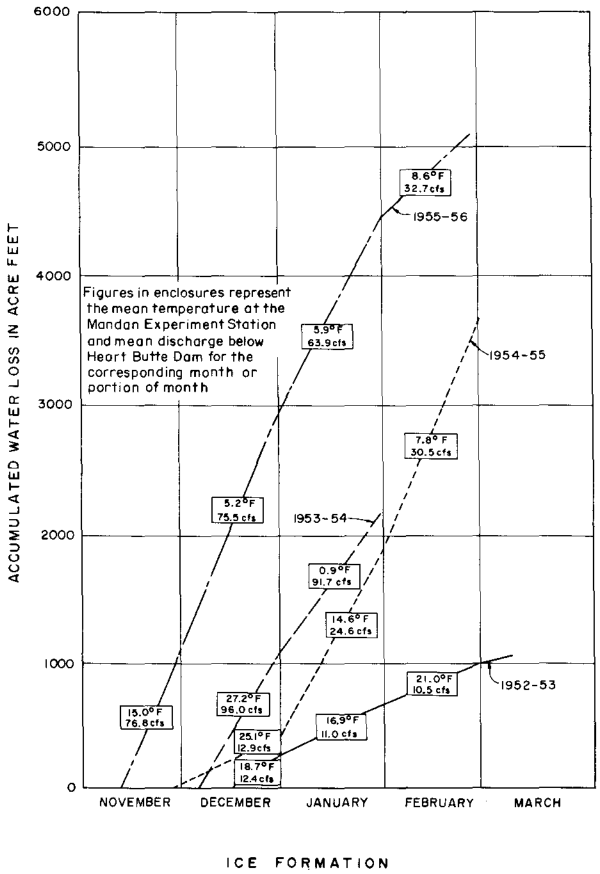


Figure 13. Indicated water losses—Heart River

From Erskine[25]

"The formation of ice in this reach has, as its direct effect, the diminution of flow from Lake Ontario. Ice jams have caused flow retardations of 40,000 cfs. The turbine units at the St. Lawrence Power Dam utilize approximately 9,500 cfs, each, so it can be seen that ice retardation can be considerable."

Stevens[27] discusses ice gorging on shallow streams where much water is stored in the form of ice. This can occur in alluvial valleys in cold regions where the banks of the river are low, a fairly steep gradient exists and the flow is shallow. There are two disadvantages to consider in the storage of water as ice. (1) In areas of hydropower production water stored as ice can reduce the power output and (2) water stored as ice can be potentially dangerous where rapid spring thaws are possible.

C. Ice floes causing damage

Laszloffy[15] points out:

"In addition to exposing the riparian regions to the danger of floods, the ice breakup also meances the permanent structures erected in the river and the boats at anchor. The movement of the ice is especially dangerous in the case of works along the shore that rest on piling in deep waters, inasmuch as the thrust of the ice operates, in this case, with considerable leverage."

Bryce and Berry[28] note the damaging effect large chunks of lake ice from Lake Erie have on power production at Niagara Falls:

"Two or three times during a winter, due to the influence of heavy storms and seiches in the lake and accompanying level changes of up to 8 feet, the ice arch would be broken, releasing tremendous quantities of thick lake ice into the river. It was this ice that caused the greatest damage and difficulty to power operation and the massive jams in the Maid-of-the-Mist Pool. The 10,000-square-mile lake surface is so vast in comparison with the Niagara River area of 24 square miles that the supply of lake ice is at times sufficient to completely glut the river."

D. Frazil ice

Frazil ice plays an important role in the formation of ice covers as mentioned earlier. However, as Michel[29] states:

"The most adverse effect of frazil ice is certainly its clogging of water passages in engineering works. Frazil ice has been known to clog partially and even completely trashracks of water intakes, wicket gates, and even propeller blades of turbines. This problem is most felt in hydro or steam powerplants because the advent of frazil ice coincides with the period of maximum load demand on the networks. A reduction in power production, at that critical time, becomes synonymous with a reduction of firm power that the plant can produce for the whole year. Where it occurs, the frazil ice problem becomes a major factor in the design of a powerplant and it might cost millions and millions of dollars."

Mosonyi[30] points out the fact that powerplants in cold regions have less ice problems than those where an alternate freeze-thaw climate occurs in the winter months:

"As proved by experience gained in northern countries, the plants built in the coldest regions near the Artic, are less subject to troubles caused by the formation of slush and anchor ice than the ones located in regions where in winter very cold periods and frost-free periods follow each other alternately. In fact, in very cold climates the gradual and slow fall of temperature in late autumn allows the formation of such ice covers as will only melt in spring, whereby all other icing processes are prevented. In less cold climates, however, the ice cover may melt more than once during the winter, and if a sudden severe cold wave happens to break in and finds an open surface of water, the rapid formation of ice throughout the body of water may be so extensive that the racks and turbines may become clogged in a short time."

Williams[31] studied the adhesion of frazil ice to different surfaces in the laboratory:

"The laboratory experiments demonstrated that the thermal properties of materials affect the ability of frazil ice to adhere to them. Under laboratory conditions and supercooling of 0.1° C, frazil will adhere to steel but not to plastic and plastic-coated steel. For supercooling of 0.2-0.3° C, frazil will adhere to plastic and plastic-coated steel but in lesser amounts than to untreated steel.

"A silicon grease was tested and found to inhibit the adhesion of frazil to metallic objects during frazil production."

Devik[32] discusses the problems of frazil ice at water intakes in Norway. He mentions several design considerations when an overall plant project is being planned:

"First, the profile of any open channel supplying water to the powerplant must be sufficiently wide to reduce the turbulence of the water and to keep the velocity below the critical value of 0.6 m/sec. Secondly, it might be advisible to accelerate the formation of an ice cover by placing wooden beams or a floating screen across the channel, as mentioned before . . . Thirdly, it is of great importance to provide for a slow and smooth flow of the water through the inlet channels, and the trashracks should be roofed in. It should also be added that the orientation of the inlet basin should be chosen in such a way that it would not be exposed to the prevailing winds in very cold weather."

Williams[4] mentions several design considerations in the planning of new projects. Michel[3] also lists several design considerations:

"The case of a water intake in a lake presents no difficulties. It is enough to arrange the water intake beneath the water in such a fashion as to avoid the frazil ice which could appear through the effect of wind before the setting of the surface ice. In the case of a river intake, we should avoid situating the gate in a rapid, above all at a short distance below a rapid where one would risk forming deposits of frazil ice beneath a partial cover of ice thereby irremediably blocking the intake for the winter."

IV. Remedial Work Around Hydraulic Structures

There are several references related to remedial work on existing structures. Michel[29] mentions the use of heat as a means of controlling ice on trashracks. He cautions that heating of the racks is generally useless if a rack is already blocked when one begins the heating.

Williams[4] lists several remedial actions available for established waterworks and powerplants. They include:

1. Heating affected structures.

2. Air–bubbling systems.

3. Artificially starting ice cover.

Devik[32] reports that:

"Based upon the observations of supercooling and the formation of frazil ice and bottom ice, it was assumed that the 'life path' of a supercooled surface element may be of the order of 20-30 meters. It was considered that if the inlet channel could be covered over by a roof outgoing radiation would practically be stopped, and that a length of the roof of 30-40 meters might be suitable. The heat loss by convection and evaporation might then be compensated by radiating heat from electric heat elements installed under the roof, directing the radiation to the surface film where the heat would be absorbed. The electric heating of the racks would be available as an additional reserve."

Pariset and Hausser[33] report that with an ice cover extending 60,000 feet upstream from a powerhouse, quantities of ice particles entering the turbines are of the order of three-fourths of the quantities produced by the ice free water surface upstream of the cover.

"If ice cover will stop local formation of frazil ice, it does not seem very effective in reducing the amount of frazil ice coming from upstream; but it certainly is effective by starting a certain melting of frazil ice and so greatly reducing its tendency to stick to trash screens and other equipment."

Bier[34] discusses the use of air bubblers to prevent ice formation on the upstream face of dams and in areas of trashracks and gates. He also discusses the use of heaters to prevent ice formation along seats and seals of gates.

V. Control of Ice Jams on Rivers

In considering the control or prevention of ice jams let us review the dynamic conditions resulting from an ice cover.

Berdennikov[35] presents the following equation:

$$P_m + W + P_\upsilon + Q_i + F_\upsilon - P_\sigma - T = 0 \qquad (22)$$

where

- P_m = thrust against edge of ice cover by the mass of ice floating down from the upper reaches
- W = friction force caused by wind
- P_υ = hydrodynamic pressure against leading edge of ice cover
- Q_i = weight component of the ice masses parallel to water surface
- F_υ = friction force of the water under the ice cover
- P_σ = normal component to the cross section of the ice stresses
- T = tangential stress component caused by friction of ice against banks

He goes on to say that P_υ, Q_i, and W are usually relatively small. F_υ, which plays the dominant role in the process of the opening of the river, is based on the shear stress, τ.

$$\tau = Hi\gamma B \qquad (23)$$

where

- H = depth of water below ice
- i = slope
- γ = specific weight of water
- B = part of total frictional force acting on ice cover

From Figure 14, he derives the following equilibrium equation,

$$(q_x + dq_x)\,Bh - q_x Bh - \tau B dx + 2\,\&fhq_x dx = 0 \qquad (24)$$

where

- $\&$ = q_y/q_x
- h = ice thickness
- f = coefficient of friction of the banks

Integrating Equation 24 for $q_x = 0$ and $x = 0$

$$q_x = \frac{\tau B}{2\&fh}\left(1 - e^{-2\&f\,X/B}\right) \qquad (25)$$

where $q_x h$ could be the force per unit length along a transverse ice boom. He points out that field data from Latyshenkov[36] shows that for $x > 4B$, q_x remains essentially constant.

Beccat and Michel[18] found that the maximum thrust occurs when the length of the cover, $L > 4B/K$,

where

- K = $2tg\phi tg^2(45^o - \phi/2)$
- B = average width of river
- ϕ = friction angle of ice

Kennedy[37] in a paper related to pulpwood holding grounds presents an analysis of the dynamic forces acting on a log jam. He develops an equation similar to Equation (25).

$$P = \frac{bf_o}{2\mu k_o}\left(1 - e^{-2\mu k_o (L/B)}\right) \qquad (26)$$

where

- P = the force with which the jam upstream is pressing against the jam downstream in a direction parallel with the current in pounds per foot width of stream
- f_o = the drag of the current on the under surface of the jam—pounds per square foot
- k_o = coefficient of lateral thrust
- μ = the sliding coefficient of wood against wood

Laboratory tests indicated $2\mu k_o = 0.40$; therefore Equation (26) can be written,

$$P = \frac{bf_o}{0.4}\left(1 - e^{-0.4\,L/B}\right) \qquad (27)$$

From Equation (27) it can be seen that P approaches a maximum value $(bf_o)/0.4$ asymptotically. When the length of the jam is six times the width, more than 90 percent of the additional force is transmitted directly to the shores.

If one considers the possibility of using an ice boom to control the location of an ice jam or to artificially create an ice cover, the maximum force acting on the

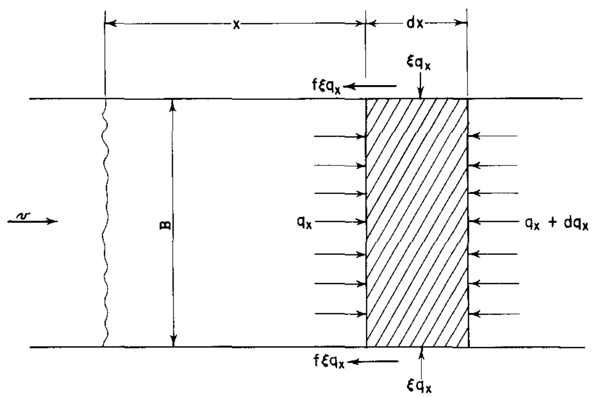


Figure 14. Stresses acting upon an element of a broken up ice field.

boom is related to the length of ice cover up to a length of four to six times the width of the cover.

Berdennikov[35] gives the following equation for the tension on a cable boom,

$$F = \frac{B^2 P}{8S} \tag{28}$$

where

- F = tension of the cable in kilograms
- B = distance between anchor points in meters
- P = ice load per unit length of ice kilogram per meter
- S = sag of cable in meters

Bryce and Berry[28] describe the need for an ice boom at the entrance to the Niagara River. They discuss some of the design considerations:

> "Ideally the boom should be located so that once a consolidated cover has formed it will become locked or keyed to the land. This can be achieved by selecting sites with irregular or converging shores or where islands can serve as anchors. In such locations, forces tending to move a consolidated ice sheet would be resisted principally by the land rather than the boom."

It was found that with surface velocities greater than 2.5 fps the ice cover was unstable. Therefore, the Niagara boom was placed so that the velocity generally did not exceed 1.5 fps.

Fould[38] discusses the ice control organization used to keep ice moving downstream on the Niagara River between Lake Erie and Lake Ontario. He describes in detail the complicated process of ice formation on the Niagara River and the corresponding procedures used to keep the ice moving.

Popel[39] discuss some of the hydraulic structures used in USSR for ice control. Among the structures is an ice boom anchored by a submerged crib pier and several types of "ice cutters."

Stothart and Croteaw[40] discuss the ice boom developed by the La Salle Hydraulic Laboratory for the St. Lawrence River in Montreal. The boom is basically a rigid structure perpendicular to the flow consisting of floating stoplogs between rigid piers.

Morton[41] approaches the criteria for the stability of ice cover on rivers much as Pariset, Hausser, Gagnon.[8] He develops the following equation for the jamming velocity:

$$V_{cz} = \frac{1.49}{n_I} u^{1/2} \left(\frac{1-r}{r}\right)^{1/2} \frac{D^{7/6}}{B^{1/2}} \left(\frac{1}{k}\right)^{1/6} \frac{X_{cz}(1-X_{cz})^{5/3}}{[1+(k-1)X_{cz}]^{1/2}} \tag{29}$$

where

- B = width of channel
- D = depth of water in channel
- k = $1 + (n_B/n_I)^{3/2}$
- n_B = Manning roughness factor for channel bottom
- n_I = Manning roughness factor for underside of ice cover
- r = specific gravity of ice—0.92
- u = coefficient of friction of ice on banks of river = 1.28
- V_{cz} = jamming velocity at cross section upstream of wide ice cover
- X_{cz} = jamming relative thickness of ice cover at cross section of maximum thrust

Figure 15 is a graphical representation of Equation (29).

> "The equation relating jamming velocity to channel dimensions and roughness coefficent (Equation 29) provides a theoretical indication of the relative efficiency of channel deepening and channel widening. Whereas the capacity for an open water channel varies as $BD^{5/3}$ the capacity of an ice-packed channel varies as $B^{1/2}D^{13/6}$. Therefore, for an open water channel it is economic to increase capacity by deepening only if the ratio of unit cost for deepening to unit cost for widening is less than

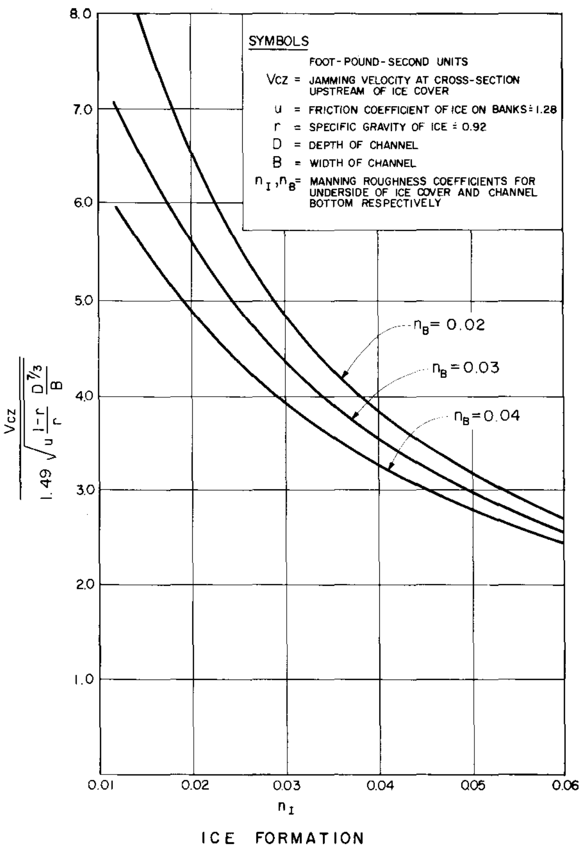


Figure 15. General relationship between jamming velocity and roughness coefficients (for wide cover).

From Morton[41]

1.67, which is quite unusual. However, in the enlargement of a channel for ice packing, it is economic to deepen whenever the ratio of unit costs is less than 4.33, so that in many cases deepening would be economic."

"The equation for jamming velocity also shows the construction of longitudinal dykes in a channel can increase the discharge capacity under ice-packing conditions by increasing the jamming velocity. A single dyke down the middle of the channel could increase the capacity by 41 percent, whereas two evenly spaced dykes could increase the capacity by 73 percent. The effect of cohesion of the ice to the banks and dykes would tend to increase these percentages, whereas the cross-sectional area occupied by the dykes would tend to decrease them."

Deslauriers[42] lists four types of remedial works to alleviate riparian damages by breakup:

1. Canalization of the channel.

2. Protection dikes.

3. Flow regulation by reservoir.

4. Artifical correction of ice regime.

Antrushin[43] reports on work done on the Dvina and Onega Rivers in Alaska using blackening substances and chemical preparations to artificially melt ice. The most effective materials are finely dispersed substances having maximum thermal capacity and conductivity. Ammonia nitrate, calcium chloride and potassium salt improve the bottom and water side flora, resulting in a beneficial effect on fish population.

Cook and Wade[44] report on the use of coal dust and fly ash to increase absorption of solar radiation and hasten breakup.

Williams and Gold[45] discuss the energy balance at a melting ice surface and how dusting the surface affects this balance:

> "A preliminary analysis, which is in general agreement with field observations, indicates the breakup can be advanced by about 2 weeks in southern Canada and about 4 weeks in northern Canada."

A table of various materials commonly used for dusting is included in the paper and also a table of absorptivity of various surfaces for solar energy.

Bolsenga[21] in his extensive literature review discusses several types and ways of using explosives in the control of river ice jams.

VI. Model Studies

Groat[46] as early as 1918 used a hydraulic model to study ice diversion. He used paraffin for surface ice.

Pariset, Hausser, and Gagnon[8] performed a rather thorough model study of ice formation on the St. Lawrence River in Montreal. From their investigations, an ice boom design was developed to trigger an ice cover formation upstream of the boom. Polyethylene was chose to represent surface ice. Although their model scale ratio was quite small (1:240 horizontal and 1:150 vertical), they reported very successful results from their model investigations. Tesaker[47] states that:

"in those situations where freezing processes are of minor significance, ice problems are in principle fit for model studies in a similar manner as sediment transport problems, with use of appropriate technique."

He developes the dimensionless ratios generally used based on Froude's model law:

"The model laws show that the scale ratios for specific weight and diameter are interrelated. By choosing the specific weights of the model particles like that of solid ice, the problem is reduced to estimating the diameter."

"The prototype conditions determine to what extent the suspended fraction of the ice must be included in a study. If a significant fraction of the ice in the prototype is suspended, then suspension of the model materials too is a definite requirement. Conditions similar to 'bed load movement' always appear where piling up of ice occurs, such conditions are therefore nearly always required in the model. If both types of movement are involved, an undistorted model will give the best conditions."

The discharge scale ratio for water or freely drifting ice is:

$$\lambda_Q = \lambda_x \lambda_y{}^{3/2}$$

The transport scale ratio for ice in contact with an ice cover is:

$$\lambda_{qB}\lambda_x = \lambda_y{}^3 \lambda_x{}^{-1/2}$$

where

λ_x = horizontal length ratio
λ_y = vertical length ratio

For an undisorted model $\lambda_Q = \lambda_{qB}\lambda_x$, but for a vertically distorted model $\lambda_Q \neq \lambda_{qB}\lambda_x$.

Tesaker describes an ice model study of the Burfell Project in Iceland where polyethylene in the range of 2-6-mm diameter was used as the ice material.

Cebertowicz[48] describes an ice model study used to test the suitability of two types of ice boom structures upstream of a powerplant. A rigid reinforced-concrete beam was chosen over a set of floating wooden beams linked together.

Kennedy[37] in a very interesting model study of forces involved in pulpwood holding grounds indicates a theoretical approach very similar to that used in the study of forces involved in an ice cover on a river.

VII. Summary

There have been many ideas and theories propounded in this review. Some have been tested under realistic conditions and verified; many others have been elusive to any universal application. The geomorphologic and meteorologic state of each specific situation seems to eliminate the application of any universal solution. There are, however, many instances of remedial work in the control of ice in rivers and on hydraulic structures which have been quite successful and should give direction in the consideration of a specific ice problem.

Further work with ice models would be beneficial in providing more information related to ice jam control on rivers. Studies to optimize the design of ice booms on rivers and lakes are needed. The ideas expressed in regard to longitudinal dikes increasing the discharge capacity of an ice-covered river should be investigated in ice models. More prototype data are needed to verify ice model designing techniques. Prototype research is also needed where freezing processes are of major significance, such as hanging dams and ice storage in rivers.

REVIEW OF ICE PROBLEMS ASSOCIATED WITH RECLAMATION FACILITIES

I. Introduction

In April of 1970, the Engineering and Research Center initiated a survey of the Regional offices concerning river, reservoir, and canal ice problems. The Regions were asked to describe ice jams occurring in natural channels either upstream or downstream from reservoirs or other facilities. They were also asked to describe damage or inconvenience that has resulted from ice formation in canals and at entrances to powerplants, spillways, outlet works, and other hydraulic structures. Information of any corrective or preventive measures that had been undertaken to alleviate the problems was also requested. It was hoped that with this information the extent and severity of the problem could be determined. This would in turn help establish a research program leading to alleviation of ice problems.

II. Problems Upstream From Reservoirs

In reply to the aforementioned survey, correspondence from the Regions indicated that problems created by ice jamming in natural channels are of considerable importance. One of the most common places that these jams occur is where a river enters the backwater of a reservoir. In the fall, as temperatures drop, the quiet water of the reservoir develops an ice cover prior to the river. Then as the river ice begins to form, it may be carried downstream to the reservoir. As the float ice reaches the reservoir, it accumulates against the lake ice and a jam is formed. In many cases the problem is worsened by other factors such as a reduction in the efficiency of the channel due to sediment deposits or the presence of a bridge or obstruction. These areas were often susceptible to jamming and flooding prior to the dam construction.

In general, the problems created by ice jams extend for several miles upstream from the reservoir and consist of lowland flooding and high water in the river channel. In nearly all cases field and ditch damage along with bank erosion has taken place. In some cases such as on the Payette River at Black Canyon Reservoir, Idaho; on the Wind River at Wind River Diversion Dam, Wyoming; and on the Gunnison River at Blue Mesa Reservoir, Colorado; the Bureau has obtained limited flood easements. Other damage that has occurred includes flooding of a sewage lagoon and an electrical substation at Townsend, Montana, on the Missouri River above Canyon Ferry Dam. However, it has not been determined whether the ice jams were either caused by, or aggravated by, Canyon Ferry Reservoir as there has been a history of ice jam flooding in the area before the reservoir was built. Flood damage caused by ice jams usually results in hard feelings between the Bureau and inhabitants of the area. It is hard to put a price on adverse public relations, but it could be quite costly.

At some sites preventive measures have been taken to solve these problems. On the Payette River at Black Canyon Reservoir attempts have been made to reduce ice jamming by reservoir level control and inflow control. The reservoir water surface has been lowered 2 to 10 feet, the river inflow has been reduced, and the river inflow has been fluctuated in attempts to reduce jamming. All three of these remedies have a negative effect on power production; likewise, all three have proven ineffective in solving the problem. Channelization was considered; however, the Corps of Engineers found that a program of dike construction and dredging would be too expensive and would require too much maintenance to be feasible.

At Arcadia Dam on the Middle Loup River, Nebraska, high water in the river channel created a bank erosion problem. As a solution jacks were placed on the bank to protect it. The jacks consisted of three angle irons placed at right angles in three planes and joined at their centers. Wire is laced through the angle irons in a standard pattern to tie them together.

At two locations on the North Platte River in Wyoming, ice jamming at reservoirs has created problems. Behind both the Glendo and the Pacific Power Reservoirs ice jamming has caused lowland flooding. In an attempt to alleviate this, river discharges are held as constant as possible so that ice cover is not broken up. This does not provide a solution to the problem but does significantly reduce the jamming and flooding.

Another problem site is on the Gunnison River at Blue Mesa Reservoir, Colorado, where jamming and lowland flooding has resulted in a limited channelization effort by the Corps of Engineers, which consisted of removing willows and sand bars from the channel. If this effort does not solve the problem, major channelization, including dikes and dredging, will be considered. This is not only aesthetically displeasing but would also require constant maintenance which would be quite expensive.

In summarizing the preventive measures that have been taken to solve jamming problems where rivers enter the backwater of reservoirs, it appears that no satisfactory solution has yet been found. Efforts to reduce jamming by lowering the reservoir water surface have shown little success. Reduction of the water surface elevation does not remove the reservoir cover ice or obstruction, and jamming will still occur and move upstream. Efforts to control the inflow have shown only limited success. Maintaining river discharges at a constant level has minimized the breakup of river ice but some jamming has still occurred. Finally, even extensive river channelization may not provide a highly effective solution. Even though the efficiency of the channel may improve, ice will still jam at the point where the floating river ice meets the cover ice over the still water. High dikes or banks can reduce the flooding problem to a high-water problem but this would still require bank erosion protection. Channelization also increases channel degradation and this in turn means increased sedimentation at the reservoir. Therefore, the channelization would require continued dredging to maintain efficiency.

III. Problems Downstream From Reservoirs

Ice jamming and its associated problems are also a common occurrence in channels downstream from reservoirs. It is often necessary to clean ice from a downstream channel in order to provide free flow from a powerplant or outlet works. In addition, the determination of downstream discharge becomes inaccurate, particularly if the flow quantity is determined at the source rather than at the delivery point. The inaccuracies occur when a portion of the discharge freezes and becomes ice storage which reduces the released flow and a second time when the storage ice melts and is added to the released flow.

Ice jamming downstream from reservoirs is usually caused by a constriction in the channel. This constriction can be either natural or man made, such as bridges and onstream structures. The jam develops as floating ice accumulates at the constriction to the point that an ice bridge, which is a continuous cover of ice across the channel, forms. From this point on the jamming procedure follows the same pattern as that for jamming at the backwater of reservoirs. An exception to this sequence is the Heart River at Mandan, North Dakota, near the conflux of the Heart and Missouri Rivers. In the spring, ice breakup on the Heart River precedes that of the Missouri. The resulting loose ice then jams against the cover ice of the Missouri.

The damage resulting from ice jamming is, in general, the same as for other lowland flooding, primarily field damage and bank erosion. At Mandan, however, the damage is intensified by the fact that it is a heavily populated area. Heavier than average damages also have occurred on the San Juan River at Bluff, Utah, where a foot bridge was damaged and oil and gas wells were endangered.

The North Platte River below Alcova Dam, Wyoming, also has had some special problems. An attempt was made to see what a quick, fairly high increase in river discharge would do to the cover ice. When the discharge was abruptly increased from near zero flow to 700 cfs, most of the ice was broken up and flowed downstream to the first obstacle, which was generally a wood pile bridge. Several wood pile bridges were damaged.

On the North Platte, below Glendo Dam, Wyoming, excessive channel degradation and bank erosion have occurred. The channel degradation resulted from an increase in velocity of the flow as it passed under the ice jam. It was felt that the fluctuation in river discharge due to power production was a major factor in the creation of the jamming and subsequent problems. For this reason power production has been discontinued at Glendo Dam in the winter.

At various locations preventive measures have been initiated in attempts to solve the problems. In general, most of the concerned facilities have established an operation procedure whereby discharges are maintained as constant as possible. If changes are necessary they are made very gradually. It has been observed that if gradual changes are made, the ice may crack but will refreeze before it can float free. This was verified at Boysen Powerplant, Wyoming, during the winter of 1967-68 when a discharge of 1,000 cfs was increased by 25 cfs every 12 hours until the outflow reach 1,500 cfs; and at Alcova Dam where on several occasions the outflow was changed by 25 cfs every 24 hours for initial flows in the neighborhood of 800 cfs. It appears that by use of these procedures a reduction in the jamming problem can be achieved.

On the North Platte below Glendo Dam, not only has winter powerplant operation been discontinued but riprap protection has been supplied to three reaches of bank and one irrigation pump was lowered because of channel degradation caused by increased flow velocities under an ice jam. The cost of these modifications was $70,000. These are, of course, only defensive modifications and at best the discontinuance of powerplant operation has only reduced the extent of jamming.

The Big Horn River below Boysen Dam, Wyoming, has also experienced frequent ice jamming. In addition to a controlled uniform discharge program, a periodic river patrol has been established to detect possible flooding conditions caused by ice jams. The periodicity of the patrols is dictated by the river conditions. Once again this program has met with only limited success.

On the North Fork of the Payette River, below Cascade Dam, Idaho, a special remedy has been used to clear the channel of an ice jam. On one occasion an ice jam formed in the river at a bridge. At this location the river had a low gradient and a sandbar had formed downstream from the bridge. To remove the jam, the discharge from Cascade Dam was changed from the spillway to the outlet works. In 1 week the warmer water from the outlet works had opened the channel and relieved the flooding. This method may be used when the jam is near enough to the dam so that the water temperature will not return to freezing prior to its arrival at the jam. It also, of course, requires that the dam have a gated spillway.

Finally, on the Heart River below Heart Butte Dam at Mandan, North Dakota, a system of dikes has been built to protect the town. These dikes do not, however, supply protection for the populated lands surrounding Mandan. In addition, the studies by H. M. Erskine[25] that were mentioned in the literature review were carried out. Mr. Erskine has attempted to correlate the amount of ice storage in the river to the river discharge. It was hoped that a discharge operational procedure for Heart Butte Dam that would minimize ice storage and thus minimize the amount of ice that could jam would be found. It was observed that the most effective procedure was to maintain a constant or slowly decreasing channel discharge. These efforts also met with only limited success.

As mentioned earlier, determination of downstream discharges can also be a problem of winter operation.

An example of this took place on the Green River below Fontenelle Dam, Wyoming. Ice storage reduced the channel discharge to the point that chemical plants were unable to obtain process water from the river. Water releases were increased and the problem was alleviated. The trouble basically is that ice in its various forms alters the flow and determination of downstream discharges becomes very difficult.

In addition to the work by Erskine[25] other ice storage studies have been carried out. At Homme Dam, North Dakota, a Corps of Engineers structure, studies similar to those at Heart Butte Dam were initiated. It was observed that for their particular case, when winter flows were increased from 3 to 20 cfs the increased flow absorbed the snow above the ice and froze. This flow was only able to go about 2 miles downstream before freezing. A discharge of 60 cfs, however, would keep an open channel under the ice in the winter. Increasing the flow to 200 or 250 cfs would lift the ice to permit flow under it.

Another factor that may alter predicted channel discharges is a reduction of flow velocity due to ice. At Heart Butte and Jamestown Dams, North Dakota, it has been observed that a slush-type ice may develop in the flow. This slush greatly reduced the flow velocity and increases the flow volume. At Jamestown Dam it took 3 days for the flow to travel 12 to 15 miles, while at Heart Butte it took 40 days for the flow to travel 89 miles. The reduced flow velocity of slush ice is also dependent on other variables including air temperature and channel cross section.

Determination of channel discharge may therefore be quite difficult. Not only can the flow be reduced by creation of ice storage but the actual flow properties can also be altered. The problem is complicated even more by the fact that these flow alteration factors are very dependent on climatic conditions and river channel characteristics. This means that determination of river discharge cannot be generalized, particular river channel characteristics and daily weather conditions must be considered.

Another problem that has been encountered during winter operation deals with the desire to clear a river channel of ice prior to the spring runoff. In 1969 the Bureau agreed to the request of the Jamestown City officials and the North Dakota State Water Commission to release water into the James River prior to the spring runoff in an effort to clear ice out of the river channel. At 10 a.m. on March 17, a discharge of 50 cfs was begun. This was increased to 75 cfs at 5:30 p.m. the same day and to 100 cfs the next day. On the morning of March 19 it was observed that water was not moving freely downsteam but was backing up in the area of a USGS water level gage near an interstate crossing, about 5 miles downstream from the dam. Release rates were then reduced to 50 cfs for 2 days and then shut off completely at 3 p.m. on March 21. A week later it was noted that the channel was fairly clear of ice from Jamestown Dam to the USGS gage at the interstate crossing. This method may prove quite effective under certain conditions, but probably is dependent on channel and climatic conditions.

IV. Problems in Natural Channels Not Influenced by Dams

Natural channels that are not affected by upstream or downstream reservoirs are still also susceptible to ice jamming. The problems developing from this jamming are the same as those discussed previously; i.e., lowland flooding and erosion. This ice jamming normally takes place at constrictions in the channel such as bridges, narrows, and sandbars. Damage due to this flooding is also similar to that discussed before. Notable exceptions are at Casper, Wyoming, on the North Platte River, and the Milk River below Fresno Dam, Montana, where there has been damage to populated and developed areas in addition to field and lateral damage. On the Yakima River the gates of Roza Diversion Dam, Washington, must be opened, and thus diversion discontinued, to allow ice jams to pass the structure. Since the diverted water supplies a powerplant, the discontinuance of diversion means a loss in power production. In only one of these three cases is a solution being sought. On the North Platte, near Casper, a prototype ice boom research study has been initiated at a point just upstream from Casper. This study, which is entering its fifth year, will be discussed later.

V. Problems in Canals

Ice has also created problems in hydraulic structures that are not directly related to natural river channels. Many of the Bureau canals are faced with extreme operation difficulties due to ice. Probably the main difficulty is jamming at bridges, tunnels, siphons, transitions from unlined to lined sections, and at various canal structures. In addition, slush ice has reduced the discharge capacity of the Wyoming Canal. The Wyoming Canal, Wyoming, Belle Fourche Distribution System, South Dakota, and the Main Canal of the Lower Yellowstone Project, Montana, have all suffered concrete deterioration due to winter operation. Also, ice accumulation in canal structures, during the winter, has delayed the startup of various systems in the spring.

Canals may be placed in two basic operational groups when dealing with ice jamming. One group is made up of those canals that operate continuously through the winter. The other group is made up of those canals that are essentially inoperative in the winter.

The causes of ice jams on canals that are operated through the winter are similar to the causes of ice jams in natural channels. Anchor ice (ice that accumulates on the bottom of the channel) may form, slush ice may develop in the flow, and cover ice may break up and jam; all reduce the discharge capacity of the canal. No attempts have been made to reduce anchor ice production but on the Wyoming Canal an effort has been made, for over 20 years, to reduce slush ice in the flow. It was found that a large portion of the slush ice in the canal flow originated in the river. An open slot nearly parallel with the river was cut in the cover ice at the canal intake structure. A system of electrically driven boat motor propellers was installed in the slot to force a large portion of the floating slush ice downstream and into the Wind River rather than allowing it to enter the canal. The best solution for the cover ice problem was to maintain a solid cover. When a solid cover is maintained, no chunks of float ice will accumulate and jam at constrictions. A solid ice cover also acts as insulation which prevents the production of more slush ice. On the Wyoming Canal, the canal is checked to increase the water depth and reduce the velocity to maintain the ice cover. This has proven fairly effective although it does not offer a complete solution. On the Roza and Chandler Canals, Washington, a dragline is used in attempts to clear the canals of their cover ice and therefore the source of the jamming. The dragline can only reach halfway across the canal. Therefore, some jamming does occur and at times operation of Chandler and Roza Canals must be curtailed. On the Truckee Canal, Nevada, the only preventive measures taken are canal observation patrols during the critical periods. One special case where ice problems have been solved is on the Grand Valley Canal, Colorado. A steam generating plant was placed on the canal and the canal water used for cooling. In cooling the plant the water temperature rises several degrees and the ice problem is removed.

Canals that are essentially inoperative during the winter face a very different basic problem. Ice accumulates at various points in the canal and then jams when discharge is started. Obviously this problem can be solved by waiting for the ice to melt before starting up the canal. This, however, is not always possible. Problems of this nature have occurred on the Rocky Coulee Wasteway and the Banks Lake Canal, Washington; the Mink Creek Creek Canal, Idaho; the Pishkin Supply Canal, Montana; the canals of the Eden Project and the Ralston Chute, Wyoming. The Eden situation is a matter of dewatering all of the siphons in the fall. If this is not done an ice plug will form and will prevent startup in the spring. The Mink Creek Canal and the Ralston Chute trap snow and ice from storms which accumulates to the point that it can cause jamming. The Mink Creek Canal and the Ralston Chute are the only two reported locations where corrective measures have been taken. On the Mink Creek Canal an overflow wasteway installed at the probable point of jamming protects the canal from overtopping. The Ralston Chute, on the other hand, is being covered to eliminate the ice problem.

Damage due to ice in canals is not extensive. In several cases deterioration of the concrete lining and structures has been observed. Also loss of power production and the inconvenience of not being able to use the system have often been experienced. Two cases of serious or very nearly serious damage were reported. On the Rocky Coulee Wasteway a highway bridge was nearly lost due to ice jamming behind it. The jam was cleared with a dragline but the bridge was greatly endangered. More damage occurred on the Truckee Canal, where ice jammed in a drop gate and the water level was raised to the point that it spilled over the canal levee. Seventy-eight feet of canal bank was lost and two farms suffered extensive damage. A section of highway also suffered slight damage.

VI. Problems on Reservoirs and Dams

Bureau dams and reservoirs have also suffered inconvenience and damage due to ice. There has been some damage due to shifting of reservoir cover ice but the main problem is icing of gates, valves, trashracks, and other outlet hardware. Dams have suffered concrete freeze-thaw deterioration. Ice accumulation from either spray, leakage or condensation has presented safety and operational hazards. Most dams are equipped with air bubble or heat tape deicing systems that have proven to be quite effective. Many dams have also developed operating procedures which help to eliminate their special ice problems.

VII. Environmental Considerations

Consideration of many of the possible solutions to ice jamming problems will lead to significant environmental questions that must be answered. The ultimate effect of channelization, channel discharge variation, flow temperature variation, and various types of channel bank protection on the total ecological balance in general, and on the onstream fishery in specific, is uncertain. It is also uncertain what the aesthetic impact of these solutions might be and how this impact could be minimized by a design which properly considers these environmental aspects.

Many studies have been undertaken to evaluate the effects of channelization on fish populations, Peters[49], Gebhardt.[50] Generally speaking, these studies have shown that when a stream or river is fully channelized the game fish population will drop 80 percent and the weight of game fish in the stream will drop 87 percent. The term "fully channelized stream" describes a stream that has been straightened to remove meanders, dredged to remove sandbars and channel vegetation growth, and had its banks improved and protected. The extent of fish population disturbances is dependent on the extent of channelization and on local conditions. A good stream fishery is generally characterized by a combination of riffles and deep pools, undercut banks, and streamside vegetation that shades portions of the stream. Any variation from these conditions will have a negative effect on the fish population. It has been observed that if basic stream cross sections and meanders are retained when channelization occurs, a fish population reduction of 50 percent can be expected. If, in addition, there is a replanting of bank vegetation this reduction may be held to 25 percent.

The question of the effects of channel discharge variation is a complex one. It is generally felt that the more constant the flow conditions and, for that matter, the more constant the entire stream living conditions, the better it is for the fish. If conditions do change, a gradual change is best. High water and flood conditions on streams may be beneficial by supplying a rejuvenation of stream nutrients.

The question of the effects of flow temperature variation yields a similar answer. It is best to maintain as constant a flow temperature as possible. If a solution similar to that used at Cascade Dam, Idaho, is applied, the transition should be made over several hours. By slowly changing from spillway to outlet works discharges the possible shock to the fish due to temperature difference would be minimized. One complication was noted. If the river gravels contain fish eggs and such a temperature change is initiated, a premature hatch could occur.

Negative effects due to various types of bank protection are similar to those due to channelization. Bank protection should be undertaken only at locations where it is absolutely required. Extensive programs of bank protection are not recommended.

Several solutions exist that are environmentally compatible. The most obvious is to work through the proper authorities to have potential flood damage areas rezoned to restrict further development of the area and therefore limit possible flood damage. If such zoning laws could not be enacted, consideration should be given to actual purchase of the land. In this case the areas could be established as strip parks. With this arrangement, development and therefore possible damage would once again be minimized. In developed areas and areas where possible flooding must be controlled, consideration could be given to building levees. Where possible, the levees could be constructed back away from the channel and thus the natural character of the river could be maintained. Once again, land between the levee and the channel could be used as a strip park.

VIII. Ice Boom Study

As was stated earlier, a prototype log boom study has been initiated by the North Platte River Projects Office of Region 7. The work has been carried out on the North Platte River 10 miles above Casper.

The basic idea behind this study was to develop a device that would prevent float ice from moving downstream and jamming in an inhabited area. To do this the device would have to create an ice cover over the river and probably would create a jam. The log boom could, however, be located so that whatever flooding did develop would not be damaging.

In the winter of 1966-67 an experimental ice boom was set up at Goose Egg Bridge. It was hoped that basic information about the boom design could be found. No consideration was given to the booms's orientation or configuration other than placing it perpendicular to the flow. It was found that either a chain or a direct attachment of the timbers to the cable was satisfactory. A system of long spikes projecting upward and downward from the timbers, to catch slush, was also found to operate satisfactorily.

In 1968 the first complete ice boom (Figure 16) was set up on the river. This was the beginning of an attempt to find the most effective configuration for creating a stable ice cover. With cold weather the ice cover started to develop from the banks toward the center of the river. As the cover formed, a high velocity area was created in the center of the channel, which made it impossible for the boom to catch and hold ice. A mild December made it possible to modify the initial configuration (Figure 17). A dynamometer was also installed in the boom cable at the southwest anchor to measure cable tension. With the advent of cold weather an ice cover developed rapidly. The first complete ice bridge developed about 200 feet upstream from the boom. As the jam grew the upstream water level rose, which lifted the ice on to the boom. As this occurred, not only did ice break free to float downstream but the boom was held beneath the water surface and ice floated over it. It was observed that this boom configuration also created undesirable high velocity concentrations and that the boom did not stop early slush. It was also noted that at the location of the boom the river had a fairly high velocity due to the narrow channel.

A new log boom was installed for the second year of prototype experimentation (Figure 18). The channel had been widened to reduce the water velocity and larger buoys had been installed in an effort to keep the boom higher in the water. A dynamometer measured cable tensions until a cable splice failed and the dynamometer was damaged. In general this new configuration worked satisfactorily.

Basic observations made from this prototype research are:

1. Ice booms perform best when the surface water velocity is less than 2 feet per second.

2. Ice booms operate better in cold weather with heavy slush.

3. Ice conditions upstream from the boom are no worse than they were prior to the boom.

4. After an upstream ice bridge has formed the water downstream from the ice boom will be clear.

5. The less sag in a log boom the better it functions. Ideally the boom should be placed perpendicular to

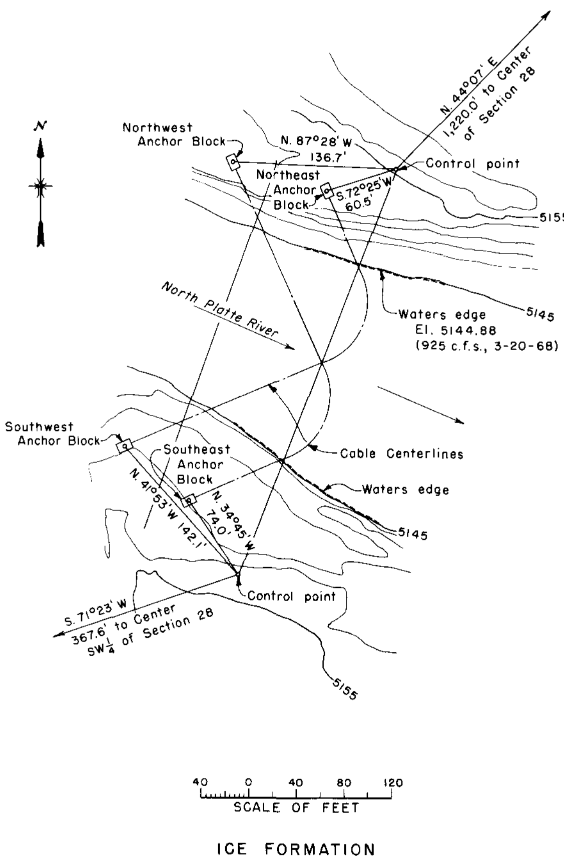


Figure 16. Initial ice boom configuration.

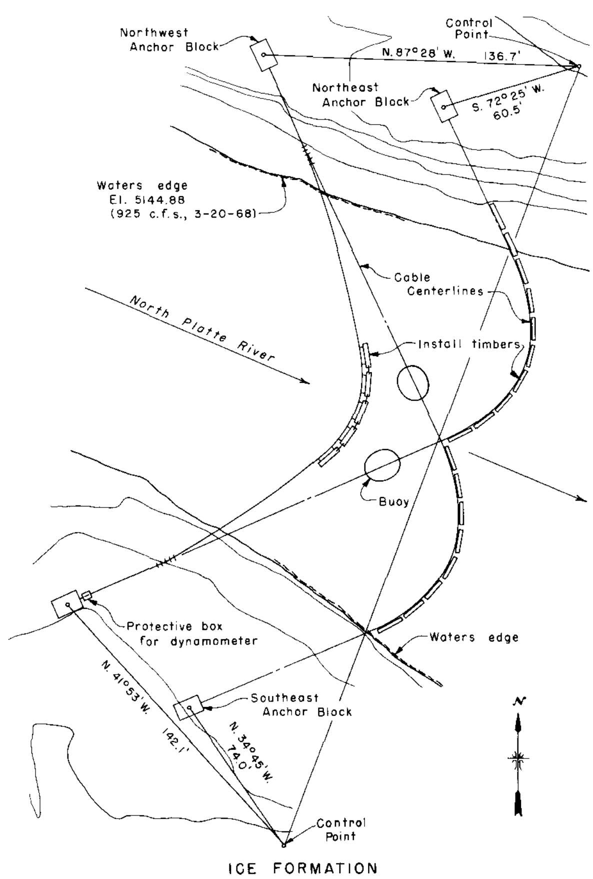
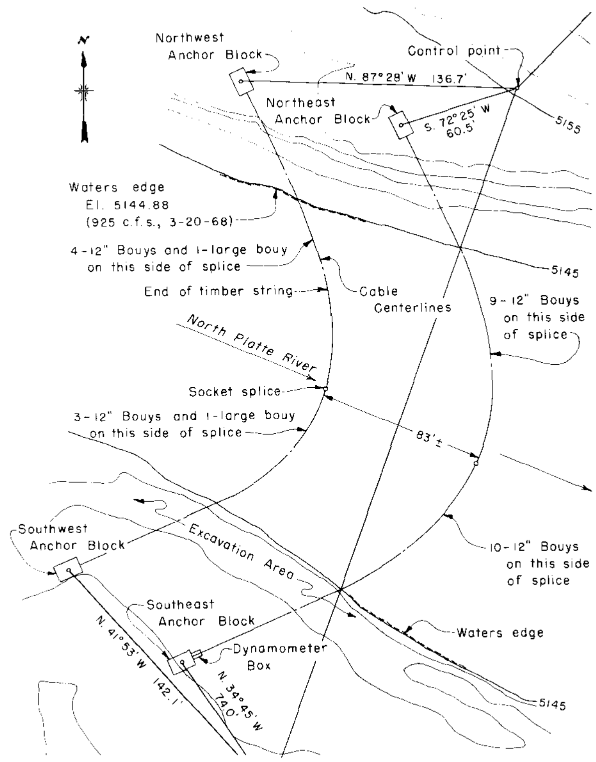


Figure 17. First modification to ice boom.



ICE FORMATION

Figure 18. Second modification to ice boom.

the flow but this would place too great a tension on the anchors.

IX. Summary

Analysis of the reports from the regions indicates that several avenues for solution of the various ice problems do exist. A general list of common solutions is as follows:

1. Channelization and levee construction may be implemented on channels susceptible to ice jamming and flooding.

2. Maintaining channel discharges as constant as possible can minimize ice cover breakup.

3. Riverbanks may require protection to stop erosion.

4. Ice booms may be constructed to force jamming at desired locations.

5. Periodic patrols and observations of ice problems can be initiated to give warning of impending adverse conditions.

6. Heat tape and air-bubble deicing systems have proved effective at most structures.

7. Many of the possible solutions to ice problems have environmental significance. This significance should be evaluated prior to implementation of alternative solutions.

A more detailed description of these solutions, their weaknesses and their strengths, is contained in this report. None of these solutions are ideal; they all have drawbacks. In addition, many special solutions exist (and are discussed in this report) that may be applicable under certain conditions.

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CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg; that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
	0.3048 (exactly)*	Meters
	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	929.03*	Square centimeters
	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	0.40469*	Hectares
	4,046.9*	Square meters
	0.0040469*	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
	0.473166	Liters
Quarts (U.S.)	946.358*	Cubic centimeters
	0.946331*	Liters
Gallons (U.S.)	3,785.43*	Cubic centimeters
	3.78543	Cubic decimeters
	3.78533	Liters
	0.00378543*	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	764.55*	Liters
Acre-feet	1,233.5*	Cubic meters
	1,233,500*	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
	1.12985×10^{6}	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
	1.35582×10^{7}	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
	0.3048 (exactly)*	Meters per second
Feet per year	0.965873×10^{-6}*	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	0.3048*	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	0.028317*	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	0.453592*	Kilograms
	4.4482*	Newtons
	4.4482×10^{-5}*	Dynes

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	0.252*	Kilogram calories
	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	1.35582*	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 deg F (k, thermal conductivity)	1.442	Milliwatts/cm deg C
	0.1240	Kg cal/hr m deg C
Btu ft/hr ft^2 deg F	1.4880*	Kg cal m/hr m^2 deg C
Btu/hr ft^2 deg F (C, thermal conductance)	0.568	Milliwatts/cm^2 deg C
	4.882	Kg cal/hr m^2 deg C
Deg F hr ft^2/Btu (R, thermal resistance)	1.761	Deg C cm^2/milliwatt
Btu/lb deg F (c, heat capacity)	4.1868	J/g deg C
Btu/lb deg F	1.000*	Cal/gram deg C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
	0.09290*	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	304.8*	Liters per square meter per day
Pound-seconds per square foot (viscosity)	4.8824*	Kilogram second per square meter
Square feet per second (viscosity)	0.092903*	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	35.3147*	Millicuries per cubic meter
Milliamps per square foot	10.7639*	Milliamps per square meter
Gallons per square yard	4.527219*	Liters per square meter
Pounds per inch	0.17858*	Kilograms per centimeter

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A review of published literature and Bureau of Reclamation experiences related to ice formation on rivers, reservoirs, and hydraulic structures is presented. The review is directed toward ice problems associated with Bureau of Reclamation projects where flooding or inefficient operation results from ice formation.

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Bur Reclam Rep REC-ERC-71-8, Div Gen Res, Feb 1971. Bureau of Reclamation, Denver, 26 p, 18 fig, 6 tab, 48 ref

DESCRIPTORS—/ *ice jams/ *frazil ice/ ice loads/ *ice breakup/ *flood damage/ *ice-water interfaces/ lake ice/ head loss/ water temperature/ roughness coefficient/ river forecasting/ *hydraulic models/ ice/ ice pressures/ bibliographies
IDENTIFIERS—/ ice forming/ ice cover/ ice sheet/ ice crystals

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