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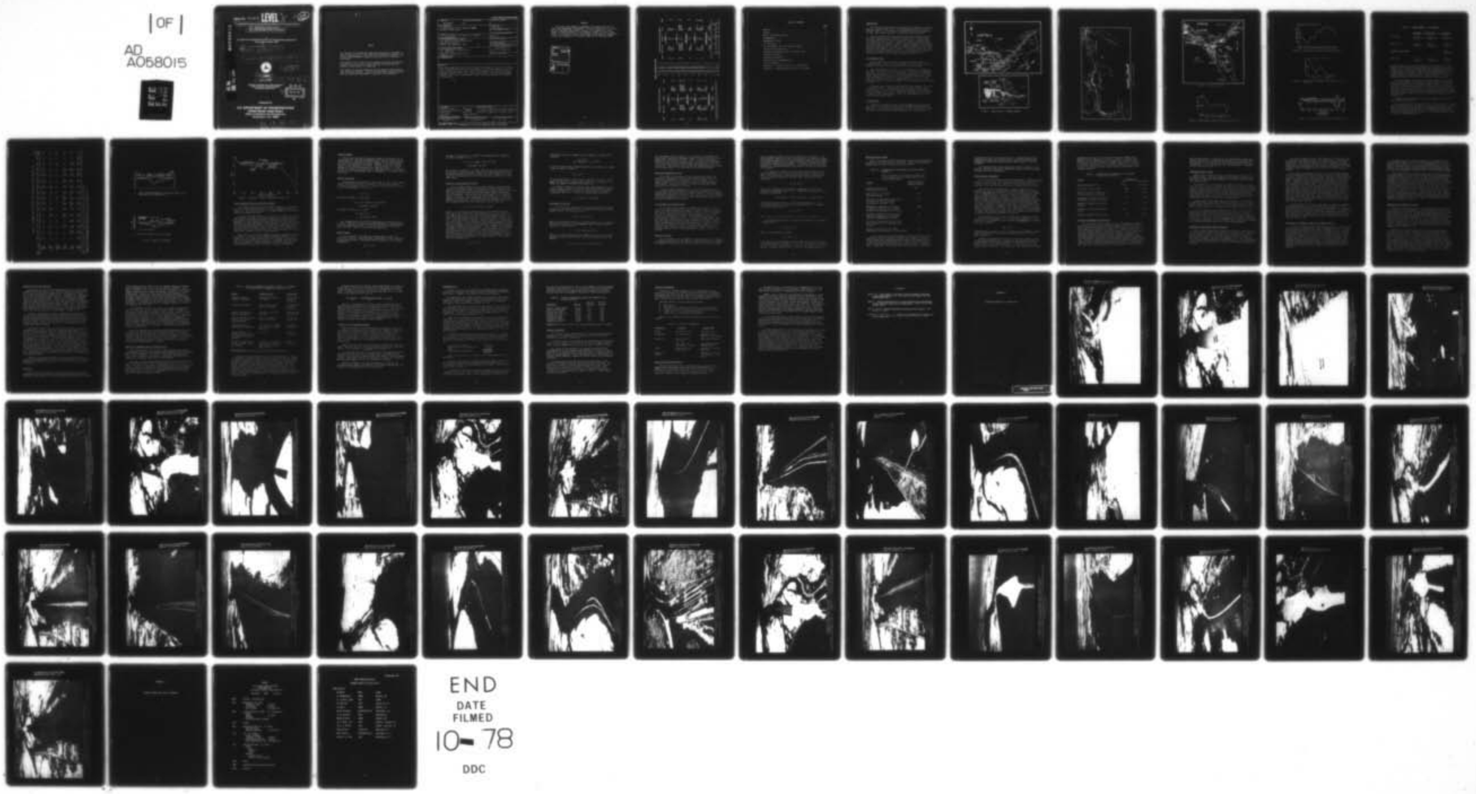

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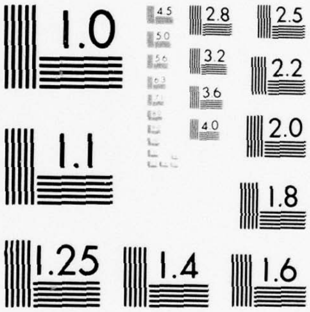

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Report No. CG-D-22-78 **LEVEL** II & ⑩

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⑥ AN INVESTIGATION OF ICE CLOGGED CHANNELS IN THE ST. MARYS RIVER

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⑱ USCG ⑲ D-22-78

⑮ MIPR-Z-70099-882249-3B

⑫ 73p.

⑪ Mar[redacted]78

⑨ FINAL REPORT. 1 Dec 77-28 Feb 78,

Document is available to the public through the
National Technical Information Service,
Springfield, Virginia 22151

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
United States Coast Guard
Office of Research and Development
Washington, D.C. 20590

78 17 08 104
037 100

NOTICE

Technical Report Documentation Page

1. Report No. CG-D-22-78

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
AN INVESTIGATION OF ICE CLOGGED CHANNELS
IN THE ST. MARYS RIVER

5. Report Date March 1978

6. Performing Organization Code

8. Performing Organization Report No. 8XX70711

7. Author(s) M. Mellor, G.P. Vance, J.L. Wuebben, G.E. Frankenstein

9. Performing Organization Name and Address
U.S. Army Cold Regions Research and
Engineering Laboratory
Hanover, New Hampshire 03755

10. Work Unit No. (TRAIS)

11. Contract or Grant No. MIPR-Z70099-882249-3B

13. Type of Report and Period Covered
Final Report
1 Dec 77 to 28 Feb 78

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
U.S. Coast Guard
Research and Development Office
Washington, D.C.

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This study addresses itself to the problem of removing brash ice from Frechette Point to Six-Mile Point of the Little Rapids Cut of the St. Marys River system. The area and river system are described and estimates are made for partially clearing a channel 250 ft wide. Rough costs, based on dollars per horsepower, indicate that it would cost between 1 and 2 million dollars per clear channel mile per year.

17. Key Words
Clogged channels
Cold weather operations
Floating ice
Ice control
Navigation conditions
Restricted channels
River ice
Winter navigation

18. Distribution Statement
Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report) Unclassified

20. Security Classif. (of this page) Unclassified

21. No. of Pages 73

22. Price

PREFACE

This report was prepared in response to a request from the U.S. Coast Guard Commandant G-DOE-3/TP54. Its basic objective is to investigate the energetics and specific powers, i.e. horsepower per unit volume of removing broken ice from shipping channels in the St. Marys River. It is part of a larger study effort to determine the feasibility of year-round navigation in the Great Lakes and St. Lawrence Seaway.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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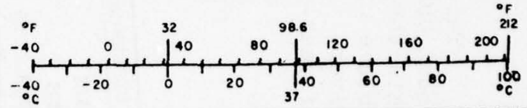
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	



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INTRODUCTION

The Navigation Season Extension Demonstration Program for the Great Lakes-St. Lawrence Seaway (Fig. 1) was authorized by Congress in the River and Harbor Act of 1970 and by the Water Resources Development Act of 1974. The program completed its sixth year on 30 June 1977.

One of the areas that has presented perennial problems for winter navigation has been the St. Marys River system (Fig. 2), particularly the Little Rapids Cut portion of the system (Fig. 3). Broken pieces of ice (brash ice) build up in the channel and prevent the passage of all but high-powered ice breaking vessels. Several solutions to the problem have been proposed; however, specific energy requirements have not been addressed in any detail. The objective of this study is to look at the specific energy and/or specific power, i.e. power per unit volume of ice removed in a certain portion of the cut, and to estimate the cost of keeping that portion of the channel relatively clear of ice.

DESCRIPTION OF AREA

The St. Marys River essentially extends from Brush Point in the southeast corner of Lake Superior (northwest of the Soo Locks) to Detour Passage which flows into the northwest section of Lake Huron.

The river flows at an average of 1 to 2 ft/sec in a southeasterly direction. The flow velocity varies somewhat with the local bathymetry and season of the year. Figure 4 indicates the variation in flow from August 1976 to August 1977. The IGLD (International Great Lakes Datum) river elevation varies from 575 ft at Lake Huron to a 602 ft at Lake Superior. Figures 5 and 6 depict water levels at the U.S. slip gage just downstream of the Soo Locks during the last 10 years and particularly in 1977.

A typical river cross-sectional profile of the Frechette Point area is shown in Figure 7. Profiles along the river are of similar shape (Alger, 1977). The river bottom is made up of pink and gray mottled clay from dredge spoil disposal. Some areas may have a very thin mantle of fine-grained sand and gravel. There are a few sandy beaches down river towards Six-Mile Point.

ICE CONDITIONS

Typically ice starts to form in late November and early December and causes severe problems in the river system from mid-December until early March. Typical average thicknesses of plate ice at various points along the river are shown in Table I and Table II. Accumulations of

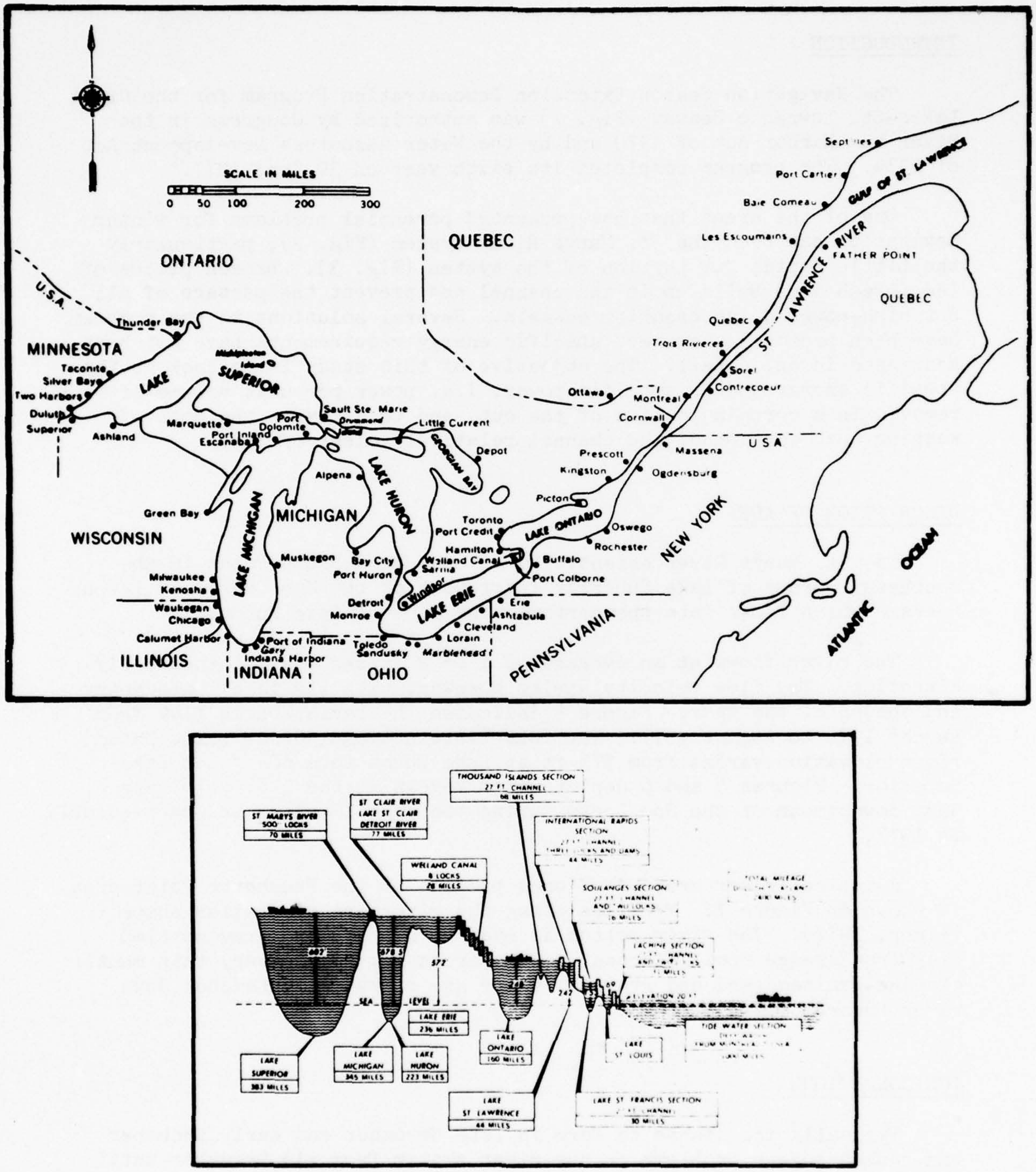


FIGURE 1. GREAT LAKES-ST. LAWRENCE SEAWAY.

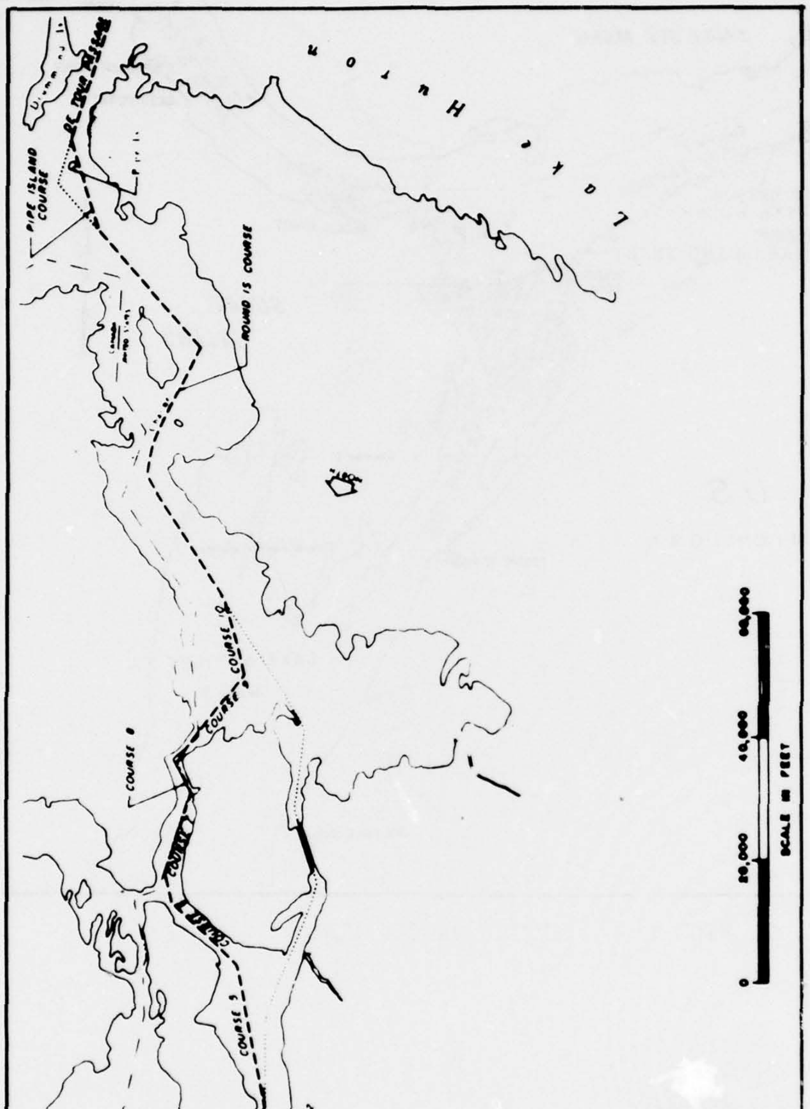


FIGURE 2. ST. MARYS RIVER.

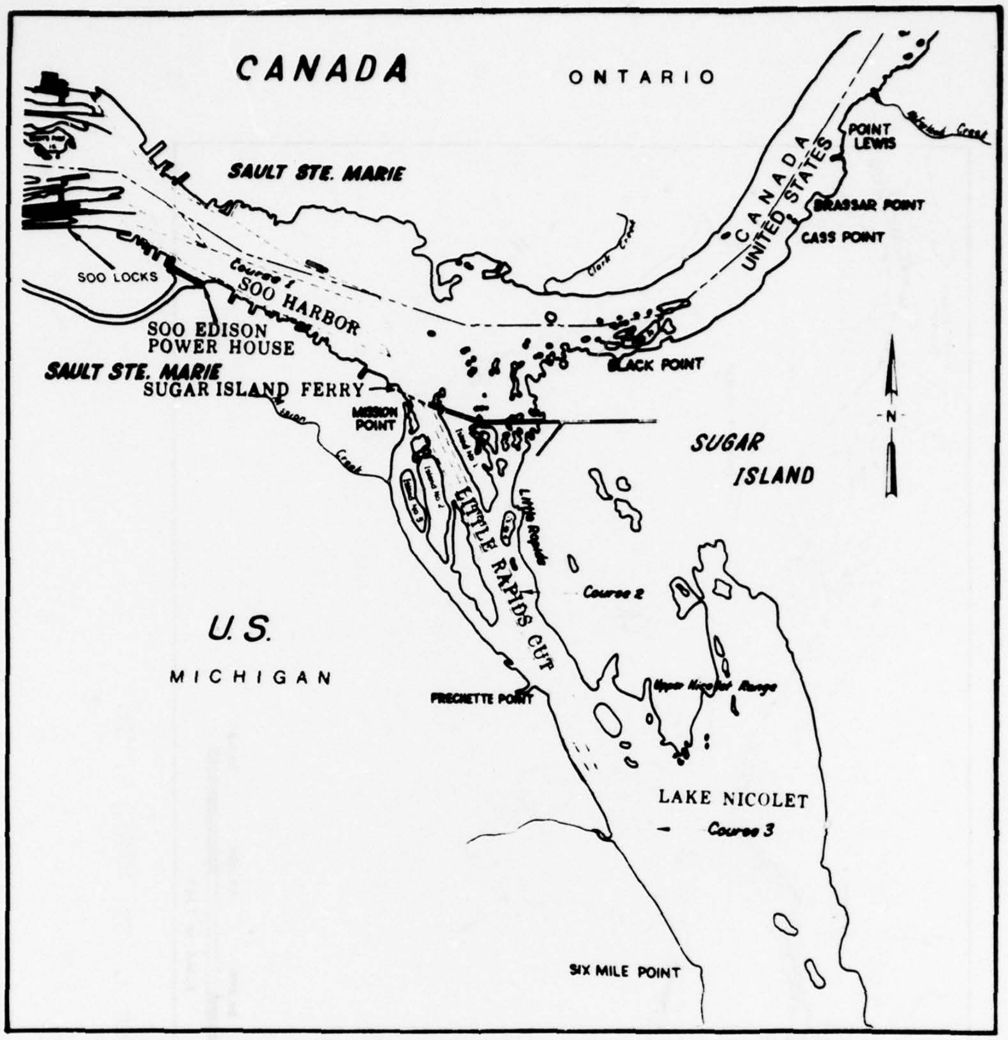


FIGURE 3. LITTLE RAPIDS CUT.

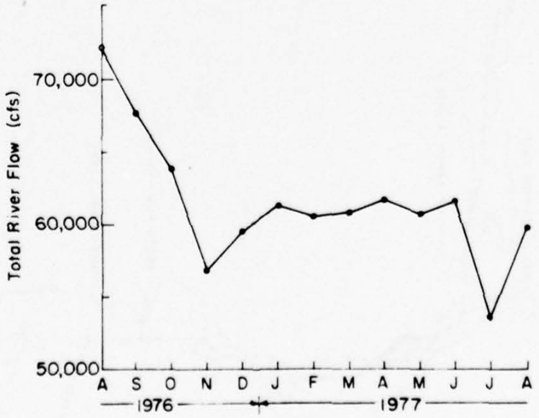


FIGURE 4. MEAN MONTHLY FLOWS (AUGUST 1976-AUGUST 1977).

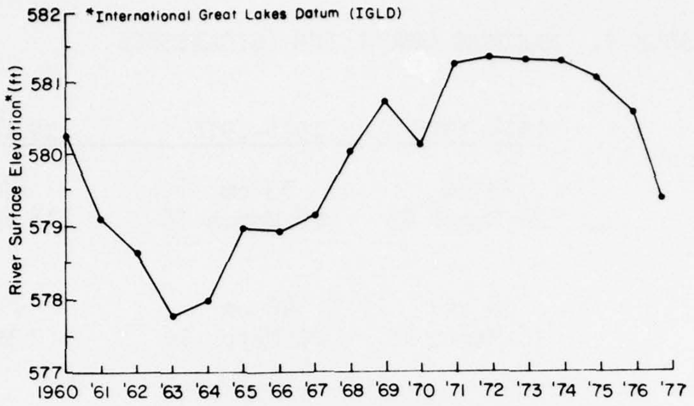


FIGURE 5. MEAN ANNUAL RIVER WATER SURFACE ELEVATION.

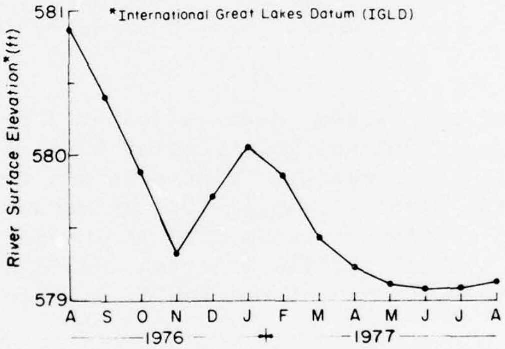


FIGURE 6. MEAN MONTHLY RIVER ELEVATIONS BELOW LOCKS AT U.S. SLIP GAGE.

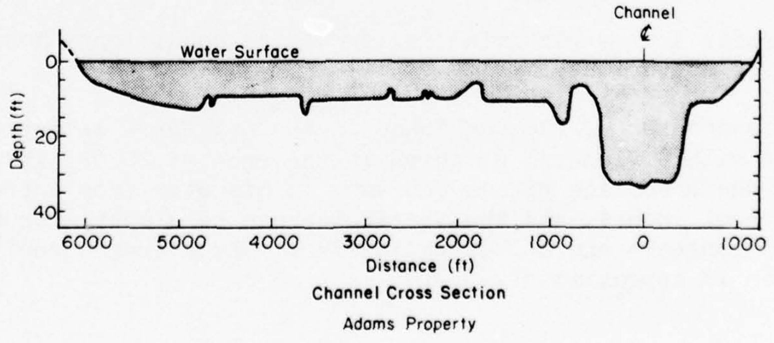


FIGURE 7. LITTLE RAPIDS CUT PROFILE, FRECHETTE POINT.

TABLE I. MAXIMUM ANNUAL ICE THICKNESSES.

	1974-1975	1975-1976	1976-1977
Gros Cap Lt.	23 cm 28 March 75	53 cm 26 March 76	69 cm 18 March 77
Mosquito Bay	36 cm 16 March 75	46 cm 20 March 76	48 cm 7 March 77
Frechette Creek Point			82 cm 6 March 77
Raber Bay	51 cm 7 March 75	13 cm 2 January 76	66 cm 18 March 77

brash and frazil ice can exceed these values by three to five times. Voelker (1974) has measured accumulations of brash and broken ice up to a depth of 52 in. in the Frechette Point area and depths over 100 in. in other areas of the river. Dean (1978) has measured several river cross sections on a continuous basis with an impulse radar system. Figure 8 depicts a typical profile of brash and frazil ice across the channel at Frechette Point and at the bow of a large ore carrier.

Figure 9 depicts a bathymetric and current anomaly found by Alger (1977). There appears to be a distinct change in grade in the river bottom as it slopes toward the deeper channel. There is usually an associated active crack and accumulation of brash ice in the vicinity of the crack. The water shoreward of the crack may be still, while the water on the channel side of the crack is very active during the passage of a large vessel. The changes in magnitude and direction of the current velocity are quite dramatic and lead to substantial activity of any submerged ice.

Appendix A is a pictorial review of ice conditions along the St. Marys River at various times.

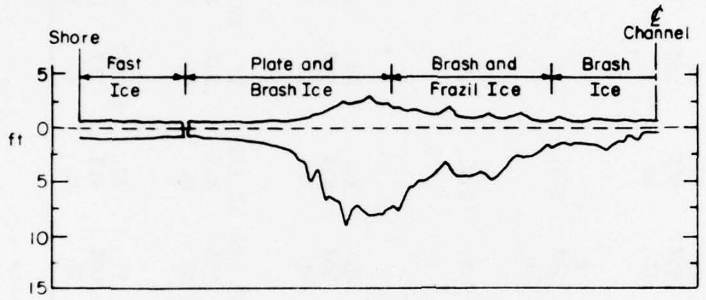
The character of the ice found in the St. Marys is typical of freshwater ice with a flexural strength in the area of 20,000 lb/ft^2. The sizes of the brash ice pieces can vary in diameter from approximately 10 ft to several inches, and the frazil ice can be almost microscopic before it congeals and builds up in size. The average specific gravity of the ice is approximately 0.9.

TABLE II. ICE THICKNESS (IN.) ST. MARYS RIVER, CORPS OF ENGINEERS, SOO AREA, WINTER 1976-1977.

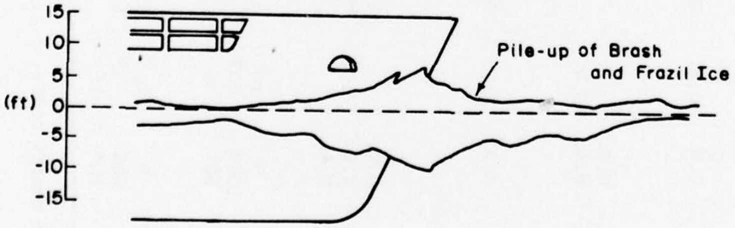
STATION	LOCATION	13 DEC 76	22 DEC 76	27 DEC 77	3 JAN 77	10 JAN 77	17 JAN 77	25 JAN 77	1 FEB 77	8 FEB 77	14 FEB 77	22 FEB 77	28 FEB 77	7 MAR 77	15 MAR 77	22 MAR 77	29 MAR 77 FINAL
1	East Center Pier	O.W.	O.W.	O.W.	O.W.	U.C.	13 62% BL	14 50% BL	16 93.7% BL	21 81% BL	21 89% BL	17 88% BL	22 55% BL	17 41% BL	O.W.	O.W.	O.W.
2	Pitts-burgh Dock	O.W.	U.C. U.A.	U.C. U.A.	O.W.	9 61% BL	9 78% BL	U.A.	U.A.	U.A. U.C.	8 50% BL	U.A.	U.A.	U.A.	O.W.	O.W.	O.W.
3	Head of Litte Rapids	O.W.	O.W.	O.W.	O.W.	O.W.	U.C.	O.W.	U.C. O.W.	O.W.	O.W.	O.W.	O.W.	O.W.	U.C. O.W.	O.W.	O.W.
4	Fre-chette Point	U.C.	U.C.	O.W. U.C. U.A.	U.C.	14 1/4 89.5% BL	16 81% BL	15 1/2 77% BL	22 3/4 61.5% BL	19 66% BL	21 60% BL	19 63% BL	20 55% BL	27 37% BL	U.A.	O.W.	O.W.
5	Six-Mile Point	U.C.	7 1/2 87% BL*	5 100% SN	10 60% BL	13 75% BL	13 54% BL	14 1/2 66% BL	11 72.7% BL	18 53% BL	15 1/2 55% BL	18 1/2 41% BL	17 29% BL	19 1/2 18% BL	6 100% SN	U.A.	O.W.
6	Upper Lake Nicolet	6 100% BL	6 1/2 85% BL*	5 20% BL*	11 73% BL	10 1/2 66.7% BL	14 79% BL	14 1/2 66% BL	18 80.5% BL	17 65% BL	17 68% BL	22 41% BL	20 1/2 51% BL	20 1/2 45% BL	12 1/2 44% BL	5 100% SN	U.C.

LEGEND: O.W. = open water; U.C. = unsafe cover; U.A. = unsafe access; BL = blue ice; SN = snow

* At Six-Mile Point readings taken 200 ft offshore on 22 Dec. 76, 400 ft offshore on 27 Dec. 76.
At Upper Lake Nicolet readings taken 1500 ft offshore on 22 Dec. 76 and 27 Dec. 76.



A. IMPULSE RADAR MEASUREMENT OF BRASH AND FRAZIL ICE AT FRECHETTE POINT, JANUARY 1978.



B. PILE-UP OF BRASH ICE AT BOW OF VESSEL.

FIGURE 8. BRASH ICE THICKNESS.

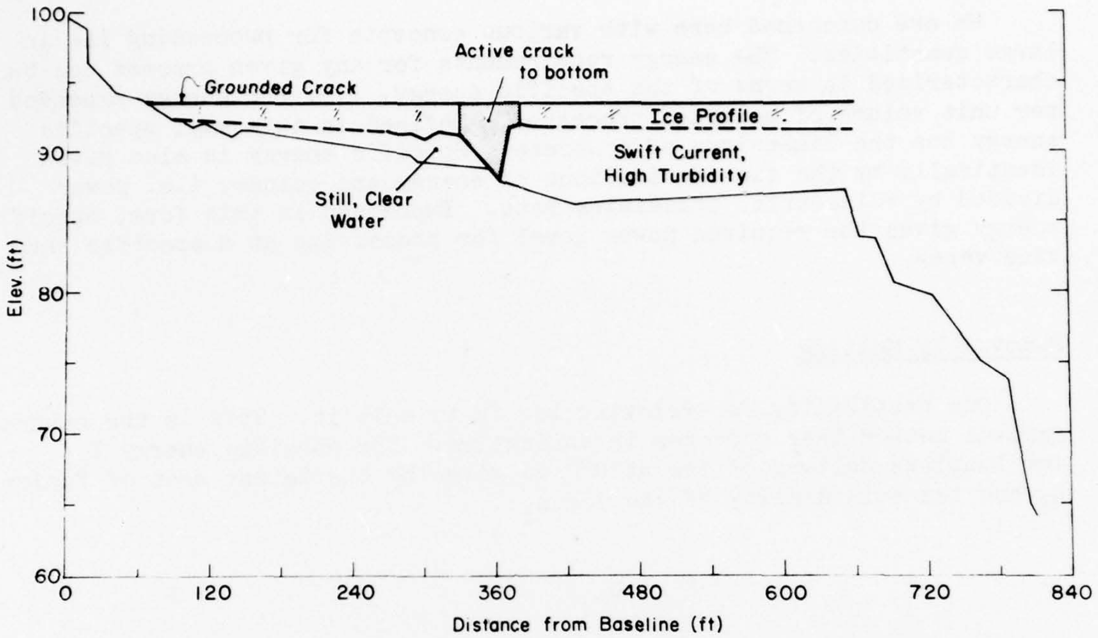


FIGURE 9. BATHYMETRIC ANOMALY ACCORDING TO ALGER, 1977.

ICE DISPLACEMENT FROM THE NAVIGATION CHANNELS

The problem essentially is that vessels operating on inland waters such as St. Marys River are unable to negotiate channels choked with broken ice. The required solution is a scheme whereby ship traffic can continue throughout the winter.

One idea, which may or may not be valid, is to develop a system for removing broken ice from the navigation channels. In principle, there are a number of thermal and mechanical concepts that are potentially applicable for this purpose, and the primary object of this report is to examine the energy requirements of such concepts. There can, of course, be a vast gulf between a basic concept and its practical application, and therefore the secondary object of this report is to consider the rate limitations of practical devices that might conceivably be used for displacing or removing ice from clogged channels.

This section of the report responds directly to questions raised by the sponsor. It should not be regarded as implying advocacy of, or support for, any of the principles that are discussed. It may well be that other factors dominate the problem. For example, heat loss from open water surfaces is clearly important, and the low efficiency of screw propulsion at low speeds is worthy of serious consideration.

Specific Energy

We are concerned here with various concepts for processing ice in large quantities. The energy requirements for any given process can be characterized in terms of the specific energy, i.e. the energy expended per unit volume of material processed. Defined in this way, specific energy has the dimensions of a stress. Specific energy is also given identically by the time derivations of energy and volume, i.e. power divided by volumetric processing rate. Expressed in this form, specific energy gives the required power level for processing at a specific rate or vice versa.

Removal by Melting

One possibility for removing ice is to melt it. This is the natural removal method that operates in springtime. The specific energy E_s for lossless melting of ice at 0°C is given by the latent heat of fusion L_f and the bulk density of the ice ρ_i:

$$E_s = L_f \rho_i$$

For solid ice with $\rho_i = 0.917\ \mathrm{Mg/m^3}$:

$$E_s = 333.5\ (\mathrm{MJ/Mg}) \times 0.917\ (\mathrm{Mg/m^3})$$

$$= 306\ \mathrm{MJ/m^3} = 306\ \mathrm{MN/m^2}$$

For bubbly ice with $\rho_i = 0.9\ \mathrm{Mg/m^3}$

$$E_s = 333.5 \times 0.9$$

$$= 300\ \mathrm{MJ/m^3} \text{ or } \mathrm{MN/m^2}$$

The rounded value of 300 $\mathrm{MJ/m^3}$ is appropriate for natural ice lying in water. However, it does not include any allowance for inefficiencies in the heat generating system, or for heat losses during application of heat to the ice. Thus it is an absolute minimum value.

Simple Lifting

It is of interest to estimate the minimum specific energy for lifting ice slowly to a specified height, neglecting any water resistance or acceleration effects. The minimum specific energy for slow lifting to height H is

$$E_s = \rho_i\, g\, H.$$

For bubbly ice having $\rho_i = 0.9$ Mg/m^3, the minimum specific energy for lifting to a height of 1 m is

$$E_s = 0.9 \times 9.807 \times 10^6 \times 10^{-3} \text{ N/m}^2$$
$$= 8.83 \text{ kN/m}^2 \text{ or kJ/m}^3$$

For lifting to a height of 3 m, which would be just about enough to pick blocks from a channel and place them on top of the adjacent ice sheet, the minimum specific energy is $3 \times 8.83 = 26$ kJ/m^3 = 0.026 MJ/m^3. This value can be rounded up to 0.03 MJ/m^3 to make some allowance for "break-away" losses.

Pushing or Towing Single Ice Slabs

For an isolated irregular ice slab being pushed or pulled through open water at constant speed, the resistance to motion is made up of a number of contributing effects, including viscous drag, turbulent (inertial) skin drag, form drag involving eddies and wakes, surface wave-making, and air resistance. Some of these are insignificant for the relevant range of conditions: pure viscous drag, for example, can be neglected because the boundary flow is turbulent, and air resistance is negligible because of the low speed. The form drag and the turbulent skin friction can be lumped together to give a resistance term R_1 in the form

$$R_1 = (1/2)\, \rho_w\, u^2 (C_{df} A_f + C_{ds} A_s)$$

where C_{df} is the form drag coefficient, A_f is the effective frontal area, C_{ds} is the skin friction drag coefficient, A_s is the wetted area, ρ_w is water density, and u is speed of the ice through the water. C_{df} is of order unity, whereas C_{ds} for a long smooth surface is about 2.5×10^{-3}. Since the length or width of a slab of broken ice is likely to be less than 10 times the ice thickness, the area ratio A_s/A_f is not likely to be much above 10. Thus the form drag will probably dominate R_1, even when C_{ds} is doubled to allow for the fact that a typical slab is "short" in terms of boundary layer development. A close estimate of wave-making resistance is not really necessary for present purposes, and we propose to estimate the total resistance as a simple form drag by using an adjusted value of C_d to allow for skin friction and wavemaking. Noting that the effective bow shapes of slabs can vary considerably, giving a statistical aspect to the problem, we simply take $C_d = 2$ and estimate the total resistance R_2 as

$$R_2 = \rho_w\, u^2\, A_f.$$

The specific energy for pushing a slab of length L a distance D is therefore

$$E_s = \frac{\rho_w u^2 A_f D}{A_f L} = \rho_w u^2 (D/L)$$

In order to push a slab a distance equal to its own length at constant speed, the specific energy is

$$E_s = \rho_w u^2.$$

If the pushing speed is 1 knot, $\rho_w u^2 = 265\ N/m^2 = 265\ J/m^2$. If the speed is 2 knots, this figure is multiplied by 4; if the speed is 3 knots, the figure is multiplied by 9, and so on.

To obtain a figure for comparison with other processes, we might assume a pushing speed of 3 knots and a distance of 100 slab lengths (which is perhaps a bit high, but it could be taken as allowing for acceleration from rest). The specific energy value then becomes

$$E_s = 239\ kJ/m^3 \simeq 0.24\ MJ/m^3.$$

Submerging a Flat Slab

If a flat slab is pushed down into the water without appreciable tilting, the resistance is made up of a bouyant force R_1 and a hydrodynamic drag R_2. The buoyancy force is

$$R_1 = h_i (\rho_w - \rho_i) g A$$

where h_i is the slab thickness, ρ_w is water density, ρ_i is ice density, and A is the slab area. The hydrodynamic drag at constant speed of submergence u can be taken as

$$R_2 = (1/2) \rho_w u^2 C_d A$$

where C_d is a drag coefficient, here taken as 1.5. To push the slab through a vertical distance equal to the ice thickness, the specific energy is

$$E_s = h_i (\rho_w - \rho_i) g + (1/2) \rho_w u^2 C_d.$$

For submergence through a depth of 1 m, the buoyancy contribution is about 1 kJ/m^3, and for a submergence speed of 1 knot (0.515 m/sec) the hydrodynamic contribution is about 2 kJ/m^3. Taking the submergence speed as 3 knots and the submergence depth as 3 times the ice thickness of 1 m, the total specific energy becomes approximately 55 kJ/m^3, or 0.055 MJ/m^3. This value does not include the acceleration effect, which could be appreciable if the slab were thrust down very abruptly.

Mechanical Comminution of Ice

If ice were to be chopped or crushed mechanically, perhaps in preparation for hydraulic conveying, the specific energy could vary considerably depending on the efficiency of the equipment used. To obtain estimates, we draw on experience accumulated during numerous CRREL studies. Details are given in a number of unpublished CRREL technical notes (available on request).

If rotary milling equipment were to be used for chopping the ice into fragments about 30 mm in size, a large well-designed machine could perhaps achieve an overall specific energy of about 0.7 MJ/m^3, neglecting hydrodynamic resistance on the rotor. Much lower values could be obtained with a good stonecrusher, but it is hard to see how such a device could be applied usefully for this purpose.

Ice Transport in Slurry Pipelines

It is possible that fragments of comminuted ice might be transported to a remote disposal area through a slurry pipeline, in the same sort of way that dredge spoil is sometimes treated. There are no available data on which to base specific energy estimates, but ice ought to be easier to transport than soils, rocks and minerals, since it is almost neutrally buoyant in water. If we assume a large diameter pipe with high flow velocity, say 3 m/sec, the data for transport of rocks and coal suggest that moderately high concentrations could be pumped for energy expenditures of less than 6 kW-hr/ton-mile. Putting this into SI units, the expectation is that an ice slurry could be pumped for one kilometer with a specific energy not exceeding 13 MJ/m^3. Taking a transport distance of 300 m, this would mean a specific energy of about 4 MJ/m^3.

Ballistic Ejection

It is conceivable that ice fragments could be moved from the channel by throwing them or by ejecting them in a stream of projectiles. Examples of comparable processes are the ejection streams from rotary snow plows and the streams of gravel that can be thrown by an air eductor. If a dense stream of particles is fired through the air, the particles inside the stream experience very little air resistance, and for present purposes we can make a specific energy estimate on the basis of simple ballistic trajectories, ignoring air resistance. It should be easy to refine the estimates by considering boundary layer shear if the idea has any appeal to the sponsor.

If a particle is fired into the air with initial velocity u and angle of elevation α, it rises to the high point of its trajectory in time t while acted upon by gravitational acceleration g, finishing up with zero vertical velocity at the high point. Thus, ignoring air resistance,

$$t = (u/g) \sin \alpha.$$

With no air resistance the trajectory is symmetrical and the total duration for horizontal range s is 2t. Since there is assumed to be no horizontal acceleration

$$s = 2ut \cos \alpha = 2(u^2/g) \sin \alpha \cos \alpha = (u^2/g) \sin 2\alpha.$$

Differentiation with respect to α gives maximum range when $\alpha = 45°$, and on this basis we can estimate the required value of u to achieve a specified casting distance:

$$u = (s\, g)^{1/2}.$$

For s = 10 m, u = 9.9 m/sec, and for s = 100 m, u = 31.3 m/sec.

The minimum specific energy required for accelerating ice fragments to velocity u is

$$E_s = (1/2) \rho_i u^2$$

which, after substitution, becomes

$$E_s = (1/2) \rho_i s g.$$

If we take 50 m as a reasonable practical range for an ejection system, E_s calculated from this equation is 221 kJ/m^3. This makes no allowance for air resistance or entrainment of water in the particle stream, so we propose to accept a rounded value of 0.3 MJ/m^3 for comparison purposes.

Energy Conversion Losses

Most of the specific energy values that have been listed (Table III) are based on the energy input to the process. There may be additional energy losses arising from conversion inefficiencies.

TABLE III. MINIMUM ENERGY REQUIREMENTS FOR VARIOUS REMOVAL PROCESSES.

(N.B. No allowance is made here for energy conversion losses from the primary power source to the operating device)

Process	Specific Energy E_s (MJ/m^3 or MN/m^2)
Lossless melting at 0°C (latent heat of fusion)	300
Slow lifting to 3 m height (potential energy)	0.03
Pushing an ice slab through open water at 3 knots for 100 slab lengths (hydrodynamic resistance - ehp)	0.24
Submerging a flat slab of 1 m thick ice through a depth of 3 m at 3 knots (buoyancy and hydrodynamic resistance)	0.055
Mechanical comminution of ice to small fragments by rotary cutting machines (excluding hydrodynamic resistance)	0.7
Transport in slurry pipeline at 3 m/sec for a distance of 300 m (includes pump losses)	4
Ballistic ejection with 50 m range (imparting kinetic energy to ice projectiles)	0.3

In most cases the required mechanical or electrical energy will be generated on site by combustion of fossil fuel, usually a petroleum product burned in an internal combustion engine. The conversion efficiency for an internal combustion engine, from the calorific value of the fuel (ignoring "free" oxygen) to the shaft output, is about one-third. Beyond this, further conversion losses are minor. Electrical generating losses and line losses are small. Mechanical power transmission is typically about 90% efficient. Electrical and hydraulic transmission systems for mechanical power might be about 65% to 70% efficient.

For melting systems, direct combustion of fuel is obviously to be desired. However, there can be substantial losses in the heat exchange process and in heat transmission.

PRACTICAL RATE LIMITATIONS

It is helpful to progress from the consideration of somewhat abstract figures to a discussion of the implications for practical processes. To do this, we have to make some assumptions about the quantities of ice that have to be dealt with, and the rates of working that are required.

Assume that with good maintenance a channel width of 100 m is adequate, and further assume that the clearing frequency will be such that the effective mean thickness of ice in the channel will not exceed 1 m. ("Effective" denotes the mean thickness of ice that has to be removed to make conditions acceptable.) Clearing frequency could be highly variable depending on location, traffic, time of year, and so forth. However, we take here a maximum clearing rate based on the need to clear a 50- km-long channel once a week with a 5-day working week. This gives 10 km/day as the working rate, which is not necessarily the rate for a single unit. Combining these figures, we arrive at a volumetric working rate of 10^6 m^3/day. If we take a 10-hour working day for arithmetic convenience, the hourly rate is 10^5 m^3/hr. It is recognized, of course, that different processes will have different characteristics as regards continuity and duration of operation.

The main point of this simple arithmetic is to emphasize that we are dealing with big numbers. If E_s is the specific energy for a process and $\dot{V}$ is the volumetric rate of working, the minimum power requirement P_{min} is given by

$$P_{min} = E_s \dot{V}.$$

Referring back to Table III, we can calculate the corresponding minimum power requirements for the various processes with $\dot{V} = 10^5$ m^3/hr, as shown in Table IV.

Keeping in mind than 1 MW is 1341 hp, some of the numbers in Table IV are obviously prohibitive, especially as they represent values of minimum power, without making allowance for conversion losses. That some of the values are large should not be too surprising, since the proposed rate is very high. For comparison, 2 in. of snow on the highway represents about 300 m^3 per lane-mile, so that the proposed daily handling rate for channel ice is equal in volume to a typical snow removal from over 3000 lane-miles of highway, and in terms of mass it is equivalent to much more than this (8 or 9 times more). Actually, it is the low values that call for comment, since it is almost inconceivable that such high clearing rates could be achieved with a few thousand horsepower.

TABLE IV. MINIMUM POWER REQUIREMENTS FOR ICE REMOVAL AT THE RATE OF 10^5 m^3/hr.

Process	Minimum power	
	(MW)	(hp, approx.)
Lossless melting at 0°C	8300	11,000,000
Slow lifting to 3-m height	0.83	1,100
Pushing ice slab at 3 knots for 100 slab lengths in open water	6.7	9,000
Submerging flat slab of 1-m thick ice through 3 m depth at 3 knots	1.5	2,000
Mechanical comminution by rotary machines	19	25,000
Transport in slurry pipelines for 300 m	110	150,000
Ballistic ejection for 50-m range	8.3	11,000

Clearing by Draglines or Excavators

The characteristics and production rates of backhoes and draglines have been discussed recently in another CRREL report (Mellor, 1978). Typical machines (excluding the special giants built for open-pit mining) have buckets with capacity up to about 5 m^3. Production rates vary with the digging conditions, the material properties, the working depth, the angle of swing, and the operating efficiency. Assuming a 5-m^3 perforated bucket, a 90° angle of swing, adequately fragmented ice, a 50-minute hour (83% operating efficiency), and no major icing problems on the equipment, a short-boom dragline might be capable of handling 400 m^3/hr. To achieve production rates of 10^5 m^3/hr, some 250 machines with a combined power of about 100 MW would have to operate. This represents much more power than might be expected from the specific energy requirement for slow lifting in Table III and the corresponding minimum power estimate in Table IV. The theoretical estimate of minimum power for slow lifting is 0.83 MW (Table IV), which is probably less than the installed power of two large machines (the installed power of a backhoe can be as much as 0.75 MW).

Clearing by Ladder Dredges

Another way of lifting ice from the water would be by means of an elevating conveyor. The ladder dredge is a mechanism that works this way, and it is reasonably well adapted for ice removal, except for its great ladder length.

The capacity of a single bucket on a ladder dredge can be as high as 1.4 m^3, or as little as one-tenth that volume. In suitably fragmented loose material, the buckets might fill to about 85% of capacity on the average. Maximum belt speeds are typically in the range 20 to 30 buckets per minute, with a tendency for an inverse relationship between belt speed and bucket size. An estimate for the typical digging power for ladder dredges is about 30 hp per cubic foot of bucket capacity, which translates to 790 kW per cubic meter of bucket capacity.

Assuming that a large ladder dredge has buckets of 1.4-m^3 capacity running at 20 buckets per minute with 85% filling, the output of the dredge is about 1400 m^3/hr. Thus, to achieve a production rate of 10^5 m^3/hr, we would require 71 such dredges - and these are very big dredges.

If it is assumed, somewhat optimistically, that a special short-ladder dredge would need only half as much power as a typical long-ladder dredge, the total power devoted solely to lifting ice would be of the order of 80 MW. This is about half the power that might be needed for an army of draglines, but if the normal power of ladder dredges were to be utilized (instead of the 50% assumed), the practical power estimates for draglines and ladder dredges are in reasonable agreement.

Sweeping the Channel with Tugs or Towboats

Under certain circumstances it might be possible to push broken ice out of the channel, either to open water or to a place where it could be flushed away by a current. Some kind of tug, towboat or icebreaker might be used to sweep ice out of the channel, but it is not easy at this stage to imagine a good operating procedure. The idea of pushing an ice slab for a fixed distance through open water, as discussed earlier, does not seem directly applicable, although the resistance estimates may be useful.

The required clearing rates of 10^6 m^3/day and 10^5 m^3/hr were based on a necessity for clearing a 100-m wide channel that is 50 km long in 5 working days. This means sweeping an average of 10 km/day, with the "haul distance" increasing as distance from the disposal area increases. The minimum power requirement for the idealized slab-pushing was 6.7 MW, or 9000 hp, which is roughly the shaft output of a "Wind" class icebreaker.

For a roughly equidimensional ice raft, the towing resistance per 100 m^2 of frontal area is about 0.027 MN at 1 knot, 0.11 MN at 2 knots, 0.24 MN at 3 knots, and 0.42 MN at 4 knots. With side friction from the edges of the channel, the resistance would, of course, be appreciably higher. Taking 20 lbf/shp as the thrust per unit power of an average tug or icebreaker, a shaft output of 5000 hp (3.7 MW) would provide a total thrust of 10^5 lbf (0.44 MN). Thus a 5000-shp vessel might be about the right size for pushing 100-m-square rafts of 1-m-thick broken ice at speeds of a few knots. If rafts of this size could be managed, something like 10 round trips would open up 1 km of channel length. Taking into account the time needed for maneuvering and positioning the rafts, this might represent about 1 day's work for a single vessel. Thus, one vessel might only clear 5 km in 5 ordinary work days. Since 5 km is only 10% of the postulated channel length, 10 such vessels might be needed to do the complete job in 5 days. This gives a total shaft power of 50,000 hp, or 37 MW.

Although 50,000 shp may seem a high power, it should be remembered that screw propulsion is very inefficient at low speeds. If it is assumed that thrust (or bollard pull) does not vary much with hull speed over the range of interest, the propulsive coefficient (i.e. ehp/shp) can drop as low as 0.05, or even to zero in the "bollard pull" condition. This suggests that it might be better to use a different kind of propulsion for sweeping, possibly winches and kedge anchors, which would be close to 100% efficient.

Displacing Ice Fragments Beneath the Adjacent Fast Ice

If there is sufficient water depth under the fast ice alongside the channel, then ice fragments can be pushed underneath the fast ice until the available space there becomes choked. Probably the most practical way to achieve this would be to use a displacement plow that sinks the ice and displaces it to both sides (use of a one-way plow would create problems). A simple way to make such a plow would be to take a gently ramped square bow, as on a barge, and fit it with a vee-skeg at some appropriate depth below the waterline. A more elegant device would probably look like an inverted version of a vee-type highway snowplow. One major problem is that double handling of the ice would probably be impractical, so that the plow would have to be almost as wide as the channel.

To achieve sufficient lateral displacement, the minimum speed of the plow would probably have to be at least several knots. The resistance would be made up of the inherent hydrodynamic resistance of the plow in a confined channel, plus the friction of ice across the plow surfaces, plus the buoyancy and hydrodynamic sinking resistance of the ice, plus the hydrodynamic resistance of the ice to horizontal movement.

From estimates made in an earlier part of this report we can make some rough guesses at probable power requirements. The submerging power for handling at the specified rate is 1.5 MW. For displacing the ice sideways, we can perhaps take 10% of the earlier estimate for surface movement, i.e. assuming a mean displacement distance of 10 slab lengths and ignoring the additional surface area. This gives about 0.7 MW. For overcoming the basic hydrodynamic resistance of the plow vessel at typical operating speeds, we might allow 0.3 MW. For frictional resistance of ice against the plow surfaces, we allow 0.7 MW. These items give a total of 3.2 MW, or 4300 hp. However, this is a power representing a resistance multiplied by a velocity, i.e. ehp. The required shp for a screw-propelled vessel is another matter; it could easily be an order of magnitude higher than the ehp, which would make the power required for plowing ice under very similar to the power required for sweeping the channel (≈50,000 hp).

Comminution Plus Hydraulic Disposal

One way to chop ice and pump it to a disposal site as slurry would be to mount rotary milling machines on barges and feed the output to slurry pipelines. Alternatively, the milling machines could be operated at the edge of the fast ice. The specific energy estimates made in Table III and the corresponding power estimates in Table IV are practical figures, and they can be used directly. The total power for chopping plus pumping is 120 MW, or 160,000 hp. Since this system might lend itself to continuous operation, the power level could perhaps be halved, to 60 MW or 80,000 hp. This would involve a large number of units; for clearing a 50-km channel in 5 days, there might be a need for about 50 separate units of 1600 hp each.

Another way to chop and pump would be to use cutterhead dredges. To obtain a rough estimate, assume the use of a 24-inch cutterhead dredge that has 5000 hp for the pump and an extra 25% power for the cutterhead (this is a fairly big dredge with plenty of power for its size). Total power for one dredge is thus taken as 6250 hp (4.66 MW). In the complete absence of data, we can only make an inspired guess at the possible production rate. Assuming a discharge line that is 100 ft (30 m) long, the attainable production rate might be about 1200 m^3/hr of solids. This means that one dredge could handle 6 x 10^4 m^3 in 5 working days. About 83 dredges would be needed at this rate, giving a total power of 520,000 hp, or 388 MW. Again, this could perhaps be halved by assuming more or less continuous operation.

Comminution Plus Free Ejection

In principle, the ice could be chopped up and shot in an airborne stream away from the channel. For the first stage of the process, comminution, we already have estimates for efficient practical devices, i.e. 19 MW at the required processing rate. Presumably the comminuting device could be adapted so that it added an ejection chute, something like those used on snow blowers. If this were to be done, we would expect the impeller power to be at least twice the theoretical minimum power for a ballistic trajectory as shown in Table IV; i.e. the impeller power for the total number of units would be about 17 MW. Thus the total chopping and shooting power for all of these custom units might be about 36 MW, or say 50,000 hp in round terms. In terms of individual units, this might involve over 50, and possibly as many as 100.

Actually, there might be trouble in separating ice and water for milling and ejection purposes, and with the kind of system outlined above the power demands might run considerably higher because of hydrodynamic resistance on the milling rotor and inclusion of water in the ejection stream. It might be more practical to chop the ice and eject a 40/60 ice-water slurry like a water jet. A rough estimate of power demand can be made as follows.

The required velocity for 50-m range with a ballistic trajectory is approximately 25 m/sec, or 82 ft/sec. We can perhaps imagine the stream of ice/water mixture being jetted through a 13° nozzle, or monitor, of about 1 ft (0.3 m) diameter. Taking the nozzle coefficient as unity, the nozzle pressure corresponding to the required exit velocity is 312 kN/m^2 or 45.2 lbf/in^2. The corresponding hydraulic power for a 1-ft-diameter nozzle is 570 kW or 760 hp. The flow rate for this nozzle is 1.82 m^3/sec, or 29,000 gal/min. For these rough estimates we can ignore the density difference between water and ice fragments, especially as the composition of the slurry is partly arbitrary and probably not controllable within fine limits. For a 40/60 ice-water mixture, the 1-ft nozzle would thus handle about 0.73 m^3/sec, or 2600 m^3/hr, of solids. For a total output of 10^5 m^3/hr, some 40 nozzles would be needed, with a total hydraulic power of some 22 MW or about 30,000 hp. The actual pump power would be higher.

Combining the power requirements for chopping and jetting, the total power is about 41 MW, or 55,000 hp, plus the power loss in the pumps. Rounding up the estimate by about 10%, we can settle for a round value of 60,000 hp.

Conclusion

Specific energy estimates for the various processes are useful for comparing intrinsic energy demands and identifying processes that make exorbitant energy demands, the outstanding example being melting. Specific energy estimates also provide a basis for making estimates of minimum power requirements once a rate of working has been specified. This again is useful in that it sets the scale of the problem, and provides a datum for assessing claims that might be made by inventors or research entrepreneurs. However, the most significant power estimates are probably those derived from consideration of the actual working capabilities of real equipment. These figures indicate that the potential advantages offered by some basic processes are not likely to be realized in practice. For example, it takes very little energy to lift ice from the channel, but a substantial amount of energy is required to run the machines that can do the job.

The remarkable feature of the final power estimates summarized in Table V is that they lie in a relatively narrow band. Although the theoretical minimum power requirements shown in Table IV vary by orders of magnitude, the practical estimates for various processes do not vary by much more than a factor of 2. While no great accuracy is claimed for these estimates, they do inspire a certain amount of confidence by virtue of their consistency. At the clearing rates specified for this study, practical power levels are of the order of 50,000 to 130,000 hp (37 to 100 MW). If these results are at all realistic, the indications are that a powerful system is required -- small exotic devices are not likely to be effective.

Since the clearing rates assumed here may be unrealistic for some situations, we can turn around the estimates in Table V to provide a practical value for specific energy. Almost irrespective of the basic principles that are involved, the overall specific energy for the clearing process is likely to be of the order of 1.3 to 3.6 MJ/m^3. If a prospective R&D contractor proposes to improve on this by a wide margin, he either has a breakthrough or a delusion.

ANALYSIS OF FRECHETTE POINT TO SIX-MILE POINT

During the workshop (see section on workshop discussion) held on 2 February 1978, the Coast Guard representatives requested that the specific power concept be applied to a specific location and some preliminary cost figures be applied to the concept, taking into consideration the comments of the various participants at the workshop.

Basically, the participants requested that the area between Frechette Point and Six-Mile Point be analyzed using the concept of specific power. The section in question is approximately 3.5 km (2.2 mi) long, has a single channel for downbound and upbound traffic with an approximate mean width of 152.4 m (500 ft) and an average depth of 8.23 m (27 ft). The average depth to the shore is approximately 0.6 m (2 ft) from the edge of the channel as shown in Figure 7.

TABLE V. PRACTICAL ESTIMATES FOR CLEARING 50 KM X 100 M CHANNEL IN 5 WORKING DAYS WITH EFFECTIVE ICE DEPTH OF 1 M.

System	Individual units	Total power
Draglines, dipper dredges or excavators	250 units, each with 5 m^3 bucket	Of the order of 100 MW, or 130,000 hp
Bucket ladder dredges	Over 70 units, each with 1.4 m^3 buckets	Of the order of 100 MW, or 130,000 hp
Sweeping ice rafts with tugs or icebreakers	10 vessels, each with 5000 shp	Approx. 42 MW, or 56,000 hp
Special equipment to chop ice and pump through slurry pipelines	50 units of 1600 hp each, or equivalent	120 MW, or 160,000 hp*
Cutterhead dredges using hydraulic disposal	83 dredges, each 24-inch with 6250 hp for pump and cutter	390 MW, or 520,000 hp*
Special machines for chopping ice and ejecting dry fragments through an impeller	50 to 100	37 MW, or 50,000 hp
Chopping ice and firing a jet of ice/water mixture for disposal	40 units, each with 1-ft-diam. nozzle. Combined power for miller and pump 1500 hp	45 MW, or 60,000 hp

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*This power could be halved by assuming continuous operation.

Discussion at the workshop led to the conclusion that it would not be necessary to remove all the ice from the channel and that the channel need not be 500 ft wide. The consensus was that only two-thirds of the ice need be removed over a width of 250 ft to facilitate the movement of traffic. No specific time frame was determined; however, there was little objection to 50 km in 50 hours or approximately 1 km/hr. This would lead to a figure of 3.5 hours for the 3.5 km. However, if the clearing is only done along the 3.5 km, we can be more conservative and allow a full 10-hour working day to clear this area and assume that it will have to be done on a continuous basis, i.e. continuous runs each day for the entire channel.

Thus the scenario boils down to clearing two-thirds of a channel 76 m wide (250 ft), 3.5 km (2.2 mi) long with an approximate mean depth of brash and frazil ice of 1.25 m (see Voelker, 1974 and Figure 8) in 10 hours. Assuming zero porosity for the brash and frazil ice, the volume of ice to be removed per hour would be:

$$\frac{\text{Vol. of ice}}{\text{hr}} = \frac{76 \times 3500 \times 1.25 \times 0.66}{10} = 21945\ \frac{\text{m}^3}{\text{hr}}$$

This is a clearing rate of 6 m^3/sec, and if a realistic value of specific energy is selected for the previous section as 2 MJ/m^3, the total power requirement is 12 MW, or 16,000 hp. If it is felt that some allowance ought to be made for the finite porosity of the ice, this figure could be adjusted appropriately, e.g. to 10,000 hp for 40% porosity. The following section utilizes these figures to estimate a capital cost and an annual operating cost for an unspecified device. In addition the 21945-m^3/hr figure is used to generate Table VI, which compares the various alternates offered in Table V.

Capital Cost of Clearing Equipment

Since this study is concerned primarily with power and energy, it is convenient to estimate unit capital costs on the basis of power. At this stage it is quite impossible to make precise estimates, since the nature of the equipment, the number of units, and the scale of the project have not been determined. However, we can estimate the approximate magnitude of unit cost for building or buying heavy equipment. The main uncertainty is development cost if novel devices are decided upon.

Drawing upon cost data for heavy construction equipment, stationary plants, and large tugs, we suggest an estimating index of not less than \$500/hp to cover capital cost exclusive of development cost.

At first sight, this may seen a high figure, since machines such as small aircraft cost as little as \$150/hp, but it is probably rather optimistic for the kind of heavy equipment that might be used for clearing channels. The figure of \$500/hp is equivalent to a unit cost of \$2.5/hp when the power/weight ratio of the equipment is 10 hp/ton.

Taking an estimated total power requirement of 10,000 hp, the estimated minimum capital cost would be of the order of \$5,000,000. For 15,000 hp, the corresponding figure is \$8,000,000.

Operating Costs

Operating costs are also difficult to estimate without knowing the nature of the equipment, the number of units, the duration of operation, and so forth. However, we can make some very rough estimates.

The energy cost can perhaps be based on the assumption that a large diesel power source will consume about 0.06 gallons/hr for each horsepower (i.e. about 0.4 lb/hp-hr). Taking a fuel cost of $0.5/gallon, this gives a unit energy cost of $0.03/hr for 1 hp.

The maintenance cost is difficult to even define at this stage, let alone estimate. One way to arrive at a figure would be to lump maintenance with amortization, or to assign a percentage of capital cost to maintenance. For want of a better number, we suggest taking 7% of the capital cost as the annual maintenance cost.

Labor costs for operators can perhaps be put on the same basis as fuel costs, i.e. cost per horsepower per hour. Taking into account fringe benefits and overhead, the unit labor cost might range from about $0.05/hr per horsepower for large units to about $0.1/hr per horsepower for small units. This makes no allowance for housing, bussing and local transport if those are factors. To cover this possible contingency, we propose taking the higher of the two figures just quoted, i.e. $0.1/hr per horsepower.

To summarize the estimated seasonal operating costs for equipment with a total of 10,000 hp, we assume 500 hours of full power operation (or equivalent), and 1000 hours of full-time duty for the operators. With these assumptions, the foregoing unit costs lead to seasonal costs of:

Energy (fuel @ 50¢/gal.)	$150,000
Maintenance (7% of capital cost)	350,000
Labor	1,000,000
Total annual operating cost	$1,500,000

This is for 10,000 hp. For 16,000 hp the corresponding total is $2,400,000.

If these costs and the volume rate for the Frechette Point to Six-Mile Point are utilized with the alternatives delineated in Table V, a comparison of costs for each alternative can be made. Such a comparison is given in Table VI.

It can thus be seen that a vehicle or systems of vehicles can cost anywhere from $6 to 30 million to build and from $2 to 8 million a year to operate and maintain. Thus, we are paying about $1 million a mile per year (not counting capital cost of the equipment) to keep the channel relatively clear of brash ice. If we amortize a $6-million vehicle or vehicles over 20 years the amortization costs would be in the area of $300,000 per year or approximately $150,000 per cleared channel mile.

TABLE VI. VARIOUS ALTERNATIVES ANALYZE FOR FRECHETTE POINT TO SIX MILE POINT.

Alternative	Req. hp	Cap. cost $ x 10^6	*OP cost $ x 10^6
Dragline, dipper dredge	28,528	14.2	4.27
Bucket ladder dredge	28,528	14.2	4.27
Sweeping ice rafts	10,973	5.5	1.64
Plowing frag under ice	10,972	5.5	1.64
Chopped ice slurry	17,556	8.8	2.63
Cutterhead dredge	57,057	26.5	8.55
Chopped ice ejection	10,972	5.5	1.64
Ice/water ejection	13,167	6.5	1.97

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*Based on a 500 hours of full power operations and 1000 hours of labor.

WORKSHOP DISCUSSION

On 2 February 1978 a workshop was held in the Forrestal Building in Washington, D.C. The agenda of the meeting as well as the list of attendees is contained in Appendix B.

A review of the existing technology and environmental condition was held. Mr. Niel Samuals of the Office of the Corps of Engineers gave a brief review of dredges and how they may fit into the overall picture.

As a result of the workshop it was decided to concentrate the investigation of an ice-clogged channel device to the area of the St. Marys River from Frechette Point to Six Mile Point. It was also decided that the channel should be 250 ft wide and need not be 100% cleared. It was felt that maintaining a channel two-thirds cleared would facilitate navigation.

Some participants felt that more specific information on the volume of ice removal throughout the whole system was necessary. This was viewed to be well beyond the scope of this brief study. It was agreed that the investigation should be limited to specific power requirements in the area discussed above. In addition, qualitative comments on ice disposal would be included as well as a rough estimate cost for each system.

DISPOSAL ALTERNATIVES

Although the original objectives of the investigation did not specify a discussion of the ultimate disposal of the ice, the workshop participants did touch upon this subject and requested a brief qualitative delineation of the pros and cons of the various alternatives that may be utilized in the Frechette Point-Six Mile Point area.

Basically there are five alternatives available:

- Melt the ice
- Displace the ice under the ice sheet at the channel edge
- Project the ice on top of the ice sheet at the channel edge
- Slurry the ice to a shoreside disposal area
- Remove the ice to some less critical area

Table VII is a summary of the pros and cons of the various alternatives:

TABLE VII. DISPOSAL ALTERNATIVES.

Alternative	Advantage	Disadvantage
Melting	No environ. effect	High energy use
Displacement	Use current tech.	High potential of relocation into channel
Projection	Can be placed on fast ice	May ground shore ice
	Less chance of relocating to channel	May aggravate flood problem at melt
Slurry	Removes ice from river system	New special locations shoreside
Removing by rafting		Requires special area for disposal in river system

CONCLUSIONS AND RECOMMENDATIONS

From the feasibility analysis undertaken in this investigation, it appears that it would cost in the area of the $2 million per mile annually to keep a channel relatively clear of ice. This figure is a very gross estimate at this stage but an attempt has been made to include both capital and operating and maintenance costs.

No specific device or mechanism can be recommended at this time. More detailed engineering and environmental studies would have to be made before such specific recommendations could be attempted.

However, from a review of the alternatives investigated it would appear that the most economical solutions lie in rafting the ice to a disposal area, plowing the ice under the ice sheet and ejection of the ice to the top of the ice sheet. Rafting would require an area in the river system where the ice could be left until melting. Preliminary studies indicate a highly active current zone under the near-channel ice sheet, particularly when large vessels transit the area. Disposal on the shore fast ice appears feasible, and the amount of ice dispersed would not significantly affect channel hydraulics; however, more work must be done on the effect of the added ice on property damage and ice disposition at melt time.

It is evident that channel clearing devices will not be a panacea for the winter navigation program, and that any such device will be very expensive per mile cleared. Yet, there may be a place for such a device where conventional techniques fail and the benefit/cost ratios are promising. Such an evaluation is beyond the scope of this investigation.

In view of the above, it is recommended that the effort be continued to obtain better definition of the system involved and better cost estimates of equipment required and to determine specific areas of the seaway where such a device would be the only alternative for clearing the channel, i.e. Little Rapids Cut, Johnson Point, etc. The topography and bathymetry, as well as particular ice conditions in these areas, should be studied with particular regard to ice disposal sites. The figures generated in this report could also be used in a comparison of other alternatives, such as increasing the river icebreaker fleet, installing extensive bubbler systems, etc. Eventually, physical model tests of several candidate devices could be conducted, should such devices be part of the solution.

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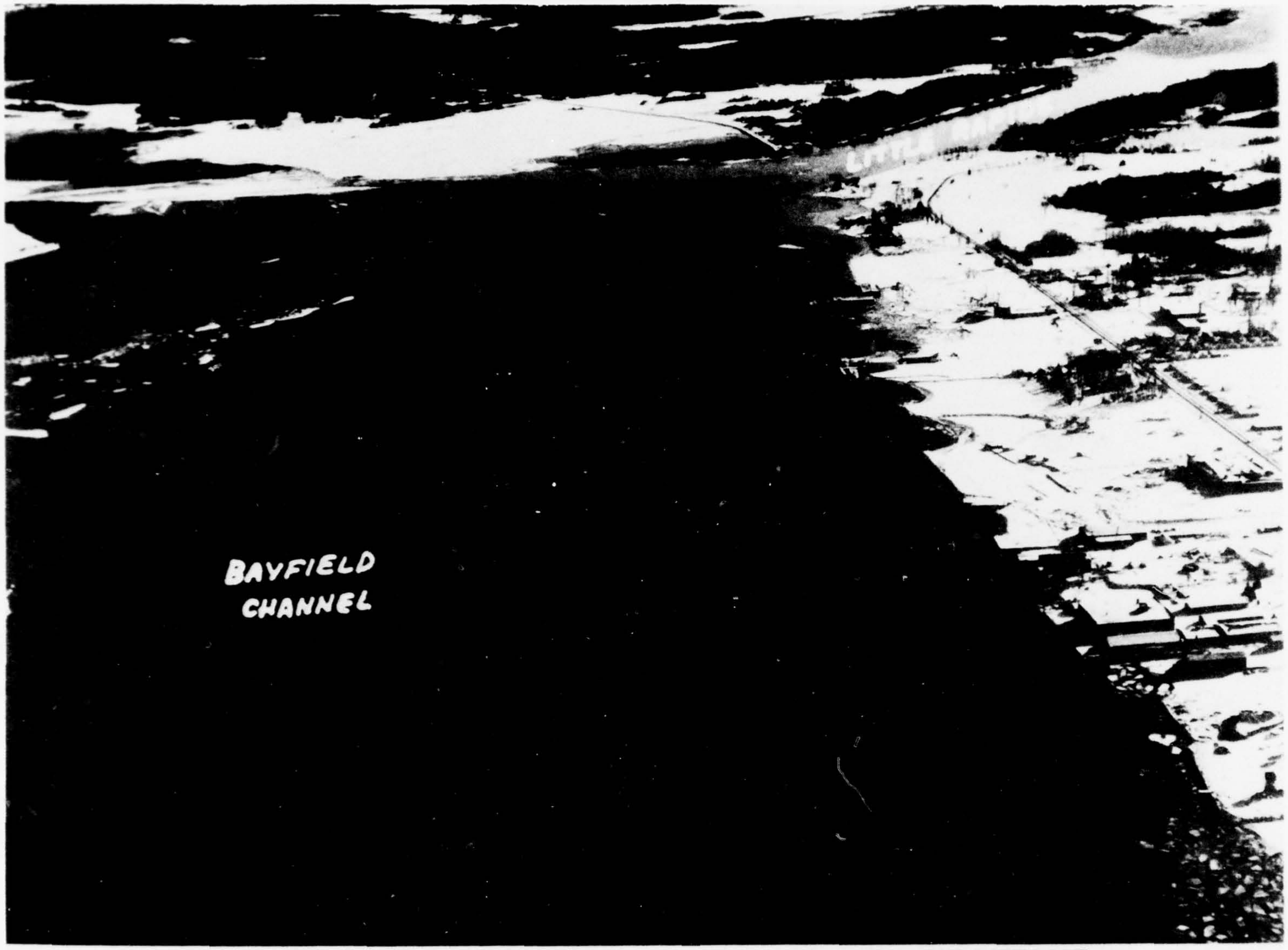
APPENDIX A

PICTORIAL REVIEW OF ST. MARYS RIVER

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING DOWNSTREAM IN UPPER ST. MARYS RIVER FROM A LOCATION ABOVE VIDAL SHOALS
CHANNEL SHOWING ICE CONDITIONS IN THE VICINITY OF THE LOCKS
26 DECEMBER 1969

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING DOWNSTREAM FROM A LOCATION AT THE HEAD OF LITTLE RAPIDS SHOWING
ICE CONDITIONS IN THAT CHANNEL
26 DECEMBER 1969



ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF PHOTOGRAPHS SHOWING ICE CONDITIONS
IEW LOOKING DOWNSTREAM FROM A POINT ABREAST OF EDISON SAULT HYDRO PLANT SHOWING ICE
CONDITIONS IN BAYFIELD AND LITTLE RAPIDS CHANNELS
26 DECEMBER 1969

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF PHOTOGRAPHS SHOWING ICE CONDITIONS
IEW LOOKING DOWNSTREAM FROM A LOCATION OVER VIDAL SHOALS CHANNEL SHOWING THE LOCKS AN
ADJACENT AREAS
18 JANUARY 1970

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ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW FROM A LOCATION OPPOSITE THE CARBIDE DOCK SHOWING ICE CONDITIONS IN BAYFIELD CHANNEL
LAKE GEORGE CHANNEL & LITTLE RAPIDS CHANNEL
18 JANUARY 1970

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING DOWNSTREAM FROM THE HEAD OF LITTLE RAPIDS CHANNEL SHOWING ICE CONDITIONS
IN THAT CHANNEL
18 JANUARY 1970

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING UPSTREAM FROM A LOCATION ABOVE THE DARK HOLE RANGES SHOWING ICE CONDITIONS IN ANGLE COURSES 7 AND 8; AND COURSE 7 OF THE MIDDLE NEEBISH CHANNEL
18 JANUARY 1970

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING UPSTREAM FROM A LOCATION SLIGHTLY DOWNSTREAM FROM EVERENS POINT SHOWING ICE CONDITIONS IN MIDDLE NEEBISH CHANNEL COURSES 8 AND 9
18 JANUARY 1970

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ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING DOWNSTREAM SHOWING ICE CONDITIONS IN COURSE 2, LITTLE RAPIDS CHANNEL AND
COURSE 3, LAKE NICOLET; ICE BOOM AND OPEN WATER IN UPPER PORTION OF LITTLE RAPIDS,CENT
5 JANUARY 1977

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
IEW LOOKING UPSTREAM COURSE 2, LITTLE RAPIDS CHANNEL, SHOWING ICE FILLED STEAMER TRACK IN
LOWER COURSE 2; OPEN WATER EXTENDING APPROXIMATELY ONE MILE BELOW ICE BOOM, UPPER CSE 2

5 JANUARY 1977

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS

VIEW LOOKING UPSTREAM SHOWING STEAMER TRACK LAKE NICOLET FROM ANGLE COURSE 5-6 TO
LITTLE RAPIDS CHANNEL - NEEBISH ISLAND, FOREGROUND; SUGAR ISLAND, RIGHT

5 JANUARY 1977

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING UPSTREAM SHOWING STEAMER TRACK AND ICE CONDITIONS IN COURSE 3, LAKE NICOLE
FOREGROUND; AND COURSE 2, LITTLE RAPIDS CHANNEL, BACKGROUND
5 JANUARY 1977

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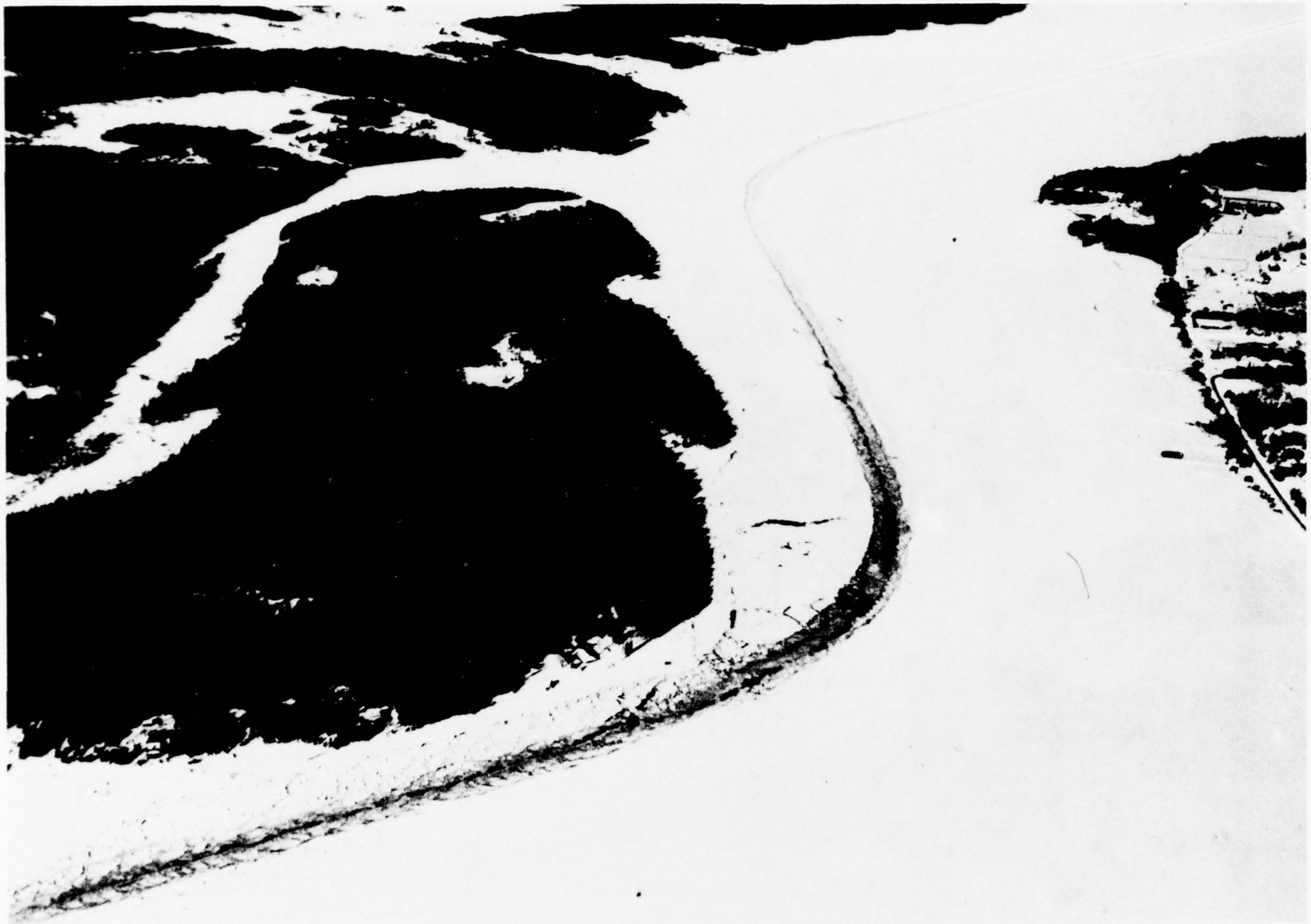
ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING UPSTREAM SHOWING ICE CONDITIONS PIPE ISLAND COURSE AND LIME ISLAND CHANNEL
PIPE ISLAND, RIGHT FOREGROUND LIME ISLAND, UPPER CENTER

5 JANUARY 1977



ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING UPSTREAM SHOWING STEAMER TRACK ANGLE COURSE 8-9, COURSE 8 AND ANGLE
COURSE 7-8, MIDDLE NEEBISH CHANNEL. JOHNSON'S POINT, CENTER FOREGROUND
5 JANUARY 1977

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ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING UPSTREAM AT DETOUR PASSAGE; DETOUR REEF LIGHT, CENTER FOREGROUND;
DRUMMOND ISLAND, ON THE RIGHT
5 JANUARY 1977

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ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING DOWNSTREAM SHOWING STEAMER TRACK FROM POINT LOUISE TO THE SOO LOCKS
POINT LOUISE, LEFT CENTER
15 JANUARY 1977

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ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING DOWNSTREAM SHOWING STEAMER TRACK THROUGH VIDAL SHOALS AND WEST APPROAC
NOTE STEAMER TRACK INTO ALGOMA STEEL, SOO ONTARIO
15 JANUARY 1977

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING DOWNSTREAM SHOWING ICE CONDITIONS IN CSF 2, LITTLE RAPIDS CHANNEL & LAKE NICOLET
OPEN WATER IN VICINITY OF SUGAR ISLAND FERRY CROSSING & ICE BOOM
15 JANUARY 1977

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING UPSTREAM IN COURSE 2, LITTLE RAPIDS CHANNEL, SHOWING ICE FILLED STEAMER TRAC
AND OPEN WATER IN VICINITY OF THE ICE BOOM AND SUGAR ISLAND FERRY CROSSING
15 JANUARY 1977

ST. MARYS RIVER, SAULT STE. MARIE. MICH.. DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING UPSTREAM SHOWING STEAMER TRACK AND ICE CONDITIONS IN COURSE 3, LAKE NICOLET
AND COURSE 2, LITTLE RAPIDS CHANNEL
15 JANUARY 1977

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING UPSTREAM FROM NINE MILE POINT SHOWING STEAMER TRACK IN COURSE 4, LAKE NIC
COURSE 3 AND COURSE 2
15 JANUARY 1977

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING DOWNSTREAM SHOWING OPEN WATER IN UPPER PORTION OF COURSE 6 ROCK CUT. WNC
PATH USED FOR ACCESS TO NEEBISH ISLAND APPEARS IN FOREGROUND
15 JANUARY 1977

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ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING UPSTREAM SHOWING A DOWNBOUND CONVOY OF STEAMERS IN ANGLE COURSE 6 - 7,
COURSE 6 AND ANGLE COURSE 5 - 6, MIDDLE NEEBISH CHANNEL
15 JANUARY 1977

ST. MARYS FALLS CANAL, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING UPSTREAM FROM JOHNSON'S POINT SHOWING STEAMER TRACK IN COURSES 8 & 7, MNC,
U. S. COAST GUARD ICE BREAKER MACKINAW WORKING AT JOHNSON'S POINT, FOREGROUND
15 JANUARY 1977

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING DOWNSTREAM SHOWING ICE CONDITIONS IN LOCK AREA, EAST APPROACH & BAYFIELD CHANNEL

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ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING DOWNSTREAM SHOWING ICE CONDITIONS FROM COURSE 2, LITTLE RAPIDS, TO ANGLE CSI
5-6, MNC -- ICE BOOM & OPEN WATER IN VICINITY OF SUGAR ISLAND FERRY CROSSING IN FOREGROUND
21 JANUARY 1977

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ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING UPSTREAM SHOWING ICE CONDITIONS IN COURSE 2, LITTLE RAPIDS CHANNEL
U S COAST GUARD CUTTER NAUGATUCK WORKING THE ICE BELOW SUGAR ISLAND FERRY CROSSING
21 JANUARY 1977

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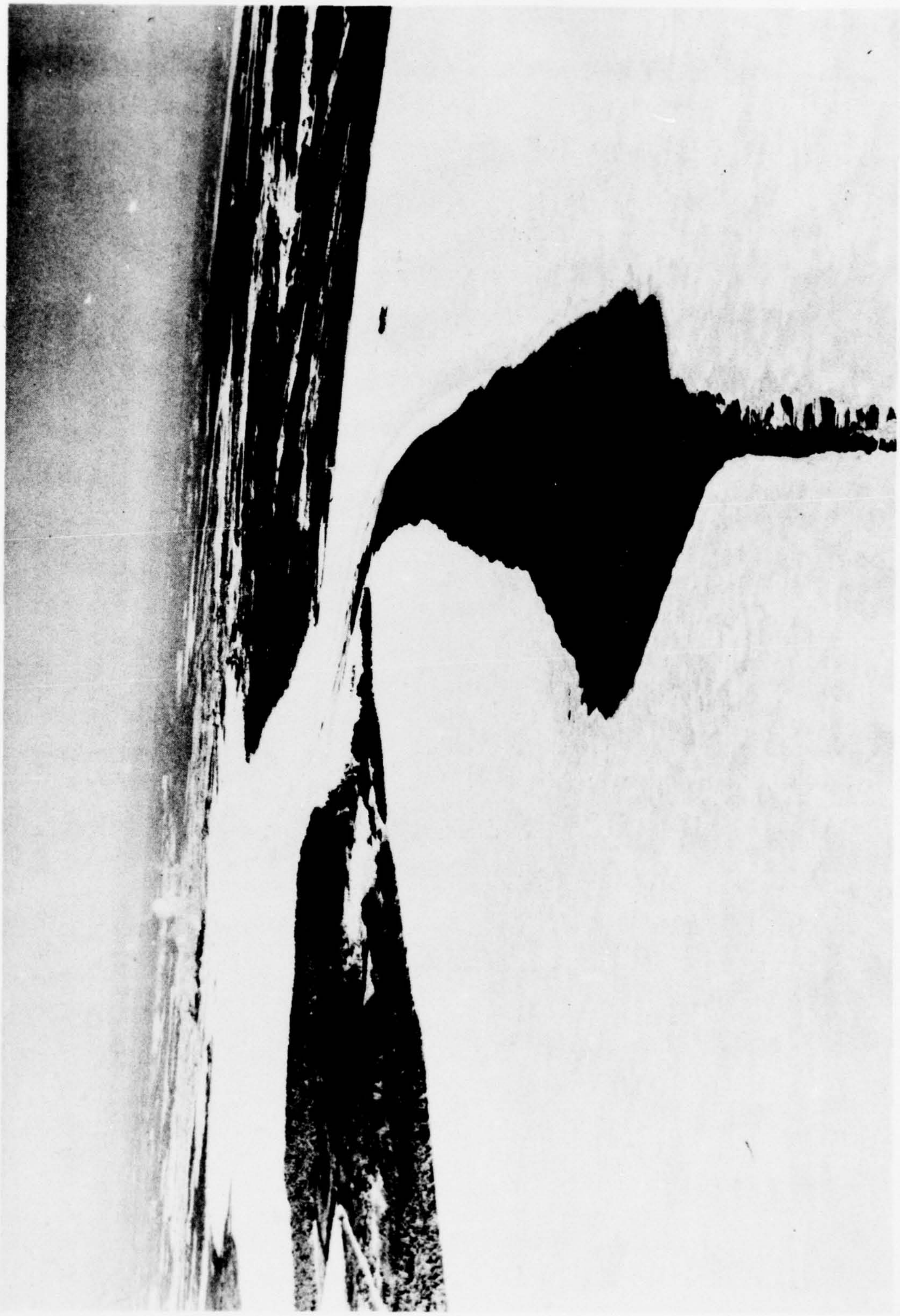

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING DOWNSTREAM SHOWING STEAMER TRACK AND ICE CONDITIONS ABOVE POINT LOUISE
THROUGH VIDAL SHOALS
15 FEBRUARY 1977

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING DOWNSTREAM SHOWING ICE CONDITIONS VIDAL SHOALS CHANNEL & WEST APPROACH T
LOCKS: BIG POINT, RIGHT FOREGROUND
15 FEBRUARY 1977

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING DOWNSTREAM SHOWING STEAMER TRACK AND ICE CONDITIONS FROM ANGLE COURSE 1
THROUGH LOWER LAKE NICOLET
15 FEBRUARY 1977

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ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
CLOSEUP VIEW LOOKING DOWNSTREAM SHOWING CONDITIONS AT ICE BOOM AREA; SUGAR ISLAND FERRY
CROSSING AND UPPER COURSE 2, LITTLE RAPIDS CHANNEL; MAINLAND AT RIGHT
1[illegible] FEBRUARY 1977

ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING UPSTREAM SHOWING ICE CONDITIONS UPPER COURSE 2, LITTLE RAPIDS CHANNEL
SUGAR ISLAND FERRY CROSSING, ICE BOOM, AND ANGLE COURSE 1 & 2 & BAYFIELD; MAINLAND AT LE
15 FEBRUARY 1977

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ST. MARYS RIVER, SAULT STE. MARIE, MICH., DETROIT DISTRICT
SERIES OF AERIAL PHOTOGRAPHS SHOWING ICE CONDITIONS
VIEW LOOKING UPSTREAM SHOWING ICE CONDITIONS IN COURSE 2, LITTLE RAPIDS CHANNEL; SUGAR ISLAND FERRY CROSSING AND ANGLE COURSE 1 & 2; FRECHETTE POINT IN LEFT FOREGROUND
15 FEBRUARY 1977

APPENDIX B

WORKSHOP AGENDA AND LIST OF ATTENDEES

AGENDA

ICE CLOGGED CHANNEL MEETING
USCG/CRREL/COE
Forrestal Building, Washington, DC

Rm 56033 0900 2 Feb 78

0900 Convene - Introductions

0915 Background - Dr. Vance
- Geographic Area — Charts
- Ice History — Slide
- Past Studies — Projectuals

0945 Current Efforts of CRREL - Mr. Frankenstein
- Booms
- Bubbler — Slides
- Coatings
- Soil Erosion/Ship Movement

1015 Coffee

1030 Theoretical Analysis - Dr. Mellor
- Specific Energy
- Applied Processes — Projectuals

1100 COE - Mr. Merden
- Types of Dredges
- Equipment in Area — Models
- Possible Applications — Slides
- Past Experience in Ice — Projectuals

1130 Coast Guard Input - Lt. Marsh
- Needs
  - Data
  - Analysis
  - Tests
- Desires
  - Current FY 78
  - Future FY 78 and beyond

1200 Lunch

1300 Workshop and interaction discussion

1500 Adjourn

2 February 1978

COAST GUARD/ACOE/CRREL

Clogged Channel Clearing Device

Participants:

LT Marsh	USCG	G-DOE
G. Frankenstein	CRREL	Hanover, NH
L. A. White, Capt.	USCG	G-OSR
LT Jack Buri	USCG	Liaison to COE
G. Vance	CRREL	Hanover, NH
Bruce McCartney	OCE(DAEN-CWE-H)	Washington, D.C.
D. H. Freeborn	USCG	Headquarters
Malcolm Mellor	CRREL	Hanover, NH
W. P. Hewel, CDR	USCG	G-000-2 - Headquarters
LT S. J. Norman	USCG	OCCGD9 Cleveland, OH
Ralph Buxton	Consultant	Nags Head, NC
Neil Samuels	OCE(DAEN-CWO-S)	Washington, D. C.
David C. N. Robb	SLSC	Washington, D. C.