A Study on the Ice Conditions and the Containment and Removal of Spilled Oil on St. Clair and Detroit Rivers

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A report for Operation Preparedness, Oil Spill
on St. Clair and Detroit Rivers

ABSTRACT

The paper studies the winter flow and ice conditions on the St. Clair and Detroit Rivers, the probability of winter oil spills, the effects of ice on winter oil spillage and the containment and recovery of the spilled oil from the rivers under winter conditions. The study shows that oil and ice may be separated and the oil contained by a floating boom (or booms) properly designed and deployed on the water surface. Equations for designing and laying the boom are derived. Large volume surface pumping seems to be the most effective way for final oil recovery.

RESUME

Les principaux points traités dan l'étude sont les suivants: le débit hivernal et l'état de la glace des rivières Sainte-Clair et Détroit, les déversements possibles de pétrole en hiver, l'incidence de la glace sur ces deversements et l'isolement et la récupération du pétrole déversé dans les rivières en hiver. L'étude démontre qu'il roit possible de séparer la glace et le pétrole et d'isoler ces derniers grâce à une ou plusieurs estacades:flottantes bien concues et correctement disposées à la surface de l'eau. Les calculs requis pour la conception et la disposition de l'estacade y sont d'ailleurs énoncés. Enfin, it semble que la meilleure facon de récupérer le pétrole soit le pompage en surface.

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I. Introduction

St. Clair River links Lake Huron and Lake St. Clair and Detroit River connects Lake St. Clair to Lake Erie. The two rivers flow through one of the most industrialized and most populated areas of U.S. and Canada. Among the numerous industrial plants on the banks of the rivers are large oil refineries. To feed the industries, the shipping on the rivers is heavy. At present, most shipping traffic is in summer months. However, heavy winter shipping may be expected if the navigation season is extended. The extension of the navigation season into winter and spring months is presently being studied by the Canadian and U.S. governments.

The presence of large oil refineries along the rivers and the heavy shipping on the rivers make oil spill a matter of high probability. Oil may reach the rivers from overland oil spills at the refineries, may spill directly on the rivers following a shipping accident, or may enter the rivers from the bottom as the result of a submarine pipeline burst. The oil spill in June, 1972 following the collision and sinking of the Sydney E. Smith off Port Huron is a good example of the probable oil spills. In case of an oil spill, emergency measures have to be taken to protect the environment. An international joint effort by the United States and Canadian Governments - Operation Preparedness, Oil Spill on St. Clair and Detroit Rivers - has been initiated to investigate the counter measures in case of an oil spill.

For the Lake Huron - St. Clair River - Lake St. Clair - Detroit River - Lake Erie system, oil may either spill over the lakes or over the rivers. When oil is spilled over the lakes, the common method of containing the spilled oil by floating booms may be used. The oil collected in front of the booms can be recovered by skimming, absorbing or other methods.

In the lakes, the current is small so the drag force on the boom is small and does not pose any operational problem. However, when oil is spilled over St. Clair and Detroit Rivers the fast flowing current will create some problems if booms are to be used. First, the drag force on the booms will be so high that the anchoring of the booms becomes difficult. Secondly, the fast flow may entrains the oil that has accumulated in front of a boom into the flow as globules; a process known as emulcification, and by which fails the containment purpose of the boom. The difficulty of containing oil in a flowing water is examplified by the fact that the 9 m^3 (2000 gallons) of oil spilled from Sydney E. Smith could not be contained and was eventually carried down to Lake St. Clair by the current. In case of a winter oil spill, the presence of ice adds more difficulties. The drift ice floes may tear the floating booms apart when ramp onto them. Many oil recovery apparatus that are effective in Summer may not even work in Winter. The containment and recovery of spilled oil on St. Clair and Detroit Rivers under Winter conditions therefore are not easy tasks.

A research and development project to study the effect of ice on oil containment and control on the St. Clair and Detroit rivers was originally proposed for Operation Preparedness. The project was later eliminated partly because the prevailing opinion at that time that the containment and recovery of spilled oil from a flowing water infested with ice appeared to be an impossible task and partly because some oil spill experiments were being planned for the Arctic waters and it was hoped that the Arctic experiments would help to solve the oil spill problems on St. Clair and Detroit Rivers also. Nevertheless, it was still decided that a theoretical investigation based on available information and knowledge should be made to evaluate the effect of ice on oil containment and control on the two rivers. This report is the outcome of such a study.

The Arctic experiments mentioned above are conducted by the U. S. Coast Guard under the Arctic Pollution Control Program. The program aims to develop a system to abate Arctic oil pollution prior to massive oil movement. Part of the program is to study the fate and behaviour of the spilled oil under various Arctic conditions and to test and evaluate the off-the-shelf oil pollution control hardware (ref. 1). It should be pointed out here that although the Arctic experiments may shed some light to the containment and control of spilled oil on the St. Clair and the Detroit rivers, the Arctic findings may not be directly applicable to the two rivers as the hydrodynamic conditions in these waters are quite different.

II. Probability of Oil Spill

As mentioned in Introduction that oil may spill over St. Clair and Detroil Rivers following either an overland oil spill, a submarine pipeline burst or a shipping accident. A major oil spill by the first two causes is not likely because an overland oil spill may be brought under control before the oil reaches the rivers and an oil spill by pipeline rupture may be quickly stopped by closing the pipeline valves. The more probable cause of an oil spill on St. Clair and Detroit Rivers, especially a more serious one, therefore is by a shipping accident.

Although both Salt water vessels and fresh water vessels use the St. Lawrence - Great Lakes navigation system, the chief users of the system are the Great Lakes Fleet and many smaller fuel barges. The number of vessels of the Great Lakes Fleet and the oil carrying capacity of the vessels are shown in Table 1 below:

Table 1. Number of Vessels and the Oil Carrying Capacity of the vessels of the Great Lakes Fleet

Type of Ship	No. of Ships	Oil Carrying Capacity	Oil Type
Tanker	60	4,500-18,000 m^3 (1-4 mil. gal)	Crude & Fuel
Oil Powered Carrier	240	180-450 m^3 (40,000-100,000 gal)	Fuel
Coal Powered Carrier	100	Nil	-

The tankers and the oil powered carriers are the potential source of spilled oil following shipping accidents. The oil barges are also potential source of spilled oil. However, they present less threat as they usually sail over short distances and carry limited quantities of oil.

The transport of oil by ship is not a very safe way. The chance of cargo oil spill, even for an open sea, has been estimated by Blumer (Ref. 2) to be one in a thousand for the volume transported. The same figure may also be expected of fuel oil spillage. For navigation on St. Clair and Detroit Rivers in winter, since the navigation channels are confined and ice hinders the manoevering of the ships, the chance of oil spill will be increased. The probability of oil spill on the rivers is further aggravated by the out-datedness of the Great Lakes Fleet vessels. The average age of the ships of the fleet is more than 40 years. The ships built before World War II were not built to strong specifications and are quite susceptible to ice damage. For example, for the Spring months of March and April in 1970 alone, 21 ice damage cases were reported. Putting all the adverse factors together, it is not unreasonable to expect that the probability of oil spill on St. Clair and Detroit Rivers in Winter would be at least twice that for an open sea, or 1 in every 500 for the volume of oil transported.

Since both fuel oil and cargo oil are carried in independent compartments in carriers and tankers, the chance that all the conpartments leak at once is remote. The quantity of the oil that would spill over St. Clair and Detroit River following a shipping accident therefore would only be a fraction of the amount shown on Table 1.

III. Flow Conditions in Winter in St. Clair and Detroit Rivers

From 74 years of outflow data from Lake Huron and Lake St. Clair (Ref. 3) the histogram of the winter discharge in St. Clair and Detroit Rivers are plotted as shown in Figure 1. It is seen from Figure 1 that for both rivers the rate of discharge decreases progressively from December to February, then it gradually increases again to April. The rate of flow in the Detroit river is slightly higher than that in the St. Clair river because of additional watershed contribution. But the difference is small, less than five percent when the mean flow is compared. Although the flow rate in the two rivers varied from 2,800 to 6,800 m^3/s (100,000 to 240,000 c.f.s.), the dominent range is from 3,700 to 5,900 m^3/s (130,000 to 200,000 c.f.s.). The probability of the discharge rate higher than 5,900 m^3/s is quite low. For the study here, the discharge rate of 5,900 m^3/s may be considered as the upper limit that one is likely to encounter at the time of an oil spill in Winter. The rate of flow shown in Figure 1 is the monthly mean discharge. The daily discharge should not differ much from the monthly mean because of the storage effect of Lake Huron and Lake St. Clair.

To describe the flow conditions in St. Clair and Detroit Rivers, the rivers are divided into sections as shown in Figures 2 and 3. To study the containment and control of oil in an ice infested water, the dimensionless flow Froude number

$$F_r = \frac{V}{\sqrt{gD}} \qquad (1)$$

where V is the flow velocity, D is the flow depth and g is the gravitational acceleration, is the best parameter to describe the flow conditions (see later part of the report). Crookshank (ref. 4) has developed a computer model to calculate the flow Froude number in the St. Clair and Detroit rivers for

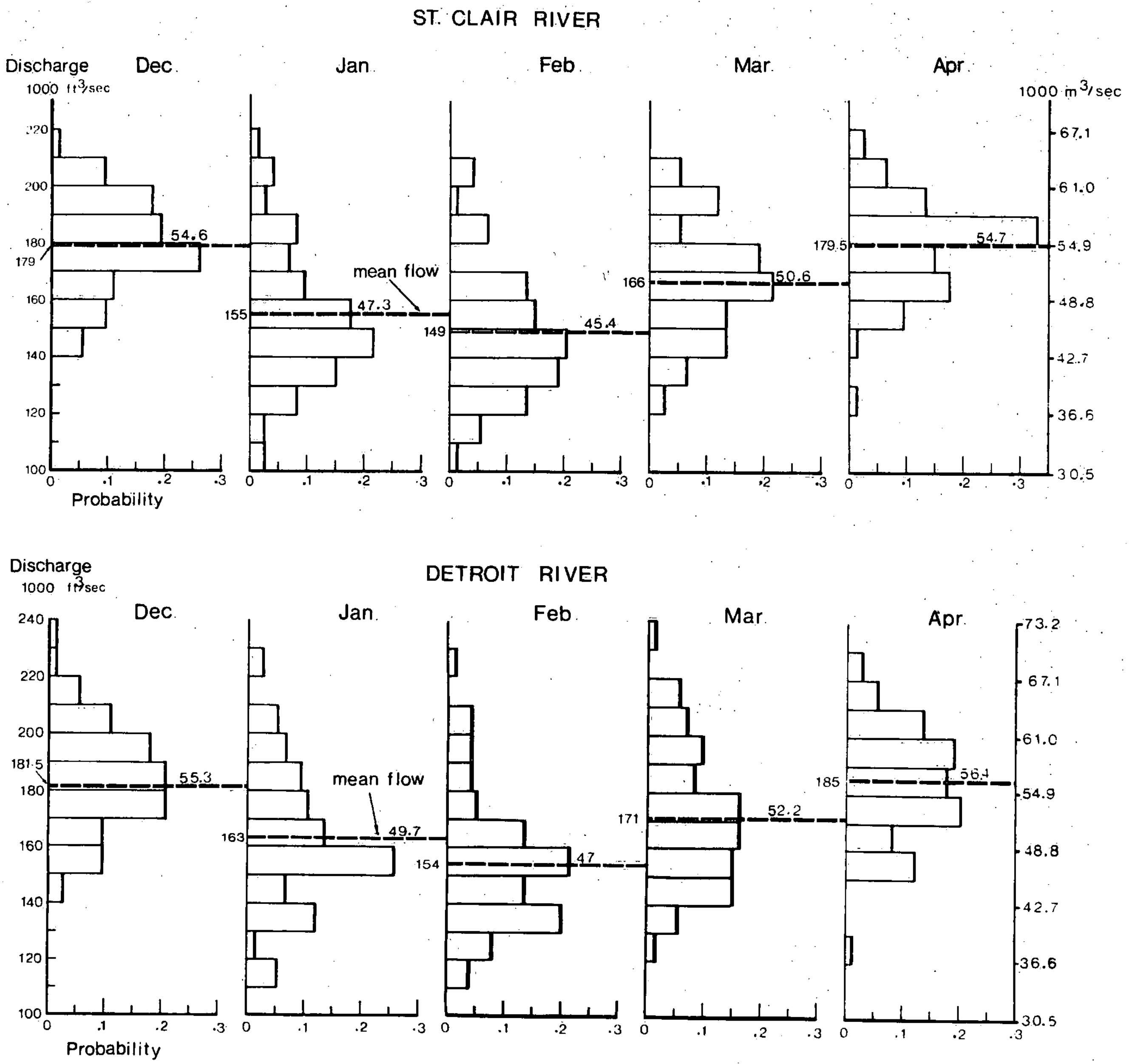

FIG. I Winter Monthly Mean Flow of St. Clair and Detroit Rivers

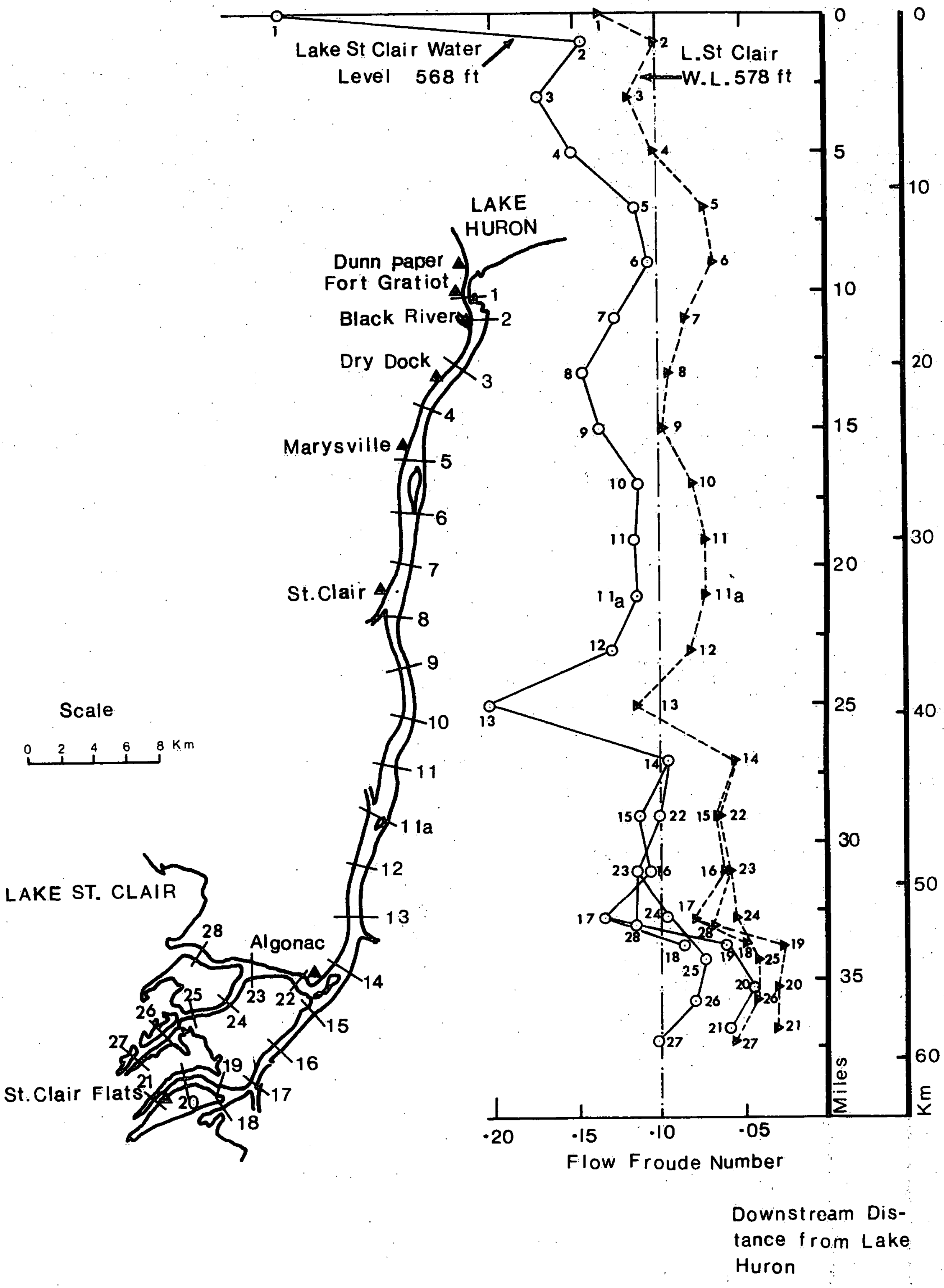

FIG. 2 FROUDE NUMBER ALONG ST CLAIR RIVER AT LIKELY WINTER PEAK FLOW OF 200,000 CFS

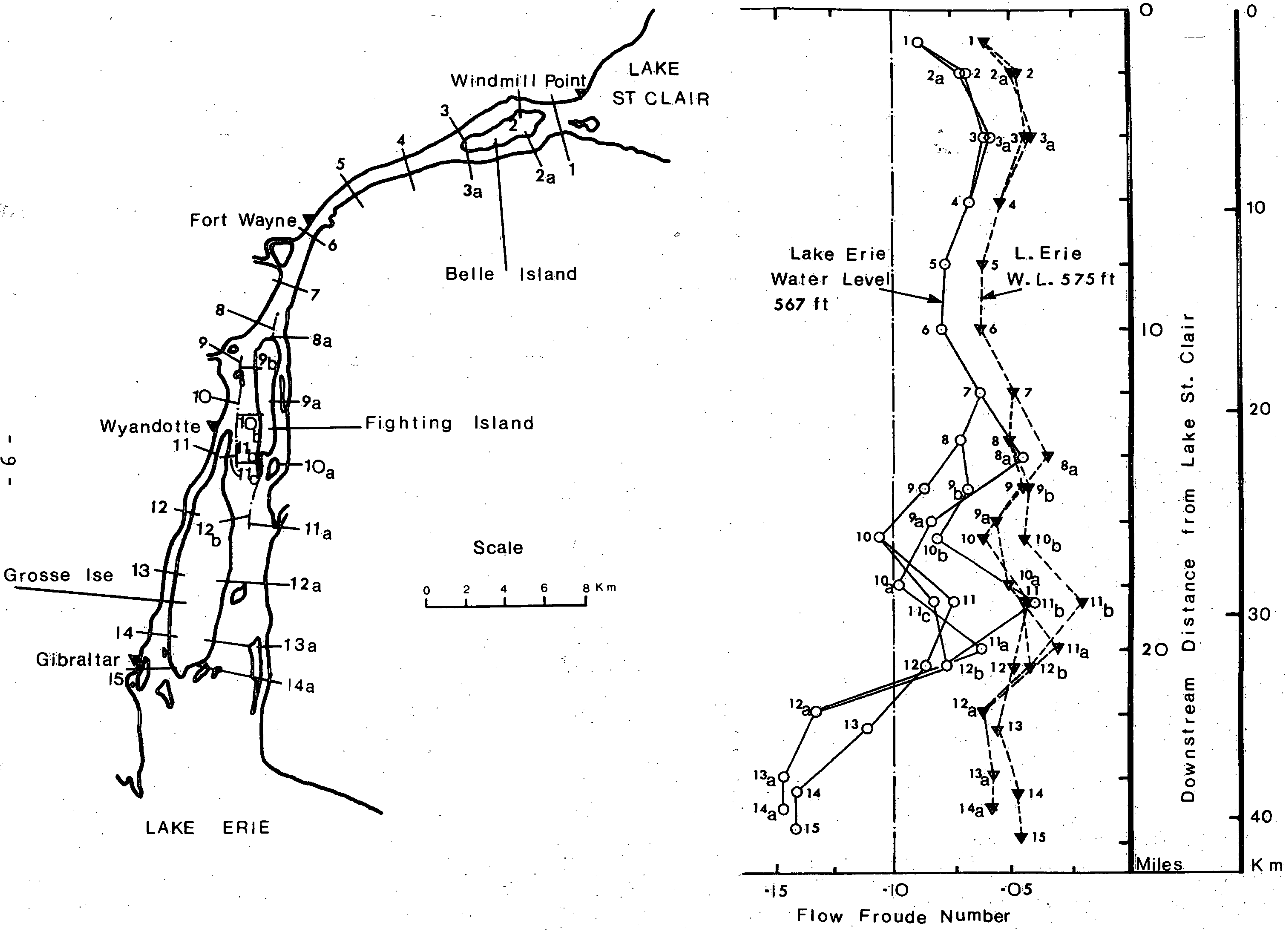

FIG. 3 FROUDE NUMBER ALONG DETROIT RIVER AT LIKELY WINTER PEAK FLOW OF 200,000 CFS

different rates of discharge and different tail water levels. Based on Crookshank's model, the flow Froude number along the St. Clair and Detroit rivers for a likely maximum winter discharge at the time of an oil spill of 5,900 m^3/s is calculated and shown on Figs. 2 and 3. It is seen from the figs. 2 and 3 that the Froude number for St. Clair River is calculated for two Lake St. Clair water levels of 173.2 m (568 ft.) and 176.3 m (578 ft.), and the Froude number for Detroit River is calculated for two Lake Erie water levels of 172.9 m (567 ft) and 175.3 m (575 ft). The head water level is assumed to adjust automatically to accommodate the flow. The lake levels shown above are measured from the International Great Lakes Datum. The flow Froude number for intermediate lake water levels may be calculated from the two curves shown by intrapolation.

It should be pointed out here that Crookshank's model is for ice free flows. The study here deals with flows at the presence of ice. The presence of ice tends to reduce the flow velocity and increase the flow depth. The overall effect is a reduction of the Froude number. Because of this, the Froude number shown on Figs. 2 and 3 tends to be over-estimated. No attempt, however, is made to quantify this ice effect and it is assumed that the ice effect will be tolerable except in the case of ice jamming.

Much will be said about the effect of Froude number on oil and ice containment. At this point, it is sufficient to know that the lower the Froude number, the easier will oil and ice be contained by a floating boom.

IV. Ice Conditions and Statistics for St. Clair and Detroit Rivers

A. Background Knowledge

Before studying the ice conditions and the ice statistics for St. Clair and Detroit Rivers, some background knowledge on ice formation will be briefly presented for easy comprehension of the later discussions.

Ice is formed when water is cooled to the freezing point. There are two kinds of ice formed in water, the static ice and the dynamic ice. Static ice is formed in the quiet parts of water where turbulence is low. The static ice first appears as interwoven ice needles on the water surface. A thin ice sheet is formed when the water between the ice needles freezes. The ice sheet thickens as a result of heat loss through it. For the shore and bay regions of St. Clair and Detroit Rivers, static ice may be expected. Static ice is also formed in Lake Huron and Lake St. Clair.

Dynamic ice is formed in turbulent waters. The turbulence may be caused by flow, by wave action or by other mechanical agitations. The water is first supercooled without crystalization. Then fine ice crystals suddenly form everywhere in the supercooled water. Immediately after their formation, the frazil crystals, as these fine ice crystals are called, are uniformly suspended in the water. However, the frazil crystals soon begin to agglomerate and float to the top as frazil slushes. The sluggish frazil slushes greatly modify the surface flow characteristics. The flow turbulence is greatly suppressed. The physical effect of the dynamic ice in a frazil slush is much more prominent than its actual proportion in the slush. For a slush pack seemingly full of ice, the proportion of ice is seldom more than 1 percent as may be proven by draining the water away. Frazil slushes may freeze into pancake ice and then into ice floes, or it may freeze to the underside and the edges of existing ice sheets. When snow falls into water, it also forms ice slushes similar to frazil slushes.

By physical appearance, ice may be either in the form of slush ice, ice floes, or ice covers. An ice cover may only cover the shore region of a river or may span across the river. A complete ice cover is usually grown out of border ice covers when the two border ice covers grow and join together. The ice bridge formed catches frazil slushes and ice floes from upstream and create a loose ice cover. The freeze of the loose ice cover produces a solid ice cover.

The formation of frazil ice in a turbulent water has been studied by Williams (ref. 5) among others. He proposed the following impirical equation for calculating the heat loss over an open water:

$$Q = 4.7\ (T_w - T_a) \qquad \text{cal/m}^2\text{s} \qquad (2)$$

where Tw and Ta are the temperature (in Celsius) of the water and the air respectively. Based on the above heat flux and assuming a 0°C water temperature for the water in a river flowing at a velocity of V m/s over a distance of L metres, the amount of ice produced at the surface can be shown to be

$$I = 5.9 \times 10^{-5} |Ta| \frac{L}{V} \qquad \text{Kg/m}^2 \qquad (3)$$

If the frazil ice is assumed to concentrate at the surface layer of t metres thick, the surface concentration of frazil ice will be

$$C_i = 5.9 \times 10^{-6} \frac{|Ta|\,L}{Vt} \qquad \% \qquad (4)$$

The above equation may be used to calculate the surface frazil ice concentration in the St. Clair and Detroit rivers.

B. Ice Season on St. Clair and Detroit Rivers

The ice season on a river may be defined as the period between the day of first ice appearances and the day of last ice appearance on the river. For St. Clair and Detroit River, the first and last days of ice appearance have been recorded by the U.S. Coast Guard since 1956. The observations were taken from the following stations:

St. Clair River

1. Dunn Paper
2. Fort Gratiot
3. Black River
4. Dry Dock
5. Marysville
6. St. Clair
7. Algonac
8. St. Clair Flats
9. Harsens Island

Detroit River

1. Windmill Point
2. Fort Wayne
3. Wyandotte
4. Gibraltar

The stations are listed in the stream-wise order and are shown on Figs. 2 and 3 except for the Harsens Island Station, which could not be identified from the available data and documentation although it is known that it is somewhere on the Harsens Island as the name itself implies.

From the observation record*, curves showing the statistical distribution of the first day and the last day of ice at the observation stations are plotted as shown on Fig. 4. For most of the observation stations, 18 years observation were recorded, but for some of the stations, the length of record is less than 18 years. In plotting Fig. 4, a month is divided into three periods for calculating the probability of occurence in each period. The data from St. Clair Flats and Harsens Island stations

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* Raw data supplied by Commander W. E. Mason, U.S.C.G., retired, and his successor, Commander C. R. Corbett, U.S.C.G.

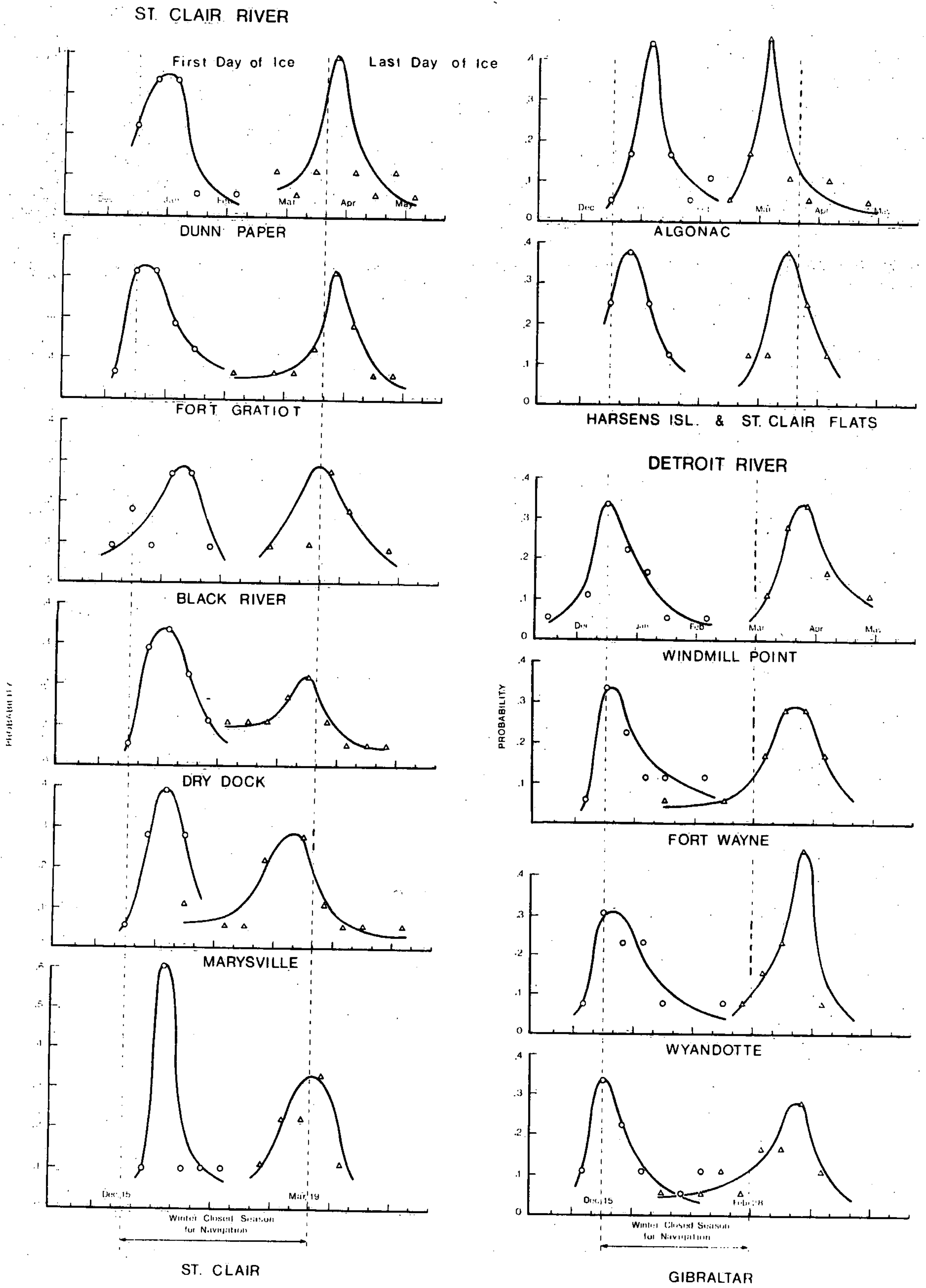

FIG. 4 PROBABILITY OF FIRST AND LAST DAYS OF ICE OCCURRENCE

are used together to plot one set of curves only. This is because the length of record for both stations is not long enough to clearly define one set of curves for each station. Since the two stations are close to each other at the downstream deltas of the river, it is thought justified to plot the data from these two stations together. It is seen from Fig. 4 that the general trend of the statistical curves is well defined although the detailed fitting of the curves is somewhat subjective because of the small statistical population of only 18 years. The study of Fig. 4 gives the ice season on St. Clair River and Detroit River.

(i) Ice Season on St. Clair River

It is seen from Fig. 4 that the time of first ice appearance on St. Clair River may spread from early December to late January or early February. The most probable time of first ice appearance is in late December and early January. Fig. 4 shows that ice will appear in the upstream and downstream sections of the river earlier than in the midstream sections. For the upstream Dunn Paper and Fort Gratiot stations, the time of most probable first ice appearance is in the beginning of January and the middle of December respectively. For the downstream St. Clair Flats and Harsens Island stations, the corresponding time is around 25th of December. However, for the midstream sections, the time of most probable first ice appearance is in the first third of January. The ice drifted from Lake Huron into the river may be responsible for the early ice appearance in the upstream section while the accumulation of the ice produced in the river itself at the downstream end may explain the early ice appearance in the downstream section. For St. Clair River, the average flow velocity is about 1 m/s. The distance from St. Clair flats and Harsens Island to Lake Huron is about 60 km. For an air temperature of $-3.6^{o}c$, the minimum monthly temperature for the region (ref. 6), the quantity of ice produced at the water surface at St. Clair Flats and Harsens Island may be calculated from equation (3) to be 4.25 kg/m^2, which is a rather significant quantity. Since at St. Clair Flats and Harsens Island, the flow is slow as may be seen from the small Froude number on Fig. 2 (as the depth of the channel does not decrease significantly), the frazil ice produced in the river will float up to the surface, agglomerate and adhere to existing ice sheets or shore.

The day of last ice spreads from early February to early May. The most probable time, however, is in March. From Fig. 4 one sees that ice will disappear from the river at a later time in the upstream sections than in the midstream sections. For the upstream Dunn Paper and For Gratiot Stations, the most probable day of last ice presence is in late March while for the midstream stations, the most probable day of last ice is in early or mid March. Between the midstream sections and the downstream sections at St. Clair Flats and Harsens Island, a comparison of the distribution curves, However, shows no noticeable difference that is beyond the scatter of the data.

(ii) Ice Season on Detroit River

For Detroit River, one sees from Fig. 4 that the first day of ice may spread from the middle of November to the middle of February. The most probable time of first ice appearance, however, is in the middle of December. For the last day of ice, it can be as early as the middle of January and can be as late as the end of May. The most probable time of last ice appearance, however, is in late March. Fig. 4 shows that with the scatter of the data, there is no systematic difference in the most probable time of first and last ice appearance between the four observation stations. In fact, the distribution curves of the four stations even show more or less the same width of spread. The short length of the Detroit river and the less varied channel conditions from section to section probably are accounted for the above fact.

(iii) Navigation Closed Season and Ice Season on St.Clair and Detroit Rivers

As the chance of oil spill is directly related to shipping, the relative timing of the navigation closed season with respect to the ice season on the St. Clair and Detroit rivers should be discussed.

For St. Clair River, the navigation season is normally closed from Dec. 15 to March 19 (ref. 7). However, shipping on the river as late as the first third of January is not uncommon, especially when outward bound ships are stopped by ice. (ref. 6). For Detroit River, the normal navigation closed season is from Dec. 12 to February 28 (ref. 7), about three weeks shorter than the St. Clair river closed season. If the shipping volume on the Montreal - Lake Ontario section of the St. Lawrence Seaway is indicative of the shipping volume on the St. Clair and Detroit rivers, the shipping volume on these two rivers in December can reach as much as one third and in April as much as two thirds of the peak summer monthly shipping volume (ref.7).

The navigation closed season for the two rivers is also shown on Fig. 4. It is seen from comparing the navigation closed season with the ice season that for St. Clair River, although the shipping season would have come to an end before the first ice is likely to appear, the new season will begin when the presence of ice is still very probable. For the Detroit river,

Fig. 4 shows that the navigation season is still not finished when the probability of first ice appearance is quite high and the new navigation season would have started when the river is still full of ice. In fact, the distribution curves for the last day of ice on Detroit River are nearly all outside the line indicating the beginning of a new navigation season. It is worth noting that although Detroit River has a longer ice season than the St. Clair river as the comparison of the distribution curves shows, its navigation season is longer than the St. Clair River's by three weeks. The above means that the probability of a ship sailing on an ice infested water is higher for Detroit River than for St. Clair River or that an oil spill at the presence of ice is more likely on Detroit River than on St. Clair River.

C. Ice Forms on the First Day and the Last Day of Ice on St. Clair and Detroit Rivers

The ice forms on the first day and the last day of ice appearance on St. Clair and Detroit Rivers were also recorded by the U.S. Coast Guard. The three different ice forms recorded are defined as; (1) Drift ice; which includes small ice floes drifting with the current or with the wind, large ice floes that may bridge the rivers and form ice gorges and solid ice covers that are broken by wind and jammed together, (2) Frazil slush; which includes the dynamic ice formed in the lakes and in the rivers and the snow fallen into the water, and (3) Solid ice cover; which includes both strong and deteriorating ice covers. From the record, the probability of the difference ice forms on the first and last days of ice is calculated for the two rivers and tabulated in Table 2 below:

Table 2. Probability of Ice Forms - percent

St. Clair River

Station	First Day of Ice Drift Ice	 Frazil Slush	 Solid Ice Cover	Last Day of Ice Drift Ice	 Frazil Slush	 Solid Ice Cover
Dunn Paper	67	22	11	88	6	6
Fort Gratiot	47	41	12	60	13	27
Black River	50	0	50	91	0	9
Dry Dock	28	11	61	42	16	42
Marysville	55	6	39	83	6	11
St. Clair	80	0	20	78	11	11
Algonac	83	6	11	71	29	0
Harsens Island St. Clair Flat	63	25	12	72	0	28

Detroit River

Station	First Day of Ice Drift Ice	 Frazil Slush	 Solid Ice Cover	Last Day of Ice Drift Ice	 Frazil Slush	 Solid Ice Cover
Windmill Point	88	0	12	94	0	6
Fort Wayne	83	6	11	99	0	1
Wyandotte	62	23	15	77	23	0
Gibraltar	94	6	0	99	1	0

It is seen from the above table that all the three forms of ice are probable for both the rivers on the days of first and last ice. The most likely ice form, however, is drift ice. There is a large variation in the probability of the different ice forms from one section to the other, reflecting the different hydrodynamic conditions at different sections. For St. Clair River, the channel is longer and shows more variation than Detroit

River. This leads to a greater variation in the ice forms probability for St. Clair River than for Detroit River. For St. Clair River, the probability of frazil slush presence can be quite high, 41 percent of the time at Fort Gratiot. As a whole, the probability of drift ice is higher for the last day of ice than for the first day of ice. This is important for oil spill containment as it is pointed out in the last section that an oil spill at the presence of ice is more likely to occur at the beginning of the navigation season than at the end of the season. Overall speaking, the probability of drift ice on Detroit River is higher than on St. Clair River.

Table 2 shows that for the main channel of St. Clair River, the presence of frazil slush at all sections is probable except at Black River, where a sudden channel enlargement upstream from the station (see fig. 2) reduces the flow velocity and enables the frazil ice to float to the surface to be detained by adhering to the existing ice cover or to shore. For Detroit River, the presence of frazil slush at the upstream windmill point and Fort Wayne Stations and the downstream Gibraltar Station is not very probable. However, the probability of frazil slush presence at the midstream Wyandotte Station is quite high.

D. Ice Conditions on St. Clair and Detroit Rivers for the Winter Months

(i) Ice data for the Winter Months of 1969-1970

The probability of ice forms on the first and last days of ice presence has little to do with the ice conditions at the time of a probable oil spill except what form of ice that one may expect if oil is spilled around the days of first and last ice appearance. To evaluate the ice conditions for all the winter months, a long record of the number of days of ice presence and the forms of ice on the two rivers is required. Such a record, unfortunately, has not been made. In the winter of 1969-70, a one-year record of the number of days of ice presence and the forms of ice was taken by the U.S. Coast Guard. Based on this record, a graph showing the days of ice appearance and ice forms on the St. Clair and Detroit rivers is plotted as shown in Fig. 5. The observation noted that more than one form of ice might be present on the rivers on the same day, although seldom this was the case.

It should be borne in mind that Fig. 5 is from samples of only one year and is far from being typical. The ice conditions on the two rivers change substantially from year to year. For instance, Fig. 5 shows that the ice season for Detroit River finished in March but the ice season for St. Clair River did not end until April. This is not in agreement with the earlier conclusion that the ice season for Detroit River is statistically speaking, longer than the ice season for St. Clair River. Fig. 5 also shows that there were more ice days on St. Clair River than on Detroit River. It is not known whether this is the general way or if it was for the winter of 1969-70 alone. Should the former be the case, the earlier conclusion that an oil spill at the presence of ice is more probable on Detroit River than on St. Clair River should be modified.

Although Fig. 5 suffers some inborne statistical inadequacy due to the small statistical population, much can still be deduced from it as shown below.

(ii) Ice Conditions on St. Clair River and Physical Explanation

For St. Clair River, it is seen from Fig. 5 that at Dunn paper Station ice appeared for a small number of days only and the ice was mostly in the form of drift ice. The number of ice days increased towards the end of the

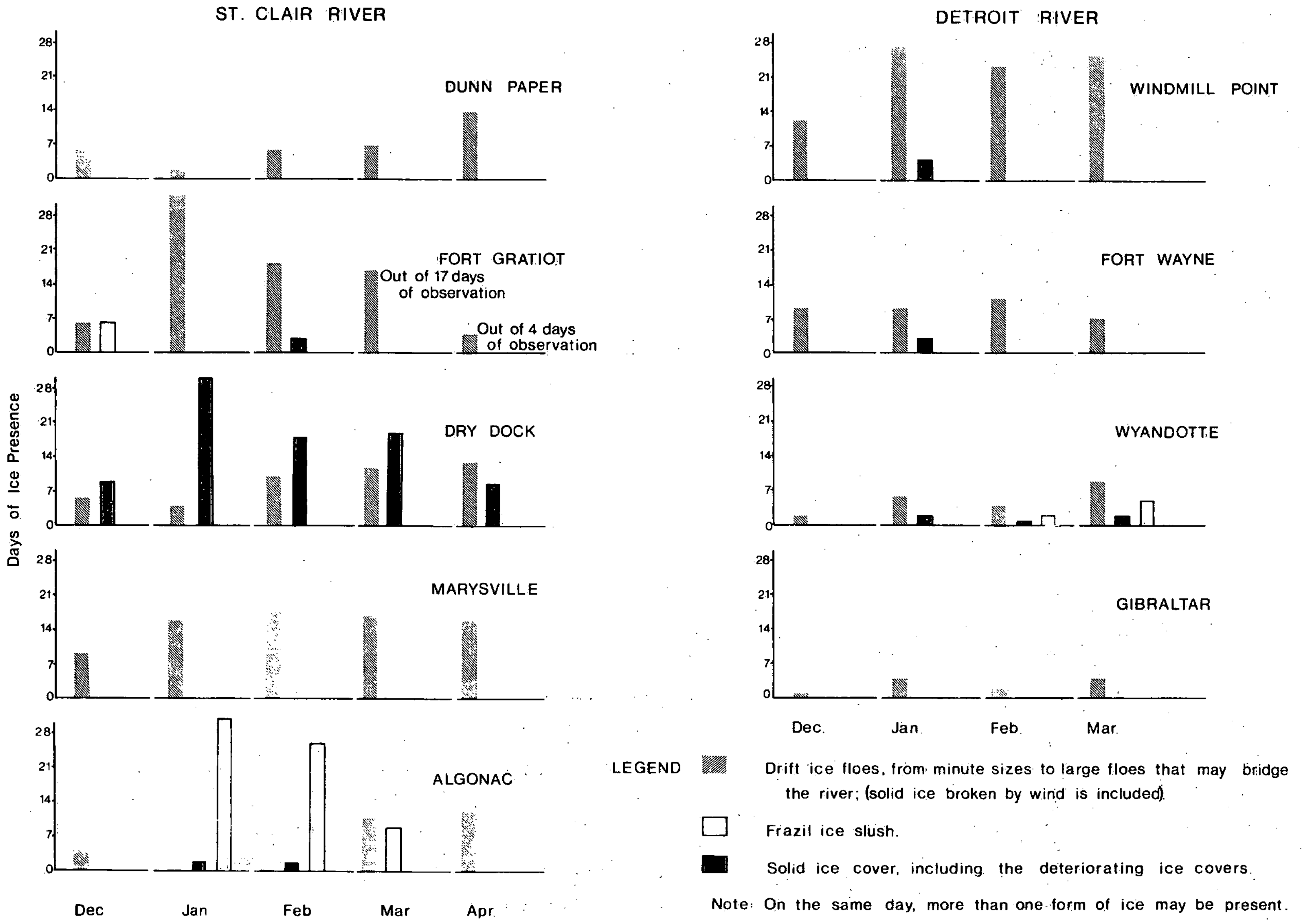

FIG. 5 DAYS AND FORMS OF ICE ON THE ST. CLAIR AND DETROIT RIVERS 1969-1970

winter, indicating increased ice discharge from Lake Huron. At Fort Gratiot, the number of days of ice appearance was much more than at Dunn Paper, especially for the mid winter months. In fact, ice was present at For Gratiot nearly every day. Although the most likely ice form was still drift ice, frazil slushes counted for half the ice days in December. At dry Dock, the number of ice days was further increased and a solid ice cover was there more than half of the time during mid winter and about one third of the time in December and in April. At Marysville, drift ice could be expected for every second day. The frequency of ice appearance was about the same throughout the winter except for December. At Algonac, the number of ice days increased again especially for the mid winter months. The most prominent ice form for the mid winter months was frazil slush.

The ice conditions on the St. Clair river may be physically traced. On Lake Huron, both static and dynamic ices are produced. The consolidation of static and dynamic ices produces solid ice covers and the agglomeration of dynamic ice produces frazil slushes. The breaking off and disintegration of the solid ice covers on the lake supply drift ice floes to the St. Clair river. The frazil slushes also drift with the current into the river. At Dunn Paper, the river is wide so the surface concentration of ice is low. This makes the detection of ice difficult and probably was the cause leading to a deceptively small number of ice days at Dunn Paper as observed in the Winter of 1969-1970. At Fort Gratiot, the narrow river surface increases the surface concentration of ice, make it easier to be detected and this probably was the reason for more ice days at Fort Gratiot than at Dunn Paper as observed by field personnel in 1969-1970. The detection of frazil slushes is particularly dependent of the surface concentration because frazil slush is suspended in water and has the same colour as water. It can hardly be detected at low concentration. Physically speaking, the frequency of ice appearance at Dunn Paper and at Fort Gratiot should be the same because the ice that passes through Fort Gratiot has to pass through Dunn Paper first.

At Fort Gratiot, because the river is narrow and the current is fast, a stable ice cover cannot be formed. However, after passing though Gratiot, the river widens and the current slows down, makes the formation of a stable ice cover possible (the criterion for forming a stable ice cover will be discussed in next section). This in fact, counts for the frequent ice cover presence at Dry Dock as examplified by Fig. 5. The stable ice cover acts as an absorber and damper of ice flow by catching ice floes and ice slushes at the upstream edge. Some ice floes, however will slip under the ice cover to the downstream sections and ice floes will break off from the downstream edge of the ice cover when the wind is strong and the wave and current conditions unfavourable. These ice floes are responsible for the ice discharge at Marysville as shown in Fig. 5. The damping effect of the ice cover can be seen from the more or less the same frequency of ice presence at Marysville for all the winter months including December. For December, only half the month should be counted because for the first half of the month the small ice discharge does not lead to solid ice covers on the enlarged sections upstream from Marysville.

Downstream from the ice cover, dynamic ice is continuously formed in the open water as a consequence of heat exchange between the water and the cold air. The frazil ice so generated has ample time to agglomerate and to float to the surface on its way from Dry Dock to Algonac. According to equation (4), if the ambient temperature is assumed to be at -3.6°c and the frazil ice is assumed to concentrate at the surface metre, the concentration of frazil ice at Algonac can be calculated to be of the order of 0.3 percent. In the calculation, the average flow velocity is approximately taken to be 1 m/s and the distance between the ice cover at Dry Dock and Algonac is approximately taken as 60 km. As mentioned earlier in the report, such a small percentage of frazil at the surface can make the river as seemingly full of ice slushes. The appearance of slush ice at Algonac therefore is expected. The more frequent frazil slush presence in the colder months of January and February is also understandable. The freezing of the surface frazil slushes can produce a solid ice cover. This, in fact, was the case in 1969-1970 as Fig. 5 shows that in the two cold months of January and February, two days of solid ice cover did exit for each month at Algonac.

(iii) Ice Conditions on Detroit River and Physical Explanations

For Detroit River, Fig. 5 shows a gradual reduction in ice days from upstream to downstream sections. This is different from St. Clair River where the number of ice days increases from upstream to downstream. The reduction in ice days means that drift ice floes are detained by the river during the process of ice cover formation. The slow flow behind the large islands provides good hydrodynamic conditions for ice cover formation. As the average velocity of flow in Detroit River is approximately 0.6 m/s, which is less than the average flow velocity of 1 m/s in St. Clair River, ice covers are more likely to form on Detroit River than on St. Clair River. This, in fact, was the case in the winter of 1969-1970 as Fig. 5 shows that ice covers did form at Windmill Point, Fort Wayne and Wyandotte. The nearly daily appearance of drift ice at Windmill Point is caused by ice floes drifting into the river from Lake St. Clair. While the drift ice floes are detained by the river as they travel downstream, frazil ice is produced in the open water sections and this results in frazil presence near Wyandotte. The small number of ice days at Gibraltar further emphasizes the detaining capacity of the river. The drift ice appeared at Gibraltar were likely the ice floes broken from the upstream ice covers.

(iv) Oil Spill Situation on St. Clair and Detroit Rivers at Different Locations

The study of the ice conditions on St. Clair and Detroit Rivers aims at estimating the situation that one has to cope with at the time of an oil spill. Following the physical tracking of the ice conditions in (i) and (ii) above, the situation on the two rivers at the time of a winter oil spill may be expected as follows:

For St. Clair River:

1. If the accident happens at the river entrance, oil may be expected to spill on a water with low surface concentration of drift ice floes. The ice floes would be mostly of lake origin.

2. If the accident happens at the bottle neck area near Fort Gratiot, oil is likely to spill over a fast flowing water with high surface concentration of drift ice floes, and occassionally, ice slushes.

3. If the accident happens in the widening section of the river after the bottle neck, oil is likely to spill on a water with a surface ice cover.

4. Downstream from the ice cover, if oil spills, it is likely to spill over an open water with a low concentration of drift ice floes. The discharge of drift ice would be higher after storms or after the collapse of the upstream ice cover. The rate of drift ice discharge would be quite

constant with the existence of an upstream ice cover.

5. The more downstream from Dry Dock, the higher the probability of frazil slush presence. An oil spill at Algonac or close to it means that oil is likely to spill on a water and slush mixture.

For Detroit River:

1. At Windmill Point, oil is likely to spill on an open water with a high surface concentration of drift ice. Oil may also spill on a water with a surface ice cover, although with a lower probability. The ice cover is likely to have propagated from Belle Island where the slow flow originates the ice cover formation.

2. Below Belle Island, Oil is likely to spill on a a water with a low surface concentration of drift ice floes broken off from the upstream ice covers. The rate of ice discharge would be rather constant except after storms or following the collapse of upstream ice covers. The frequency of ice presence would be one in every three days. The above ice conditions would prevail to and beyond Fort Wayne.

3. At Wyandotte or at the Fighting and the Grosse Islands, oil may spill on a water with all the three forms of ice. The probability of ice appearance, however, is not more than 50 percent of the time.

4. The detention of ice by the slow flowing water at Fighting Island and Grosse Island means that below these islands, oil is likely to spill over a water with a low surface drift ice concentration. The frequency of ice appearance at this downstream end is also low.

The above conclusions are deduced from physical reasoning and have to be verified or modified by field observations. Without the backing of observational facts, the conclusions can at best be treated as hypothetical. It is understood that a study of the ice conditions on the St. Clair and Detroit rivers by H. G. Acres Consulting Engineers under contract from the

U. S. Army Corp of Engineers, Detroit District, has just been completed.* The final report of the study has not yet been released. Once released, the report should be referred to for evaluating the conclusions made above.

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* J. E. Cowley, H. G. Acres Consulting Engineers, Niagara Falls, Personal Communication.

V. Containment, Control and Recovery of Spilled Oil from St. Clair and Detroit Rivers under Winter Conditions

A. Interaction between Ice and Oil

From the preceding analysis one sees that oil may spill over the St. Clair and Detroit Rivers at the presence of drift ice floes, ice covers or frazil ice slushes. For the three different ice conditions, oil and ice interact differently.

When oil spills over a water with surface drift ice, the situation is probably the easiest to handle. The oil patches and the ice floes drift downstream together but remain their own identity. If the ice floes and the oil can be separated by some means, the spilled oil may be removed.

The interaction between oil and an ice cover is more complicated. An ice cover may be made up of loose ice floes packed together or may be a single consolidated ice sheet. For St. Clair and Detroit Rivers, the ice covers will be more likely of the first kind, especially for the upstream part of the ice cover, so the discussion here will be mainly concerned with the interaction between oil and the upstream pack ice part of an ice cover. When an oil patch reaches the upstream edge of an ice cover, its advance is stopped. In this case, the ice cover acts as an oil boom. As oil accumulates in front of the ice cover, the oil slick thickens and may spill over or under the ice cover. The oil spilled over the ice cover will remain in the depressions or will mix with the snow on the surface. The oil slipped under the ice cover will collect into oil pockets. As air pockets under an ice cover, the oil pockets will hardly move downstream. As the upstream part of an ice cover is made up of packed ice floes, the oil will also find its way into the ice pack through gaps and passages in the ice cover. The continuing detention of the drift ice floes from upstream by the ice cover further helps to trap the oil in the ice pack. A small part of the spilled oil may even find its way into the ice floes themselves through the minute channels and voids in the ice. The oil caught between ice floes and trapped in the floes themselves will remain where they are. When the atmospheric temperature drops to subfreezing, heat will flow from the water through the oil slick and the ice cover to the atmosphere. As a result, ice will form under the oil slick. Although the low temperature makes the oil more viscous, it remains to be a liquid. Depending on whether the specific gravity of the oil is greater, equal to or less than that of ice, the newly formed ice may float into the oil slick and then to the underside of the surface ice cover, may mingle with the oil and form a slushy mixture, or may accumulate under the oil slick, thicken and consolidate into a solid ice layer and sandwich the oil slick between it and the surface ice cover. For the first case, a slow clean up of the spilled oil probably will not cause much additional problem because the oil pockets will remain where they are. In fact, a stronger ice cover after a cold spell would also help to support the pumping gears or other apparatus to pump the oil through the ice cover. For the second and the third cases, a delay in cleaning up the oil means the oil will become a part of the ice cover and a much greater effort will be required to separate the oil from the ice. In case the ice cover breaks up, the entrapped oil will be carried a long way downstream. In the literature, the formation of ice under an oil slick has been reported a number of times. On the other hand, the floating of the newly formed ice under an oil slick into the oil slick so far had not been mentioned. Apparently, more experiments are needed to understand the behavior of the ice formed under a slick of heavy oil.

Although the above discussions concern the interaction of spilled oil with a river ice cover, the same interaction may be expected when oil drifts from a river into a lake covered with ice. It is therefore important to contain and remove spilled oil on St. Clair and Detroit Rivers before it enters Lakes St. Clair and Erie. Once in the lakes, the affected area will be multiplied because now the oil and ice are not confined to a small area.

When oil spills over a water infested with frazil ice slushes, a slurry of oil globules and frazil clusters suspended in water may be expected. With our present state of the knowledge, no one knows what will be the interaction between oil, water and ice in such a state. Intuitionally, one can be sure that the clean up of the spilled oil will be difficult. When the frazil slushes are frozen and consolidated, the oil will be trapped among the ice crystals. This again leads to a similar, but more difficult situation for clean up as when oil is trapped under an ice cover.

Following the above discussions, it becomes clear that the spilled oil should be stopped before it reaches an established ice cover. Once reaching the ice cover, the oil will be trapped in the ice and its removal will be difficult especially after cold spells. Also, frazil slushes sould be prevented from mingling with the spilled oil. The oil patch should be contained as close to the point of spill as possible so the oil will not spread over a large area and to be affected by more ice. The short travel distance also means that one does not have to deal with more frazil slush that is produced over the open water travelled by the oil. The containment of oil in a flowing water infested with drift ice and frazil slush therefore becomes the focus of oil spill control on St. Clair and Detroit Rivers.

B. The Containment of Oil and Ice by a Floating Boom

(i) The Physical Principle of Oil and Ice Containment by a Boom

Both oil and ice may be contained by a floating boom spanning across the flow at the surface. The physical basis of such a containment is simple; since both oil and ice are lighter than water they float to the surface and may be stopped at the surface by a boom.

The hydrodynamic condition of containing oil in a flowing water by a boom is shown in Fig. 6. The boom consists of a buoyant tube, a retaining skirt and a counter weight. The boom causes a constriction in the flow as shown by the contracting streamlines. The idealized velocity distribution in front of the boom is shown by the solid line while the actual velocity distribution is shown by the dashed line. A reasonable depth of the skirt is necessary for effectively containing the oil. Too short a skirt means the accumulated oil may reach the lower edge and spill underneath into the main stream. Too long a skirt, on the other hand, means excessive force on the boom. These two considerations should come to a compromise for a good oil boom design.

There are two mechanisms that will pull the retained oil into the main stream. The first is by turbulent entrainment and the second is by pressure differential.

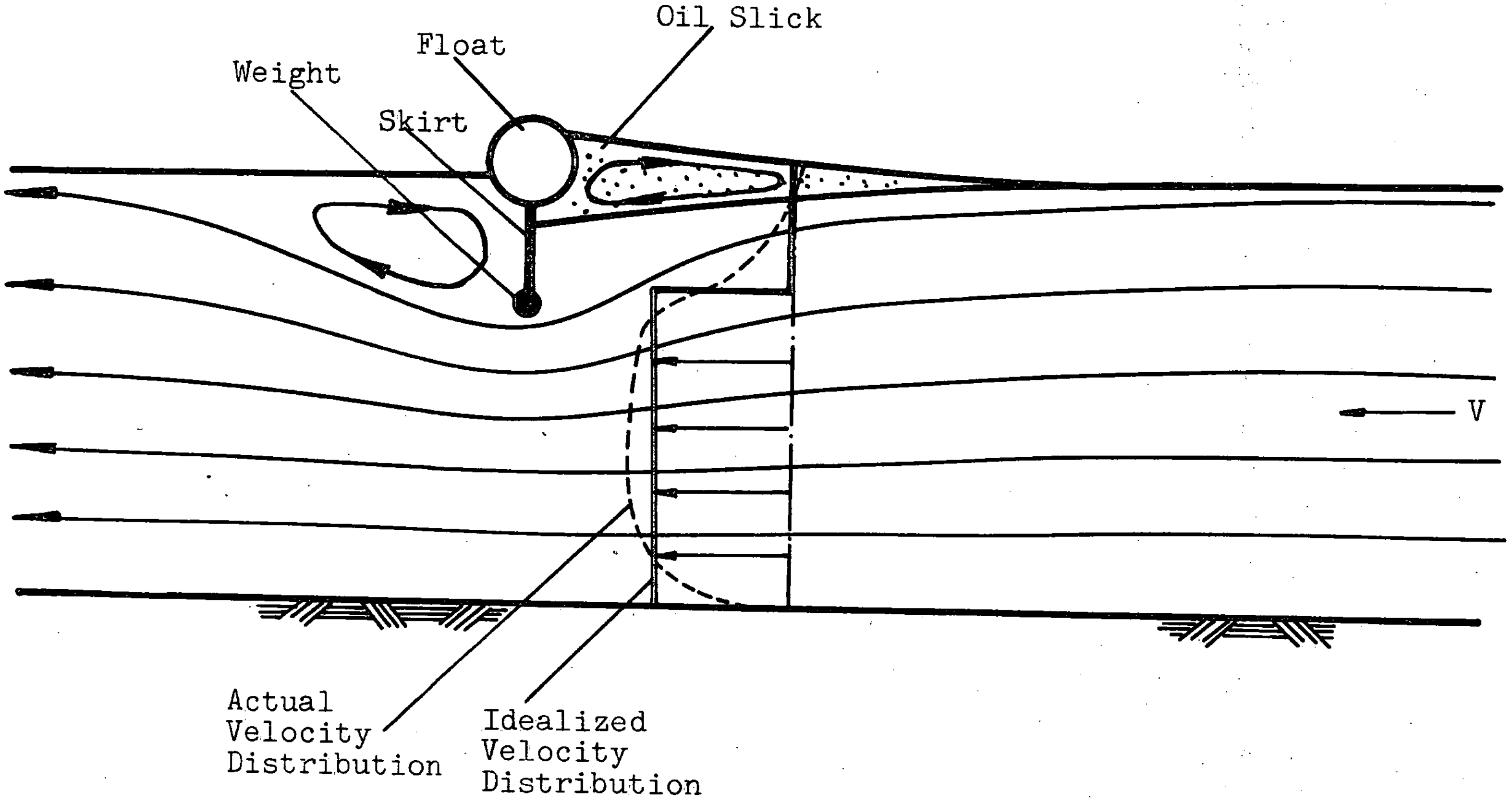

Fig. 6. Flow Condition at an Oil Boom

Turbulence in a flow is produced in the shear layer where a velocity radient exists. At the lower surface of the oil wedge, because the existence of a velocity radient as shown by the velocity distribution on Fig. 6, turbulence is produced. Turbulence means that besides the average motions, the fluid particles are now subject to additional eddy motions. The eddy motions, in fact, can be detected from the ripple motions of the under surface of an oil slick. If the eddy motions are sufficiently vigorous, the oil particles will be brought down into the mainstream and be carried downstream beyond the boom.

The negative pressure under the hoil slick at the constriction also tends to upset the stability of the oil slick. From Bernoulli's equation, one knows that for a flowing fluid, the faster it flows, the lower will be the pressure. By writing the Bernoulli equation between a point under the oil wedge and an upstream undisturbed point, the pressure at the point under the oil wedge can be calculated. If this pressure is sufficiently negative that it exceeds the buoyant force of the oil, the oil will be pulled into the main steam. If this happens, the oil boom also fails its purpose.

The hydrodynamic condition in front of an ice boom is very much the same as that of an oil boom. The entrainment of ice by turbulence, however, is less likely because the massive ice floes and slush clusters do not respond to the minute eddy motions as readily as the small oil droplets. The submergency of ice by the negative pressure under the ice therefore is the main consideration in treating the problem of ice cover stability.

By treating the problem of ice cover the oil slick stability along the lines shown above, theoretical and experimental investigations showed that oil may be contained by a boom if the flow Froude number obeys

$$Fr \leq A(1-S)^{\frac{1}{2}} \tag{5}$$

and ice may be contained by a boom if

$$Fr \leq B \tag{6}$$

where S is the specific gravity of the oil and A and B are constants. The rough value of A is 0.4 and the rough value of B is 0.1 although their exact values are still a subject of debate. In this report, however, these values of A and B will be used.

The specific gravity of ice is 0.92. For an oil with a specific gravity as that of ice, the critical value of the Froude number for containing it is calculated from equation (5) to be 0.113. This value is slightly higher than the critical Froude number of 0.1 for containing ice. This outcome is not unexpected because for an oil slick it is only subject to the downpull force while for an ice floe the areal distribution of the downpull force produces an additional moment to upset its equilibrium also.

(ii) Boom for Winter Oil Containment in a Flowing Water

Pneumatic booms of canvas or other synthetic materials are generally used for oil containment in summer months. A boom is either tied to boats or ground anchoring points by its two ends. The drag force of the flow produces a tensile load on the boom. The arch shape of a boom in a flowing water means that the highest stress is at the ends of the boom.

A pneumatic boom is not designed to stand a high stress. For this reason, a conventional oil boom can only be expected to operate satisfactorily on a calm water or a slow flowing water. For St. Clair and Detroit Rivers, even in summer months, the fast flowing water probably would have produced too high a stress on a conventional boom. In winter months, with the presence of ice, the stress on the boom will be further increased. On St. Clair and Detroit Rivers, ice floes hundreds of feet in linear dimension are not uncommon. When such floes ramp onto a conventional oil boom, the boom will likely fail. Thus, a conventional oil boom does not work on St. Clair and Detroit Rivers for winter oil containment.

Timber booms are generally used for ice containment. Although bulkier, the sturdier timber boom has the strength to stand the stress produced by the ice. It should be noted at this point that although the ice cover in front of an ice boom may extend to a great distance upstream, not all the load is taken by the boom. The boom only takes the full load when the ice cover is short. As the ice cover grows, most of the force is transmitted to the river banks. For the common design, a timber boom is made up of timber log sections. Each timer log of approximately 10 m long is chained by its two ends to a subsurface anchoring cable. The subsurface anchoring cable spans between two joint plates over a distance of 1-200 meters depending on engineering considerations. The joint plates are chained to bottom anchors and floated to the desirable position by subsurface buoys. With such a design, a timber boom will yield by pivoting about the anchoring cable when the ice force on it becomes excessive. This temporary submergency relieves the stress on the boom and permits some ice to override the boom and discharge downstream. Because of this load relief feature, the force on an ice boom can be limited to a design value.

From the above discussions, one can see easily that a conventional oil boom will not work on St. Clair and Detroit Rivers for winter oil containment. The ice force can only be handled by an ice boom of proper design. Since an ice boom works on the same principle as an oil boom and can contain oil just as good as ice, an ice boom should be used for winter oil containment on St. Clair and Detroit Rivers. The boom members can be of timber or other suitable materials as judged by other considerations.

(iii) Dynamic Analysis of a Winter Oil Boom

The force and ice condition of a section of a winter oil boom is shown in Figure 7. From the dynamics point of view, the presence of oil does not affect the force analysis so the winter oil boom may be analysed as an ice boom.

It is seen from Fig. 7 that the buoyant force on the boom is

$$F_b = \gamma bd - \gamma_w bH \qquad (7)$$

where γ and γ_w are the specific weight of water and the boom respectively, and the total drag force on the boom is given by

$$F_D = C_{D_f} d \frac{\gamma V^2}{2g} + C_{D_S} L \frac{\gamma V^2}{2g} + C_V \frac{\gamma_i q_i}{g} V \qquad (8)$$

wher C_{D_f} is the form drag coefficient of the boom, C_{D_S} is the skin drag coefficient of the ice cover, g is the gravitational acceleration, γ_i is the specific weight of ice, q_i is the rate of discharge of ice and C_V is the coefficient of virtual mass. In the above equation, the first term on the right is the form drag by the boom, the second term is the drag on the ice cover in front of the boom and the third term is the impulsive force that the boom has to exert to arrest the drift ice. The coefficient

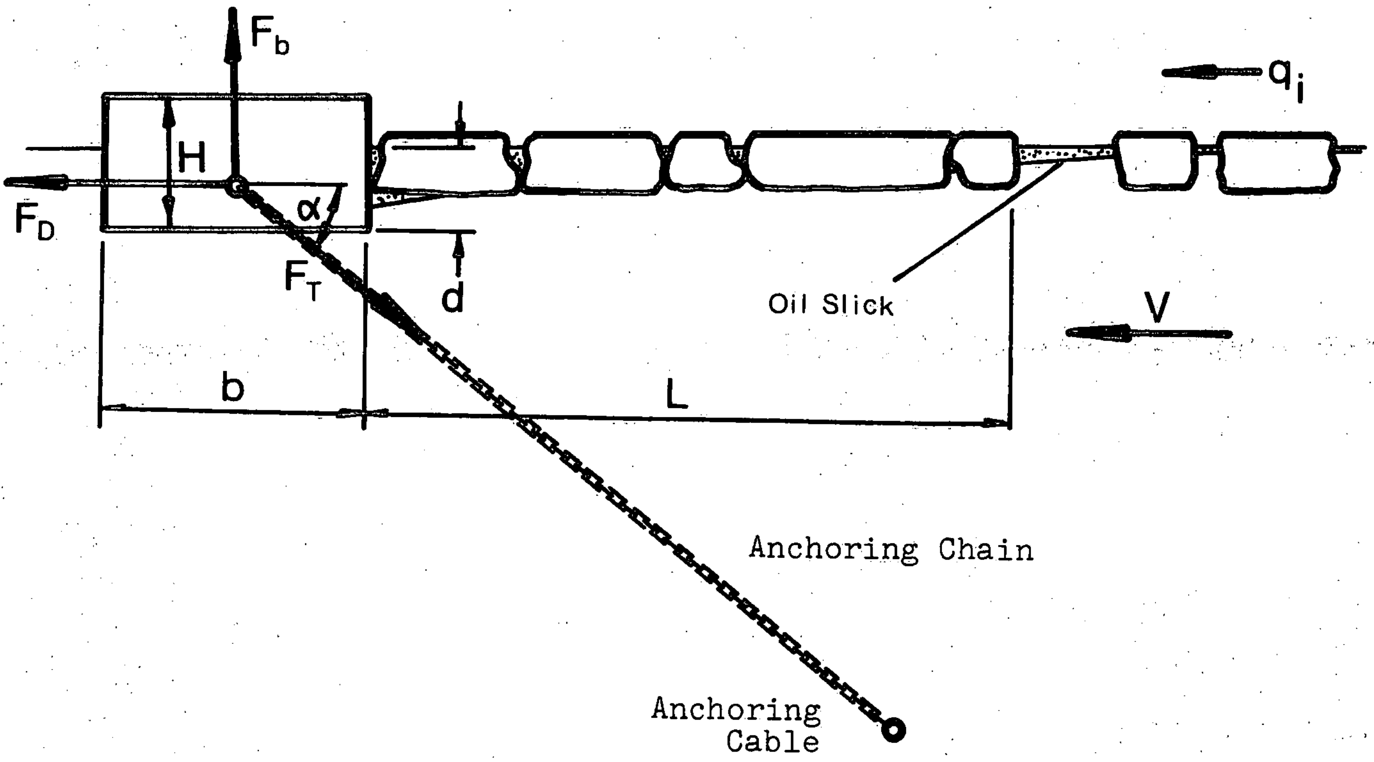

Fig. 7. Force and Ice Retaining Condition of a Winter Oil Boom

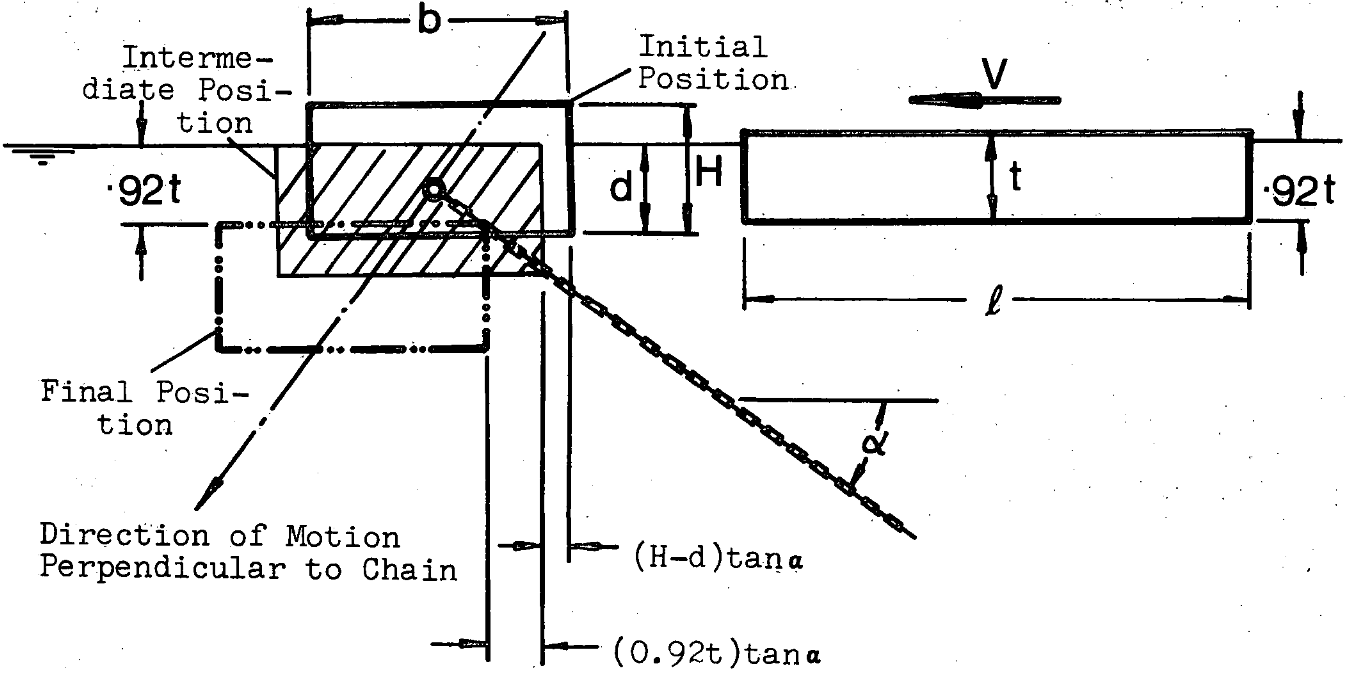

Fig. 8. Interaction between an Ice Floe and a Winter Oil Boom

of virtual mass taken into account the water whose movement is affected by the stoppage of the drift ice. From static equilibrium of the boom, one has

$$F_b = F_D \tan\alpha \tag{9}$$

The substitution of equations (7) and (8) into the above equation and the later simplifying lead to

$$q_i = \frac{g}{C_V \gamma_i V} \left[\frac{b(\gamma d - \gamma_W H)}{\tan\alpha} - (C_{Df} d + C_{DS} L) \frac{\gamma V^2}{2g} \right] \tag{10}$$

When the boom is completely submerged, d becomes H and q_i reaches the maximum value. Thus the maximum ice discharge the boom can contain is given by

$$q_{im} = \frac{g}{C_v \gamma_i V} \left[\frac{bH\ (\gamma - \gamma_w)}{\tan\alpha} - (C_{Df} H + C_{DS} L) \frac{\gamma V^2}{2g} \right] \tag{11}$$

When the rate of ice discharge is greater than q_{im}, the ice will spill over the boom.

From static equilibrium, one also has

$$F_T = \frac{1}{\cos\alpha} F_D \tag{12}$$

The substitution of equation (8) into the above equation under the fully submerged condition gives the maximum force on the anchoring cable to be

$$F_{Tm} = \frac{1}{\cos\alpha} \left[(C_{Df} H + C_{DS} L) \frac{\gamma V^2}{2g} + C_v \frac{\gamma_i q_{im}}{g} V \right] \tag{13}$$

Equations (11) and (13) are for the condition when the boom is just fully submerged. For the ice to pass, the boom has to rotate and tip back also. This means the boom will meet the flow broad-side-on and by which increases the form drag. To accommodate the increased form drag, equations (11) and (13) should be modified to

$$q_{im} = \frac{g}{C_v \gamma_i V} \left[\frac{bH\ (\gamma - \gamma_w)}{\tan\alpha} - (C_{Df} b + C_{DS} L) \frac{\gamma V^2}{2g} \right] \tag{14}$$

and

$$F_{Tm} = \frac{1}{\cos \alpha} [(C_{Df} b + C_{DS} L) \frac{\gamma V^2}{2g} + C_v \frac{\gamma_i q_{im}}{g} V] \qquad (15)$$

The above two equations are for ice discharged as discrete fragments. When a larger ice floe ramps onto the boom, the dynamic situation will be different and a new analysis is needed. Fig. 8 shows the case when a large ice floe is about to hit the boom. It is noted that an ice cover is not present in front of the boom. This is because otherwise the momentum of the ice floe will be gradually absorbed by the loose ice pack and the problem can be considered as belonging to the case already treated. Before the ice floe reaching the boom, the boom is in dynamic equilibrium. The buoyant force on it is given by equation (7) and the drag force on it is given by the first term on the right hand side equation (8). Substituting these two forces into equation (9) leads to the following equation:

$$\frac{d}{H} = \frac{\gamma_w}{\gamma} [\frac{1}{1 - \frac{C_{Df}}{b} \tan \alpha \frac{V^2}{2g}}] \qquad (16)$$

which gives the depth of immergency at the time of equilibrium. From the above equation, the excessive buoyancy that the boom processes for the purpose of containing ice is seen to be:

$$b(H-d)\ \gamma = bH [\gamma - \frac{\gamma_w}{1 - \frac{C_{Df}}{b} \tan \alpha \frac{V^2}{2g}}] \qquad (17)$$

With this excessive buoyant force, the horizontal force for arresting drift ice may be calculated from equation (9) to be

$$F_D' = \frac{bH}{\tan \alpha} [\gamma - \frac{\gamma_w}{1 - \frac{C_{Df}}{b} \tan \alpha \frac{V^2}{2g}}] \qquad (18)$$

It is seen from Fig. 8 that as the ice floe of thickness t hits the boom, the boom will go down to a depth of 0.92 t for the ice floe to glide over it. The displacement of the boom may be divided into two stages: (a) from the initial position to the position when the boom is just fully immersed in water, and (b) from this intermediate position to the final position of 0.92 t below the water surface. For the first stage of the displacement, the average arresting force of the boom can be seen to be $\frac{1}{2} F_D'$. For the second stage, the arresting force is F_D'. From Fig. 8 one sees that if the anchoring chain to the boom is long, the boom may be approximately considered as moving in a straight line perpendicular to the chain. With such motion, for a total vertical movement of $(H - d) + 0.92t$ of the boom, its horizontal movement is $(H - d + 0.92t)\tan\alpha$ and the work required to produce this horizontal movement is:

$$\tfrac{1}{2} F_D' (H - d) \tan\alpha + 0.92\, t\, F_D' \tan\alpha$$

Multiplying the above expression by the length of a section of the boom W gives the work required for submersing the boom section. Equating this work with the kinetic energy of the drifting ice floe $\frac{1}{2g} C_v (0.92\gamma)\, t\, \ell^2 V^2$, where ℓ is the linear dimension of the floe, and combining the resultant equation with equations (16) and (18) lead to:

$$\ell_m = \left\{ \frac{WbH}{0.92C_v} \left[\frac{H}{2t} \left(1 - \frac{\frac{\gamma_w}{\gamma}}{1 - C_{Df} \frac{\tan\alpha}{b} \frac{V^2}{2g}} \right) + 0.92 \right] \left(1 - \frac{\frac{\gamma_w}{\gamma}}{1 - C_{Df} \frac{\tan\alpha}{b} \frac{V^2}{2g}} \right) \frac{2g}{V^2} \right\}^{\frac{1}{2}} \qquad (19)$$

The above equation gives the floe size greater than which the boom can no longer contain.

For a rectangular obstacle in a flow, the form drag coefficient is $C_{Df} = 2$. The coefficient of virtual mass of a cylindrical body of the same density as water is 2. For an ice floe of elongated rectangular shape, the coefficient of virtual mass has yet to be obtained from future research . As a rough estimate, a value of $C_v = 2$ may be used. With the above values of C_{Df} and C_v, for a section of timber boom of $W = 10$ m, $b = 0.6$ m, $H = 0.3$ m and $\gamma_w/\gamma = 0.5$ chained to the anchoring cable at an angle of $\alpha = 45^\circ$ in a water flowing at $V = 0.5$ m/s and infested with ice floes $t = 0.4$ m thick, from equation (19) the minimum linear dimension of the ice floes that the boom section can no longer contain is calculated to be $\ell_m = 6.5$ metres. On St. Clair and Detroit Rivers most of the ice floes are smaller than this size.

Equations (14), (15) and (19) may be used for designing a winter oil and ice boom. Further discussion on these equations is beyond the scope of this report. It is seen from these equations, however, that the design of a boom for winter oil and ice containment is engineering feasible.

C. The Containment and Recovery of Spilled Oil from St. Clair and Detroit Rivers.

Following the preceding theoretical investigations, one may now proceed to study the ways to recover the spilled oil from St. Clair and Detroit Rivers which really is the ultimate goal of Operation Preparedness. The three aspects of oil spill control that will be looked into are: (1) How to contain ice and oil on St. Clair and Detroit Rivers by a floating boom, (2) How to separate oil and ice after they are contained, and (3) How to finally remove or recover the oil. These aspects will be studied in the above order.

(i) The Containment of Oil and Ice on St. Clair and Detroit Rivers by a Floating Boom

The criterion for containing oil and ice on a flowing water by a floating boom is given by equations (5) and (6). These equations state the containment of oil and ice on St. Clair and Detroit Rivers is determined by the Froude number of the river alone.

The value of the flow Froude number along the St. Clair and Detroit rivers with a probable maximum winter discharge of 5,900 m^3/S is shown on Figs. 2 and 3. If a floating boom is placed across the stream perpendicular to the flow, it is seen from Fig. 2 that for St. Clair River the containment of ice is only possible when the lake level in Lake St. Clair is high. For low Lake St. Clair levels, the containment of ice or the formation and maintenance of a stable ice cover is not possible except at the downstream sections. Since in winter months, the lake level is likely to be low because the run off is retained by the land in the form of ice and snow. This leads to a higher Froude number and a less favourable condition for ice containment. Although at the time of a winter oil spill, the rate of discharge is likely to be less than the maximum probable discharge, the Froude number for ice containment would still be border-lined. The containment of ice by a boom across St. Clair River therefore is not a promising way. Parallel discussion may be easily extended to oil containment once the specific gravity of the oil is known.

For Detroit River the containment of ice and oil by a boom perpendicular to the flow is easier as it is seen from Fig. 3 that the Froude number for Detroit River is mostly less than 0.1. But for some downstream sections under low Lake Erie level conditions, the containment of oil and ice will still be a problem.

There is no reason why a floating boom must be placed perpendicular to the flow. The stability of the ice cover or the oil slick in front of the boom is affected by the normal velocity of the flow to the boom alone. By placing the boom at a suitable angle to the flow, the normal velocity component can be limited to any value and the ice and oil can be restricted to the upstream side of the boom (see Fig. 9)

The Froude number based on the normal component of the velocity may be written as

$$F_{r_n} = \frac{V \sin \theta}{\sqrt{gD}} = F_r \sin \theta \qquad (19)$$

and be called the normal Froude number. Apparently, the stability of an oil slick or an ice cover in front of an oblique boom is largely determined by the value of the normal Froude number. The velocity component

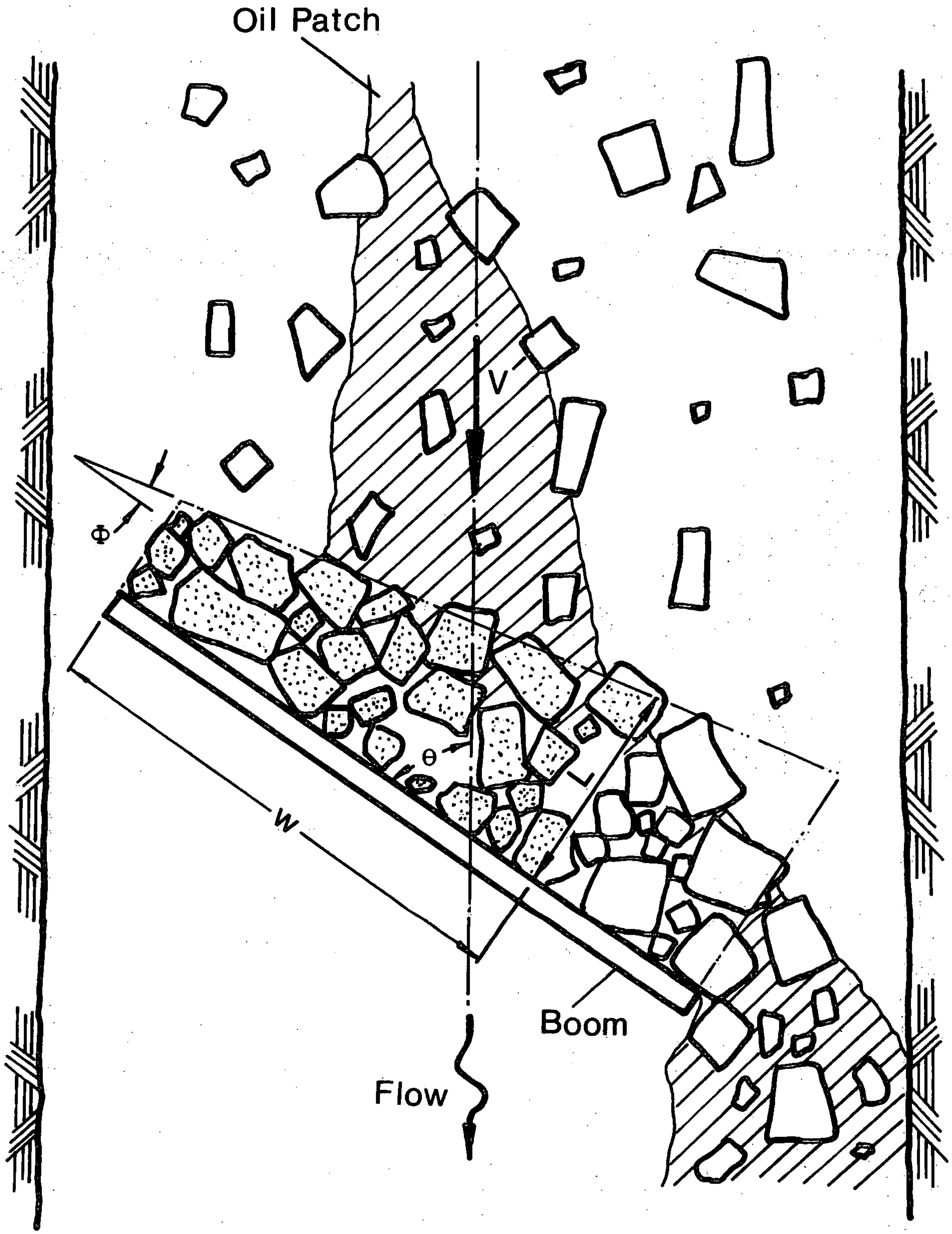

Fig. 9. Containment of Oil and Ice by an Oblique Boom

parallel to the boom will cause the oil or the ice to move along the boom, but its effect on this stability would be insignificant.

The substitution of Frn in place of Fr in equations (5) and (6) leads to:

$$\Theta \leq \sin^{-1} \left[\frac{0.4\ (1 - S)^{\frac{1}{2}}}{F_r} \right] \tag{20}$$

$$\Theta \leq \sin^{-1} [\ 0.1/Fr] \tag{21}$$

When the above two equations are satisfied, oil and ice can be contained.

From the above, it is seen that a high Froude number really is not a deterrent matter for ice and oil containment. By making a proper angle to the flow a boom can always stop ice or oil.

After being stopped by an oblique boom, ice will glide along the boom and move to a side. Before the ice spills around the end, it accumulates in front of the boom. At the upstream end, ice will accumulate the least because only the drift ice from the flow will add to its growth. At the downstream end, ice will accumulate the most because ice comes from both the flow and the upstream part of the boom. Fig. 9 shows a boom making an angle of Θ to a flow of velocity V and surface ice concentration C_i. At a point w from the leading end, the length of the accumulated ice cover is L. From conservation of mass, for the shaded area one may write

$$C_i V \sin \Theta\ w - V \cos \Theta\ L = \frac{\partial A}{\partial t} \tag{22}$$

Where A is the shaded ice area. In the above equation, the first term on the left is the influx of the ice from the flow and the second term is the outflux of the ice along the boom from the control volume and the right hand side term is the rate of increase of the area of ice cover. Since an increasing ice cover in front of a boom means an increasing load, a boom should be so placed that $\partial A/\partial t = 0$ and this leads to:

$$\Theta = \tan^{-1} \left[\frac{L}{C_i w} \right] \tag{23}$$

The above equation says that knowing the surface concentration of drift ice, the amount of accumulated ice in front of a boom can be reduced to minimum by properly adjusting the angle of the boom. The equation also shows a linear relationship between L and w, or a triangular ice accumulation in front of the boom.

Equation (23) is obtained assuming that the ice moves along the boom at a velocity equal to the tangential component of the flow velocity. In reality, because of the friction between the ice floes and the boom and the mutual hinderance of the ice floes, the ice floes will move along the boom at a slower velocity. If a coefficient η of less than unity is introduced into the second term of equation (22) to take the above into account, then equation (23) changes to

$$\Theta = \tan^{-1} \left[\frac{\eta}{C_i} \tan \phi \right] \tag{24}$$

Where ϕ is the angle between the upstream edge of the ice cover and the boom as shown in Fig. 9. Not much is known about the friction between ice floes and between ice floes and booms of different material. A good estimate of the value of η therefore can not be made before a systematic investigation is conducted. In deriving the above equation, the ice concentration C_i is also assumed uniform. If C_i varies laterally, some adjustment will be needed. A parallel analysis involving the variation of C_i can be done following more or less the same step as shown above.

It may be noted that although ice floes are used in the above discussions, the discussions are equally valid for frazil slushes.

From earlier discussions in the report, one knows that an extensive ice cover in front of a boom is not desireable. Besides increasing the drag force on the ice boom, an extensive ice cover also traps oil in it and makes the later recovery difficult. On the other hand, small ice accumulation required a long boom and more anchoring gear. A compromise therefore should be reached between many factors.

(ii) The Separation of Ice and Oil

To recover oil from a winter spill, ice and oil should be separated. The separation of oil and ice includes the separation of oil and drift ice floes and the separation of oil and frazil slushes. The separation of oil and drift ice floes will be discussed first.

In a flowing river, oil and ice can be separated by a perforated boom laid at an angle to the flow as shown in Fig. 10. The perforated boom may be made of two timber logs bolted together one on top of the other with a small gap between them, or of other designs. When an oil patch and ice floes drift down with the flow and meet the boom, the ice floes will be detained and deflected to one side while the oil will pass through the gap. If a conventional boom now is placed behind the perforated boom on the ice free water, oil may be contained and removed as if it had spilled over an ice free flowing water. To catch the oil that may have been deflected to the side with the ice floes, multiple pairs of perforated and non-perforated booms may be used together as shown on Fig. 10.

The above way of ice and oil separation is applicable for whatever value of the Froude number of the flow and for oils of all specific gravities. For light oil in a fast flowing water, however, a single non-

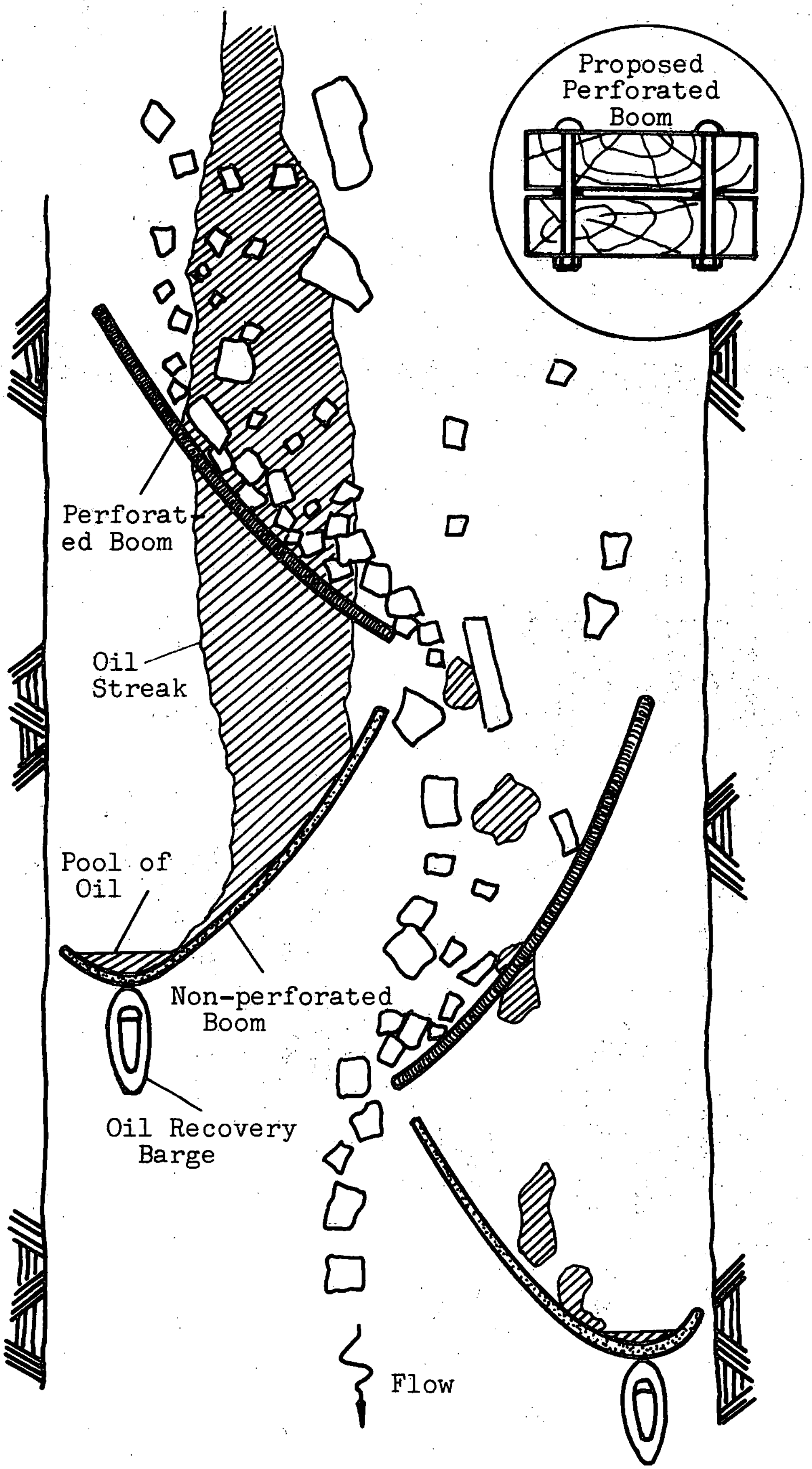

Fig. 10 Separation of Oil and Ice and Oil Containment by Pairs of Perforated and Non-perforated Booms

perforated boom appears to be capable of both separating the oil and ice and retaining the oil. It is shown by equations (5) and (6) that the critical Froude number for containing oil and ice is respectively $0.4\ (1-S)^{\frac{1}{2}}$ and 0.1. From these two Froude numbers, the specific gravity of the oil that will be critcally contained as ice is calculated to be 0.9374. If a spilled oil is lighter than this oil, from equation (20) a critical angle Θ_1 may be calculated. When a boom makes an angle less than Θ_1 with the flow, the spilled oil will be contained. From equation (21), another angle Θ_2 may be calculated. When the boom makes an angle less that Θ_2 with the flow, ice also will be contained. Now if the angle between the boom and the current is between Θ_2 and Θ_1, only oil will be contained while ice will dive under the boom and discharge downstream. By so placing a boom, both the goals of separating ice and oil and containing oil can be accomplished. The oil, once contained, may be directed to slow flow and ice free regions for final recover. A fast flow with a Froude number greater than 0.1 is necessary for the above oil and ice separation. If the Froude number is less than 0.1, there is no way for one to get rid of the ice.

The above discussions are for separating oil and ice floes. When ice is in the form of frazil slushes, the separation of oil and ice will be more difficult. With our present state of knowledge, the interaction between oil and frazil slush, as mentioned earlier, is still not well known. This makes the proposal of separation methods difficult. From common sense, it is however, apparent that ice slushes should be prevented from interact with the spilled oil whenever possible. The ice slushes formed upstream from an oil spill site therefore should be prevented from entering the site and that the detention site should be as close to the spill site as possible so the open water area for frazil ice production and the time for the oil to spread will be minimum. The first aim may be achieved by placing a boom in front of the spill site to deflect the ice away from the spill area and the second aim may be achieved by a prompt response to the oil spill event, which, really, is what Operation Preparedness is all about. If the oil spills out as a patch or that the leaking has already stopped before the containment operation can get into the act, the deflection of the upstream slush ice, of course, will be unnecessary.

Both oil and ice slushes, of course, may be stopped by a properly placed boom and be pumped out together for later out of water separation.

(iii) Final Recovery and Removal of Spilled Oil

Once contained, the spilled oil or the mixture of oil and ice slushes may be recovered or removed. The removal and recovery of oil only will be dealt with first. Some ways of recovering and removal of oil from water in a cold environment were mentioned in Reference 8. Following are some comments on the various ways of oil recovery and removal that are relevant to Operation Preparedness:

1. Skimming - The oil collected in front of a boom may be recovered by using skimmers or vacuum trucks. Skimmers have not been proved effective in open water or under ice conditions. Field experiments of one commercially available skimmer showed a disappointing collection rate of 30 percent. It is, however, believed that small skimmers used in gangs may be effective (ref. 8). Small skimmer gangs therefore may be used for St. Clair and

Detroit Rivers in case of a winter oil spill.

2. Absorbing - The spilled oil may be removed by absorbants. Laboratory experiments showed that polymetric foams have a high absorption capability. However, there is still no field evidence to this effect. Experiments in the Arctic have shown that the absorption rate of peat moss and straw is not affected by the arctic low temperature and straw is a better material because it is much easier to handle although its absorption rate is lower than that of peat moss. For St. Clair and Detroit Rivers, straw should be used for oil clean up if absorbant is decided to be used. Polymetric foams may be used if in the mean time field experiments confirm their superiority.

3. Dispersion - The use of chemical dispersants in Arctic and subarctic oil spills has been quite discouraging apart from ecological considerations (ref. 8). If oil spill at the presence of slush and solid ice, the low temperature would increase the viscosity of the oil to such a point that dispersants have little effect. Thus dispersants should not be used for St. Clair and Detroit Rivers.

4. Biodegradation - At a freezing temperature, there is no bacteria that would degrade hydrocarbons. Biodegradation apparently is not a way out for St. Clair and Detroit Rivers oil spill control.

5. Burning - The collected oil may be burned in front of the boom. Various degrees of success have been experienced in the Arctic. There are two factors which may hinder the successful

burning of the oil. The first factor is that the cold water lowers the temperature of the oil to such a point that it is lower than the flash point. The second factor is that the combustion heat heats up the oil that its viscosity lowers and this makes the oil to spread too thin to sustain the combustion. The combustion of the oil may also damage the boom itself. The main objection to burning oil is probably that we simply substitute one form of pollution for another. Based on the above, the removal of oil by burning is not recommended for St. Clair and Detroit Rivers.

6. Herding - Herding agents have not been extensively tested. However, it is believed that they would have a neglegible effect at a freezing temperature because of the high viscosity of the oil (ref. 8). The use of herding agent for the St. Clair and Detroit rivers therefore is not recommended.

7. Pumping - Although pumping is not mentioned in Reference 8, it seems to be the best and probably the cheapest method for recovering oil. The surface layer of oil and water may be pumped from the river to a barge by a submergeable pump installed to the floor of the barge. If the suction line is below the waterline, cavitation will not pose a problem. The pump casing, of course, should be insulated and heated so ice particles will not deposit on the pump wall to block the flow. A schematic diagram for a pumping barge is shown in Fig. 11.

When one comes to it, pumping really is a kind of slimming, only that now skimming is by pumping rather than by vacuum suction

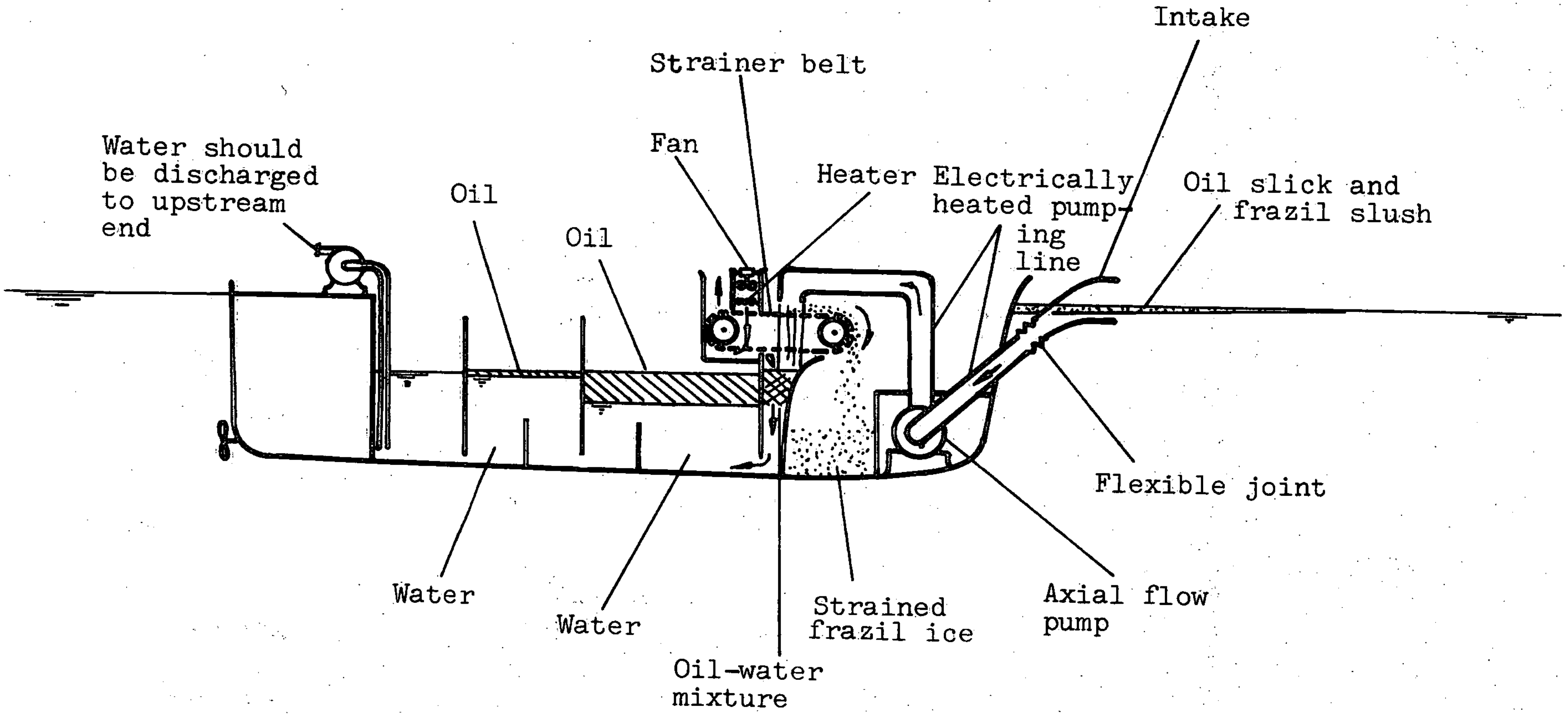

Fig. 11. Schematic Diagram of a Proposed Oil Recovery Barge

or by gravity flow and thus the rate of skimming can be greatly increased.

When the mixture of oil and slush ice is to be dealt with, pumping appears to be the only effective way. For a frazil slush infested water, the frazil laden layer and consequently the oil contaminated layer of the water is thick. This means the volume of oil, water and frazil that has to be skimmed off the water surface for oil recovery is much larger than in the slush ice free case. Only by high volume pumping can such a requirement be met. Since the skimming process now requires a high volumetric rate of discharge against a low head, axial flow pumps should be used. In addition to their capability to deliver a large discharge rate, axial flow pumps are also more tolerant to the small solid ice fragments that may still remain in the water.

Absorbants will not work in a slush ice infested water for oil clean up because only a small part of the oil would be in contact with the absorbants on the surface, the remainder will be mixing with the ice clusters over a great depth and has little chance to float up to the top.

Once collected, the frazil ice may be separated from the oil and water by straining. The straining element is also shown in the schematic drawing of the oil clean up barge shown on Figure 11.

VI. Conclusions, Discussions and Proposals for Future Work

The theoretical investigation by now has come to an end and the following conclusions may be summerized:

(1) The probability of an oil spill on the St. Clair and the Detroit rivers is far from remote even with the existing navigation season. The probability will be further increased if the navigation season is extend-end. The probability of an oil spill at the presence of ice is higher for the spring break-up period than for the winter freeze up period. The probability of a winter oil spill is higher for the Detroit river than for the St. Clair river.

(2) Ice may be in the form of drift ice floes, frazil ice slushes and stable ice covers on St. Clair and Detroit Rivers. At the upstream sections, the ice is likely to be in the form of drift ice floes. In slow sections, the formation of a stable ice cover by the detention of ice floes by the banks, the border ice and the river constrictions is possible. For the downstream sections, the probability of frazil slush presence is high. The chance of stable ice cover formation is higher for the slower Detroit River than for the faster St. Clair River.

(3) The interaction between ice and oil depends on the form of the ice. For drift ice floes, there is little interaction. For ice covers composed of packed ice floes, the oil will be trapped and hard to be recovered. For slush ice, the oil and the ice will form a thick layer of mixture. The specific gravity of the oil plays an important role in affecting the interaction between oil and ice.

(4) Spilled oil should be stopped before it reaches an ice cover.

This requires a prompt action following an oil spill accident.

(5) Oil and ice can be contained by a floating boom. For fast flows, the boom has to be laid at an angle to the flow. Formulae are derived for laying the boom to meet various ice conditions and for designing the boom.

(6) Perforated booms may be used to separate oil and drift ice floes. The oil passed through the perforated gap may be collected by a non-perforated second boom. For light oil spilled on a fast flowing water, a single non-perforated boom may serve both the purposes of oil containment and oil and ice separation if the boom is laid at a proper angle to the flow.

(7) When oil is spilled over a water infested with slush ice, the frazil slush from upstream sections should be prevented from entering the spill site. Deflecting booms may be used to achieve this goal. The recovering site should be as close to the spill site as possible to reduce the area of oil spread. The oil-frazil mixture should be contained, deflected and removed as one matter.

(8) Surface skimming by high volume pumping appears to be the best way for removing oil and the oil-frazil mixture. Special barges may be constructed for the clean up operation. In case frazil ice is not present, straw may be used as an absorbent.

It must be kept in mind that the above conclusions are obtained from a theoretical investigation based on available data and knowledge only. They have yet to be substantiated by systematic laboratory and field experiments. More field observations are needed to better define the ice conditions on the two rivers. For instance, at the moment there is no data on the rate of discharge of ice on the rivers nor the statistical distribution of the size of the drift ice floes. Without such data, one cannot effectively design an ice and oil boom.

A careful review of all the work done on oil pollution control in a cold environment is needed. As always the case, the communication between scientific research and technological application is weak. A good review will give a good picture of the present state of the art about oil spill control on a flowing water under a freezing temperature.

Although some proposals have been suggested. They are not readily workable and require further study. From the report itself one sees ample room for future research and development work. Some are more basic such as the interaction between oil and ice slushes and the transport of an oil pocket under an ice cover. Others are more application oriented such as the separation of oil and ice by a perforated boom. From the study, it becomes clear that the containment and control of spilled oil on St. Clair and Detroit Rivers under ice conditions after all are not as formidable a task as one first thought it might be. With more work and effort, an action plan to contain and recover oil from St. Clair and Detroit Rivers under winter conditions does not seem to be too distant a reality. The earlier decision to terminate Project 6 now does seem too pesimistic and too premature a move. If at all possible, the research and development project should be reinstated.

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