Dr. Ashton

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EVALUATION OF ICE MANAGEMENT PROBLEMS ASSOCIATED WITH OPERATION OF A MECHANICAL ICE CUTTER ON THE MISSISSIPPI RIVER

George D. Ashton

October 1974

PREPARED FOR
DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
CONTRACT NO. MIPR Z-70099-3-32744
BY

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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PREFACE

This report was prepared by Dr. George D. Ashton, Hydrologist, Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. The work was sponsored by the U.S. Coast Guard (Contract No. MIPR Z-70099-3-32744).

Technical review of the report was performed by Darryl Calkins and Guenther Frankenstein of USA CRREL.

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SYMBOLS

A	Cross-sectional area of river (ft^2)
A_a	Cross-sectional area at accumulation location (ft)
B	Width of ice slab (ft)
B_a	Width of an accumulation of ice (ft)
C	Constant (eq 9)
C_D	Drag coefficient
C_L	Lift coefficient
C_1	Constant of integration (eq 4)
D	Depth of flow (ft)
D_a	Depth of flow at accumulation location (ft)
F_b	Buoyancy force (lb)
F_D	Drag force (lb)
F_f	Friction force (lb)
F_L	"Lift" force (lb)
H	Wave height (ft)
H_{max}	Maximum wave height experienced at a point (ft)
L	Length of ice slab (ft)
L_a	Length of an accumulation of ice (ft)
Nu	Nusselt number ($\equiv q_w R/[(T_\infty - T_m)k_w]$)
Pr	Prandtl number ($\equiv \mu c_p/k_w$)
R	Hydraulic radius (ft)
Re	Reynolds number ($\equiv UR\rho/\mu$)
S_a	Distance between accumulation locations (ft)
S_d	Daily contribution of degree-days of freezing (°F-days)
T	Period of wave (sec)
T_m	Melting point temperature (°F)
T_0	Top surface temperature (°F)
T_{max}	Daily maximum air temperature (°F)

T_{min}	Daily minimum air temperature (°F)
T_{∞}	Temperature of flow (°F)
U	Mean flow velocity (ft sec^{-1})
V	Flow velocity (ft sec^{-1})
V_s	Vessel speed (ft sec^{-1})
ΔV	Velocity increase (ft sec^{-1})
b_c	Cleared channel width (ft)
c_p	Specific heat (Btu lb^{-1} °F^{-1})
g	Gravitational constant (ft sec^{-2})
k_i	Thermal conductivity of ice (Btu sec^{-1} ft^{-1} °F^{-1})
k_w	Thermal conductivity of water (Btu sec^{-1} ft^{-1} °F^{-1})
q_i	Heat flux in ice (Btu sec^{-1} ft^{-2})
t	Time (sec)
t_0	Initial time (sec)
x	Distance from sailing line of vessel (ft)
α	Coefficient (see eq 7)
β	Areal fraction of open water
γ_{ice}	Weight per unit volume of ice (lb ft^{-3})
η	Ice thickness (ft)
η_a	Thickness of ice accumulation (ft)
η_c	Thickness of ice slab (ft)
η_0	Initial ice thickness (ft)
η_r	Thickness of ice resistant to breakage (ft)
η_s	Total thickness of ice cut over a season (ft)
η_{max}	Maximum ice thickness under natural conditions (ft)
θ	Angle of wave pattern with sailing line
Θ	Angle of turn of channel axis
λ	Heat of fusion (Btu lb^{-1})
λ	Wavelength (ft)
λ_d	Wavelength of diverging waves (ft)
μ	Coefficient of friction
μ	Dynamic viscosity (lb sec ft^{-2})
ρ	Density of water (slugs ft^{-3})
ρ_i	Density of ice (slugs ft^{-3})
ρ_w	Density of water (slugs ft^{-3})
σ_f	Failure strength of ice (bending) (lb ft^{-2})
ϕ	Angle between direction of travel of diverging waves and sailing line

CONVERSION FACTORS

Quantity	*Units*	*Multiply by*	*To obtain*
Acceleration	ft sec^{-2}	0.3048	m sec^{-2}
Angle	degrees	0.01745	radians
Area	ft^2	0.0929	m^2
	$in.^2$	0.000645	m^2
Dynamic viscosity	lb sec ft^{-2}	47.88	N sec m^{-2}
Energy	Btu	1054.4	Joule
Force	lb	4.448	N
Length	mile	1609	m
	ft	0.3048	m
	in.	0.0254	m
Mass	slugs	14.59	kg
Mass density	slugs ft^{-3}	515.4	kg m^{-3}
Pressure	lb ft^{-2}	47.88	N m^{-2}
	lb $in.^{-2}$	6895	N m^{-2}
Velocity	ft sec^{-1}	0.3048	m sec^{-1}

EVALUATION OF ICE MANAGEMENT PROBLEMS ASSOCIATED WITH OPERATION OF A MECHANICAL ICE CUTTER ON THE MISSISSIPPI RIVER

by

George D. Ashton

INTRODUCTION

The purpose of this study was to evaluate ice management problems associated with operation of a Mechanical Ice Cutter for use in icebreaking as an aid to winter navigation. A Mechanical Ice Cutter (hereafter abbreviated MIC) is a concept employing three circular saws mounted on runners forward of a barge. When the barge is pushed into the ice sheet three longitudinal cuts are made. Once cut, the slabs break by bending under the cutter barge and are deflected laterally under the adjacent ice sheet by a skeg mounted beneath the barge. The result of the cutting pass is an open channel free of ice immediately behind the craft.

This study concentrated on the subsequent effects of this operation. Included in the evaluation are assessments of refreezing rates, movement and disposition of the slabs produced by the cutting, and an examination of effects related to ice jams. The evaluation is specific to the upper Mississippi River. In particular, Pool 19 above Lock and Dam 19 at Keokuk, Iowa, and Lake Pepin above Lock and Dam 4 near Alma, Wisconsin, are subjected to detailed analysis. Nevertheless, many of the results, and certainly most of the analysis, may be applied to other waterways where the MIC concept might be used. Of the two sites (Pool 19 and Lake Pepin) the emphasis is on Pool 19 although Lake Pepin is subjected to some detailed analysis, primarily since it presents more severe restrictions to navigation simply as a result of the colder average wintertime temperatures.

SITE CHARACTERIZATION

Monthly air temperatures

Before proceeding to the detailed evaluation, it is useful to summarize characteristics associated with the two sites. Table I presents monthly air temperature data which have been extracted from climatological data records[23 24] for the two sites. The greatest use of the data is for comparison with other potential sites and as an aid in evaluating the representativeness of particular years selected for more detailed analysis. As will become clearer below, the monthly averages tend to obscure the detailed daily and weekly variations in air temperature which largely govern the strategies of operation of the MIC. It is also worthy of note that the temperatures at the two stations were measured near the river valley and tend to be about 1°F warmer than corresponding

Table I. Summary of air temperature data, Keokuk L&D 19 and Alma L&D 4.
Extracted from ref. 23 and 24.

	Dec	*Jan*	*Feb*	*Mar*	*Apr*
Monthly mean temperature (°F), 10 year period 1951-1960					
Keokuk L&D 19	31.0	25.4	29.3	36.6	52.3
Alma L&D 4	24.2	17.1	20.3	29.3	47.0
Mean daily maximum temperature (°F)					
Keokuk L&D 19	39.3	24.1	39.1	45.9	62.7
Alma L&D 4	31.8	25.7	29.4	38.1	56.9
Mean daily minimum temperature (°F)					
Keokuk L&D 19	23.0	17.1	21.3	27.6	42.6
Alma L&D 4	16.6	8.4	11.1	20.6	37.1
Lowest temperature, 10 year period 1951-1960 (°F)					
Keokuk L&D 19	−9	−15	−13	−11	22
Alma L&D 4	−16	−36	−28	−10	9
Mean number of days with temperature ≤ 32°F					
Keokuk L&D 19	26	28	24	22	3
Alma L&D 4	30	31	28	28	10

adjacent stations out of the valley. Finally, a simple comparison of the two sites shows that Alma Lock and Dam 4 experiences, on the average during winter months, about 8°F lower temperatures than Keokuk Lock and Dam 19. This difference will be shown to yield significant differences in terms of frequency of operation and other characteristics associated with operations in ice conditions.

Ice conditions

Table II summarizes ice conditions for the two sites extracted from periodic reports.[21] [22] The thicknesses for recent years are also plotted in Figures 1 and 2 and provide an indication of the year-to-year variability. In general, the thicknesses were measured adjacent to the locks and may deviate somewhat from corresponding conditions away from the locks. The deviation is considered small, however, and probably overestimates slightly the average ice thicknesses in the associated river reaches.

Winter discharges

Figure 3 shows median flow discharges for the months December through April for the Mississippi River at Keokuk, Iowa, and St. Paul, Minnesota.[25] At Keokuk, the discharge is ordinarily at its lowest during December and January, rises somewhat through February and rapidly increases during March and April, the latter rise generally being associated with the spring snow melt. By contrast, the rapid rise occurs about a month later (late March) at St. Paul. Median discharges tend to obscure unusual events and it is not too unusual to have an increase in discharge in late January or early February as a result of a sudden period of warming or a heavy rainstorm. Such midwinter flow increases are important since they may cause early breakup and result in ice movement,

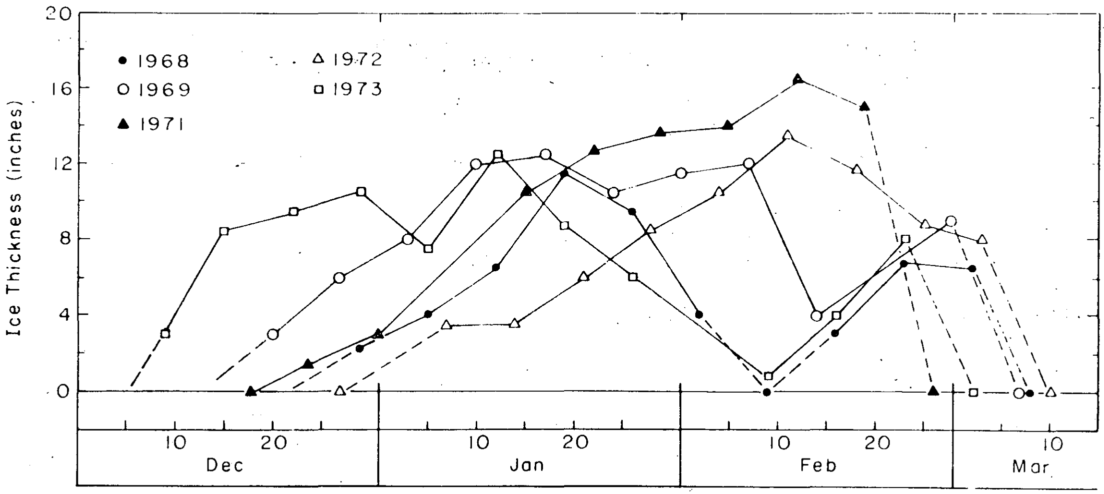


Figure 1. Ice thicknesses at Keokuk Lock and Dam 19.

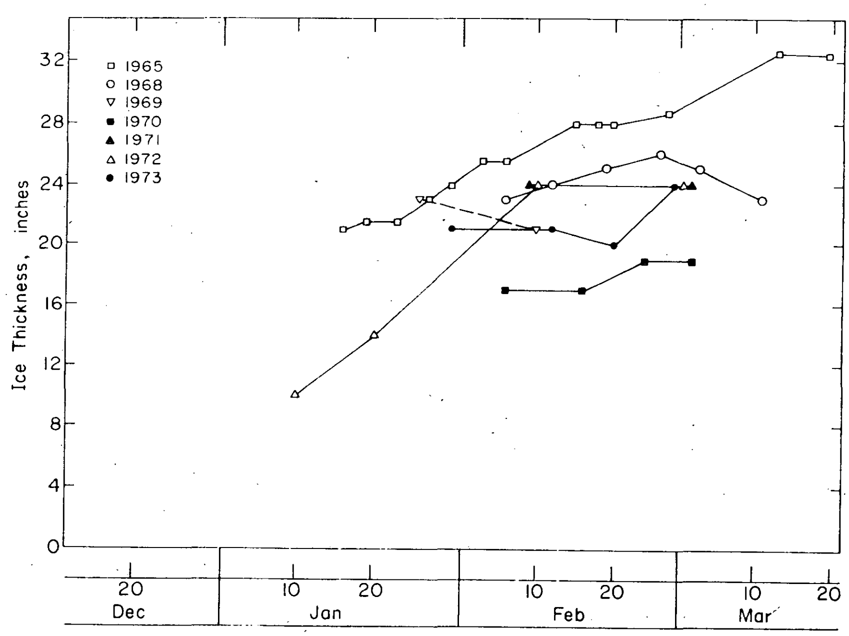


Figure 2. Ice thicknesses at Alma Lock and Dam 4.

Table II. Ice conditions, Keokuk L&D 19 and Alma L&D 4.

Extracted from ref. 21 and 22.

Date	*Thickness*	*Date*	*Thickness*	*Date*	*Thickness*
Keokuk Lock and Dam 19 (thicknesses in inches)					
15 Dec 1960	2	7 Feb 1964	5.5	23 Feb 1968	6.75
22 Dec	3	14 Feb	5	1 Mar	6.5
29 Dec	6.5	20 Feb	-	8 Mar	-
6 Jan 1961	7	28 Feb	2	20 Dec	3
13 Jan	9.5	6 Mar	0	27 Dec	6
20 Jan	2-5	30 Dec	0	3 Jan 1969	8
27 Jan	8	8 Jan 1965	7	10 Jan	12
3 Feb	10	15 Jan	3.5	17 Jan	12.5
10 Feb	11	22 Jan	5.5	24 Jan	10.5
17 Feb	8	29 Jan	4.5	31 Jan	11.5
24 Feb	-*	5 Feb	7	7 Feb	12
14 Dec	6	12 Feb	4.5	14 Feb	4
21 Dec	2	19 Feb	0	28 Feb	9
28 Dec	4	26 Feb	4	7 Mar	-
5 Jan 1962	7.5	5 Mar	3-4	14 Mar	0
12 Jan	11	12 Mar	3-4	18 Dec 1970	-
19 Jan	12.5	19 Mar	1	24 Dec	1.5
26 Jan	13.5	26 Mar	-	31 Dec	3.0
2 Feb	13.5	23 Dec	-	15 Jan 1971	10.5
9 Feb	10.5	30 Dec	2	22 Jan	12.75
16 Feb	15	7 Jan 1966	-	29 Jan	13.5
23 Feb	5.5	14 Jan	3	5 Feb	14.0
2 Mar	9	21 Jan	4.75	12 Feb	16.5
9 Mar	-	28 Jan	9	19 Feb	15.0
16 Mar	10	4 Feb	13.5	26 Feb	0
13 Dec	2	11 Feb	8	27 Dec	0
20 Dec	-	18 Feb	2	7 Jan 1972	3.5
27 Dec	8.5	25 Feb	-	14 Jan	3.5
4 Jan 1963	6	4 Mar	-	21 Jan	6.0
11 Jan	5.5	6 Jan 1967	5	28 Jan	8.5
18 Jan	9.5	13 Jan	6	4 Feb	10.5
25 Jan	14.5	20 Jan	6.5	11 Feb	13.5
1 Feb	16	27 Jan	-	18 Feb	11.75
8 Feb	17	3 Feb	1.5	25 Feb	8.75
15 Feb	14	10 Feb	-	3 Mar	8.0
21 Feb	15	17 Feb	3	10 Mar	0
1 Mar	15	24 Feb	4	8 Dec	3.0
8 Mar	6	3 Mar	5	15 Dec	8.5
15 Mar	-	10 Mar	2.5	22 Dec	9.5
4 Dec	2	17 Mar	-	29 Dec	10.5
11 Dec	1-2	22 Dec	-	5 Jan 1973	7.5
18 Dec	3.5	29 Dec	2.25	12 Jan	12.5
24 Dec	4	5 Jan 1968	4	19 Jan	8.75
31 Dec	4	12 Jan	6.5	26 Jan	6.0
3 Jan 1964	11	19 Jan	11.5	2 Feb	-
10 Jan	9	26 Jan	9.5	9 Feb	0.75
17 Jan	9.5	2 Feb	4	16 Feb	4.0
24 Jan	8	9 Feb	0	23 Feb	8.0
31 Jan	9	16 Feb	3		

Table II (cont'd).

	Thickness			*Thickness*	
Date	*Dam 4*	*Pepin*	*Date*	*Dam 4*	*Pepin*
Alma Lock and Dam 4 and Lake Pepin (thicknesses in inches)					
16 Jan 1965		21	10 Jan 1969	12	
19 Jan		21½	20 Jan	14	
23 Jan		21½	26 Jan		23
27 Jan		23	30 Jan	14	
30 Jan		24	10 Feb	21	21
3 Feb		25½	20 Feb	12	
6 Feb		25½	28 Feb	11	
15 Feb		28	10 Mar	7	
18 Feb		28			
20 Feb		28	10 Jan 1970	6	
27 Feb		28¾	20 Jan	9	
13 Mar		33	30 Jan	8	
20 Mar		32½	6 Feb		17
			10 Feb	11	
10 Jan 1966	6		16 Feb		17
20 Jan	14		20 Feb	14	
30 Jan	17		24 Feb		19
10 Feb	11		28 Feb	9	
20 Feb	10		2 Mar		19
6 Feb	6				
10 Dec	4		12 Jan 1971	10	
20 Dec	3		19 Jan	9	
30 Dec	4		29 Jan	14	
			9 Feb	19	24
10 Jan 1967	6		19 Feb	16	
17 Jan		14	2 Mar	14	24
20 Jan	10				
30 Jan	10		10 Jan 1972	8	10
10 Feb	11		20 Jan	11	14
20 Feb	12		30 Jan	12	
28 Feb	14		10 Feb	14	24
23 Mar		24	20 Feb	15	
30 Dec	6		29 Feb	13	24
			10 Mar	13	
10 Jan 1968	11		15 Mar	13	
20 Jan	8				
6 Feb		23	2 Jan 1973	5	
12 Feb		24	10 Jan	12	
19 Feb		25	20 Jan	7	
20 Feb	2		30 Jan	7	21
26 Feb		26	12 Feb	9	21
28 Feb	3		20 Feb	10	20
3 Mar		25	28 Feb	10	24
11 Mar		23	2 Mar	9	
10 Dec	4				
20 Dec	6				
30 Dec	5				

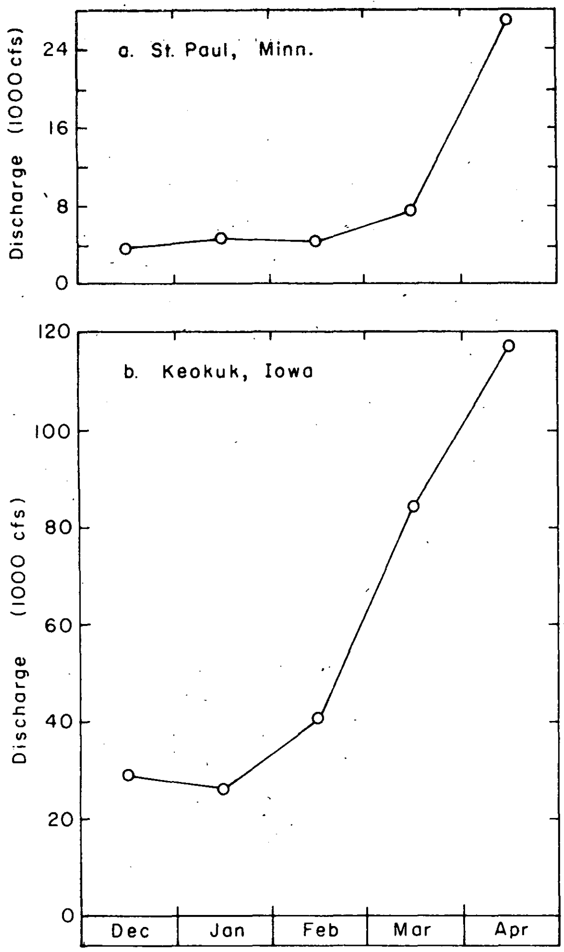


Figure 3. Median monthly discharges, Keokuk Lock and Dam 19 and Alma Lock and Dam 4.[5]

or ice jams, which present considerably more operational difficulty to navigation than does a uniform ice sheet. Detailed examination of historical flow records (not attempted in this study) should enable a probability to be assigned to such events which would be useful in developing an operational strategy for these events. The water temperature increases during midwinter flow increases, both as a result of the runoff and the warm air conditions associated with the thaw periods which generate the runoff.

The median discharges provide a means of estimating typical mean velocities over various reaches of the river. To do this accurately requires systematic and accurate calculations of cross-sectional areas and information describing the change in water level with change in discharge. However, for the relatively low discharges associated with winter conditions, a reasonable estimate of the mean velocity at a particular location may be made by dividing the discharge by the area of the cross section. The depth for calculating the cross-sectional area may be estimated using an appropriate estimate of the head loss in a reach, adding this increment to the pool elevation, and then calculating the cross-sectional dimensions using existing sounding data. This procedure yields estimates of the mean flow velocity sufficient for the present purposes, particularly since the mean flow velocities are reasonably low (of the order of 1 ft sec^{-1}) in most of the reaches of concern. The velocity in the channel is somewhat higher than the mean velocity averaged over the cross section. For want of actual field data it will be assumed that the velocity in the channel is 1.5 times the mean velocity over the entire cross section. Table III presents mean and estimated maximum velocities for a number of arbitrarily chosen locations in the vicinity of Keokuk, Iowa, and corresponds to the median monthly discharges at the Keokuk gaging station. Examination of these data suggests that the maximum velocities to be expected during the months of January and February are below 2 ft sec^{-1} in reasonably normal years. The locations examined are considered typical of this general reach of the Mississippi River, the first three characterizing narrow reaches below dams, and the last two characterizing a reach above Lock and Dam 19. The data are intended only to indicate the range of velocities expected in this area.

Winter water temperatures

Accurate wintertime water temperature measurements during the times when a substantial ice cover is present are nearly nonexistent for the Mississippi River. Such temperatures are rarely above 32.2°F (except near sources of artificial thermal effluents) and generally closer to 32.0°F than to 32.2°F. Since nearly all routine water quality observations utilize thermometry with a resolution no

Table III. Estimated cross-sectional areas, mean and maximum velocities at selected cross sections.

Velocities are estimated using median monthly discharges.
Maximum velocity is assumed to be 1.5 times the mean velocity.

Location (cross-sectional area)	*Velocity*	*Month*			
		Dec	*Jan*	*Feb*	*Mar*
Mile 290 ($35{,}000\ ft^2$)	$\bar{V}$ ($ft\ sec^{-1}$)	0.98	0.95	1.15	2.40
	V_{max} ($ft\ sec^{-1}$)	1.47	1.43	1.78	3.60
Mile 304 ($41{,}000\ ft^2$)	$\bar{V}$ ($ft\ sec^{-1}$)	0.83	0.81	0.98	2.05
	V_{max} ($ft\ sec^{-1}$)	1.25	1.22	1.47	3.08
Mile 349 ($39{,}000\ ft^2$)	$\bar{V}$ ($ft\ sec^{-1}$)	0.88	0.85	1.03	2.16
	V_{max} ($ft\ sec^{-1}$)	1.32	1.28	1.55	3.24
Mile 369 ($83{,}000\ ft^2$)	$\bar{V}$ ($ft\ sec^{-1}$)	0.41	0.40	0.48	1.02
	V_{max} ($ft\ sec^{-1}$)	0.62	0.60	0.72	1.53
Mile 390 ($63{,}000\ ft^2$)	$\bar{V}$ ($ft\ sec^{-1}$)	0.54	0.53	0.64	1.34
	V_{max} ($ft\ sec^{-1}$)	0.81	0.80	0.96	2.01

better than 0.5°F these measurements are useless for our purposes. This is unfortunate since temperatures as low as 32.1°F may result in significant melting. Nevertheless, we may characterize the typical water temperature regime of a river through the winter period sufficiently well to provide reasonable bounds on the resultant effects. Ordinarily, a river first freezes over during an intense cold period and, except at very low flow velocities, then undergoes a short period of slight supercooling. Thus the coldest water temperatures are ordinarily experienced at the onset of the ice cover and are so close to 32°F (within a few thousandths of a degree) as to be undetectable except with precision thermometry. As the winter season progresses, the water temperature gradually warms, but so long as the ice cover remains intact, the warming amounts to a few hundredths of a degree at most. The water temperature is ordinarily uniform over depth with temperature differences in the vertical of the order of at most a few thousandths of a degree. In the horizontal, there is a tendency for near-shore regions to be warmer than central regions, with differences typically of the order of 0.02° to 0.04°F. With the onset of a thaw period sufficiently intense to generate significant runoff, the water temperature increases and may exceed 32.1°F near the conclusion of the ice period. However, the input runoff is delivered to the near-shore areas in most cases and the long lengths required for transverse mixing together with the forced convection heat transfer to the undersurface of the ice result in the central regions remaining the coldest regions of the cross section.

Finally, it should be noted that large discharges of waste heat (as occur from both conventional and nuclear power plants) may alter the picture of temperatures drawn above for large distances downstream from the point of release. This is particularly true if the effluent is not diffused across the cross section at its source. Generally, the affected areas are easily delineated by aerial observation of open water areas during the period of ice cover.

For additional background on wintertime water temperatures in rivers, the reader is referred to the measurements of Ashton and Kennedy,[1] Ashton ahd Hibler,[2] or Sayre and Schwarz.[17]

The above characteristics provide a general description of the average conditions that may be expected in a reasonably normal year. Many other characteristics could have been assembled and

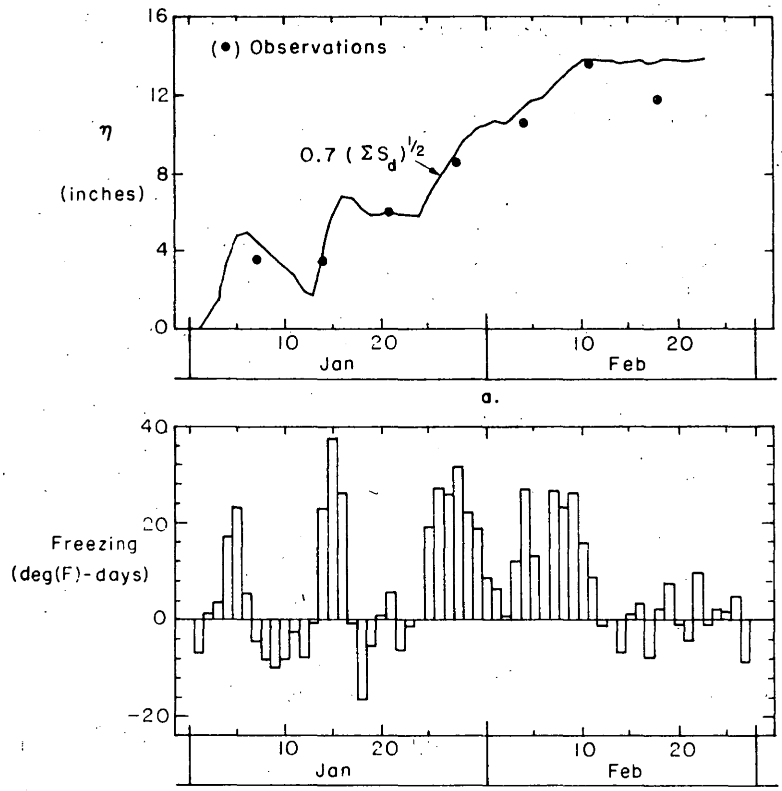


Figure 4. Degree-days of freezing and ice thicknesses for Keokuk Lock and Dam 19, January - February - March 1972.

tabulated, particularly those parameters useful in a complete energy budget analysis. As will be shown in the refreezing analysis presented below, the daily variations in air temperature are most useful for present purposes and provide results considered adequate for evaluation. As an example, the daily contributions of degree-days of freezing and the observed ice thicknesses for the year 1972 at Keokuk Lock and Dam 19 and for 1970 at Alma Lock and Dam 4 are plotted in Figures 4 and 5. To place these particular years in the context of averages, it is noted that January 1972 at Keokuk was nearly an average January while February 1972 was about 2.5°F colder than corresponding averages over the 1951-1960 ten-year period. Thus 1972 may be considered a reasonably average year. Similar comparisons show 1970 to be a colder than average winter at Alma Lock and Dam 4.

The daily contributions of freezing-degree days were calculated on the basis of

$$S_d = 32°F - \frac{T_{max} + T_{min}}{2} \tag{1}$$

where S_d is the daily contribution, and T_{max} and T_{min} are the daily maximum and minimum air temperatures. In a later section, these periods will be used in example calculations of refreezing to assess the relative merits of different operating strategies for an ice cutter. Examination of this and other similar data for Pool 19 suggests that there are significant periods during these two months (generally the most severe winter months) when, if the ice were removed from the channel at the completion of the coldest periods, the new ice cover would not thicken significantly for some time afterwards. There is a considerable element of hindsight in this suggestion, of course, which will not be available in operational situations.

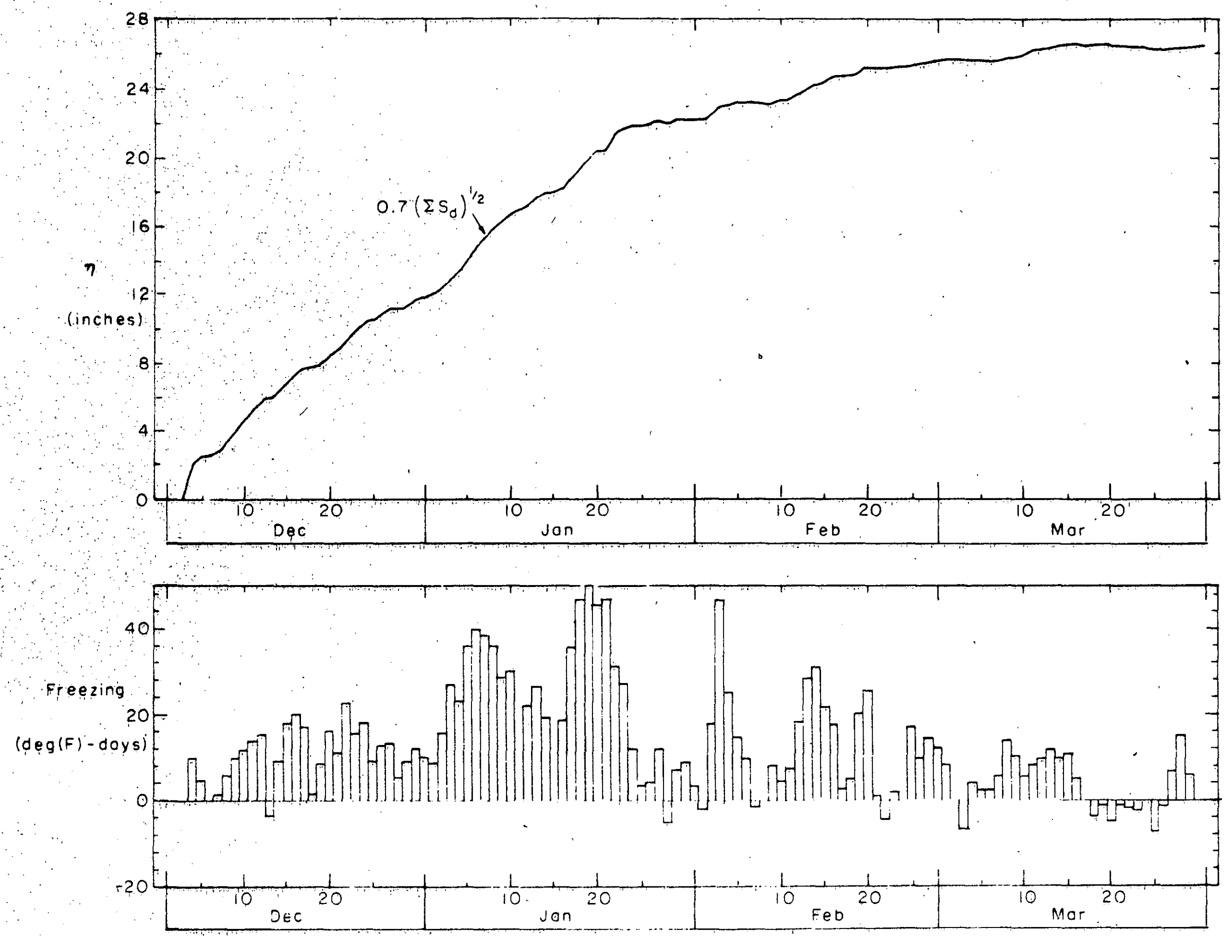


Figure 5. Degree-days of freezing and ice thickness for Alma Lock and Dam 4, December - March 1970.

Refreezing analysis

With the background information provided above we may now proceed to an analysis of the refreezing of a cleared channel. Initially, we will consider the idealized case of a channel area completely cleared of ice. In a later section the effects of brash, which will invariably be present to some degree, will be considered by appropriately modifying the analysis. To provide a framework, we consider the simple case of a constant top surface temperature $T_0 < T_m$ where $T_m = 32°F$ is the melting point. Assuming an always linear temperature distribution in the ice slab, the governing heat conduction equation reduces to

$$q_i(t) = k_i \frac{T_m - T_0}{\eta(t)} \tag{2}$$

where $q_i(t)$ is the heat flux through the ice slab at time t, k_i is the thermal conductivity of the ice, and $\eta(t)$ is the thickness of the ice at time t. The energy boundary condition at the ice/water interface is given by

$$q_i(t) - q_w(t) = \rho_i \lambda \frac{d\eta}{dt} \tag{3}$$

where $q_w(t)$ is the heat flux to the underside of the ice from the water below, ρ_i is the ice density, and λ is the heat of fusion. Assuming $q_w = 0$ for the moment, substituting eq 2 into eq 3 and integrating with respect to time yields

$$[\eta(t)]^2 = \frac{2k_i(T_m - T_0)t}{\rho_i \lambda} + C_1 . \tag{4}$$

The constant of integration C_1 is evaluated by specifying an initial thickness η_0 at time t_0 and yields

$$[\eta(t)]^2 = \eta_0^2 + \frac{2k_i(T_m - T_0)(t - t_0)}{\rho_i \lambda} . \tag{5}$$

If $\eta_0 = 0$ at time $t_0 = 0$ eq 5 reduces to

$$\eta(t) = \left[\frac{2k_i}{\rho_i \lambda}\right]^{1/2} [(T_m - T_0)t]^{1/2} . \tag{6}$$

It is clear that eq 6 is identical in form to the often-used empirical relationship (see ref. 13, p. 79)

$$\eta(t) = a(\Sigma S_d)^{1/2} \tag{7}$$

where ΣS_d is the summation of degree-days of frost since the time of initial ice formation, and a is an empirical coefficient. For certain cases (windy lakes with no snow) a approaches the value given by eq 6 while for more usual cases a is significantly less.

The use of eq 7 has been particularly convenient in countries using the English system of units since use of days as units of time, degrees Fahrenheit for the temperature difference, and

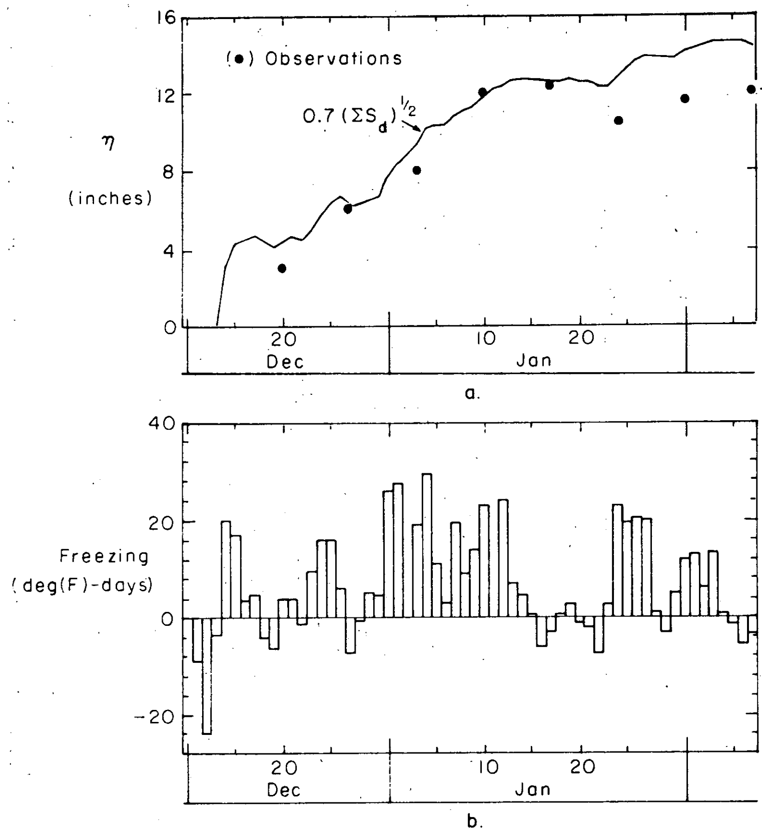


Figure 6. Example comparison of thickening analysis, Keokuk Lock and Dam 19, 1969.

inches for the thickness results in a having a (theoretical) magnitude of 1.04 in. $°F^{-1/2}$ $days^{-1/2}$, which is very close to unity. However, there are a number of deficiencies in the derivation of eq 6 when it is applied to the case of natural ice thickening. First, the top surface temperature of the ice has been used while the air temperatures are the usual available temperature data. The top surface temperature could be calculated if the heat transfer coefficient h between the ice and the air were known; however, h is a complicated function of wind speed, atmospheric stability, surface roughness and other parameters rarely available on a local daily basis. The effect of neglecting the thermal resistance associated with h is to overestimate the thickening rate, particularly at small ice thicknesses. In fact, at small ice thicknesses growth tends to go as t to the first power rather than $t^{1/2}$ (e.g. ref. 5). Similarly, the insulating effect of a layer of snow on the top surface has been ignored although it is a simple matter to include it in the analysis.[6] The effect of this neglect is to overestimate the thickening rate. Other effects have also been ignored, including the specific heat capacity of the ice sheet, alternate freezing and melting of the top surface during periodic air temperature excursions above 32°F, radiation absorption and release, and finally the heat flux to the undersurface. There are means available for simulating the top surface temperature[14] but the detail involved is excessive for the present purposes.

To circumvent these difficulties, the simple expedient suggested by eq 7 will be adopted with $a = 0.7$ (units of inches, degrees Fahrenheit and days). In performing the summation of degree-days, both positive (freezing) and negative (thawing) degree-days will be included to provide at least a recognition of the effects of thaw periods. The value 0.7 was selected by evaluating several cases of thickening as represented in detail in Figures 4, 6 and 7, as well as other more limited data.

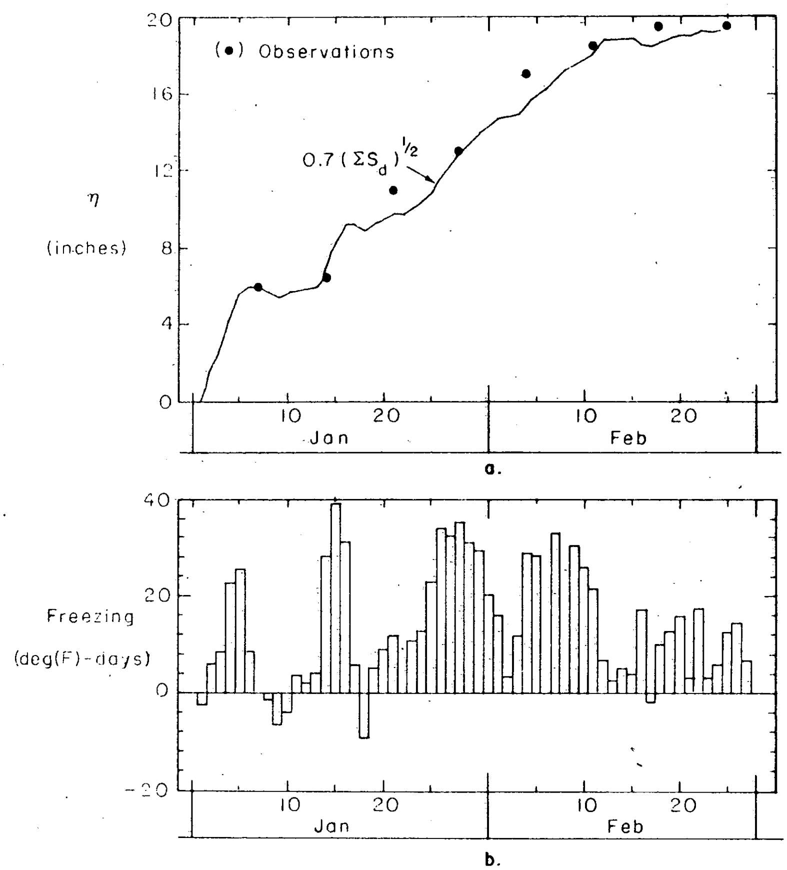


Figure 7. Example comparison of thickening analysis, Bellevue Lock and Dam 12, 1972.

The first two cases, Figures 4 and 6, present the data of Keokuk Lock and Dam 19 for January-February-March 1972 and for 1969 during which times there were significant thaw periods. The agreement is satisfactory. By contrast, the data for Bellevue Lock and Dam 12 (Fig. 7) represent a more-or-less continual freezing period. The model fails during extreme thaw periods which is not unexpected since use of thawing degree-days does not correctly represent the thawing processes. For present uses, this is not a serious deficiency.

To implement the refreezing analysis in a realistic way, we have chosen to operate on real temperature data using two basic operational strategies, a "fixed interval" ice cutting operation and a "specified thickness" ice cutting operation. In the fixed interval strategy, cutting is assumed to occur at fixed intervals regardless of the ice thickness. If the ice thickness is zero, the cutting schedule will not be changed. In calculating the thickening after a zero thickness occurs, thickening will be assumed to begin on the first freezing day thereafter. Three fixed intervals will be examined: 7 days, 10 days and 14 days. In the specified thickness strategy cutting is assumed to occur on the day a specified thickness is attained, without regard to the time elapsed since the last cutting operation. Three thicknesses will be examined: 6 in., 8 in. and 10 in. It is also probable that a combination of the two basic strategies has some advantage, e.g. cutting only after a fixed interval has elapsed but only if a specified thickness has been attained.

The results of the analysis for the winter of 1970 for Keokuk Lock and Dam 19 and for Alma Lock and Dam 4 (Lake Pepin) are presented graphically in Figures 8 and 9. From the detailed results for these and other years, a number of criteria for effectiveness have been extracted and are

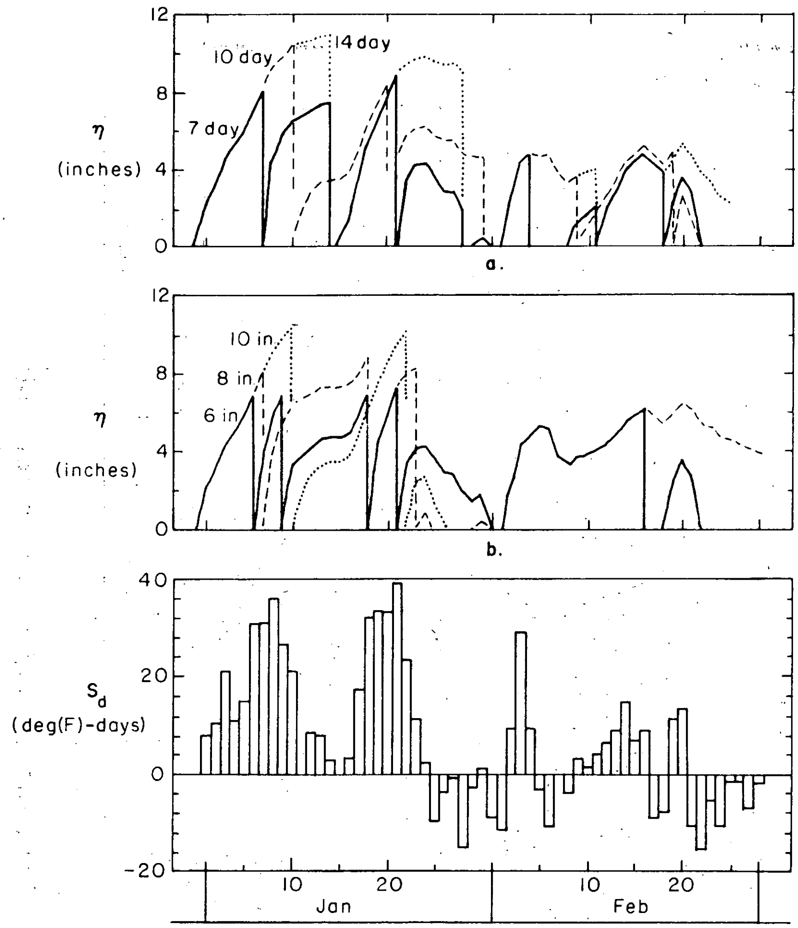


Figure 8. Results of different operating strategies, Keokuk Lock and Dam 19, 1970.

presented in Tables IV (Keokuk) and V (Lake Pepin). These criteria include total number of cuts, maximum thickness cut, total number of days with thickness ≥ 6 in., ≥ 8 in. and ≥ 10 in., the total thickness cut, the shortest cutting interval, the longest duration with thickness > 6 in., and the longest duration with thickness > 8 in. Lest the reader place too much faith in these results, it should be pointed out that there are compromises to this idealized implementation of the strategies which are discussed in later sections.

Heat transfer from the flow to the undersurface

In the development of the refreezing analysis it was assumed that $q_w = 0$ in the integration of eq 3. In this section, the case of a non-zero q_w is briefly considered and a framework developed by which the effects of water temperatures above freezing may be included in a refreezing or melting analysis. In general, for natural wintertime water temperatures and relatively thin ice covers, neglect of q_w is a reasonable assumption during freezing periods. For cases where there is an imposed thermal source, or a thick ice cover, or during the breakup season, neglect of q_w can lead to serious deficiencies in a freezing model. Examples will be used to illustrate these contentions.

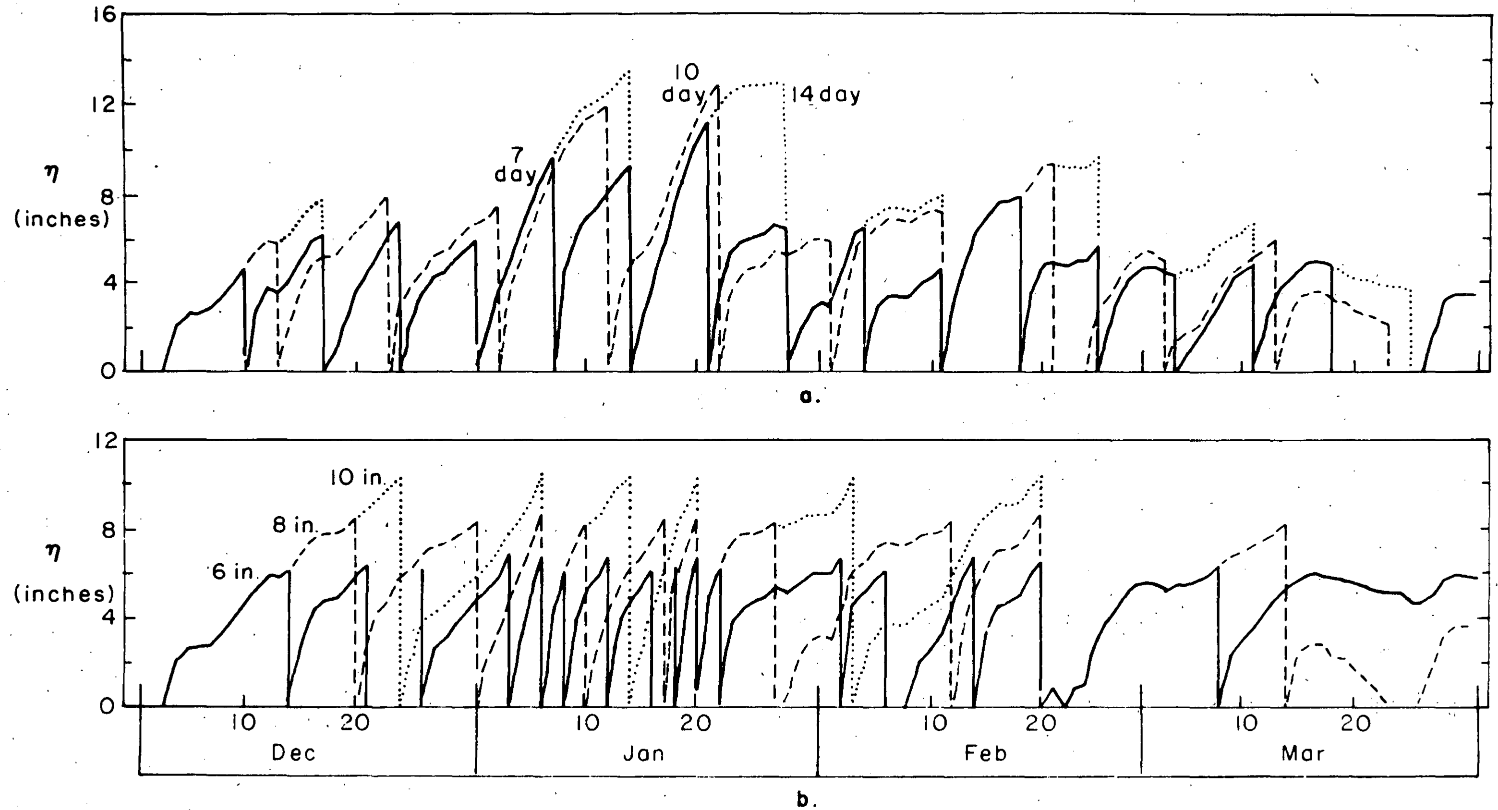


Figure 9. Results of different operating strategies, Alma Lock and Dam 4, 1970.

Table IV. Effects of different operating strategies.
Data for Keokuk Lock and Dam 19.

Criterion	Year	*Fixed interval cutting* 7 day	10 day	14 day	*Specified thickness cutting* 6 in.	8 in.	10 in.	*Brash ice considered* 10 day	8 in.
Number of cuts in season	1968	6	5	4	5	3	1	5	4
	1969	10	7	5	5	3	2	8	6
	1970	7	5	4	5	3	2	5	4
	1971	8	6	4	6	3	2	6	5
	1972	8	5	4	4	3	1	5	4
Maximum thickness cut (inches)	1968	8.22	8.83	10.82	6.51	8.49	10.01	11.89	8.79
	1969	7.31	8.85	10.02	6.36	8.39	10.17	12.04	8.74
	1970	8.78	10.29	10.86	6.98	8.91	10.29	13.74	9.32
	1971	7.14	7.92	9.81	6.60	8.49	10.18	10.43	9.07
	1972	7.59	8.52	10.20	7.10	8.30	10.20	11.12	9.16
Days channel ice thickness greater than 6 inches in season	1968	6	13	17	5	18	45	18	29
	1969	4	14	19	5	21	34	19	43
	1970	10	8	19	5	17	13	20	33
	1971	12	15	25	6	22	35	24	41
	1972	5	6	11	4	30	33	14	11
Days channel ice thickness greater than 8 inches in season	1968	1	5	6	0	3	15	10	4
	1969	0	2	6	0	3	13	7	6
	1970	1	5	16	0	3	7	7	4
	1971	0	0	9	0	3	14	6	5
	1972	0	2	6	0	3	24	6	4
Longest duration with channel ice thicker than 6 inches (days)	1968	3	7	9	1	7	21	8	16
	1969	2	6	9	1	21	34	8	12
	1970	5	5	10	1	9	5	8	13
	1971	4	6	11	1	10	11	8	17
	1972	1	3	8	1	21	23	5	4
Longest duration with channel ice thicker than 8 inches (days)	1968	1	3	6	0	1	11	6	1
	1969	0	2	6	0	1	9	5	1
	1970	1	4	8	0	1	4	5	1
	1971	0	0	6	0	1	9	3	1
	1972	0	1	5	0	1	20	3	1
Total thickness cut in season (inches)	1968	35.5	31.6	25.5	31.7	24.8	10.0	40.7	33.6
	1969	45.3	35.0	32.1	31.2	24.8	20.2	51.2	51.6
	1970	36.7	31.6	26.1	34.1	25.2	20.3	42.0	34.8
	1971	44.7	38.9	31.5	37.7	24.7	20.2	50.6	43.6
	1972	38.0	27.7	25.1	27.5	25.0	10.2	37.9	34.8
Shortest cutting interval (days)	1968	7	10	14	4	8	12	10	5
	1969	7	10	14	5	9	22	10	6
	1970	7	10	14	3	5	10	10	4
	1971	7	10	14	5	12	20	10	7
	1972	7	10	14	5	9	30	10	6

Table V. Effects of different operating strategies.

Data for Alma Lock and Dam 4.

		Fixed interval cutting			*Specified thickness cutting*			*Brash ice considered*	
Criterion	*Year*	*7 day*	*10 day*	*14 day*	*6 in.*	*8 in.*	*10 in.*	*10 day*	*8 in.*
Number of cuts in season	1968	14	10	7	12	7	4	9	11
	1969	16	11	8	17	10	6	11	14
	1970	16	11	8	16	10	6	11	15
	1971	16	11	8	18	11	7	11	15
Maximum thickness cut (inches)	1968	10.64	12.08	14.26	7.27	8.84	10.84	16.62	9.37
	1969	10.37	12.16	13.91	7.24	8.63	10.51	16.75	9.47
	1970	11.15	12.72	13.31	6.98	8.70	10.39	17.08	9.18
	1971	9.66	10.88	13.49	7.10	8.83	10.43	14.78	9.31
Days channel ice thickness greater than 6 inches in season	1968	24	29	44	12	34	73	39	46
	1969	29	48	53	17	60	76	65	47
	1970	27	38	58	16	54	71	58	47
	1971	28	41	57	18	50	74	61	49
Days channel ice thickness greater than 8 inches in season	1968	8	14	17	0	7	49	24	11
	1969	8	17	29	0	10	45	38	14
	1970	7	14	30	0	10	44	31	15
	1971	12	26	35	0	11	39	35	15
Longest duration with channel ice thicker than 6 inches (days)	1968	5	8	11	1	14	30	8	13
	1969	5	9	12	1	19	25	9	4
	1970	5	8	12	1	10	23	8	7
	1971	5	7	12	1	8	21	8	8
Longest duration with channel ice thicker than 8 inches (days)	1968	4	7	9	0	1	25	7	1
	1969	4	6	11	0	1	22	7	1
	1970	3	6	10	0	1	11	7	1
	1971	3	6	10	0	1	12	7	1
Total thickness cut in season (inches)	1968	68.4	60.1	51.6	79.0	59.1	41.9	82.2	93.7
	1969	95.1	75.9	66.2	110.4	83.1	62.1	107.2	122.0
	1970	97.8	81.1	73.5	103.3	83.5	61.3	109.7	125.0
	1971	104.2	87.3	74.8	116.4	91.7	71.8	117.2	129.4
Shortest cutting interval (days)	1968	7	10	14	3	4	7	10	3
	1969	7	10	14	3	4	8	10	3
	1970	7	10	14	2	3	6	10	3
	1971	7	10	14	2	4	8	10	4

Integrating eq 3, using eq 2 for the q_i term, and assuming q_w constant yields an implicit equation for the thickness as a function of time in the form

$$t - t_0 = \frac{-\rho_i \lambda(\eta - \eta_0)}{q_w} - \frac{k_i \rho_i \lambda(T_m - T_0)}{q_w^{\,2}} \log_e \left\{ \frac{1 - [(q_w \eta)/k_i(T_m - T_0)]}{1 - [(q_w \eta_0)/k_i(T_m - T_0)]} \right\} \qquad (8)$$

where an initial thickness η_0 at time t_0 has been used to evaluate the constant of integration.

While eq 8 is not explicit for η in terms of t, it is a simple matter to calculate the η versus t curve for particular values of q_w and $T_m - T_0$. Before numerical results of this type are examined, estimates of q_w are presented in terms of the readily measured or estimated parameters of flow velocity, depth and temperature.

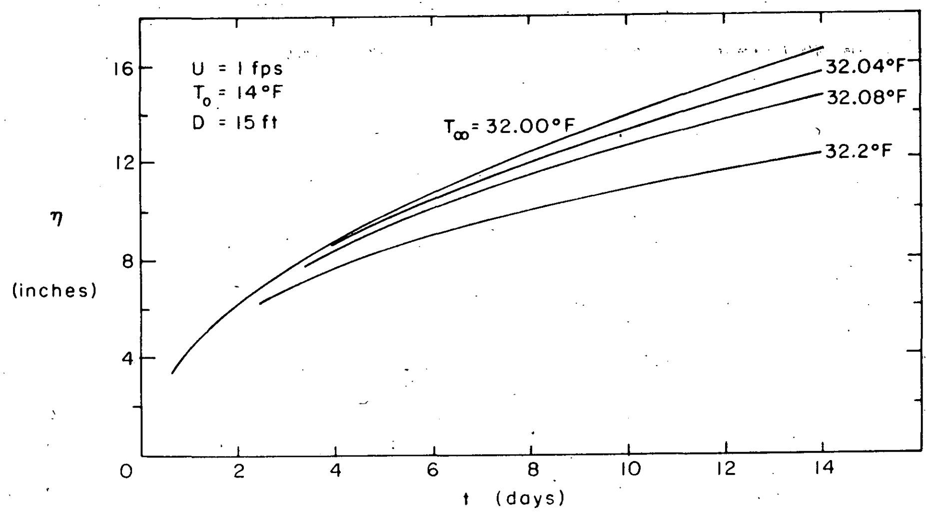


Figure 10. Effect of q_w on ice thickening for $U = 1.0$ ft sec^{-1} and $T_0 = 14°F$.

There are a number of empirical relationships for predicting the heat transfer rate from the flow to the boundaries of a closed conduit. One such relationship which has found wide use is of the form[16]

$$Nu = C\,Re^{0.8}\,Pr^{0.4} \tag{9}$$

where $Nu = q_w R/[(T_\infty - T_m)k_w]$ is the Nusselt number, $Re = UR\rho/\mu$ is the Reynolds number, and $Pr = \mu c_p/k_w$ is the Prandtl number. Here μ is the dynamic viscosity, c_p is the specific heat, ρ is the water density, k_w is the thermal conductivity, U is the mean velocity, T_∞ is the water temperature, and R is the hydraulic radius. The constant C is approximately 0.017, and for water near the freezing point $Pr = 13.6$. Writing eq 9 explicitly for q_w results in

$$q_w = \frac{C(T_\infty - T_m)k_w}{R}\,Re^{0.8}\,Pr^{0.4}. \tag{9a}$$

To demonstrate the relative effects of water temperature on the growth of an ice cover, eq 8 has been solved for q_w values corresponding to T_∞ of 32.04°F, 32.08°F and 32.2°F, a depth of flow of 15 ft, and a mean flow velocity of 1.0 ft sec^{-1}, and for top surface temperatures of 14°F and −4°F. The results are presented in Figures 10 and 11.

Inspection of Figures 10 and 11 suggests that the effect of q_w may be neglected at small thicknesses during initial growth, and only when a thaw period is present and the water temperatures become relatively warm (32.2°F) does significant melting occur. Even then, breakup is apt to occur after only a fraction of the total thickness has melted. The analysis could also be applied to river reaches subjected to thermal effluents which cause unnaturally warm water temperatures; however, such reaches are not expected to require the assistance of an MIC when compared with other reaches.

Finally, it should be noted that flow velocity alone, i.e. without above-freezing water temperatures, does not inhibit the thickening of an ice cover once the initial cover is formed. For most of the river reaches under consideration, the flow velocity is sufficiently low that an intact initial cover will form relatively quickly in the previously cleared channel. Thus, the major importance of flow velocity is to transport ice fragments, and this influence is discussed in a later section.

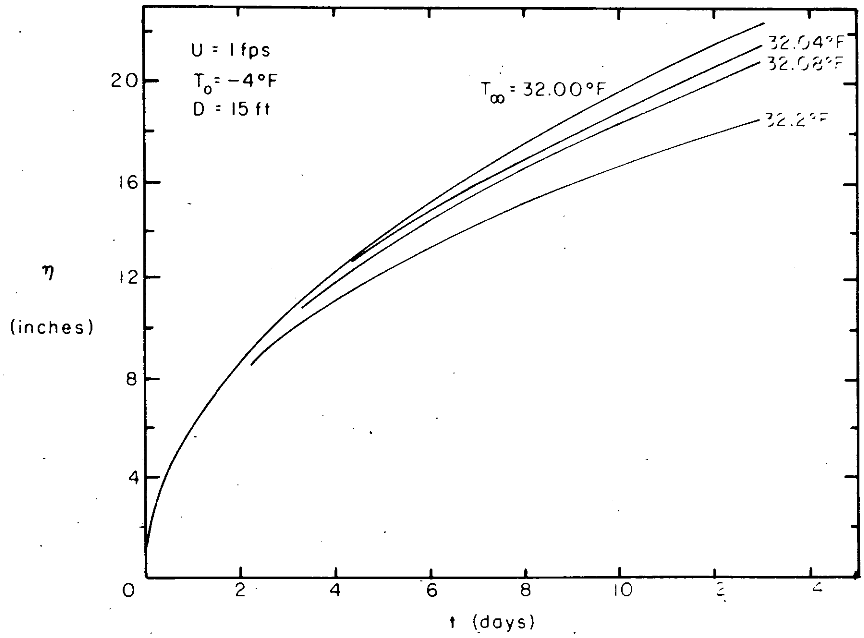


Figure 11. Effect of q_w on ice thickening for $U = 1.0$ ft sec^{-1} and $T_0 = -4°F$.

Effects of brash ice

While the result of a cutting pass by an MIC is a channel clear of ice, it is unlikely that it will remain ice-free for long. First, the natural refreezing and subsequent passage by towboats will continually generate a brash ice coverage. Second, under some conditions the ice cut by the MIC will be returned to the channel area by river currents. Finally, except under rather careful operational control of the towboats utilizing the cleared track, the waves created by the towboats will result in side breakage of ice which will be contained in the cleared channel. Generally, the presence of brash tends to compromise the ideal result of operation of an MIC and accordingly these subjects are considered briefly in this section.

Generation of brash by traffic

The result of a transit by a towboat in a refrozen cover of nominal thickness is a more-or-less uniform coverage of small fragments floating in a loose accumulation with some open water between the pieces. After a single pass, there is a tendency for the gross coverage to be nonuniform, i.e. patches of open water alternating with patches of brash coverage. Several passes, however, result in a more or less uniform coverage of the channel area. The percentage of open water surface area within the areas of brash coverage is probably of the crder of 20 to 30%. As a result of this open water area, the production of ice in the channel areas during freezing periods is greater than would be the case if the refrozen cover were left intact.

To estimate additional production, the refreezing analysis may be modified as follows. On the first day after clearing, the ice is assumed to thicken as before. On each day of traffic it is assumed that a fraction β of open area is exposed in the channel and this fraction freezes and thickens as an initial ice cover. The other fraction $(1 - \beta)$ continues to thicken but the effective initial thickness at the start of the freezing interval is assumed to be $\eta_{i-1}/(1 - \beta)$ to account for the fact that the broken ice is contained in the channel track and hence presents an effective thickness greater than before. Thus the average thickness, or, more precisely, the volume per unit area on the *i*th day, is given by

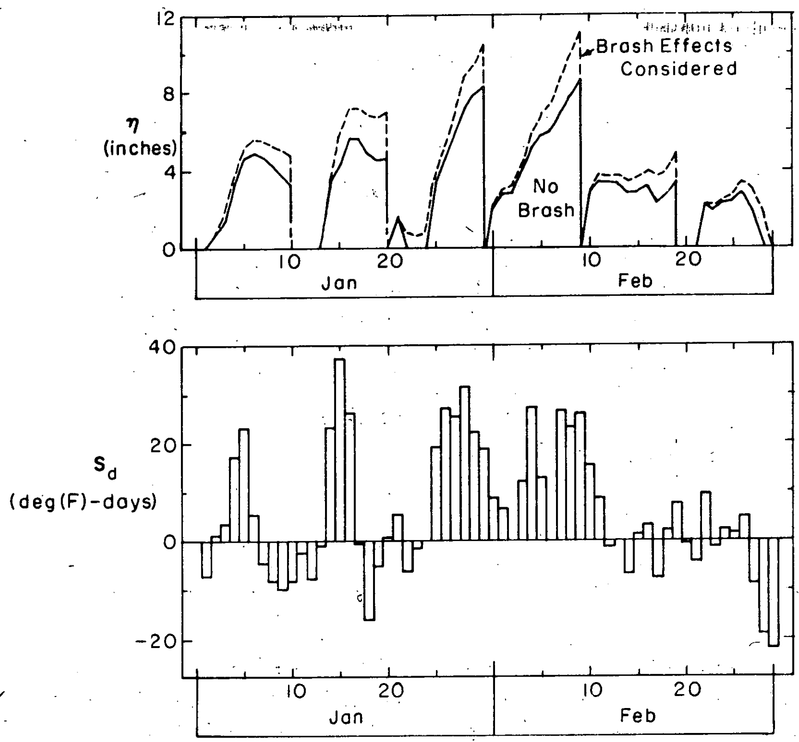


Figure 12. Results of 10-day fixed-interval strategy including effects of brash, Keokuk Lock and Dam 19, 1972.

$$\eta_i = (1-\beta)\left[\left(\frac{\eta_{i-1}}{1-\beta}\right)^2 + a^2 S_d\right]^{1/2} + \beta a S_d^{1/2} \tag{10}$$

where η_i is the average thickness at the completion of a day of thickening during which S_d degree-days of freezing occurred, and η_{i-1} is the effective thickness on the previous day. Experience suggests that β is of the order of 0.25. As before, $a = 0.7$ will be used. To illustrate the method, the analysis has been applied to the temperature data of January-February 1972 for Pool 19 for the case of a 10-day fixed interval strategy and an 8-in. specified thickness strategy assuming traffic on a daily basis. The results are presented as plots of average ice thickness versus time in Figure 12. In Tables IV and V, a comparison of the results of the analysis including brash effects is presented for other years using the same criteria previously used to evaluate various operating strategies. In general, the differences are not large but show, as expected, somewhat more severe ice conditions. In Table VI, monthly average temperatures for the example years are presented for comparison with the 1951-1960 averages.

Side breakage by vessel waves

Another consequence of the passage of a towboat in a previously cleared channel is the potential for breakage of the adjacent ice sheet by the divergent waves generated in the vicinity of the bow. (A similar wave pattern originates at the stern but the amplitude of these waves is generally less than that of the bow waves.) The characteristics of these waves are little documented in a form useful for present purposes. In particular, the decrease in amplitude with distance away from the sailing line is uncertain. Nevertheless, the information available at the time of writing is sufficient to allow some general statements to be made. That side breakage is of real concern was demonstrated in a recent study[3] in which a conventional towboat pushing up to 6 barges (2 wide)

Table VI. Average temperatures (°F) of winter months of example years.

Year	*Dec*	*Jan*	*Feb*	*Mar*
Keokuk Lock and Dam 19				
1951-1960	31.2	25.6	30.2	36.8
1968	32.8	26.4	28.1	46.5
1969	29.5	22.8	31.0	35.8
1970	28.7	19.2	31.2	38.3
1971	34.3	22.7	29.3	39.0
1972	37.4	25.1	27.8	–
Alma Lock and Dam 4				
1951-1960	24.2	17.1	20.3	29.3
1968	25.4	18.6	18.2	40.5
1969	20.6	11.9	22.1	26.6
1970	22.8	8.6	19.4	28.9
1971	20.7	8.6	18.2	28.1

was navigated in ice conditions during February 1972. The first passage through an intact ice cover left a relatively straight-edged track. In succeeding passages, the diverging waves generated at the bow region caused breakage of the adjacent ice cover even when the tow was not engaging the edge of the 8- to 12-in.-thick ice cover. The breakage was most severe when the tow was close to the cleared edge and, once the breakage occurred, succeeding passages tended not to cause additional breakage at further distances away from the sailing line. Photographs of the observed side breakage are presented in Figure 15. It was also clear during that investigation that higher speeds were more conducive to side breakage than were lower speeds. The consequence of the breakage, of course, is the existence of additional brash of thickness greater than that which would be generated in breaking the ice which forms in a previously cleared channel.

To properly analyze the interaction between the waves and the adjacent ice cover requires knowledge of the height H_{max}, period T, and wavelength λ as a function of the vessel speed and configuration. In particular, it would be desirable to have data for barge configurations operating in limited depths, and ideally obtained from measurements near the vessel. Since such data are not available at the time of writing, the analysis below relies heavily on some approximations derived from readily available data. The data summarized by Sorensen[19] for a wide variety of ship forms are presented in Figure 13. The height of the maximum wave at a distance of 100 ft from the sailing line is seen to be reasonably approximated by

$$H_{max,\ 100} = 0.32 \frac{V_s^2}{2g} \tag{11}$$

where g is the gravitational constant and V_s is the vessel speed. However, 100 ft from the sailing line is farther than desired for our purposes. To extrapolate to points nearer the sailing line (in the case of blunt-ended barges, the side of the barge) we assume that the decay in wave height is of the form[10]

$$\frac{H_{max,\ x}}{H_{max,\ 100}} = \left(\frac{x}{100}\right)^{-1/3} \text{ (feet).} \tag{12}$$

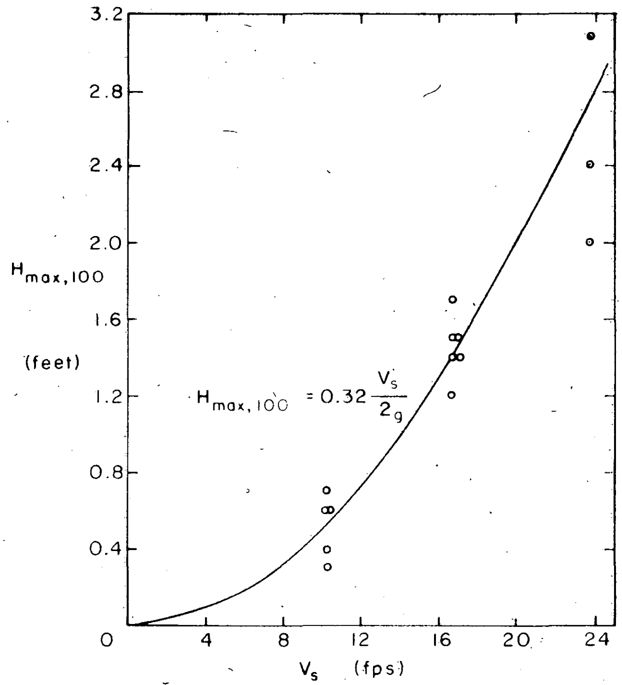


Figure 13. Maximum wave heights 100 feet from sailing line for variety of hull forms (after Sorensen, 1973).

Combining eq 11 and 12 yields an expression for the wave height at distance $x(H_{max,\,x})$ as a simple function of the ship speed in the form

$$H_{max,\,x} = 0.32\,\frac{V_s^2}{2g}\left(\frac{x}{100}\right)^{-1/3} . \qquad (13)$$

No claims are made that eq 13 is of theoretically correct form. In particular, it obviously is incorrect as $x \to 0$ since wave heights are finite. Further, it ignores depth effects, draft effects, hull form and other parameters known to influence wave heights. H is limited to subcritical vessel speeds ($V_s/(gd)^{1/2} < 1.0$, where d is the depth) which is almost invariably the case for towboats. H will be assumed applicable beginning at a distance 10 ft from the barge side. Figure 14 is a plot of the maximum wave height as a function of distance and vessel speed. The wave length of the diverging waves is given by[9]

$$\lambda_d = \frac{2\pi V_s^2}{g}\cos^2\phi \qquad (14)$$

where ϕ is the angle between the direction of travel of the diverging waves and the sailing line. Approximately, $\phi = 2\theta$ where θ is the angle of the wave pattern with the sailing line.[11] For low Froude numbers (less than about 0.6) $\theta = 19°28'$. Equation 14 utilizes the deep water wave length which is a reasonable approximation for our purposes.

With knowledge of the wave heights and wave lengths, we may now proceed to a simple approximation of the breakage induced by the waves. We assume a wave of length λ and height H_{max} passes

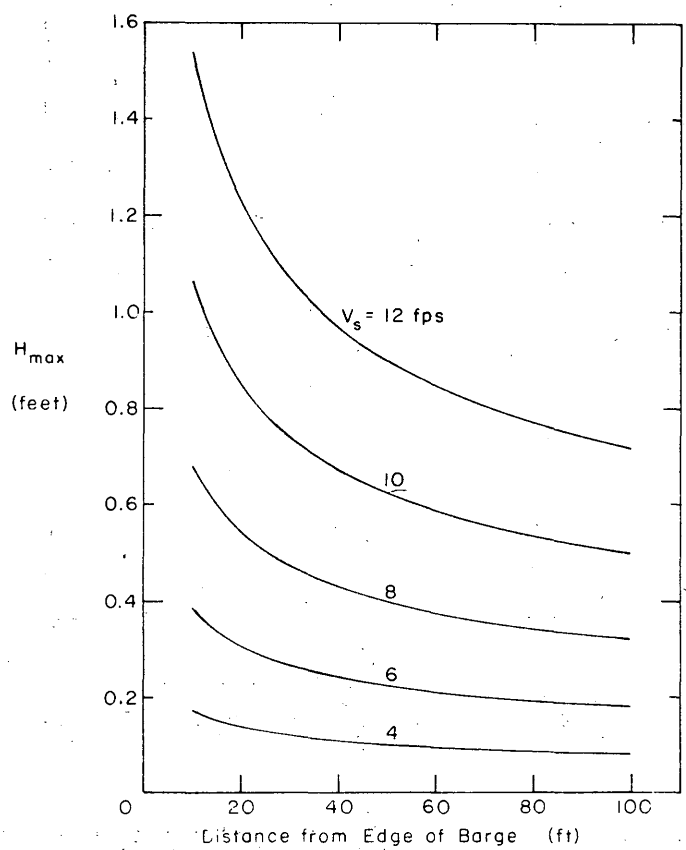


Figure 14. Maximum wave height as function of distance from sailing line and vessel speed.

under an ice sheet of thickness η and tensile failure strength σ_f. The failure occurs as a cantilever bending downward and the maximum moment occurs when the wave has its trough beneath the outer $\lambda/2$ distance of the ice sheet (see Fig. 16). The maximum moment is given simply by

$$M_{max} = \frac{2}{\pi}\frac{H_{max}}{2}\frac{\lambda}{2}\frac{\lambda}{4}\gamma_{ice} = \frac{H_{max}\lambda^2}{8\pi}\gamma_{ice}. \tag{15}$$

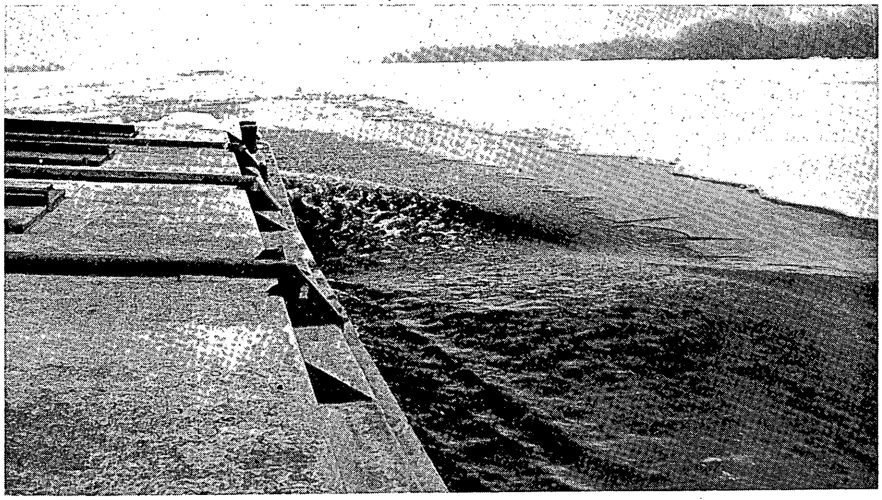
Failure occurs when

$$M_{max} = \frac{\sigma_f \eta^2}{6} \tag{16}$$

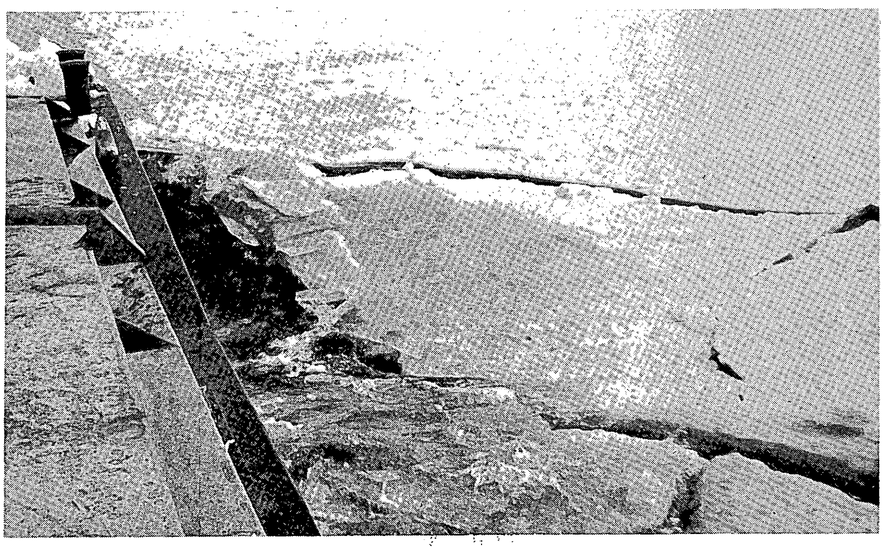
so that the thickness of ice which resists breakage by a wave of length λ and height H_{max} is

$$\eta_r = \left(\frac{3}{4\pi}\frac{\gamma_{ice} H_{max}}{\sigma_f}\right)^{1/2}\lambda. \tag{17}$$

Substituting for H_{max} using eq 13 and for λ using eq 14 results in



a. *Bow wave pattern in open water.*



b. *Initial breakage by collapse into wave trough.*

c. *View of broken ice from stern of barge.*

Figure 15. Ice breakage resulting from bow wave, MV Renee G, Mississippi River near Keokuk, 1972.

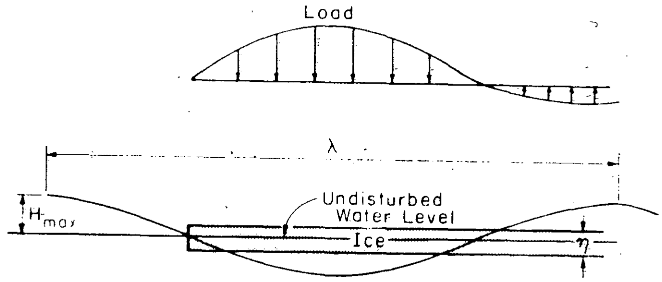


Figure 16. Definition sketch for analysis of wave breakage.

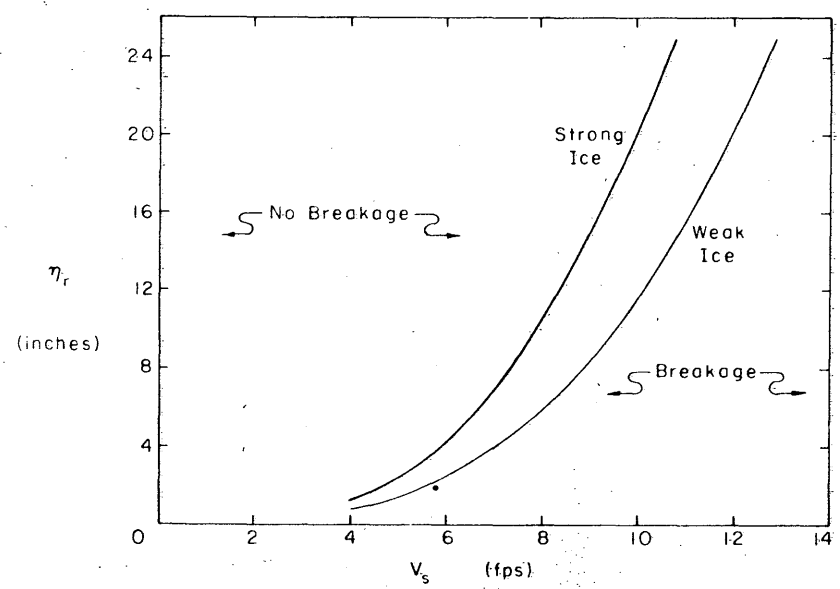


Figure 17. Ice thickness resistant to side breakage by a vessel moving at a speed V_s.

$$\eta_r = 0.066 \frac{V_s^{\,3}}{\sigma_f^{1/2} x^{1/6}} \text{ (ft-sec-lb).} \qquad (18)$$

Inspection of eq 18 shows that the thickness of ice able to resist breakage by ship-generated waves depends most upon the ship speed. In Figure 17 the resisting thickness is plotted as a function of V_s, assuming $x = 10$ ft and $\sigma_f = 10{,}000$ lb ft^{-2} ($\approx$ 5 kg cm^{-2}) and 30,000 lb ft^{-2} ($\approx$ 15 kg cm^{-2}) which corresponds roughly to weak and strong freshwater ice.

Few data are available to verify eq 18. In the investigation referred to earlier,[3] breakage of 10- to 12-in. weak ice occurred at a tow velocity of 12 ft sec^{-1}, which is reasonably consistent with the results in Figure 17.

Return of disposed ice slabs

Under certain conditions, the ice pieces disposed laterally under the adjacent ice cover may be expected to be transported by the flow back to the cleared channel area. A detailed analysis of the conditions for movement of individual slabs is presented later. Most likely, however, the slabs will not be returned to the channel area except at those places where the channel is not aligned with the velocity vector. In an attempt to characterize the extent of the regions in which non-alignment may be expected, the navigation charts of the Upper Mississippi River[12] were examined from mile 225 (just above the mouth of the Illinois River) to mile 450 (just below Muscatine). The following data were extracted: locations where the channel axis "crossed" the river from one side to the other; and locations and angle of turn where the turn was accomplished in a distance less than about 1 mile and the angle of turn was greater than 20°. Determination of crossing locations was somewhat subjective since the channel line is often reasonably well centered on the river width. The angle of turn was measured simply by extending the tangent lines and measuring the angular deviation with a protractor. The results for the 225-mile reach are summarized in Table VII. In terms of averages, there is a crossing every 5 miles and a significant turn ($\theta > 20°$) every 3 miles. Every one of these turns and every one of the crossings would probably not result in transport of cut slabs back to the channel area even if the velocity was high enough, but they do give a quantitative indication of the potential problem areas.

Table VII. Channel alignment characteristics Mile 225 to Mile 450.

Number of crossings of channel axis relative to river centerline:

Location	*Crossings*
Mile 225 - 300	14
Mile 300 - 375	15
Mile 375 - 450	14

Turn geometry:

Location	*$20° \leq \theta < 30°$*	*$30° \leq \theta < 40°$*	*$40° \leq \theta \leq 50°$*	*$50° \leq \theta$*
Mile 225 - 300	5	9	4	3
Mile 300 - 375	5	11	6	2
Mile 375 - 450	8	6	6	4
Mile 225 - 450	18	26	16	9

MIC operating schedule

The results thus far suggest that there is an optimum operating schedule for the MIC although specific choice of a schedule must consider other than a simple thickness criterion. It is clear that there may be compromises to the idealized concept of an ice-free channel. For the Keokuk area, it appears (see Table IV) that either a 10-day fixed interval strategy or an 8-in. specified thickness strategy would allow winter navigation for all but a small portion of the winter season. The compromises that may occur include the generation of excessive brash in the channel, contributions of brash due to side breakage, and difficulties at turns. For much of the winter season the cutting capability is probably less important than the capability of removing ice from the channel area by the action of the skegs. This is not to say that the cutting capability is superfluous, merely that the presence of brash ice often offers more problems than the ideally refrozen ice cover.

It is also significant that the greater portion of the thickening of the ice cover is confined to a fraction of the winter season, and that if this contribution can be disposed navigation may proceed

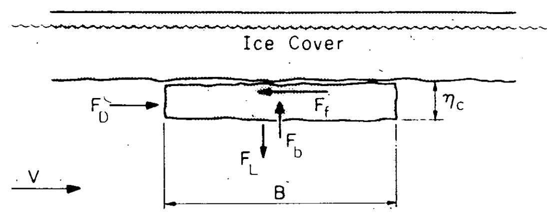


Figure 18. Definition sketch for analysis of ice slab transport.

during most of the winter season. The same reasoning suggests that a flexible operating strategy may offer significant benefits by combining real-time observations of ice thickness with short-term weather forecasts to yield not only an optimum operating schedule for the MIC but valuable advice to the shippers.

ICE SLAB STUDY

Transport of submerged ice slabs

We now consider the conditions under which an ice slab which has been deposited under the ice cover remains in place or is transported by the currents. The slab is assumed to be rectangular with width B, length L, thickness η_c, and density ρ_i. The flow velocity is, for the moment, assumed to be uniform and denoted by V. The forces acting on the ice slab (see Fig. 18) are the upward buoyancy force F_b, the downward "lift" force F_L, the horizontal drag force F_D, and the resisting force F_f due to friction between the top of the ice slab and the bottom of the ice cover. Because of stability considerations, the block will ordinarily be oriented with the long dimension perpendicular to the velocity vector, and we will arbitrarily denote L as the long dimension, i.e. $L \geq B$. For the dimensions anticipated for the cut slabs, we may neglect the water frictional forces on the bottom surface of the slab relative to the drag forces.

The drag force is given by

$$F_D = \frac{\rho_w V^2}{2} C_D L \eta_c \qquad (19)$$

where C_D is a drag coefficient and ρ_w is the density of the water. Tests on rectangular blocks against a flat boundary yield a value of C_D of about 1.2 for blocks with $\eta_c/L = 0.25$ (see ref. 20). As η_c/L decreases, C_D increases, but considering other uncertainties in this analysis the value 1.2 will be adopted for calculations.

The buoyancy force is simply given by

$$F_b = g(\rho_w - \rho_i)\eta_c LB \qquad (20)$$

where ρ_w and ρ_i are the densities of the water and the ice, respectively. It is likely that ice regularly cut from a channel will have little snow ice content and the value for pure ice, $\rho_i/\rho_w = 0.916$, will be used in the calculations.

The lift force is given by

$$F_L = \frac{\rho_w V^2}{2} C_L LB \tag{21}$$

where C_L is a lift coefficient. Again, tests on rectangular blocks adjacent to a smooth boundary yield values of C_L of about 0.5 for a height-width ratio of 0.25 (see ref. 20).

The resisting force due to friction is given by

$$F_f = \mu(F_b - F_L) \tag{22}$$

where μ is a coefficient of friction. There is considerable uncertainty regarding the magnitude of μ. For ice surfaces which are not actively growing into the melt, μ is probably of the order of 0.03 to 0.1 (see ref. 8). The possibility of the surfaces being active and μ correspondingly larger will be briefly considered below. This is not, however, the most likely situation. Before the resisting force can act, of course, $F_b > F_L$ and the critical velocity V_c for equality is easily found from eq 20 and 8 to be

$$V_c = \left[\frac{2g\eta_c}{C_L}\left(1 - \frac{\rho_i}{\rho_w}\right)\right]^{1/2}. \tag{23}$$

Assuming $C_L = 0.5$, and $\rho_i/\rho_w = 0.916$ yields the simple relationship between velocity and the thickness in the form

$$V_c = 3.3\,\eta_c^{1/2} \text{ (ft-sec)}. \tag{24}$$

The thinner the slab the more likely that a low velocity will be critical. As an example, a 0.25-ft-thick slab is inherently unstable at a velocity of 1.6 ft sec^{-1}. In the following analysis it will be assumed that V is less than V_c and thus the buoyancy force exceeds the lift force.

The more general condition for incipient transport is found by equating F_D to F_f and results in

$$V = \left\{\frac{2\mu g B[1 - (\rho_i/\rho_w)]}{C_D[1 + (\mu C_L B/C_D \eta_c)]}\right\}^{1/2}. \tag{25}$$

This same result may be rearranged into the form of a densimetric Froude number Fr with the thickness as the length parameter. The critical Froude number is, then,

$$\mathrm{Fr}_\eta \equiv \frac{V}{\{g\eta_c[1 - (\rho_i/\rho_w)]\}^{1/2}} = \left[\frac{2\mu}{C_D[(\eta_c/B) + (\mu C_L/C_D)]}\right]^{1/2}. \tag{25a}$$

Examination of eq 25a shows the importance of the thinness ratio η_c/B. Large, thin blocks tend to be more stable than short, thick blocks. The dimension B is determined by the width of cut or the slab breaking length, whichever is less, and the slab breaking length depends in part on the geometry of the undersurface of the cutting barge. Figures 19 and 20 show the results of calculations in nondimensional form (Fig. 19) and dimensional form (Fig. 20) for $\mu = 0.03$ and $\mu = 0.1$ which provide

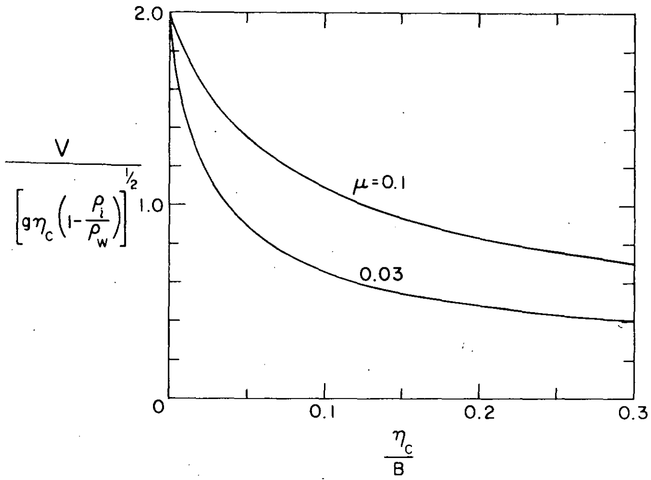


Figure 19. Incipient transport condition for ice slab beneath ice cover.

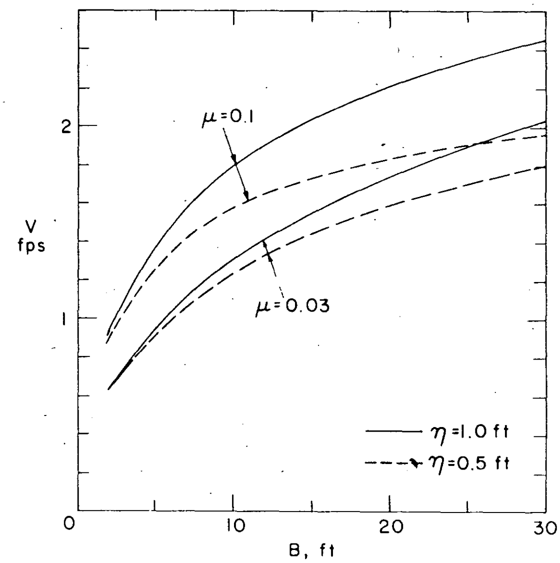


Figure 20. Incipient transport velocity for ice slab beneath ice cover.

reasonable bounds on the friction coefficient. There is considerable approximation in the analysis presented above. Nevertheless, examination of the results and comparison with the velocities ordinarily expected (see Table III) suggests that it is desirable that the slabs cut during the channel clearing process be as large as possible, of the order of 10 ft or more, to be conducive to deposit of the slabs adjacent to the cut channel. If the slabs have smaller dimensions they will tend to be transported by the flow and to collect in regions of low velocity or at obstructions. Once deposited, the slabs will adhere and freeze to the ice cover during any period of thickening of the natural ice cover. The disposition of these slabs will be discussed in more detail in later sections.

Before leaving the subject of transport of individual ice slabs, one further case deserves discussion. If the cutting is performed while the air temperature is substantially below freezing, both the undersurface of the adjacent ice cover and the top surface of the newly cut and discarded ice slab are in an active state, the latter resulting from heat flux into the slab to "warm" the below-freezing ice slab interior. Under such conditions it is quite possible for the slab to adhere by freezing to the undersurface if it comes to rest for a short interval. For these conditions, the critical velocity could be considerably greater than predicted by Figure 19. It is difficult to evaluate this case without experiment except to note that cutting does not always take place at below freezing conditions, and the slab must first come momentarily to rest.

Containment of ice in a cleared channel

In this section the conditions under which ice fragments will be contained in a cleared channel are briefly considered. Two cases are considered: an individual ice slab and an accumulation of ice. It has been shown[4, 26] that an individual ice slab of thickness η arrested by a surface obstacle on a flow of depth D will be unstable, underturn, and accumulate at a velocity given by

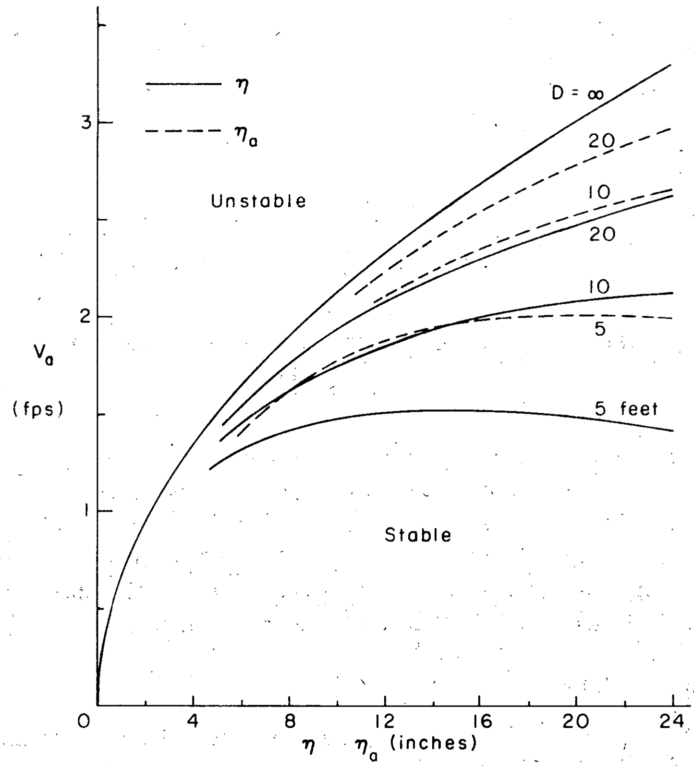


Figure 21. Stability diagram for single blocks (solid lines) and accumulation thickness (dashed lines).

$$V_c = \left[g\eta\left(1 - \frac{\rho_i}{\rho_w}\right)\right]^{1/2} \frac{2\left(1 - \frac{\eta}{D}\right)}{\left[5 - 3\left(1 - \frac{\eta}{D}\right)^2\right]^{1/2}} \qquad (26)$$

For very small ratios of η/D eq 26 reduces to

$$V_c = \left[2g\eta\left(1 - \frac{\rho_i}{\rho_w}\right)\right]^{1/2} \qquad (27)$$

and these results are presented in Figure 21 for $\rho_i/\rho_w = 0.916$. Quite obviously the occurrence of the critical velocity is unlikely for a slab of specified thickness. If the flow velocity is less than V_c, the slabs will accumulate in a single layer on the water surface. If the velocity is greater than V_c, the slabs will accumulate in a manner such that the thickness of the accumulation η_a is given by[15]

$$V_c = \left[2g\eta_a\left(1 - \frac{\rho_i}{\rho_w}\right)\right]^{1/2} \left(1 - \frac{\eta_a}{D}\right) \qquad (28)$$

which for small values of η/D is of the same form as eq 27. This result is also presented in Figure 21 (dashed lines).

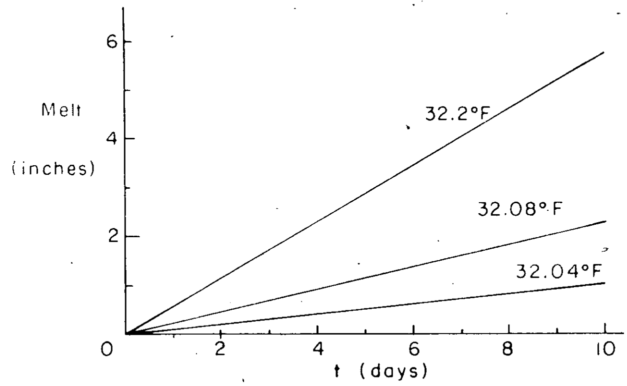


Figure 22. Melting of submerged slabs 20 feet long in a flow at 1 ft sec^{-1}.

If the flow velocity is greater than the critical velocity corresponding to the adjacent ice cover thickness then the ice will accumulate until that thickness is exceeded, after which spillage out of the channel will occur. In general, the velocities expected in normal winter seasons (see Table III) are such that an adjacent ice cover thickness of 6 to 8 in. is conducive to containment of loose brash. The major compromise to this idealized picture is the spillage of ice that results from passage of a tow with width nearly that of the cleared channel.

Melting of submerged ice slabs

In this section the possibility of melting of the submerged slabs is examined. It is shown that significant melting is unlikely, or at least occurs only at times when the entire cover is undergoing significant melting. In this latter case it would seem to be of little concern since 1) no ice cutting would be taking place and 2) the melting of the disposed slabs would have no significance relative to the possibilities of imminent breakup.

It is reasonable to neglect any conduction heat transfer through a submerged slab. Thus eq 3 becomes

$$\frac{-q_w(t)}{\rho_i \lambda} = \frac{d\eta}{dt} . \qquad (29)$$

While the analysis of $q_w(t)$ in the previous treatment utilized closed conduit heat transfer results, in this case it is more appropriate to use boundary layer formulas to calculate $q_w(t)$ when determining the rates of melting. For a turbulent boundary layer with free-stream velocity V and temperature T_∞ acting on a flat surface of length L, the heat transfer rate averaged over the slab length is given by[13]

$$q_w = \frac{0.037(T_\infty - T_m)k_w}{L} \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4} \qquad (30)$$

where the Reynolds number is defined using L as the length scale ($\mathrm{Re} = UL\rho/\mu$). In Figure 22, the thickness η_m melted off the surface of a 20-ft-long submerged slab is presented as a function of time, assuming the flow velocity is 1 ft sec^{-1} and the temperature of the water is 32.04°F, 32.08°F or 32.2°F. Except at the unnaturally high water temperature of 32.2°F, the melting is considered insignificant.

EFFECTS OF SLABS ON RIVER FLOW

In this section the effects on river flow of the slabs which have been cleared from the channel are considered. Necessarily the results must be regarded as approximate, primarily because the distribution of the disposed slabs along a river reach will most likely be nonuniform and the degree of nonuniformity largely controls the magnitude of the effects. On the one extreme is a uniform distribution of the cut slabs along the cleared channel edges. On the other extreme is accumulation of all cut slabs at discrete locations along the reach. The first, uniform distribution, will be shown to have negligible effect. The second, discrete accumulation, has the most effect and will be analyzed within the context of some simplifying assumptions. Somewhere between is the likely case.

Uniform distribution of cleared ice slabs

The case of a uniform distribution along the channel length of the ice slabs which have been cut from the channel is easily analyzed by approximate means. The cleared channel width is denoted by b_c, the total thickness cut over the duration of the season is denoted by η_s, the flow depth by D, the cross-sectional area of the river by A, and the mean flow velocity in the absence of any channel clearing by V. The blockage of the cross section is then given by $\eta_s b_c$, and we neglect the additional area available in the cleared channel. A reasonable approximation to the increase in velocity is then found from simple continuity considerations to be

$$\Delta V = V\left(\frac{1}{1 - \frac{\eta_s b_c}{A}} - 1\right). \qquad (31)$$

If $\eta_s b_c / A << 1$ then eq 31 is well approximated by

$$\Delta V = V \frac{\eta_s b_c}{A}. \qquad (32)$$

As an example we will use the data for a 7-day fixed interval strategy in 1972 (see Table IV) at Keokuk Lock and Dam 19. For this case η_s = 38.0 in. Assuming a cleared channel width of 100 ft, a cross-sectional area of 40,000 ft^2, and a mean velocity of 1.0 ft sec^{-1} the increase in velocity is found to be 0.008 ft sec^{-1}, which is a negligible increase. In deriving eq 32, we have neglected the increase in cross-sectional area which would result from effects of the added frictional and blockage resistance due to the slabs. Similarly we have neglected the redistribution of velocity which is also likely as a result of the locally increased roughness associated with the presence of the cut slabs. Consideration of all these factors leads to the conclusion that the mean velocities are insignificantly affected by a uniform distribution, along the channel length, of the cut slabs.

On a local basis, it is likely that the surface velocity in the cleared channel before an ice cover re-forms will approach the maximum flow velocity in the cross section as a result of the removal of the resistance associated with the ice cover. Adjacent to the channel, the surface resistance originating from the presence of the disposed slabs will be greater and hence the boundary layer will be thicker. Again, these are local, minor effects which are expected to be of little consequence.

Discrete accumulation of cut slabs

It is unlikely that the slabs will be uniformly distributed along the channel, particularly in narrower reaches with higher velocities which exceed the incipient velocity for transport of the slabs beneath the ice cover. As a result, the slabs may be expected to accumulate in regions of low velocity or at places where channel alignment changes. If the detailed characteristics of these critical reaches are known, it should be a relatively straightforward matter to estimate the effects of discrete accumulation for each location. For present purposes, we will estimate the effects using numerical values of the pertinent quantities that are considered reasonable and typical. This approach will at least allow an estimate to be made of the severity of the problems involved.

We denote the length between accumulation points by S_a, the cross section at the point A_a, the depth by D_a, and the mean velocity in the absence of accumulation by V. The length of the accumulation is denoted by L_a and the width by B_a. Other notation is defined in the previous section.

The volume of ice that accumulates at a critical point over a season is $S_a \eta_s b_c$. If the length of the accumulation were known, the blockage and the increase in velocity could be estimated as before. The length of accumulation will rarely be known beforehand; accordingly we must calculate it on the basis of a simplified analysis of accumulation mechanics. It may be shown[15] that the analysis leading to eq 28 also leads to a maximum accumulation thickness of about one-third the flow depth. Assuming the ice accumulates to this thickness without forming a severe jam and blockage, then volumetric conservation requires that

$$S_a \eta_s b_c = L_a \frac{D}{3} B_a \tag{33}$$

from which we find that

$$L_a = \frac{3S_a \eta_s b_c}{B_a D}. \tag{34}$$

The width of accumulation can be related to the depth and cross-sectional area if the form of the cross section is known. For a rectangular cross section $B_a = A/D$, while for a triangular cross section $B_a = 2A/D$. The cross-sectional shapes of the Mississippi River lie somewhere between these two extremes and a reasonable choice would seem to be $B_a = 1.5\, A/D$. Substituting into eq 34 then yields

$$L_a = \frac{2S_a \eta_s b_c}{A}. \tag{35}$$

Before proceeding further, an example is in order. Assuming S_a = 10 miles, η_s = 38 in., b_c = 100 ft, and A = 60,000 ft^2 yields L_a = 627 ft. The choice of area A is probably too low for an accumulation location of low velocity while the choice is probably too high for an accumulation location at a turn in the river. In any case, the length required for storage is sufficiently small that it is expected the river can accommodate the ice storage requirements with little difficulty. The numbers used in the example above are considered typical for reaches of the Mississippi River in the general vicinity of Keokuk Lock and Dam 19. More northerly reaches of the river, as in the general vicinity of Lake Pepin and Alma Lock and Dam 4, are much more tortuous and narrow. While these factors would tend to increase L_a, it is also likely that the length S_a would be correspondingly shorter and the results are not expected to be significantly different from a practical standpoint. As will be discussed in the section on ice jams, it is concluded that the volumetric production by channel cutting is small, especially when compared with the total ice production of the river. This is a result of the simple observation that the channel width is generally much less than the total width of the river.

The analysis presented above is a cursory one. It is justified on the simple basis that the results indicate little significant effect for the cases presently under consideration. Other situations might require a more sophisticated treatment but it appears unwarranted at the present.

ICE JAM STUDY

In this section the causes of ice jams and the effects of operation of an MIC in creating or alleviating ice jams are briefly reviewed. Finally, possible operating procedures for an MIC encountering an ice jam are suggested.

Causes of ice jams

An ice jam is defined for present purposes as a piling of broken ice fragments sufficiently thick to cause a blockage of the cross section and a corresponding increase in water level. Not all jams cause complete blockage nor do they all cause significant rises in water level. An ice jam can vary in intensity from a simple accumulation of broken ice across a river's width, a few feet or less in thickness, to an extensive and deep accumulation several miles long and tens of feet thick. On a fundamental level, the formation of an ice jam requires first, a supply of ice, and second, an obstruction to the transport of the ice downstream. The obstruction can be a turn, a constriction, a widening, an artificial structure, or an intact ice cover. Whether or not a particular obstruction leads to jamming depends not only on the geometry and characteristics of the obstruction but also on the supply of ice, both the total amount and the rate of supply. Ice jams of the type described are usually associated with breakup, which in turn is nearly always associated with a thaw period and/or a rise in discharge. Often the breakup is on a tributary and the jam is initiated when the ice released from the tributary encounters the intact ice cover of the main river. The other most common situation exists when an ice discharge carried along by a particular flow velocity encounters a reach of lower velocity and consequent lesser transport capability. This is particularly the case at the upper ends of reservoir pools. Finally, ice jams generally occur with little warning and develop very rapidly. The above description is brief; for more background information the reader is referred to the annotated summary of literature prior to 1968[7], the summary of practice in the USSR[18], or the proceedings of recent symposia on the subject[27 28 29]. We have excluded from discussion other forms of jams such as frazil hanging dams since they occur mostly at the time of freezeup and there is little that can be done with an MIC that would aid in their dissipation. Further, the small amount of open water exposed by a cutting pass, relative to the total width of the river, is not expected to result in a significant production of frazil during midwinter periods, particularly since the low velocities ordinarily encountered in the reaches under consideration are conducive to rapid re-formation of a thin ice cover.

Effects of MIC operation

It is reasonable to ask whether operation of an MIC and the associated winter navigation will create a greater potential for ice jamming. The potential could be increased if the operation modifies the ice supply or modifies the obstructions that initiate the jams.

There is no question that the total ice production of the river will be increased by winter navigation. The periodic removal of the ice cover results in new ice formation at a faster rate than would otherwise occur. A quantitative indication of the additional ice production may be gained by comparing the total thickness cut η_s (see Tables IV and V) over a season to the naturally occurring maximum ice thickness η_{max} experienced without ice cutting. The additional volume of ice production per unit length of channel is then given by $(\eta_s - \eta_{max})b_c$ where b_c is the width of the cleared channel. The percent of additional ice production, relative to the natural ice production of the entire river width, is given by

$$\frac{(\eta_s - \eta_{max})b_c}{\eta_{max} B} \times 100$$

where B is the river width. As an example, the total thickness cut at Keokuk Lock and Dam 19 using a 7-day fixed interval strategy averages 40 in. (1968-1972), while the naturally occurring maximum ice thickness is about 14 in. The width B of the main river is of the order of 2000 ft. Thus a cut channel of 100-ft width would produce about 3% more ice than is produced naturally. It may be concluded that the total supply of ice in the river is negligibly changed by operation of a cutter, and it is not anticipated that ice jams would be caused by this small additional contribution.

It may be possible, by providing a cut channel in an otherwise intact ice cover, to induce an earlier than usual breakup since the cut channel prevents the ice cover from spanning the cut. In fact, this very technique, establishing a longitudinal cut in an ice cover, is sometimes used as a preventive measure for ice jams.[18] The purpose of the cut is to weaken the ice cover enough so that it breaks up when ice from upstream encounters it. It is noteworthy that the cut alone is generally not sufficient to induce the breakup. This is in harmony with the observations made on the Mississippi River in 1972,[3] i.e. the presence of a broken channel did not appear to induce or delay breakup. On a local scale, just before breakup the presence of a cut channel may allow large pieces to break from the adjacent ice cover and block the cleared path. Ordinarily this is expected to occur only when the ice is in a weakened state, as during major thaw periods. Subsequent cold periods will then result in stronger ice and could interfere with navigation. In this case the cutting capability becomes more advantageous since these local blockages may be cut through to allow navigation to resume.

In summary, it is concluded that operation of an MIC and the associated traffic will not result in increasing the hazards of ice jamming. The continual cutting of the ice cover may reduce the incidence of jamming by weakening the cover and reducing its potential to act as an obstacle to ice arriving from upstream. Since the severe ice jams on the Mississippi River generally result from a large ice supply associated with a rise in discharge or from the discharge of ice from a tributary it is considered unlikely that navigation will cause ice jams.

Operating procedures when encountering gorge

In this section operating procedures are suggested for use when an ice cutter encounters a limited accumulation of ice which blocks the channel. Similar procedures are also applicable to operations on a major jam although it must be recognized that the effectiveness may be minuscule simply because of the immensity of such jams.

The destruction of an ice accumulation should begin from the downstream end and work upstream. Ordinarily the quantities of ice in a jam are so large that the river currents must be relied upon to transport the ice away from the jam. By working into the jam at the point of maximum flow velocity through the jam it is sometimes possible to induce movement of adjoining ice towards the axis of the "notch" and thus multiply the amount of ice physically moved by the vessel by many times. The ultimate objective in the cases of both large and small accumulations is to clear a path through the jam to allow passage of water and ice with ease. In general the location of operations should be in the main channel. If a path is cleared through a shallow depth region, the lowering of water levels upon clearing may result in grounding of the entire mass and may stabilize the jam further.

During operations on an ice jam of substantial magnitude it is desirable to have at least two vessels in operation. The second vessel is required for reasons of safety in the event the jam should suddenly rupture, move, and trap one of the vessels. In addition, by working in tandem it may be possible to increase the effectiveness of breaking operations by clearing a path on one side with one vessel and utilizing the other vessel to aid movement of the ice toward that escape path.

Before concluding it is worthwhile to point out that ice cutters are often used in the USSR to weaken the ice cover prior to breakup in selected reaches of high jamming incidence. It is beyond the scope of this study to attempt identification of such sites on the Mississippi River. Techniques of analysis are under development which should eventually complement historical observations of ice jam locations.

CONCLUSIONS

In this study the ice management problems associated with operation of a Mechanical Ice Cutter to clear ice from the navigation channel of the Mississippi River have been evaluated. The study is based on the presumption that the MIC leaves in its wake an ice-free channel. Under normal wintertime temperatures this cleared channel will refreeze and subsequent traffic will repeatedly break the refrozen cover, generating in turn a newly frozen cover with significant brash content. Perhaps the most significant result of the study is the observation that most of the ice production occurs during a small fraction of the period of ice cover. In the vicinity of Keokuk Lock and Dam 19 this is particularly true and removal of the ice from channel areas after the relatively short periods of major production should enable navigation to continue for most of the winter season without encountering extended reaches of very thick ice. Farther north, in the vicinity of Lake Pepin, the production of ice occurs for a longer period and would require more frequent cutting and clearing over a longer period.

Besides the refreezing analysis, a number of other problems were examined including movement and disposition of the cut slabs, breakage of the adjacent cover by vessel waves, melting of submerged slabs, and effects relating to ice jams. It was found that the ice slabs may be expected to be transported by the river currents at intermediate velocities and consequently may be expected to accumulate in regions of low velocity. The additional production of ice resulting from repeated clearing was found to be but a small part of the total production of ice in the river. A relation was found between vessel speed and thickness of ice cover resistant to breakage by waves produced by the vessel. While such breakage may require operation of vessels below a certain speed to avoid side breakage the speeds are not much lower than normal operating speeds and are not considered a serious restraint. Melting of submerged slabs was found to be small; hence, it is expected that the ice slabs will be present somewhere in the river until the natural dissipation period.

The examination of effects related to ice jams resulted in the conclusion that wintertime navigation will not increase the natural incidence of jamming. The presence of a cut channel may, in fact, weaken the ice cover enough to reduce the potential for jamming. As a practical matter, however, the serious jams on the Mississippi will probably not be much affected by operation of an MIC unless the operations are specifically planned and directed at preventing or reducing the incidence of jamming. Unfortunately, our present state of knowledge precludes detailed recommendations in this regard, although research efforts are underway which show promise of not only forecasting locations of jams but also providing a means of alleviating them.

LITERATURE CITED

1. Ashton, G.D. and J.F. Kennedy (1970) Temperature and flow conditions during the formation of river ice. International Association for Hydraulics Research Ice Symposium, Reykjavik, Iceland, Paper 2.4, 12 p.

2. Ashton, G.D. and W.D. Hibler III (1972) Evaluation of thermal discharges at Cordova, Illinois. Report to North Central Division, Corps of Engineers.

3. Ashton, G.D., S.L. DenHartog and B. Hanamoto (1973) Icebreaking by tow on the Mississippi River. U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) Special Report 192.

4. Ashton, G.D. (in prep) Entrainment of ice blocks – secondary influences. *Proceedings International Symposium on River and Ice, Budapest*, January 1974.

5. Assur, A. and W.F. Weeks (1964) Growth, structure, and strength of sea ice. USA CRREL Research Report 135. (AD 450186).

6. Bilello, M.A. (1960) Formation, growth, and decay of sea ice in the Canadian Archipelago. USA CRREL Research Report 65, p. 14-16. (AD 653137).

7. Bolsenga, S.J. (1968) River ice jams – A literature review. U.S. Lake Survey Research Report 5-5, Lake Survey District, Corps of Engineers, Detroit, Michigan, 587 p.

8. Bowden, R.P. and D. Tabor (1954) *The friction and lubrication of solids*. Oxford: Clarendon Press.

9. Comstock, J.P., Ed. (1967) *Principles of Naval architecture*. New York: The Society of Naval Architects and Marine Engineers.

10. Havelock, T.H. (1908) The propagation of groups of waves in dispersive media, with application to waves on water produced by a travelling disturbance. *Proceedings, Royal Society of London*, London, England, Series A, p. 398-430.

11. Kostyukov, A.A. (1968) Theory of ship waves and wave resistance, Russian translation by M. Oppenheimer, Effective Communications, Inc., Iowa City, Iowa.

12. Kostyukov, A.A. (1968) Upper Mississippi River navigation charts. U.S. Lake Survey District, U.S. Army Engineer Division, North Central, Chicago, Illinois.

13. Michel, B. (1971) Winter regime of rivers and lakes. USA CRREL Cold Regions Science and Engineering Monograph III-B1a.

14. Outcalt, S.I. (1973) The development and application of a simple digital surface-climate simulator. *Journal of Applied Meteorology*, vol. 11, no. 4, p. 629-636.

15. Pariset, E. and R. Hausser (1961) Formation and evolution of ice covers on rivers. *Transactions of the Engineering Institute of Canada*, vol. 5, no. 1, p. 41-49.

16. Rohsenow, W.M. and H.Y. Choi (1961) *Heat, mass, and momentum transfer.* New Jersey: Prentice-Hall, Inc.

17. Sayre, W.W. and J. Schwarz (1972) Background data on temperature and ice conditions in the Mississippi River near Cordova, Illinois during 1971. Final Report, Institute of Hydraulic Research, The University of Iowa, Iowa City, Iowa.

18. Sinotin, V.I., et al. (1973) Recommended practice for combatting ice jams. Draft Translation 400, 106 p.

19. Sorensen, R.M. (1973) Water waves produced by ships. *Journal of the Waterways, Harbors and Coastal Engineering Division, ASCE*, vol. 99, no. WW2, Proc. Paper 9754, p. 245-256.

20. Task Committee on Wind Forces (1961) Wind forces on structures. *Transactions ASCE*, Paper no. 3269, vol. 126, part II, p. 1124-1198.

21. U.S. Army, Corps of Engineers (1961-1973) Ice reports, Rock Island District.

22. U.S. Army, Corps of Engineers (1968-1973) Ice reports, St. Paul District.

23. U.S. Department of Commerce (1964) Climatography of the United States no. 86-11, Decennial Census of United States Climate – Supplement for 1951 through 1961 – Iowa.

24. U.S. Department of Commerce (1965) Climatography of the United States no. 86-41, Decennial Census of United States Climate – Supplement for 1951 through 1961 – Wisconsin.

25. U.S. Department of the Interior, Geological Survey, Water resources review for November 1973, ... January 1973, ... February 1973, ... March 1973, ... April 1973.

26. Uzuner, M.S. and J.F. Kennedy (1972) Stability of floating ice blocks. *Journal of the Hydraulics Division, ASCE*, vol. 98, no. HY 12, Proc. Paper 9418, p. 2117-2133.

27. Williams, G.P. (1973) Seminar on ice jams in Canada. Edmonton, Alberta, Technical Memorandum no. 107, National Research Council Canada, Ottawa, Canada, 182 p.

28. Williams, G.P. (1970) I.A.H.R. Symposium, Ice and its action on hydraulic structures, Reykjavik, Iceland, 67 papers.

29. Williams, G.P. (1972) Second International Symposium on ice and its action on hydraulic structures, I.A.H.R., Leningrad, USSR (in press).

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13. ABSTRACT

Ice management problems associated with operation of a Mechanical Ice Cutter for use in icebreaking as an aid to winter navigation are examined. The study concentrates on effects occurring after the cutting operation. Included in the evaluation are assessments of refreezing rates, movement and disposition of the slabs produced by the cutting, and an examination of effects related to ice jams. The evaluation is specific to the upper Mississippi River, in particular Pool 19 above Lock and Dam 19 at Keokuk, Iowa. It was found that most ice production during a winter occurs during a small fraction of the period of ice cover; hence removal after these short periods may allow navigation to proceed for significant wintertime periods. A relation was found between cut slab dimensions and critical velocity to move them that will enable estimates to be made of accumulation. Breakage of adjacent ice by vessel waves was found to impose a possible restraint on vessel speed but not a serious one.

14. Key Words

Icebreakers
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