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EFFECT OF SHIP PASSAGE THROUGH AN UNCONSOLIDATED SINGLE-LAYER ICE COVER ON ICE JAM INITIATION

by

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UNPUBLISHED REPORT
RAPPORT NON PUBLIE

EFFECT OF SHIP PASSAGE THROUGH AN UNCONSOLIDATED SINGLE-LAYER ICE COVER ON ICE JAM INITIATION

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May 1978

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SUMMARY

Experiments were performed in the environmental flume of the Hydraulics Laboratory at the Canada Centre for Inland Waters, using real ice, in order to determine the effect of ship passage on ice jam initiation in an unconsolidated single-layer ice cover. The critical flow Froude Number must be lower than 0.04 to permit ship passage in the direction of flow without initiating an ice jam. Upstream ship passage does not initiate ice jams at Froude Numbers below 0.08, the normal critical value for ice jamming without ship passage.

The test results show that conditions were critical for ice jam initiation in the Beauharnois Canal on December 11, 1976. The ice jam that occurred following the downstream passage of the ice breaker Simon Fraser could have been predicted.

RÉSUMÉ

Des expériences ont été faites dans le canal d'amenée environnemental du laboratoire d'hydraulique du Centre canadien des eaux intérierures en utilisant de la glace véritable, afin de déterminer l'effect du passage de bateaux sur la formation d'embâcles dans une couverture de glace d'une seule couche non compacte. Le nombre de Froude relatif à l'écoulement critique doit être inférieur à 0.04 pour permettre aux bateaux de passer dans le sens de l'écoulement sans entraîner d'embâcle. Le passage de bateaux vers l'amont ne cause pas d'embâcle à des nombres de Froude inférieurs à 0.08, chiffre critique ordinaire pour les embâcles sans passage de bateau.

Les résultats des essais révèlent que les conditions étaient critique relativement à la formation d'embâcles dans le canal Beauharnois, le 11 décembre 1976. L'embâcle qui s'est produit par suite du passage vers l'aval du brise-glaces Simon Fraser aurait pu être prévu.

FOREWORD: MANAGEMENT PERSPECTIVE

In a selected reach of a river or navigation channel, an ice cover formed from an accumulation of ice floes is considered stable if the flow velocity does not exceed a critical value. Since the critical value is also a function of channel depth, typical values of the critical velocity are:

Depth	Critical Velocity	
m	$m.s^{-1}$	knots
5	.56	1.1
10	.79	1.5
15	.97	1.9

The experimental tests show that when ships attempt to pass downstream through an ice pack, the critical velocity is reduced by one half. That is, a previously stable situation will become unstable and a jam will occur. There is no effect on the stability, according to the tests, if ships attempt to go upstream.

The propensity to jamming also increases as the ship speed relative to the bottom increases. Therefore, one way to avoid jamming is to traverse the ice pack slowly. However, the tests indicate that in real situations, the necessary ship speed reduction would take the ship below safe steerage way. Therefore, the management alternatives are reduced leaving as one option the reduction of channel discharge velocities. For power canals such as the Beauharnois, the costs of power reduction are formidable and justifiably could be a direct charge to navigation in ice.

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AVANT-PROPOS: PERSPECTIVE - GESTION

Dans une section rectiligne choisie d'un cours d'eau ou d'un chenal de navigation, une couverture de glace formée par l'accumulation de floes est considérée comme stable si la vitesse de l'écoulement ne dépasse pas un chiffre critique. Puisque celui-ci est fonction de la profondeur du chenal, les valeurs caractéristiques de la vitesse critique sont les suivantes:

Profondeur	Vitesse critique	
m	m/s^{-1}	noeunds
5	.56	1.1
10	.79	1.5
15	.97	1.9

Les expériences révèlent que lorsque les bateaux essaient de passer en aval en traversant un pack, la vitesse critique est réduite de moitié, c'est-à-dire qu'une situation auparavant stable devient instable et qu'il se produit un embâcle. Il n'ya aucun effect sur la stabilité, selon les essais, si les bateaux essaient de se diriger vers l'amont.

La tendance à produire un embâcle augmente également à mesure que la vitesse du bateau par rapport au fond de l'eau est plus grande. Par conséquent, une façon d'éviter de créer un embâcle consiste à traverser le pack lentement. Cependant, les essais indiquent que dans des situations réelles, la réduction nécessaire de vitesse du bateau obligerait celui-cià avancer à une vitesse inférieure à celle qui est requise pour le gouverner de façon sûre. Les options de gestion sont donc réduites, la solution qui reste consiste à réduire la vitesse d'écoulement des eaux dans le chenal. En ce qui concerne les canaux utilisés pour l'énergie hydroélectrique comme le canal Beauharnois, les coûts de la réduction d'énergie sont considérables et pourraient à juste titre être imputés directement à la navigation dans les glaces.

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1.0 INTRODUCTION

This study explores the effect of a ship on ice accumulated in a canal under normal flow conditions.

Working rules have been established for the formation of a stable ice cover subjected to hydraulic forces in a canal. Pressures to permit ships to pass through a canal with developed ice cover require the assessment of the effect of ship passage on the ice cover.

The results are relevant to the situation on the Beaurhanois Canal where the production of electric power depends on the ice cover remaining in dynamic equilibrium. Navigation of the canal may cause ice jams resulting in loss of power production.

2.0 BACKGROUND INFORMATION

In this section, a description of the conditions at the Beauharnois Canal and an ice jam event is given, as a prelude to discussions of the laboratory work.

2.1 Description of the Canal

The Beauharnois Canal joins Lake St. Francis and Lake St. Louis on the St. Lawrence Seaway system. The Melocheville Lock and Beauharnois Power Dam are located at the downstream end of the canal, 40 kilometers (25 miles) southwest of Montreal (see Figure 1). The canal is 24 kilometers (15 miles) long with a width of 1000 meters (3300 feet) and depths varying from 6 to 12 metres (20 to 40 feet) outside the navigation channel.

2.2 The Ice Jam Event

On December 11, 1976 at 1600 hours, the ice breaker Simon Fraser travelled downstream through the ice cover from Lake St. Francis toward Melocheville Lock. Approximately three kilometers (two miles) of ice cover, accumulated from ice cutting operations on Lake St. Francis, remained unsolidified from a point 15 kilometers (eight miles) upstream of the powerhouse. The cover was built up from rough three meter (ten foot) square ice floes, about 0.15 meters (six inches) thick. The exact time and progression of the jam is not known but after the ship passage the jammed ice measured 1830 meters (6000 feet) long, 490 meters (1600 feet) wide and extended 3.7 meters (12 feet) below the water free surface. Figure 2 shows the location of the jam between chainages 320 and 390, surveyed by Quebec Hydro on December 15, 1976. A cross-section of the channel and ice cover was taken also. The location of the jam can also be seen in Figure 1.

2.3 Flow Conditions

Information on discharge, water levels and channel properties were provided by Quebec Hydro. The discharges at the power canal and water levels at Lake St. Francis and the forebay are shown in Table 1, Appendix A and plotted in Figure 3. To maintain the minimum forebay elevation required for navigation purposes, discharge was reduced following the ice jam because of the increase in channel slope caused by the head loss at the ice jam. Figure 3 shows the sharp increase in slope through the canal sections affected by jamming. The cross-sections provided are for open water conditions and are listed in Table 2, Appendix A. For any discharge the water levels never vary from a range of 0.15 meters (six inches) so the areas are practically constant (within 2%). The station numbers represent chainage in hundreds of feet from the upstream end of the channel. The areas at different sections vary from the average by less than 5 percent and the area at section 370 after the ice jam was only 2 percent higher than the open water area in Table 2. The depth used for the model study was the depth in the channel under the ice jam, 11.6 metres (38 ft).

No information on the operation of the ice breaker could be obtained, although plans of the ship hull of the Simon Fraser were available Coast Guard.

3.0 LABORATORY TEST PROGRAMME

A series of tests were devised to explore the effects of ship passage through ice cover on ice jam initiation. In order to ensure that the test results could be projected to field situations, including the Beauharnois Canal, a dimensional analysis was first performed to guide the planning of the experiments.

3.1 Dimensional Analysis

The analysis of the phenomenon of ice cover stability is further complicated by ship passage. Dimensional analysis was performed to yield the parameters that guided the experiments for ship passage through an unconsolidated ice cover. The characteristic parameters affecting ice jamming with ship passage through an unconsolidated ice cover are:

U - flow velocity (m/s)
H - flow depth (m)
ρ - water density (kg/m³)
μ - dynamic viscosity of water (kg/ms)
B - channel width (m)
k_c - channel side rougness
g - acceleration of gravity
ℓ_b - surface length of square ice floes (m)
t_b - ice floe thickness (m)
ℓ_c - initial ice cover length (m)
t_c - initial ice cover thickness (m)
ρ^1 - ice density (kg/m)
V_s - absolute ship speed (m/s)
ℓ_s - ship length (m)
w_s - ship width (m)
d_s - ship draft (m)
P - ship penetration into the cover at jam initiation (m)
S - ship stopping during passage
D - direction of ship passage
M - ship mass (kg)

Water temperature should not affect the phenomenon beyond the influence on water viscosity. The initial porosity of the single-layer ice cover is a function of ice block geometry and hydraulic conditions.

Any property A of the phenomenon can be expressed in dimensional form as a function of the above parameters.

$$A=f_A(U,H,\rho,\mu,B,k_c,g,\ell_b,t_b,\ell_c,t_c,\rho^1,V_s,\ell_s,w_s,d_s,P,S,D,M) \qquad \ldots(1)$$

where f_A denotes a dimensional function for the property A.

This functional relationship can be expressed in non-dimensional form with ρ, g and H as repeating variables as:

$$\pi_A=\psi_A\left(\frac{U}{\sqrt{gH}},\frac{\sqrt{gH}\,H\rho}{\mu},\frac{B}{H},k_c,\frac{\ell_b}{H},\frac{t_b}{H},\frac{\ell_c}{H},\frac{t_c}{H},\frac{\rho^1}{\rho},\frac{V_s}{\sqrt{gH}},\frac{\ell_s}{H},\frac{w_s}{H},\frac{d_s}{H},\frac{P}{H},S,D,\frac{M}{\rho H^3}\right) \qquad \ldots(2)$$

where π_A is the dimensionless form of the property A and ψ_A denotes a dimensionless function for the property A.

Combining the dimensionless parameters yields

$$\pi_A=\psi_A\left(\frac{U}{\sqrt{gH}},\frac{UH\rho}{\mu},\frac{B}{H},k_c,\frac{\ell_b}{H},\frac{t_b}{H},\frac{\ell_c}{H},\frac{t_c}{H},\frac{\rho^1}{\rho},\frac{V_s}{U},\frac{\ell_s}{\ell_b},\frac{w_s}{\ell_b},\frac{d_s}{\ell_b},\frac{P}{\ell_s},D,S,\frac{M}{\rho H^3}\right) \qquad \ldots(3)$$

This is the most general form of the functional relationship defining a property of the phenomenon in terms of its characteristic parameters. Depending on the property of the phenomenon in question and test conditions, a number of parameters will not affect the phenomenon and can be eliminated. The property of the phenomenon under investigation for this study is the critical Dimensionless Ship Speed to initiate jamming for ship passage through an unconsolidated single-layer ice cover so V_s/U cannot be regarded as an independent parameter. The first parameter is the Froude Number of the flow Fr. Based on previous studies of ice jams, the Froude Number is expected to be the most important independent parameter. The second term is the Reynolds Number Re. If the flow is sufficiently turbulent, the effect of viscous forces is constant and Re can be left out of Equation 3. The lowest Reynolds Number tested was 2.15×10^3, in the turbulent flow range for open channels. The initial ice cover thickness t_c was the ice block thickness t_b. Arching of the ice floes in the flume occurred for sections of ice cover as short as 0.5 m. Because short sections of the cover acted independently, it was assumed that ice cover length would not influence ice jam initiation and was held constant. Also, ship penetration at jam initiation should not vary. The ship models were geometrically similar so only one linear ship parameter was required. Also, ship draft was not considered important if deeper than the cover thickness.

Jam initiation could be caused in two ways. The impact of the ship could cause individual floes to underturn which could "snowball" into a large jam or the additional shear force of the ship on the cover could increase internal ice cover stress above that which the cover could sustain resulting in crushing throughout the cover. It was assumed that only the latter mechanism is important so that $M/\rho H^3$ was left out.

Given the above considerations, the functional relationship of Equation 3 can be reduced to:

$$\left(\frac{V_s}{U}\right)_{cr} = \psi_{V_s}\left(Fr, \frac{B}{H}, k_c, \frac{\ell_b}{H}, \frac{t_b}{H}, \frac{\rho^1}{\rho}, \frac{\ell_s}{\ell_b}, D, S\right) \qquad \ldots(4)$$

The flume width B, water depth H, ice block thickness t_b, ice density ρ^1 and water density ρ were constant for all of the tests. Flume side wall roughness was assumed to be constant. Time limitations did not allow a complete study of the effect of stopping the ship after a jam was initiated. Therefore, for these tests, the critical Dimensionless Ship Speed ratio $(V_s/U)_{cr}$ was a function of four independent parameters, i.e.

$$\left(\frac{V_s}{U}\right)_{cr} = \psi_{V_s}\left(\frac{\ell_b}{H}, \frac{\ell_s}{H}, D, Fr\right)$$

Experiments were carried out in an attempt to obtain the dependence of $(V_s/U)_{cr}$ on these parameters.

3.2 Experimental Set-Up

A linear scale n_ℓ=1/90 was selected for the model test to allow a clearance between the ship and the flume walls of 0.23 m or the length of six ice floes on either side.

Two models of the hull of the ice breaker Simon Fraser were formed from polyurethane foam coated with fibreglass resin and using sand as ballast. One hull was at 1/90 scale while the other was half that size.

Ice was formed in two-foot square trays with adjustable grids to form 0.038 m or 0.076 m squares of ice. Thickness was controlled by the volume of water in the trays. Individual variations in trays and uneven freezing levels resulted in significant relative, if not large absolute, thickness variations. (The model ice was from 1½ to 3 times thicker than the scaled prototype ice). Model and prototype relationships are listed in Table 3, Appendix A.

The flume working section is 11 m long with a 0.6 m wide by 0.5 m deep rectangular cross-section (see Figure 5). There are observation windows on one side of the flume trough. The flow range is from 0 to 0.15 m^3/s. The air temperature of the test chamber was maintained at -10^oC to prevent excessive melting of the model ice floes.

A variable speed reversible ship towing system was mounted on the flume rails, Figure 6. A vertical barrier extending 0.02 m below the water free surface was installed to hold the unconsolidated ice cover in place. The barrier was equipped with a gate permitting the passage of the ship through the ice cover completely from either upstream or downstream (see Figure 7).

3.3 Experimental Procedure

To establish some baseline conditions a series of tests were performed to determine the critical Froude Number for ice cover stability without ship passage. A single-layer ice cover was established and the flow rate was gradually increased until the cover jammed. With each increase in flow, five ice floes were released about 0.5 m upstream from the leading edge. The number of floes to underturn and the effect on the leading edge of the cover were noted. While the flow was increased, the cover was kept unfrozen by gently "stirring" the ice.

A second series of tests were performed in which passes of the ship through the cover at increasing ship speed were made, noting ice jam initiation, for a range of Froude Numbers with ice floe length and ship length held constant.

Ice floes were fed by hand at a low flow rate and allowed to drift into place against the ice barrier. Then the desired uniform flow condition was established in the flume. The exact model depth may not have been achieved (see footnote to Table 3, Appendix A). The cover was "stirred" with a thin rod to produce a uniform, single-layer cover compacted characteristically to the particular flow conditions and, most importantly, to keep the ice floes from freezing. With depth and discharge determined by point gauge and manometer readings respectively, the model ship was towed through the ice cover. Ship speed was determined from the time to travel a measured distance. Ice cover length was kept approximately 3.0 m. As the majority of the ice jam initiations occurred when the ship penetration was less than 1.0 m, the ice cover length was not varied (see Figure 21).

While the ship was towed at a given speed, the interaction of the ship and the ice cover and the progression of any ice jamming were noted. Ship speed was increased and the test procedure was repeated.

The majority of tests were performed with the larger (0.694 m long) ship proceeding downstream through an ice cover of small (0.038 m long) ice floes. Additional tests were performed with the smaller model ship and larger ice floes. Tests were performed with the ships travelling upstream through the ice cover.

4.0 OBSERVATIONS AND DISCUSSION

A total of 268 tests were performed to determine the effect of ship passage on ice jam initiation. An additional 68 tests were performed to establish a base critical Froude Number for ice cover stability without ship passage Fr_{cr}. The data are tabulated in Appendix C.

4.1 Critical Froude Number for Ice Cover Stability Without Ship Passage

The data gathered on ice cover stability without ship passage have been plotted in Figures 8 to 11. In addition to ice jamming caused by hydraulic conditions, the stability of the leading edge and the stability of incoming ice floes were investigated. Observations made during these tests led to the investigation of the effect of sudden disturbances on ice cover stability. All of the tests were performed with small ice floes.

Figure 8 is a plot of non-dimensionalized ice cover length ℓ_c/ℓ_b against Froude Number. The data points represent the ice cover conditions observed at different hydraulic conditions. Jams were characterized by widespread crushing and shifting of ice floes originating at some point downstream from the leading edge. Jams usually occurred for Froude Numbers greater than 0.12. Stable covers did exist for Froude Numbers as high as 0.15. Different results for the same test conditions were probably due to variations in ice cover/flume wall contact as discussed later (Section 4.3). The results do not reveal any dependence of ice jamming on ice cover length.

The leading edge was defined as unstable if incoming floes underturned or dislodged other ice floes or if the leading edge failed spontaneously. The instability of the upstream edge was limited to a short section of the cover at the upstream edge and could occur independently or simultaneously with ice jamming. As expected, ice cover length had no effect on the stability of the leading edge (see Figure 9). Above a Froude Number of 0.12, the leading edge became unstable. In Figure 10, the percent of incoming floes underturning is plotted against Froude

Number. The results are too scattered to precisely determine the relationship between underturning and Froude Number. At a Froude Number of 0.10, 40 percent underturning was recorded. At a Froude Number of 0.12, the percentage of underturning ice floes ranged from 40 to 80 and increased above that Froude Number.

The nature of the edge contact between the ice cover and the flume walls was investigated by studying the effect of sudden disturbances on ice jam initiation. Two types of disturbances were considered. When the flow rate was increased the water depth increased as well. To maintain the test depth, the tailgate was lowered and the Froude Number increased. If this adjustment was not made smoothly, a surge of a few millimeters in height travelled upstream suddenly breaking the edge contact between the ice cover and the flume walls and the cover failed on several occasions. The delivery of a mild shock to the flume walls would also suddenly disrupt the ice cover contact at the flume walls. A number of the non-jam events were from tests of ship passage when a shock was delivered to the flume walls prior to ship passage. The results of these tests, shown in Figure 11, were the same as the results obtained without the disturbance, shown in Figure 8. At and above the same Froude Number 0.12, the cover failed when disturbed. Jams could be initiated at lower Froude Numbers but were relatively few in number.

From the different tests and observations, it can be concluded that, for these tests, the Froude Number 0.12 was critical for all aspects of ice cover stability. Above that value, ice cover failures occurred with or without a disturbance. The leading edge of the cover became unstable and the proportion of incoming floes that underturned increased markedly at that Froude Number.

Theoretical developments and field studies are limited in most cases to the conditions for stability of the leading edge or upstream progression of the cover. In the present tests, initiation of internal crushing failures was compared with and without ship passage. The theories listed in Table 4, yielding critical Froude Numbers from 0.04 to 0.12, do not apply directly to the crushing type of failure. The most widely accepted critical Froude Number is that of Kivisild (1959) 0.08 for upstream progression of an ice cover based on field observations, lower than the critical Froude Number 0.12 established in the present tests. Only the results of field tests reported by Cartier are in the range established in the present tests.

4.2 Ship/Ice Interaction

Three reactions of the ice cover to ship passage were identified. They were "no jam", "mild shove" and "heavy jam".

For the "no jam" condition, the cover remained intact with no movement in excess of the displacement of the ice as the ship passed (See Figure 12).

The "mild shove" condition was characterized by a gentle shifting of the ice cover intact between the ship and the flume walls. The passage of the ship disturbed the contact between the ice cover and the flume side walls removing support to the ice as it turned ice floes aside and compacted the cover. More ice joined the moving ice pack as the ship progressed through the ice cover. When the ship reached the downstream barrier, the momentum of the moving ice pack caused the cover to fold at that obstacle until the momentum was dissipated. Jamming was confined to a short section at the downstream end of the cover against the barrier. The cover upstream remained unthickened. The jamming mechanism might have been quite different if there had been edge support to the cover to balance the ship shear when the internal stress distribution in the cover supporting the cover from downstream was disturbed by the ship passage. The cover seemed to shift too easily along the flume walls when disturbed.

The "heavy jam" condition was a true jam (see Figure 13). The passage of the ship caused crushing throughout the entire cover radiating outward from the ship, not just at the downstream barrier. The jamming, once initiated, could advance ahead of the ship if the propogation of the jam was faster than the ship speed. The majority of floes in the cover were jammed thickly.

The interaction between the ship and the ice was visibly different at different ship speeds. At slow ship speeds (less than 0.03 m/s) the ship inched its way through the ice pack. With little momentum, the ship was forced to move around the ice floes causing only a localized disturbance (see Figure 15a). At faster ship speeds, the ship pushed the ice aside and underturned floes depositing them under the cover alongside of the hull. The ship forced the ice outward to the flume walls. In several cases the compressed ice cover reexpanded to partially fill in the channel after the ship had passed (see Figure 14). At very fast ship speeds (greater than 0.25 m/s) the ship/ice interaction seemed unnaturally violent (see Figure 15b). Ice floes were completely submerged by the impact of the ship and would then rise up alongside the ship under the ice cover or surface in the channel behind the ship after it had passed. A model ship speed of 0.25 m/s is only 2.37 m/s or 4.6 knots for prototype conditions. Probably, 3 m ice floes, 0.15 m thick, would be broken by the ship impact rather than so violently and completely displaced. The strength of the model ice floes relative to their mass must have been too great so they were not broken.

Because of the great downward thrust on the ice floes, the effect of high speed ship passage was more localized, i.e. the ship hull did not seem to contact the rest of the ice cover and the ice cover was not compacted by the ship passage as it was at lower ship speeds. Ship passage at very high speed was possible without initiating ice jams while at lower speeds jams occurred for the same Froude Number. That seems to be a result of the violent displacement of the model ice floes by the ship which does not seem reasonable at the prototype scale. Therefore, high ship speed data indicating non-jamming ship passage is likely to be subject to a scale effect because of the ice strength/ice mass relationship in the model.

4.3 Ship Passage Data Interpretation

Figure 16 is a plot of V_s/U against Fr for tests of downstream passage of the large ship through a 3.05 m long cover of small ice floes ($\ell_s/H=5.38$, $\ell_b/H=0.29$). To the upper right of the curve representing $(V_s/U)_{cr}$, many failures of the cover occurred, many of them heavy jams, particularly above a Froude Number of 0.09. To the lower left of the critical Dimensionless Ship Speed $(V_s/U)_{cr}$ curve, very few jams occurred, all of them being mild shoves. Furthermore, all of those failure points were from the second and only day of testing when there was no ice on the flume side walls (except for three runs on the fourth day). From the $(V_s/U)_{cr}$ curve, it can be seen that, at lower Froude Numbers, a higher ship speed, hence a greater shear force, is required to cause a jam. Very few tests were performed above a Froude Number of 0.10 due to instability of the cover. In all but one case, the cover failed with ship passage. At dimensionless ship speeds below 0.2, no jams occurred.

Different results obtained for apparently identical experimental conditions can be explained by variable channel side roughness. There was a bead of border ice on the flume walls at the water surface. It is the variability of the contact between that bead of border ice and the ice cover that is questionable. If the effect had been consistent, then compensation could be made for it.

The importance of the border ice condition is heightened by the relative narrowness of the experimental flume. For the prototype conditions, a 12.8 m wide ship caused a 488 m wide ice jam illustrating the three-dimensional nature of the phenomenon. The border ice condition was important under experimental conditions because the ice floes were forced outwards to the flume walls, an unnaturally straight, smooth failure plane, making cover failure too easy for some ship passage runs.

The difference in results is more pronounced on a day-to-day basis which led to the conclusion that border ice conditions accounted for the scatter in the results. With no bead of ice, as was the case on the second day of testing, it was difficult to establish an ice cover at a Froude Number as low as 0.063. When the ship entered the ice cover and pushed the ice outward to the sides, internal support was removed in the cover. With no side support, the ice moved with the ship, sliding along the flume walls, a typical mild shove. It was felt that, under prototype conditions, there would be some support to the cover from the continuation of the ice pack and that would be better approximated with the bead of border ice intact. A better approximation of the continuation of the ice pack would be a saw-tooth border to force the jamming portion of the ice cover to shear away from the simulated continuation of the cover as well as overcome the downstream support provided by the cover.

Figure 17 is a plot of V_s/U against Fr for downstream passage of the small ship through a 3.05 m long cover of small ice floes ($\ell_s/H=2.69$, $\ell_b/H=2.69$). The failures of the cover fell on the upper range of jamming in Figure 16. There were relatively few failures considering the high range of Froude Number tested suggesting a shift to the right of the $(V_s/U)_{cr}$ curve. Visually, the small ship had little effect on the individual ice floes or on the cover as a whole. It could not underturn the floes or compact the cover. The resulting mild shoves were much less severe and extensive than for the passage of the large ship through a cover of small ice floes.

Figure 18 is a plot of V_s/U against Fr for downstream passage of the large ship through a cover of large ice floes ($\ell_s/H=5.38$, $\ell_b/H=0.59$). Again, few failures occurred considering the range of Froude Number tested. The ℓ_s/ℓ_b ratio was the same as for the tests in Figure 17 and a similar shift to the right of the $(V_s/U)_{cr}$ curve is suggested. The large ice was not readily displaced by the ship and was not fully underturned. The resulting mild shoves were more of an overlapping of ice floes than a jam.

The visual differences in the ice floe/ship hull interaction and the differences in jam severity observed suggest that there is an effect of ship and ice size. There is not enough data to fully evaluate the effect of these parameters.

Figure 19 is a plot of V_s/U against Fr for upstream passage of the large ship through a cover of small ice floes ($\ell_s/H=5.38$, $\ell_b/H=0.29$). There was only one failure for upstream passage, a mild shove at a Froude Number of 0.126. Even for violent, high-speed ship passage, only the upstream edge of the cover would fail at Froude Numbers greater than 0.12. That type of failure was restricted to a few floes at the upstream edge of the cover which turned under with no under-ice transport forming a small hanging dam at the upstream edge of the cover. It can be concluded that upstream passage will not cause wide spread jamming of the cover, that it is the additional stress from the ship shearing force added to the existing stress in the cover that causes failure, not just disruption of individual floes.

Figure 20 is a plot of V_s/U against Fr for downstream passage of the large ship through a cover of small ice floes with a shock delivered to the flume walls prior to ship passage. The conditions are similar to those of Figure 16 except for that action ($\ell_s/H=5.38$, $\ell_b/H=0.29$). The results obtained were the same as without a shock. Therefore, it can be concluded that, although a sudden shock can initiate jamming itself, it will not affect the ice cover/flume wall contact for the ship passage immediately following. Because the delivery of a sudden shock breaks any freezing bond between the ice cover and the flume walls, the scatter in the results must depend on some other aspect of that contact.

On the first day of testing, three tests that had resulted in jams were repeated. After the jamming had started, the ship was stopped in the cover upstream of the barrier. The jamming stopped as well. Apparently, continued ship motion is required to prolong jamming in an otherwise stable ice cover. Unfortunately, all of the tests were limited to mild shove cases. A heavy jam advancing ahead of the ship might not stop jamming. Time limitations prevented a complete evaluation of the effect of stopping the ship on jamming.

From Figures 21 and 22, it can be concluded that the relative length of ship penetration at jam initiation had no effect on jam initiation beyond the observation that jamming was not initiated before the penetration reached one ship length, when the full shearing force had developed. The relative penetration at jam initiation did not vary with relative ship speed or Froude Number. The severity of jamming did not vary with the relative penetration.

4.4 Comparison with Prototype Conditions

In the Beauharnois Canal on December 11, 1976, the Froude Number was 0.052, a normally stable condition for an unconsolidated ice cover.

From the test results in Figure 16, the Dimensionless Ship Speed must exceed 4.0 for downstream ship passage to initiate jamming at that Froude Number. For a prototype flow velocity of 0.5 m/s, the corresponding absolute ship speed is 2.0 m/s (4.0 knots). The ship speed relative to the water is only 1.5 m/s (2.8 knots), which is well below ordinary navigational standards.

Therefore, on December 11, 1976, ice jamming occurred as a result of the passage of the ice breaker Simon Fraser downstream through the cover, not from hydraulic conditions alone, according to the results of the present experiments.

5.0 CONCLUSIONS

Subject to the limitations of the parameters tested, the following conclusions can be reached:

5.1 Ships passing through an ice cover in the direction of flow may initiate consolidation of the cover or an ice jam even though the cover is "safe" by the accepted Froude Number criteria.

5.2 To avoid initiating jams, the flow Froude Number must be reduced or the ship speed very much reduced.

5.3 The tests indicate that, to avoid ice jams in covers through which ships will navigate in the downstream direction, the critical Froude Number should be 0.04.

5.4 Ships proceeding upstream do not lower the critical flow Froude Number below 0.08, which is the generally accepted value.

5.5 In a narrow channel, ice cover length does not affect ice jam initiation. Jamming will start when the ship has penetrated fully into the cover. Jamming can be stopped by stopping the ship.

5.6 The dimensionless ship length and ice floe size also appear to have an effect on the critical Dimensionless Ship Speed for initiation of jamming.

5.7 The results may not be conservative since the narrow experimental canal tends to assist cover stability. Wider channels may reduce the critical Froude Number further.

ACKNOWLEDGEMENTS

Mr. K. Hill, Research Technologist, constructed the ship towing system and assisted in the experimentation. The writer wishes to thank Dr. G. Tsang for his suggestions regarding the experimental procedure.

Mr. L. Racicot, Quebec Hydro, provided the information on the Beauharnois Canal.

The report was reviewed by Dr. Y. L. Lau, Head, Environmental Hydraulics Section and Dr. T. M. Dick, Chief, Hydraulics Research Division. Their contributions to the preparation of this report were invaluable.

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APPENDIX A

TABLES

[illegible]ble 1 Discharge and Stage at Beauharnois Canal Provided by Quebec Hydro

Date	Time	Water Level (ft)		Slope ($\times 10^5$)	Discharge	Power	Air Temperature
		Forebay	Lake St. Francis				
Dec. 11	0700	149.45	152.33	3.69	180300 cfs	1010 kw	-7°C
	1700	149.80	152.23	3.04	158900	890	
Dec. 12	0700	148.95	152.10	4.04	160600	890	-2
Dec. 13	0700	149.15	152.16	3.86	153400	855	-15
Dec. 14	0700	148.30	152.10	4.87	130900	721	-15
Dec. 15	1100	148.70	152.70	5.13	134100	739	-2
Dec. 16	1100	148.50	152.80	5.51	136100	750	-7

Table 2 Beauharnois Canal Cross-Section Areas

Station	Area	Station	Area	Station	Area
315	97000 ft^2	345	98100	380	97800
320	100200	350	98500	385	106900
325	93800	360	94300	390	105700
330	96200	365	97700	395	105700
335	97200	370	101800	400	100000
340	100700	375	103600	405	97000

Average Area = 99567 ft^2

Table 3 Prototype and Model Parameter Values

Parameter	Prototype Value	Model Value	Scale
ice floe size, ℓ_b	3.42 m, 6.84 m	.038 m, .076 m	1/90
ice floe thickness, t_b	0.27 m to 0.45 m	.003 m to .005 m	1/90
ship length, ℓ_s	62.5 m, 31.2 m	.694 m, .347 m	1/90
ship beam, w_s	12.8 m, 6.4 m	.142 m, .071 m	1/90
ship draft, d_s	4.9 m, 2.4 m	.054 m, .027 m	1/90
discharge, Q	5,106 m^3/s	---	
channel area, A	9,250 m^2	---	
average flow velocity, U	0.552 m/s	0.058 m/s	$1/\sqrt{90}$
channel depth, H	11.6 m	0.129 m	1/90 *
Froude Number	0.052	0.052	1

* It was not possible to alter depth easily when the fragmented ice cover was in place, particularily at high flow rates, as a sudden surge associated with even a .001 to .002 m depth change could cause a jam. The channel flow depth was not always exactly modelled to scale.

Table 4 Summary of Criteria for Ice Cover Stability

INVESTIGATOR	CRITERION	APPLICABILITY	CORRESPONDING TEST VALUE
Cartier (1959)	U_{cr}=1.5 fps	Ice floes underturned in a 9' deep canal above this flow velocity.	$Fr_{cr}=0.09$
	U_{cr}=2.2 fps	Some incoming ice underturned but the cover still advanced upstream.	$Fr_{cr}=0.13$
	U_{cr}=3.0 fps	The upstream edge of an established ice cover failed above this flow velocity.	$Fr_{cr}=0.18$
	U_{cr}=2.3 fps	Individual stationary ice blocks underturned as flow velocity exceeded the critical value.	$Fr_{cr}=0.14$
Kivisild (1959)	$Fr_{cr}=0.08$	Incoming ice floes were carried under the ice cover rather than attached to the leading edge of the cover above this Froude Number.	$Fr_{cr}=0.08$
Pariset & Hausser (1961)	$U \leq K\sqrt{2g\left(\frac{\rho-\rho^1}{\rho}\right)}\ t_b$ K=1.3 for thin floes K=0.6 for cubic floes	The cover advanced upstream by juxtaposition of floes up to this flow velocity.	$Fr_{cr}=0.07$ K=0.97 (from Figure 1, $\ell_b/t_b=9.5$)
	$U=\sqrt{2g\left(\frac{\rho-\rho^1}{\rho}\right) t_c}\left(1-\frac{t_c}{H}\right)$	Based on the field tests by Cartier and laboratory experiments with artificial ice blocks, the non-submersion criteria for the upstream edge of an ice cover was established.	$Fr_{cr}=0.07$
Michel (1966)	$Fr_{cr}=\sqrt{2\left(\frac{\rho-\rho^1}{\rho}\right)}\ (1-\varepsilon)\ \frac{t_c}{H}\left(1-\frac{t_c}{H}\right)$ (For ideal conditions of progression, a porosity ε equal to 0.73 is required).	The upstream edge of an ice cover will be in equilibrium if the critical froude Number is not exceeded.	$Fr_{cr}=0.04$

Table 4 (cont'd)

Summary of Criteria for Ice Cover Stability

INVESTIGATOR	CRITERION	APPLICABILITY	CORRESPONDING TEST VALUE
	$U \leq K\sqrt{2q\left(\frac{\rho-\rho^1}{\rho}\right)}\, t_b$ (The form coefficient K equals 1.3 for "flat" blocks).	An ice cover can progress simply by juxtaposition if the blocks are large enough.	$Fr_{cr}=0.09$
Oudshoorn (1970)	$Fr_{cr}=0.06$ to 0.09 $Fr_{cr}=0.08$ (average)	Based on observations on the various branches of the River Rhine, the critical Froude Number range was established for the formation of ice dams.	$Fr_{cr}=0.08$
Uzuner & Kennedy (1972)	$Fr_{cr}^2= \dfrac{2\,\frac{t_b}{H}\left(1-\frac{\rho^1}{\rho}\right)}{C_s t\left(1-\frac{t_b}{H}\right)^{\frac{1}{2}}-(1+\beta)}$ C_s is the surface velocity-head coefficient taken equal to 1.3. β is a function of geometric and flow variables and equals zero for long blocks.	The critical Froude Number at incipient underturning of an ice block was established for laboratory tests with artificial ice blocks. The formula is limited to blocks of intermediate length ($0.1<t_b/\ell_b<0.8$).	$Fr_{cr}=0.06$ $t_b/\ell_b=0.11$ $\beta=0$
Ashton (1974)	$Fr_{cr}=\left(1-\frac{t_b}{H}\right)\sqrt{\dfrac{4\,\frac{t_b}{H}\left(1-\frac{\rho^1}{\rho}\right)}{5-3\left(1-\frac{t_b}{H}\right)^2}}$	The critical froude Number for "no-spill" conditions at the upstream edge of an ice block criterion was derived using dimensional analysis.	$Fr_{cr}=0.07$

APPENDIX B

FIGURES

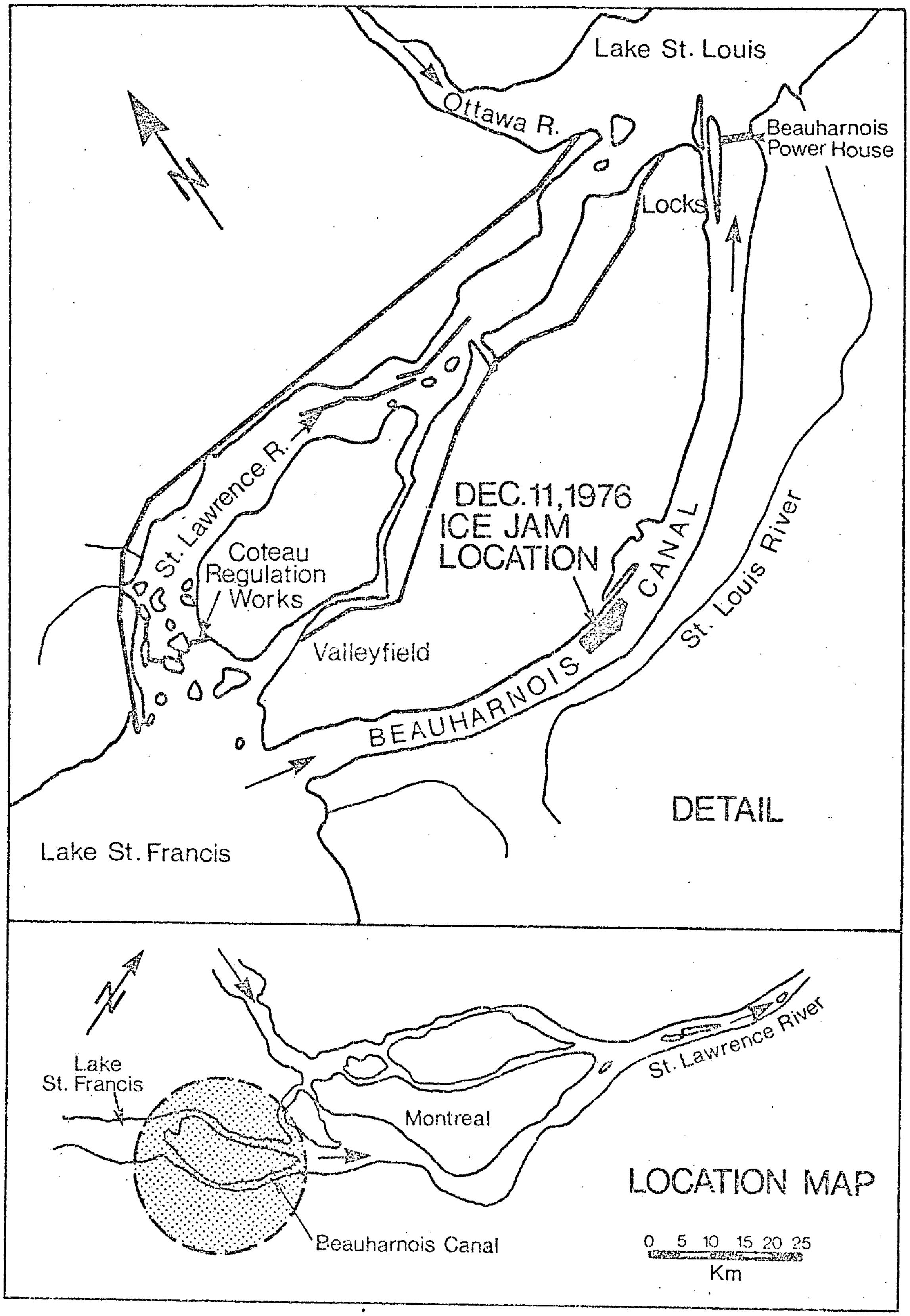
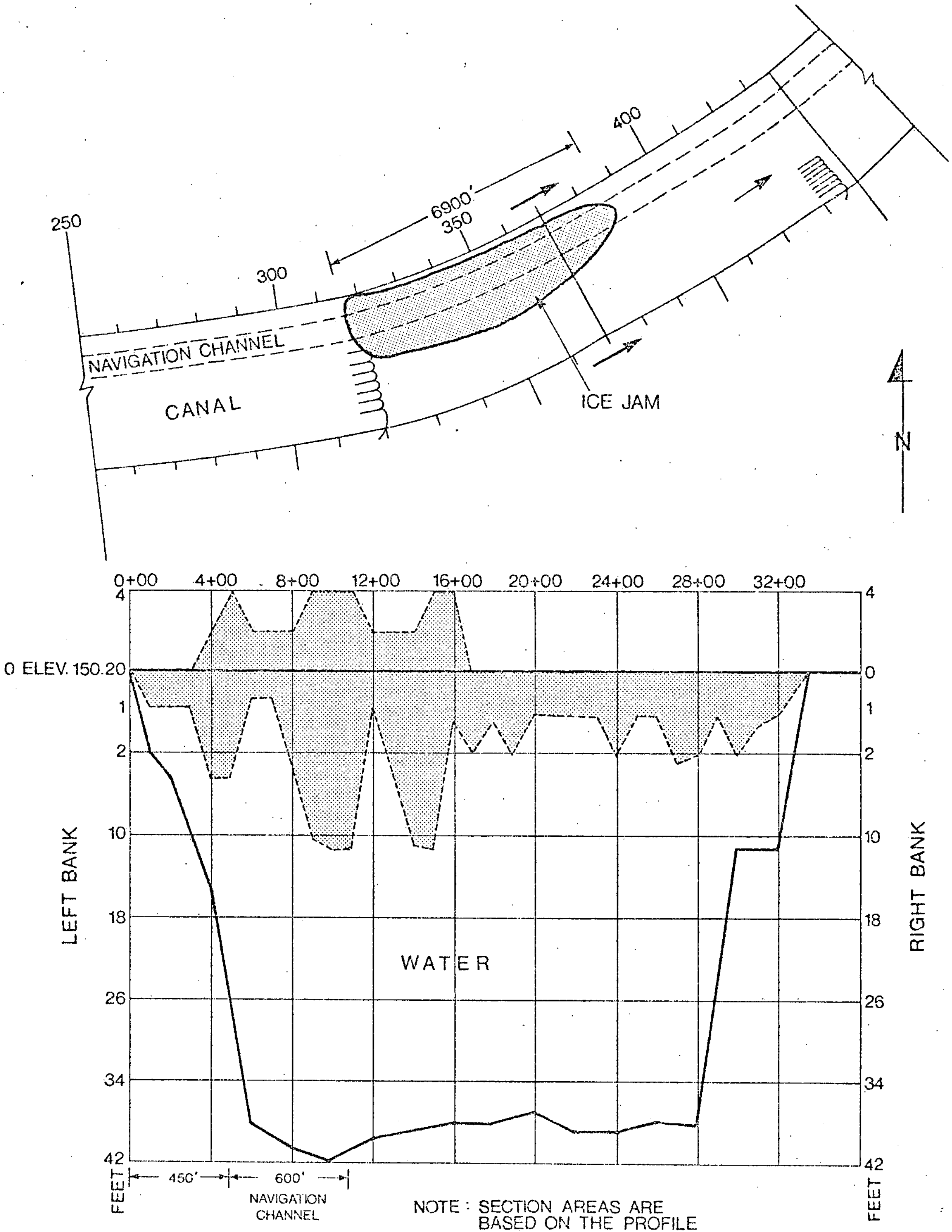


FIGURE 1 LOCATION OF THE BEAUHARNOIS CANAL



NOTE : SECTION AREAS ARE BASED ON THE PROFILE OF 15 DECEMBER 1976

SECTION 370+00

ICE AREA 9.768 ft²
SECTION AREA 104.290 ft²
% OBSTRUCTION 9.4 %

FIGURE 2 ICE JAM BETWEEN CHAINAGE 320 TO 385
ON THE BEAUHARNOIS CANAL

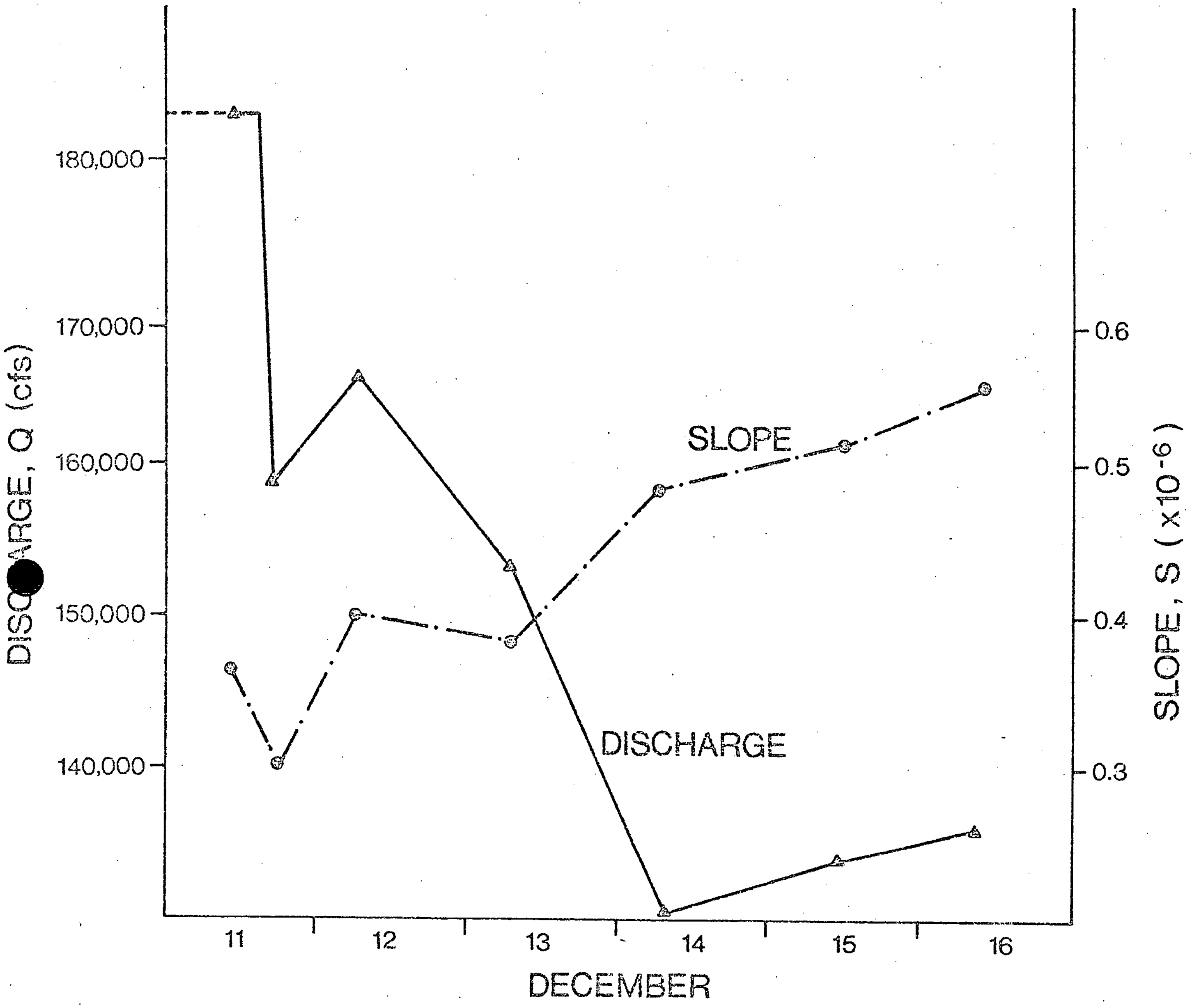
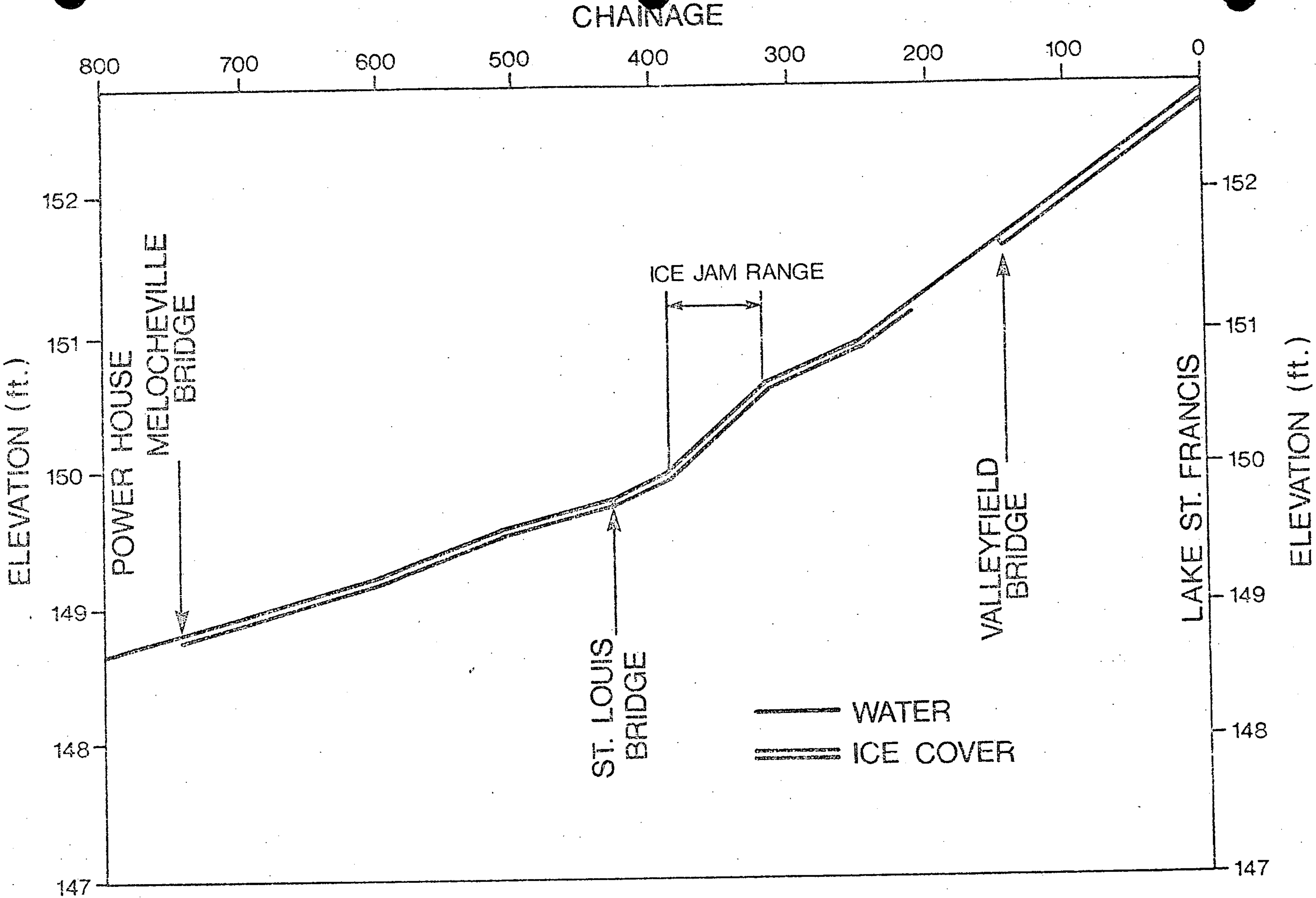
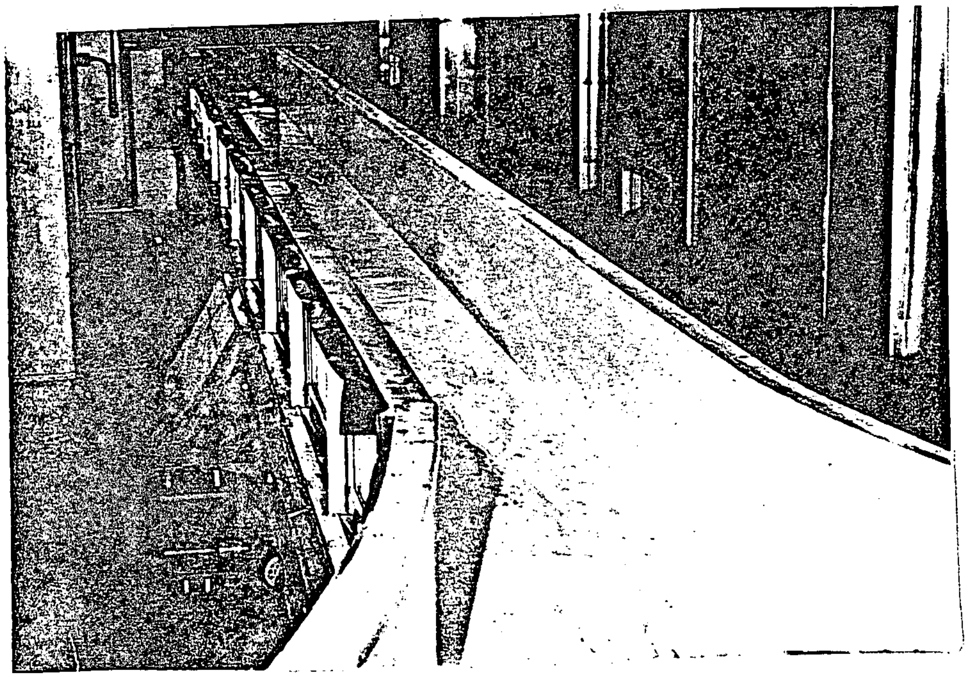


FIGURE 3 BEAUHARNOIS CANAL DISCHARGES AND SLOPES FROM TABLE 1. NOTE THE INCREASED SLOPE AND REDUCTION IN FLOW TO MAINTAIN THE MINIMUM FORE BAY ELEVATION AT THE BEAUHARNOIS POWER HOUSE FOR NAVIGATION



POWER PRODUCTION : 789 MW
FLOW : 143,100 cfs
TIME : 09h00
DATE : 15 DECEMBER 1976

FIGURE 4 WATER LEVELS ALONG THE BEAUHARNOIS CANAL, 15 DECEMBER 1976



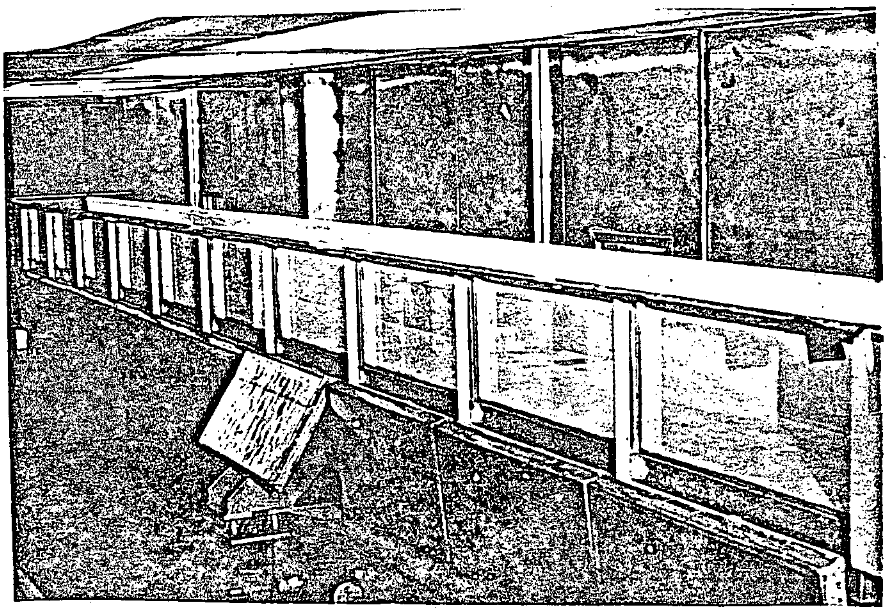


Figure 5 Recirculating Flume in CCIW Cold Room

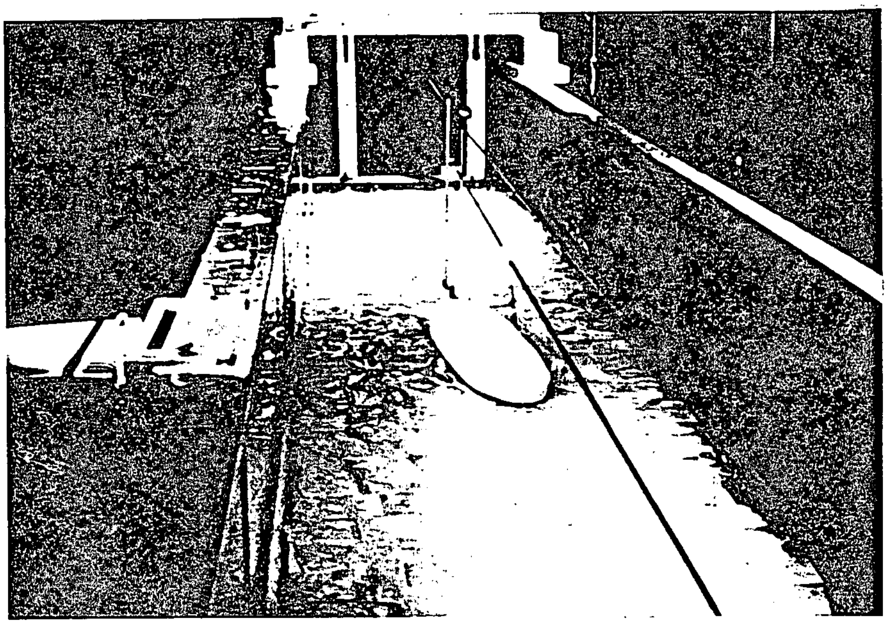


Figure 6a Towing System Guide (See Figure 12a also)

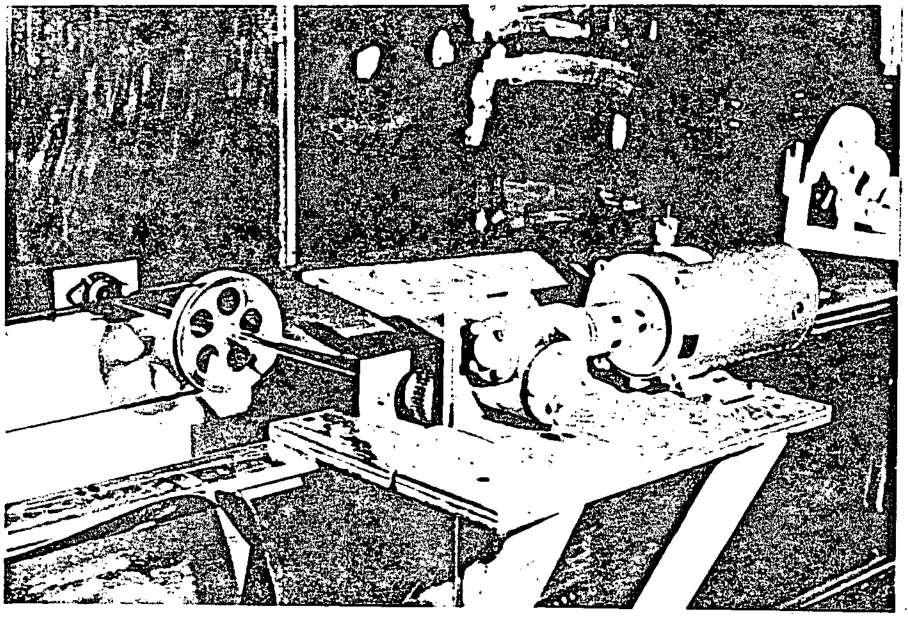


Figure 6b Towing System Drive Motor and Pulley

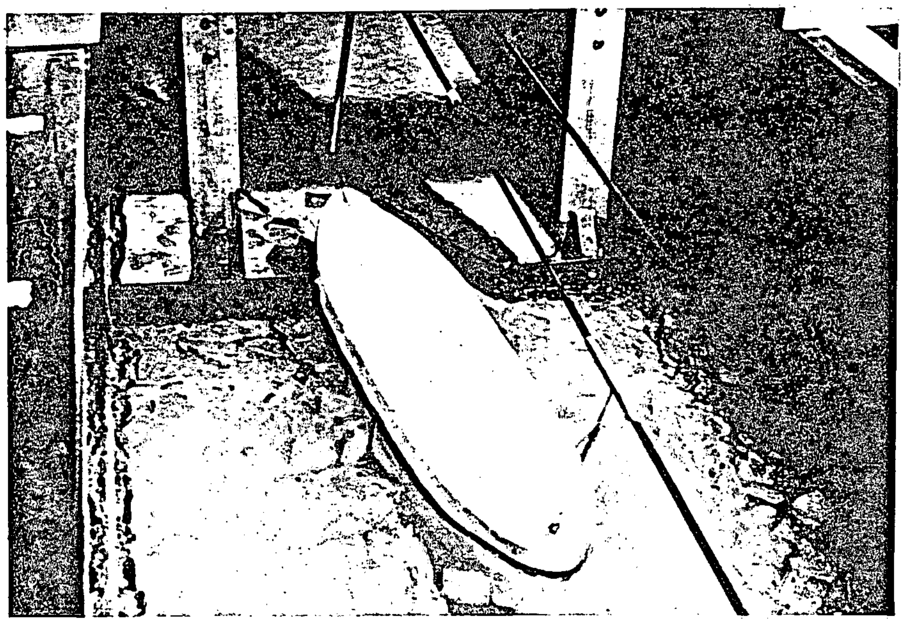


Figure 7 Ship Passing Through the Gate in the Downstream Barrier

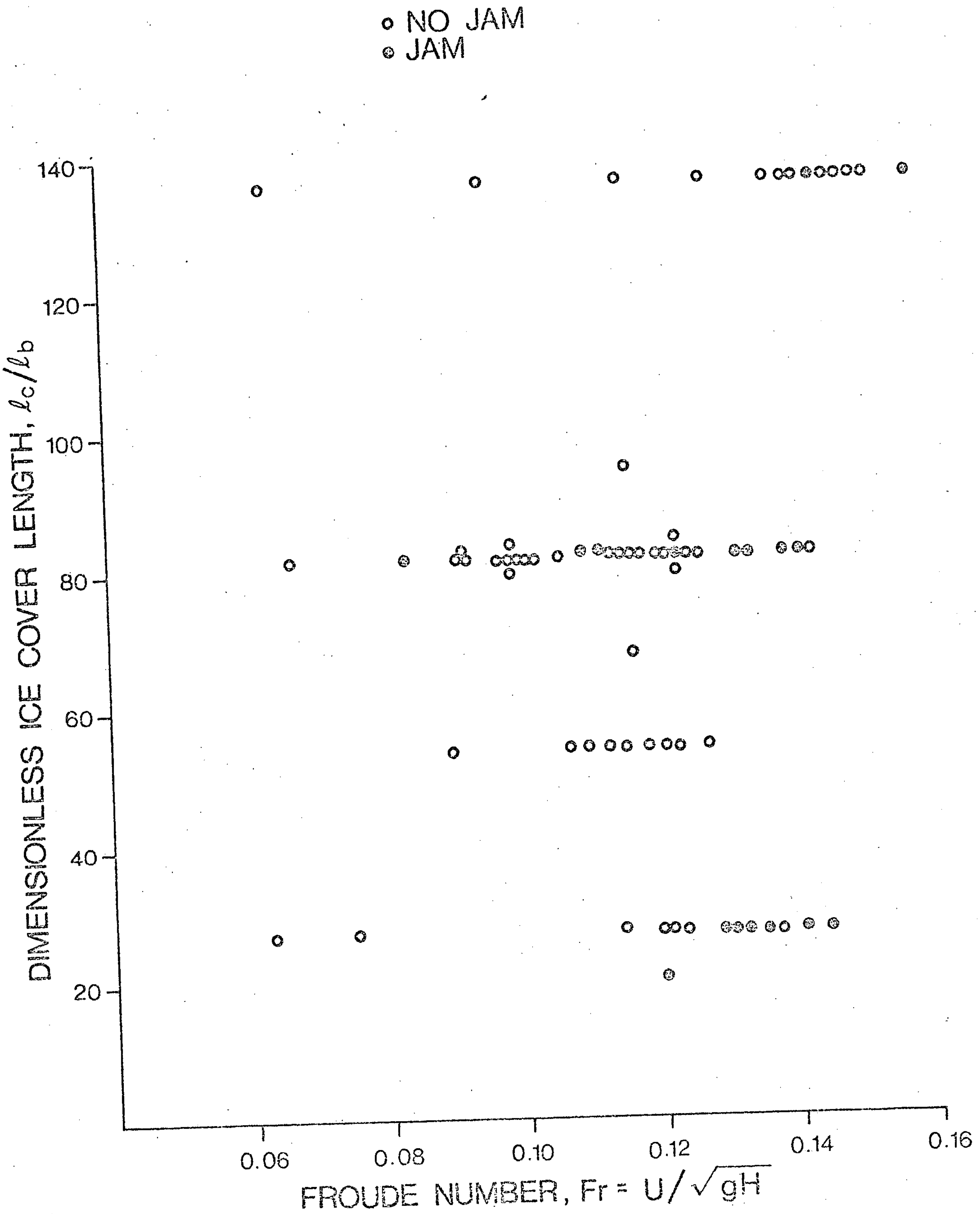


FIGURE 8 ICE COVER STABILITY WITHOUT SHIP PASSAGE

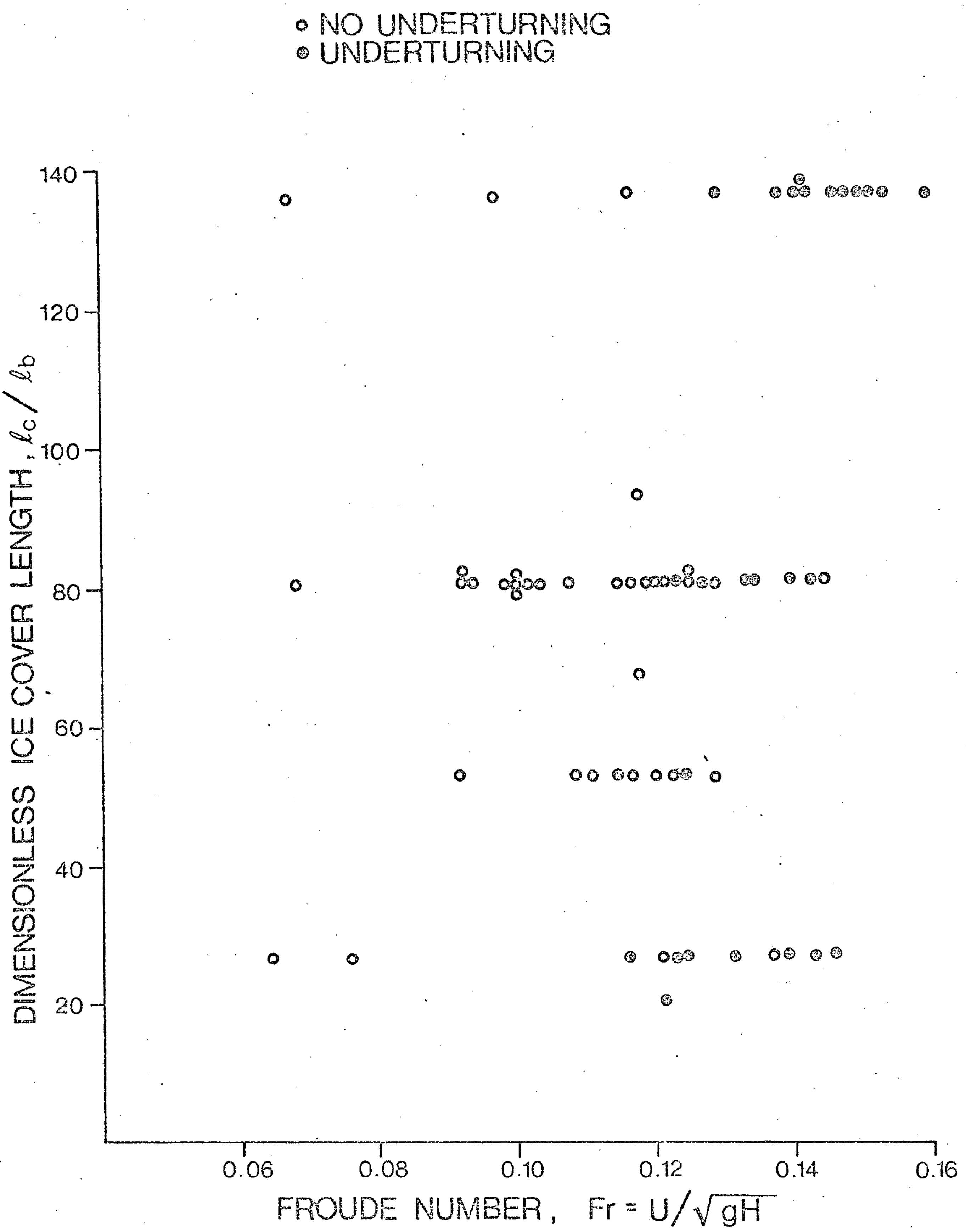


FIGURE 9 STABILITY OF THE LEADING EDGE OF THE ICE COVER

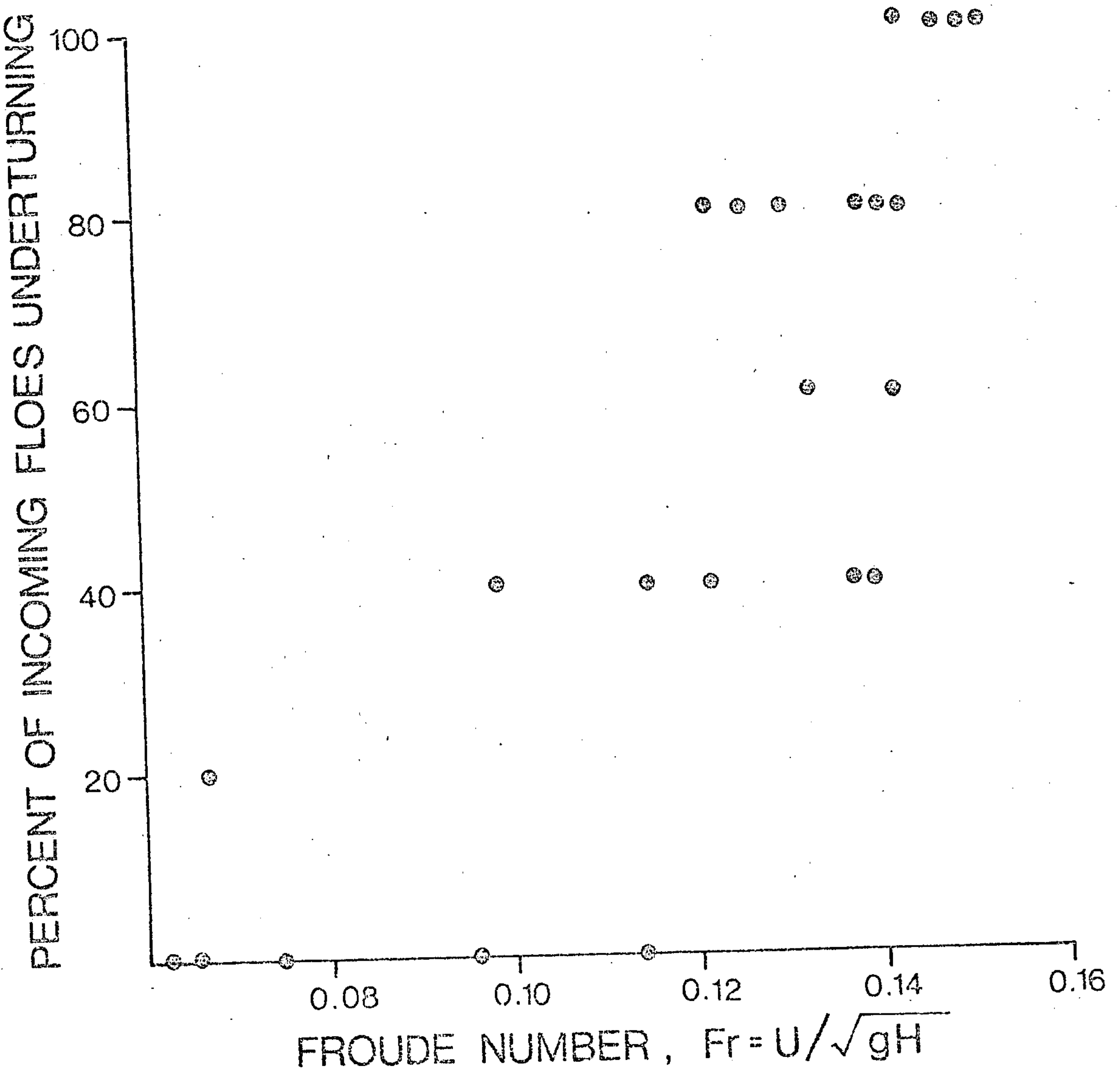


FIGURE 10 UNDER TURNING OF INCOMING ICE FLOES

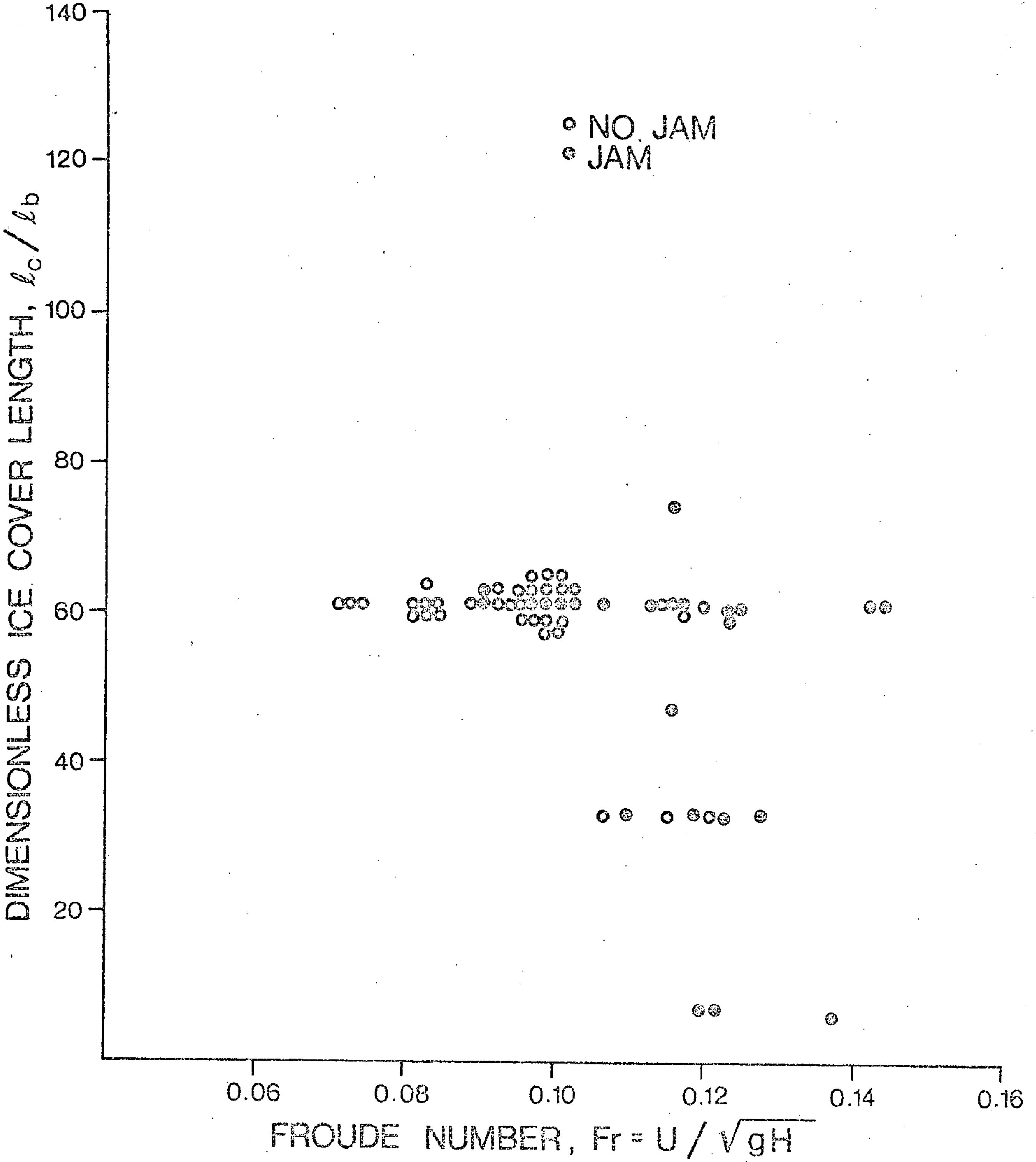


FIGURE 11 ICE COVER STABILITY WITHOUT SHIP PASSAGE WITH A DISTURBANCE

Figure 12 Series of photographs showing "no jam" conditions.

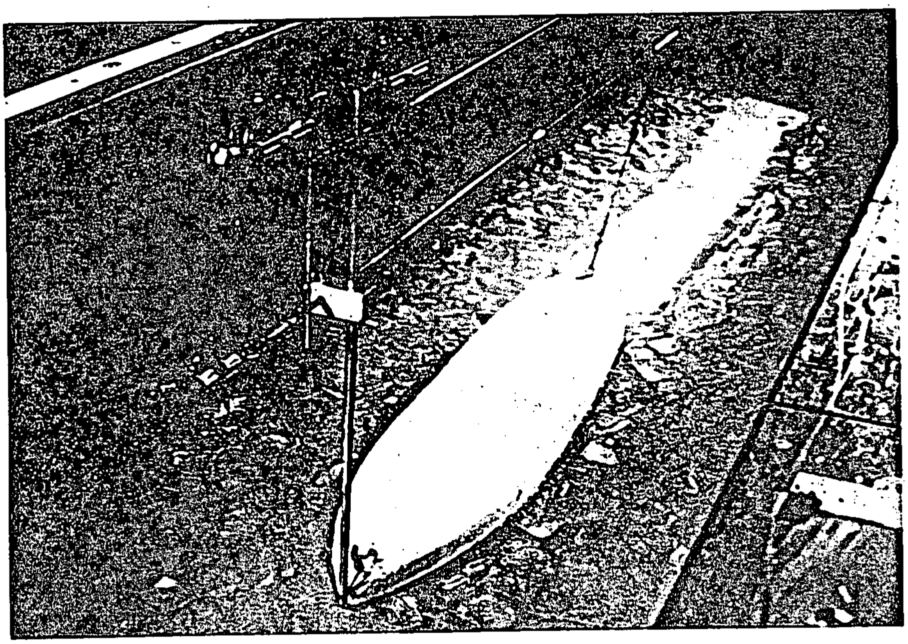


Figure 12a The ship is proceeding downstream forming a clear channel without jamming.

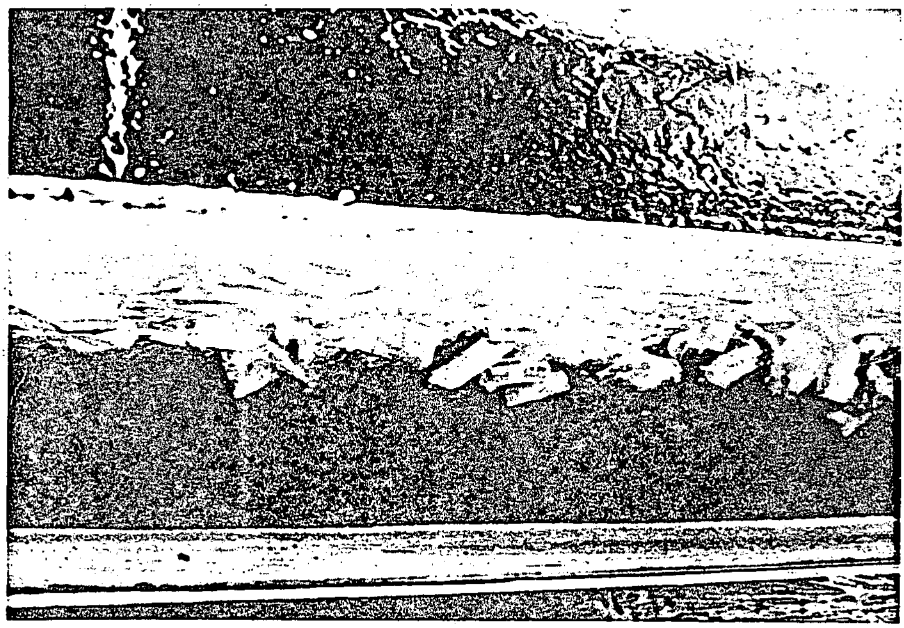


Figure 12b Floes are underturned by the ship and deposited alongside the channel.

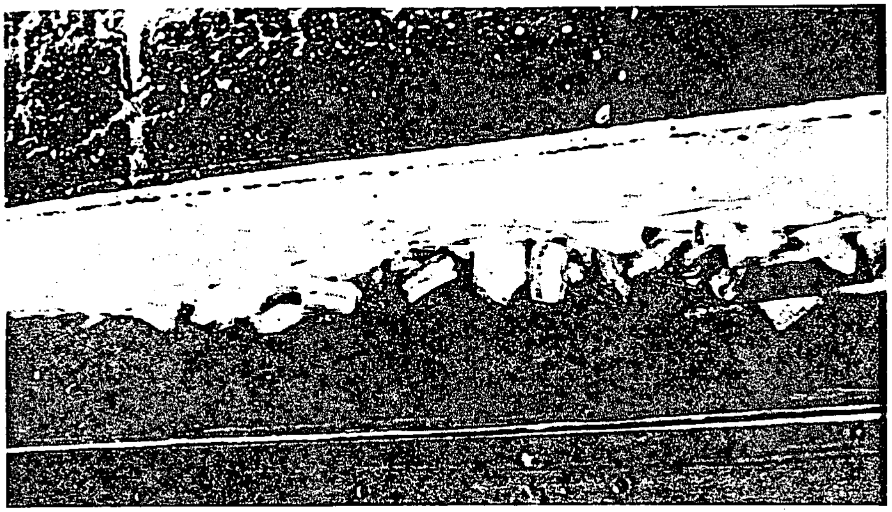


Figure 12c The ship is displacing floes, depositing them alongside the channel, breaking through the single layer ice cover without jamming. Note the border ice.

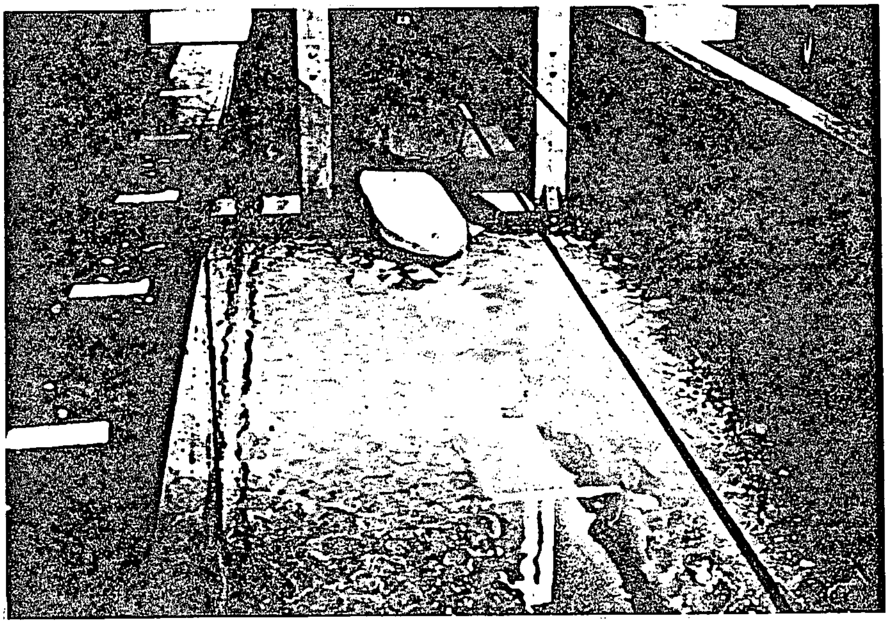


Figure 12d After clearing a channel, the ship passes through the gate in the downstream barrier not disturbing the cover other than depositing floes along the channel.

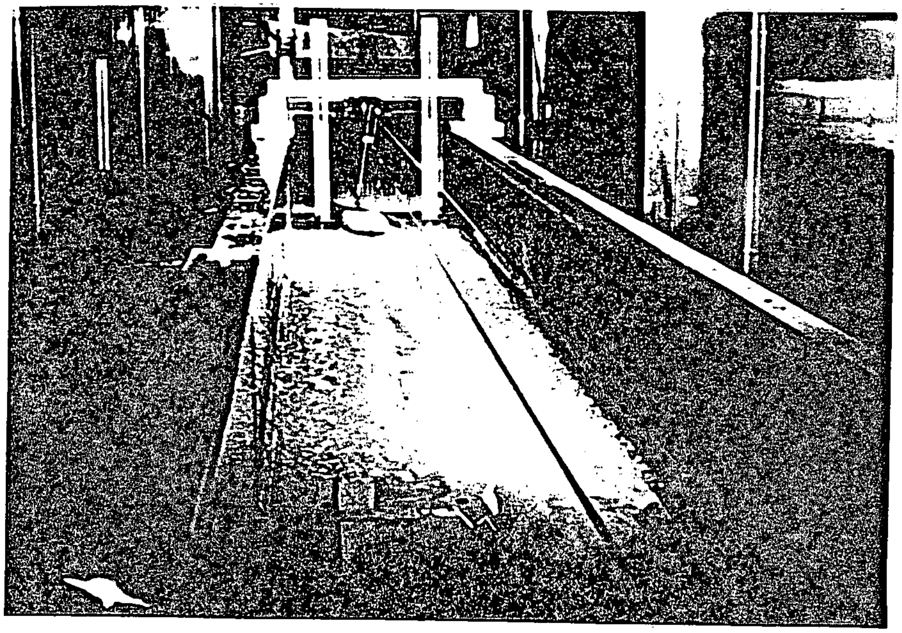


Figure 12e The ship has passed leaving a clean channel. The ice cover is the same length as before ship passage.

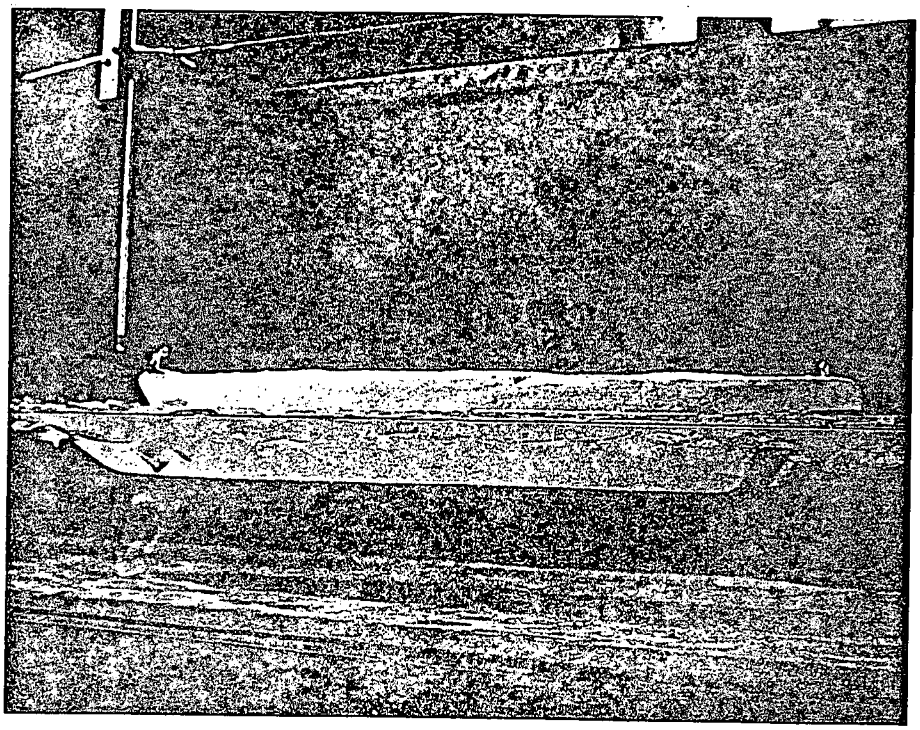


Figure 12f The ship passing through a single layer cover without jamming.

Figure 13 Series of photographs showing "heavy jam" conditions.

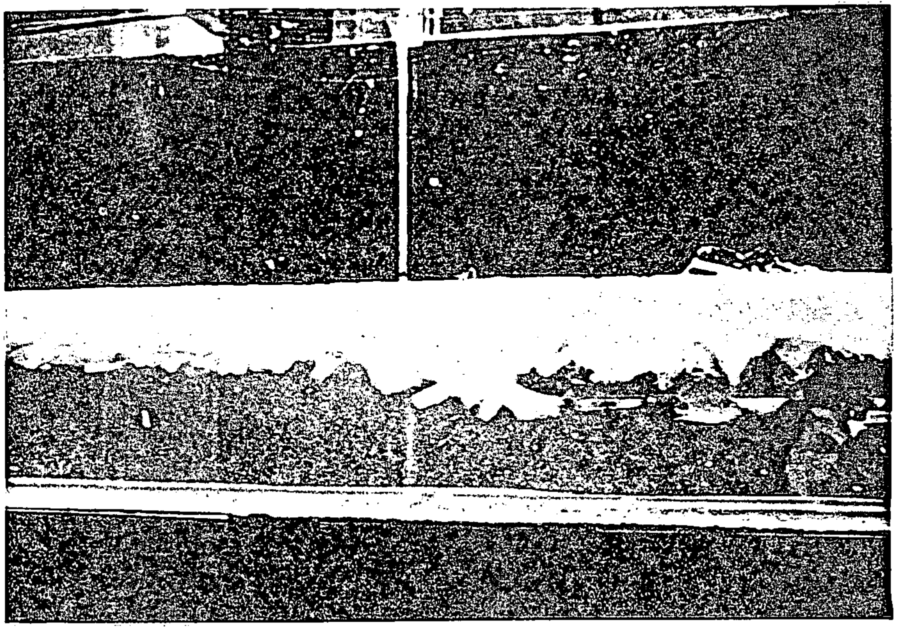


Figure 13a The cover is crushing locally beside and at the bow of the ship as well as in the cover ahead.

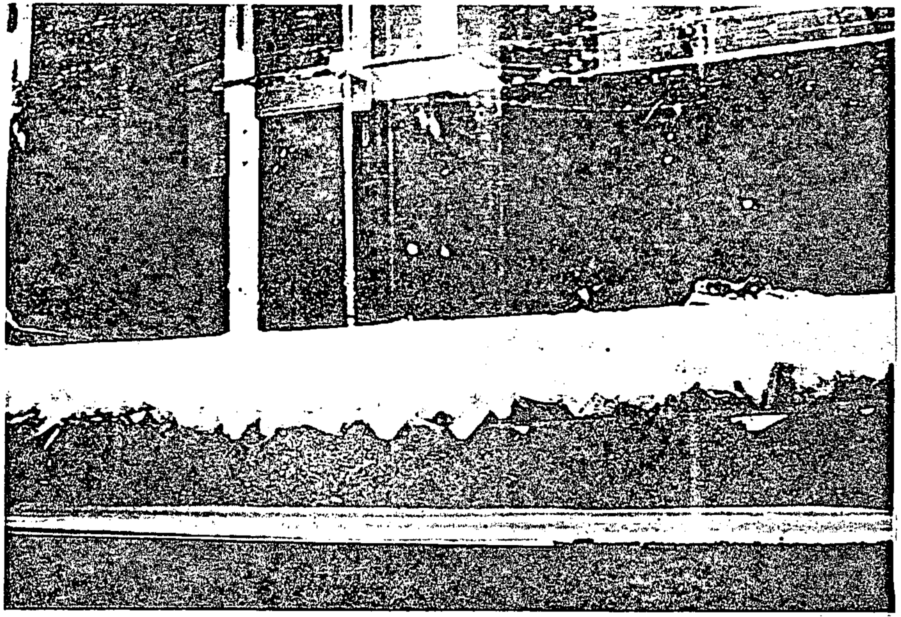


Figure 13b A very thick cover around the ship as it approaches the barrier.

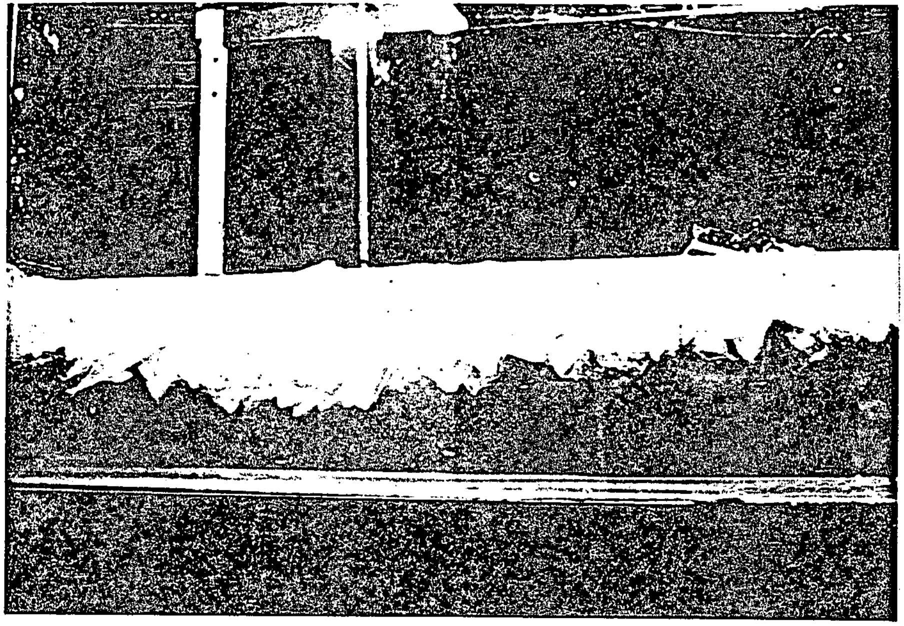


Figure 13c   As moving ice reaches the barrier, local crushing increases the ice thickness more.

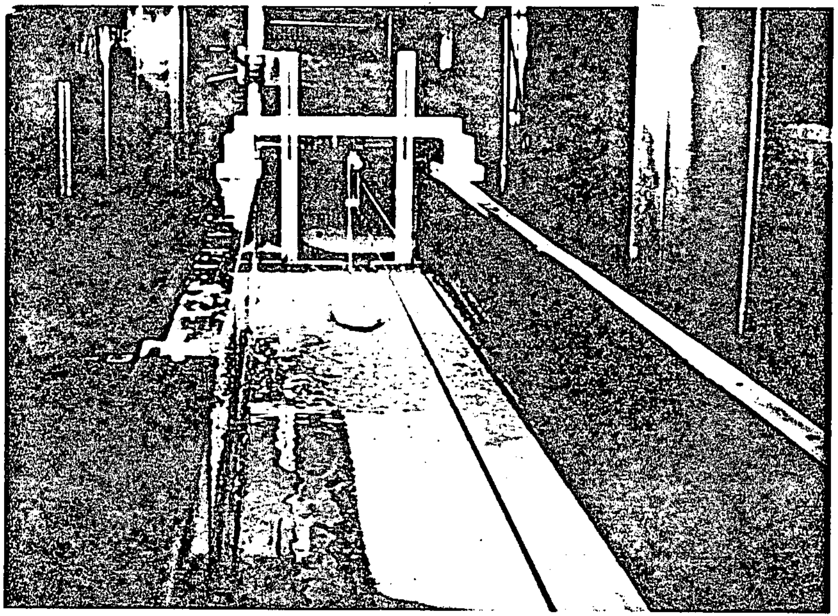


Figure 13d   The entire cover has shifted to half of the original length and thickened.

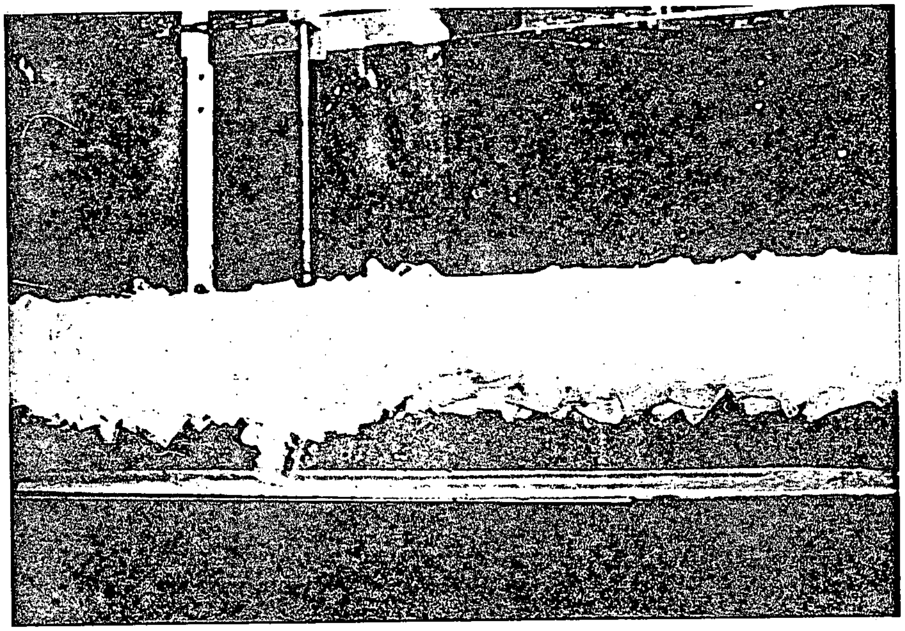


Figure 13e The ship is completely obscured by the jammed ice. The entire cover is heavily jammed to half of the flume depth and a considerable amount of ice travelled under the barrier.

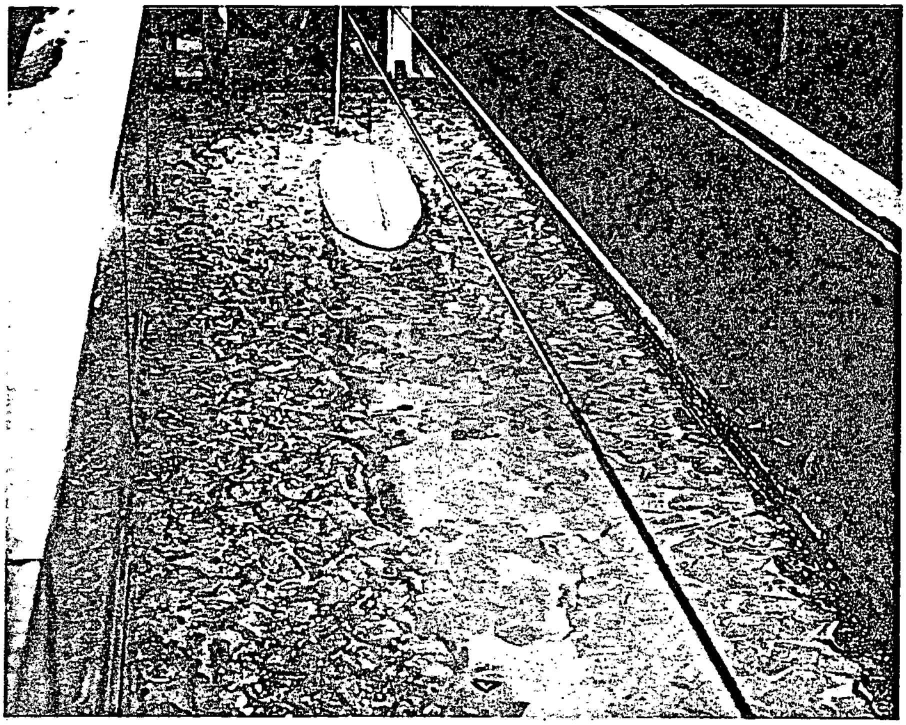


Figure 14a Ice rebounds into the channel after the ship passed. Note the compacted condition of the cover on the left hand side while the right hand side has expanded.

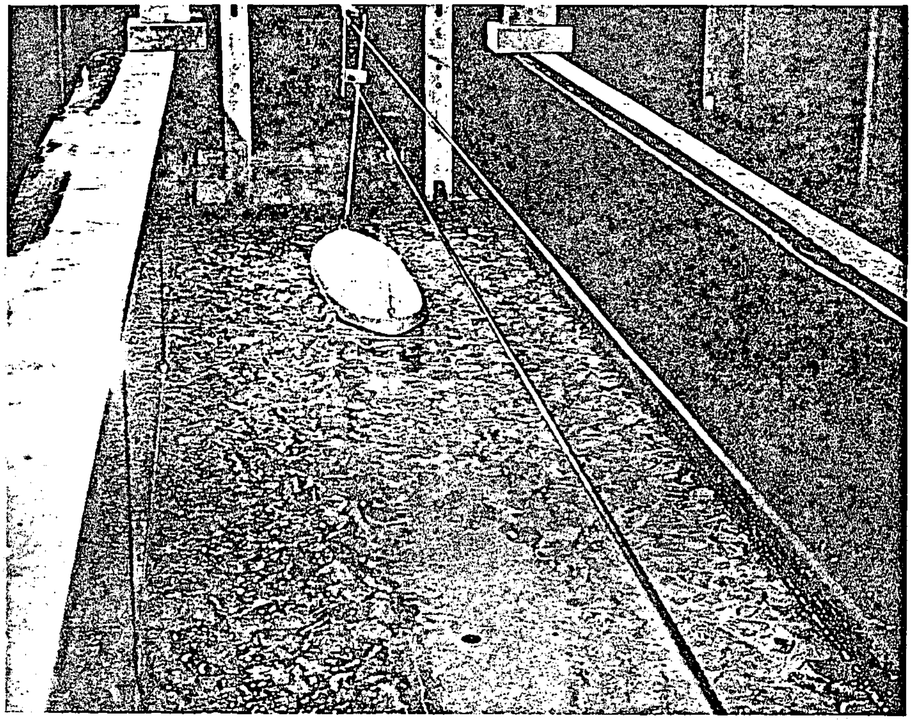


Figure 14b Ice in the channel drifts downstream to catch the ship.

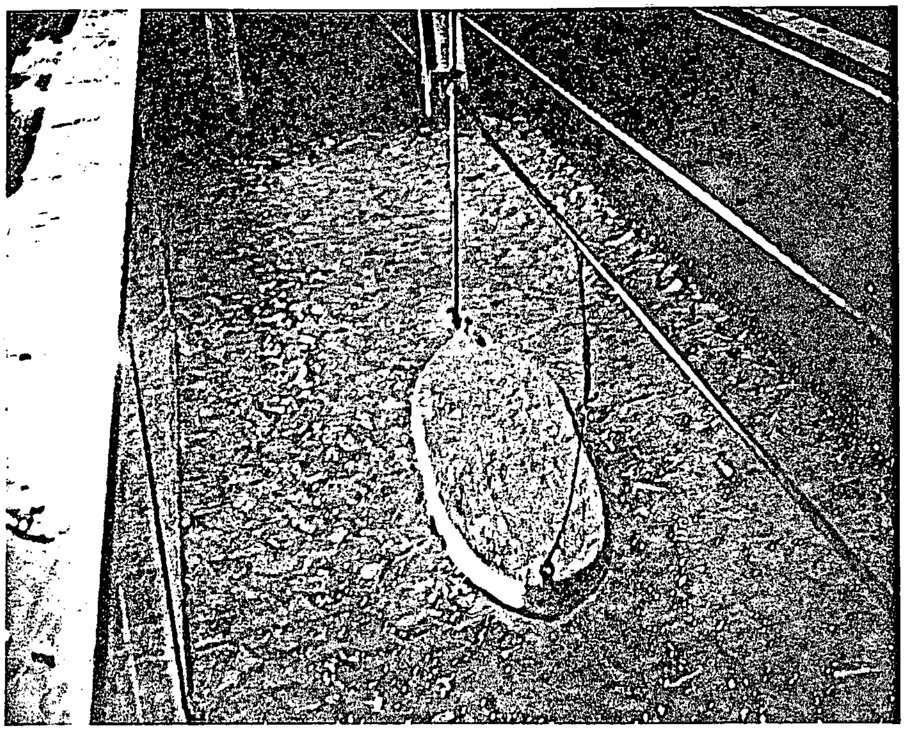


Figure 15a At low ship speed the ship inches its way through the floes which move in behind the ship and are not underturned.

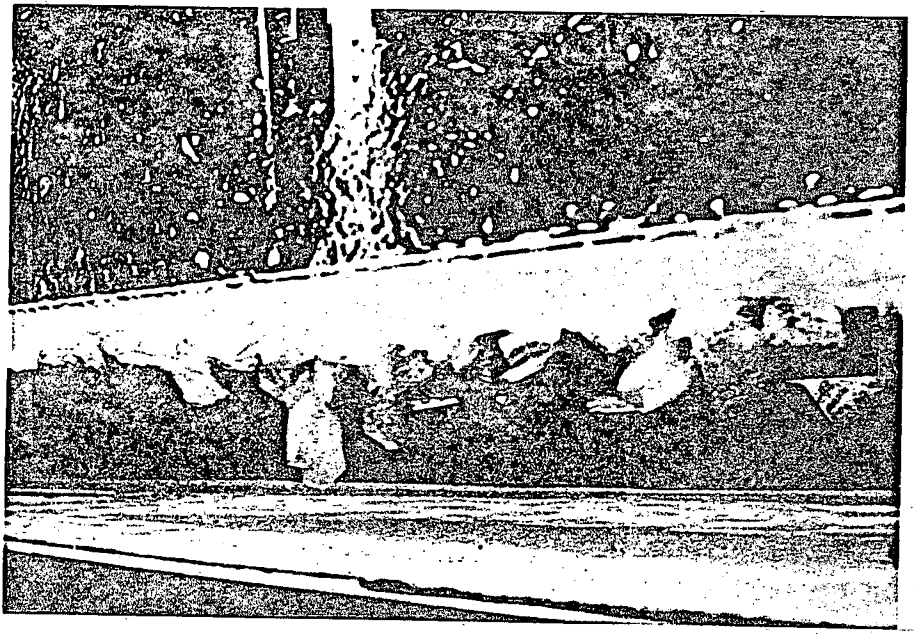


Figure 15b At high ship speed, floes are driven down violently. The cover was compressed around the bow but did not jam here.

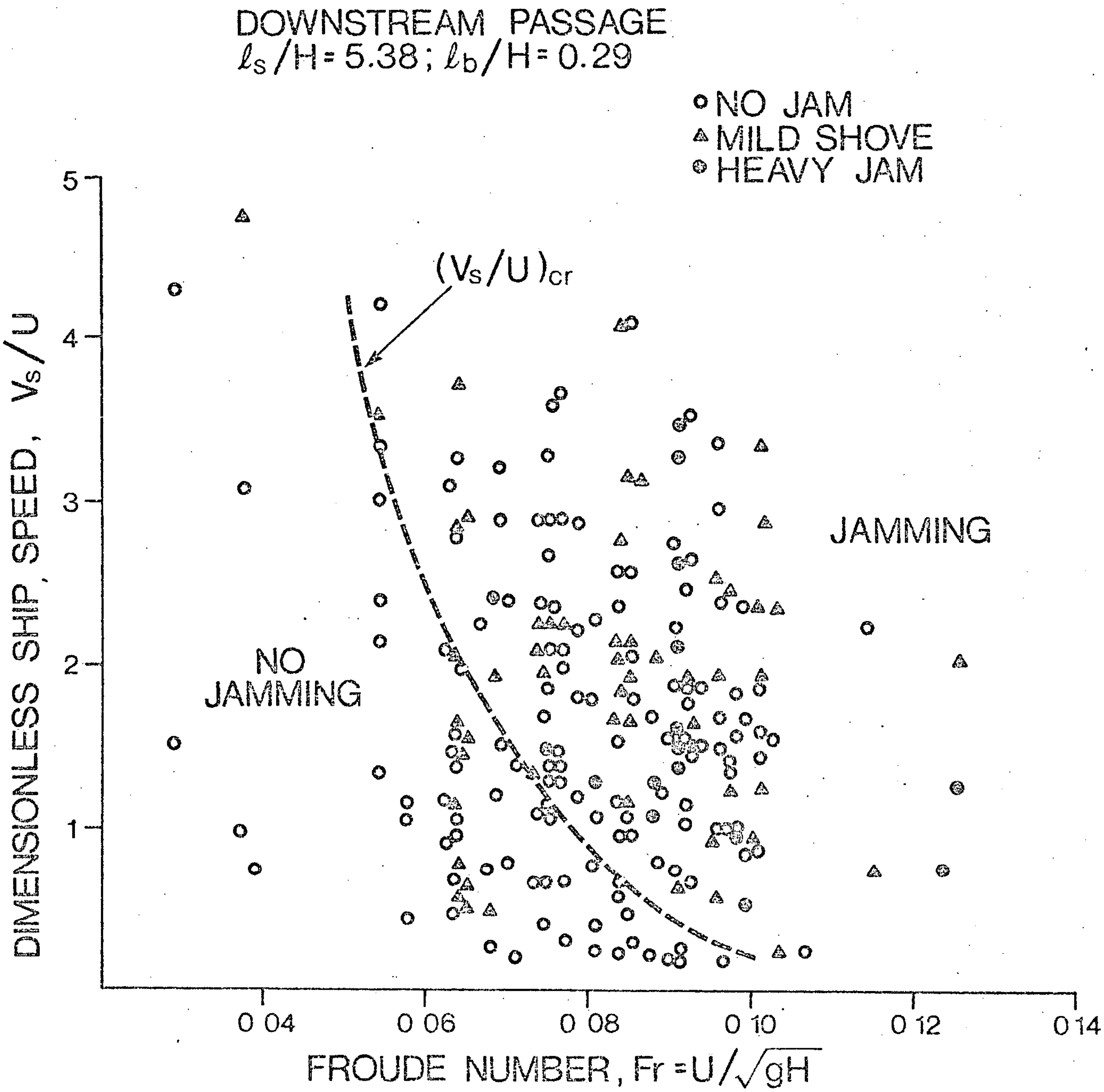


FIGURE 16 ICE JAM INITIATION FOR DOWNSTREAM SHIP PASSAGE (LARGE SHIP, SMALL ICE FLOES)

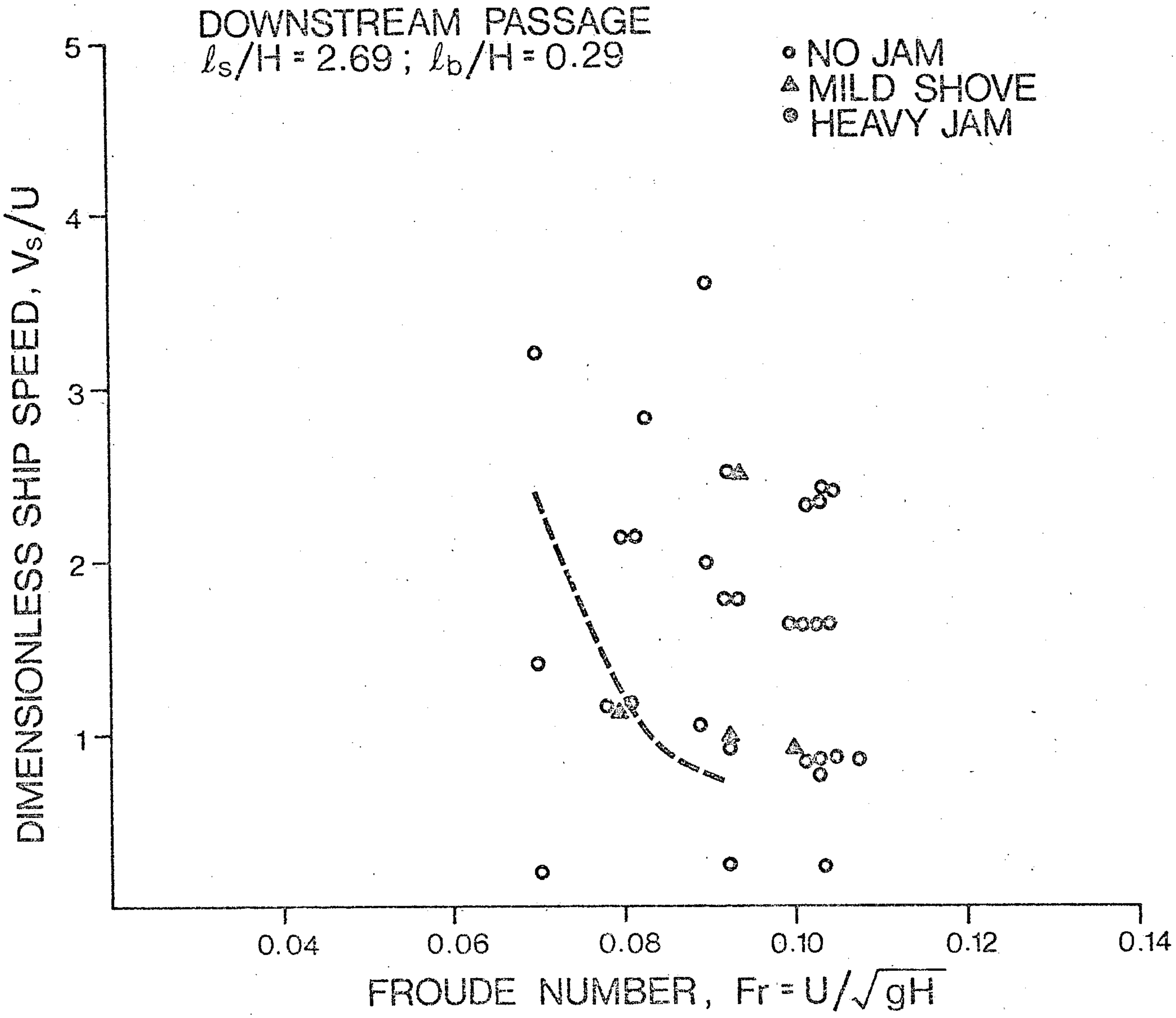


FIGURE 17 ICE JAM INITIATION FOR DOWNSTREAM SHIP PASSAGE (SMALL SHIP, SMALL ICE FLOES)

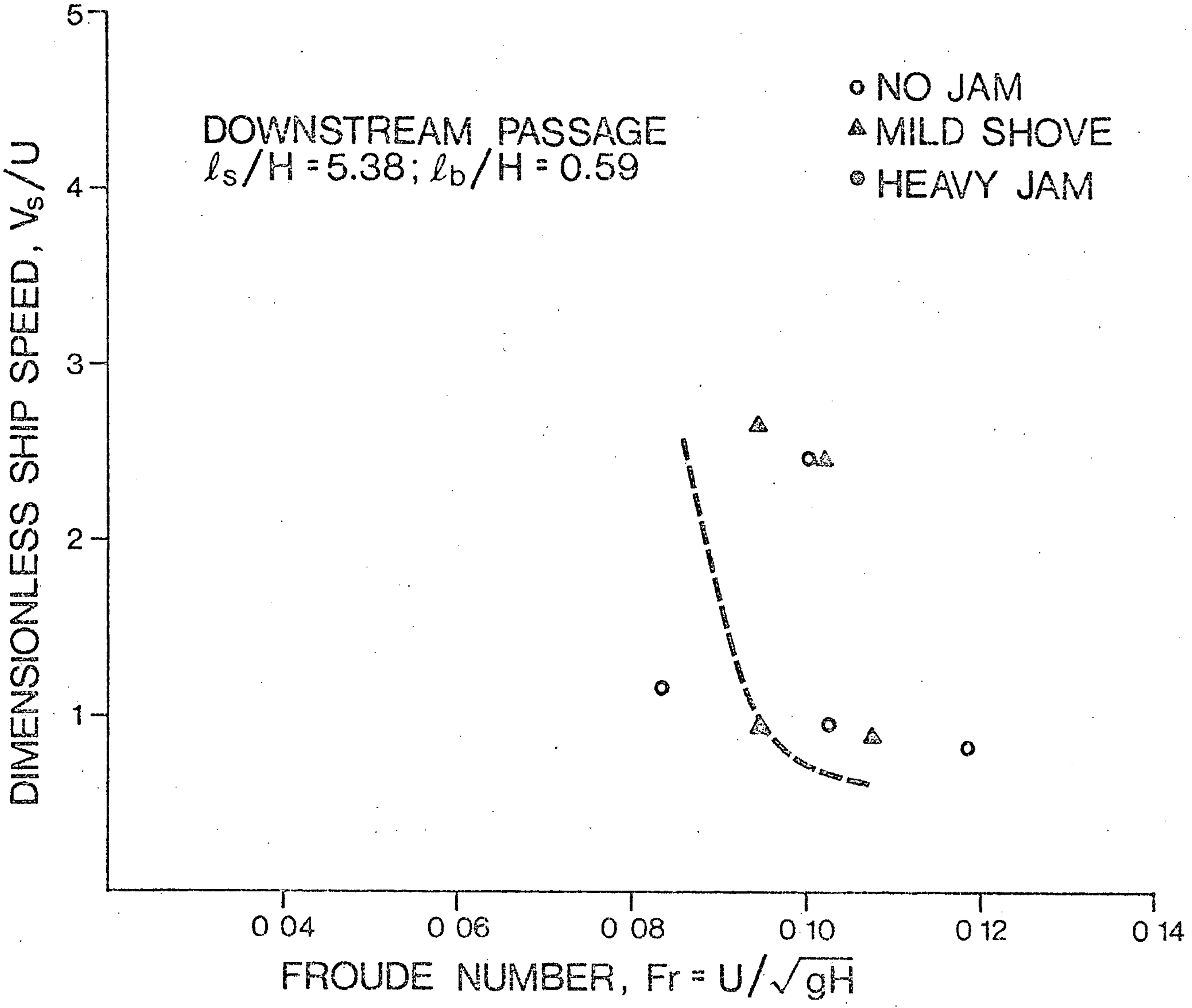


FIGURE 18 ICE JAM INITIATION FOR DOWNSTREAM SHIP PASSAGE (LARGE SHIP, LARGE ICE FLOES)

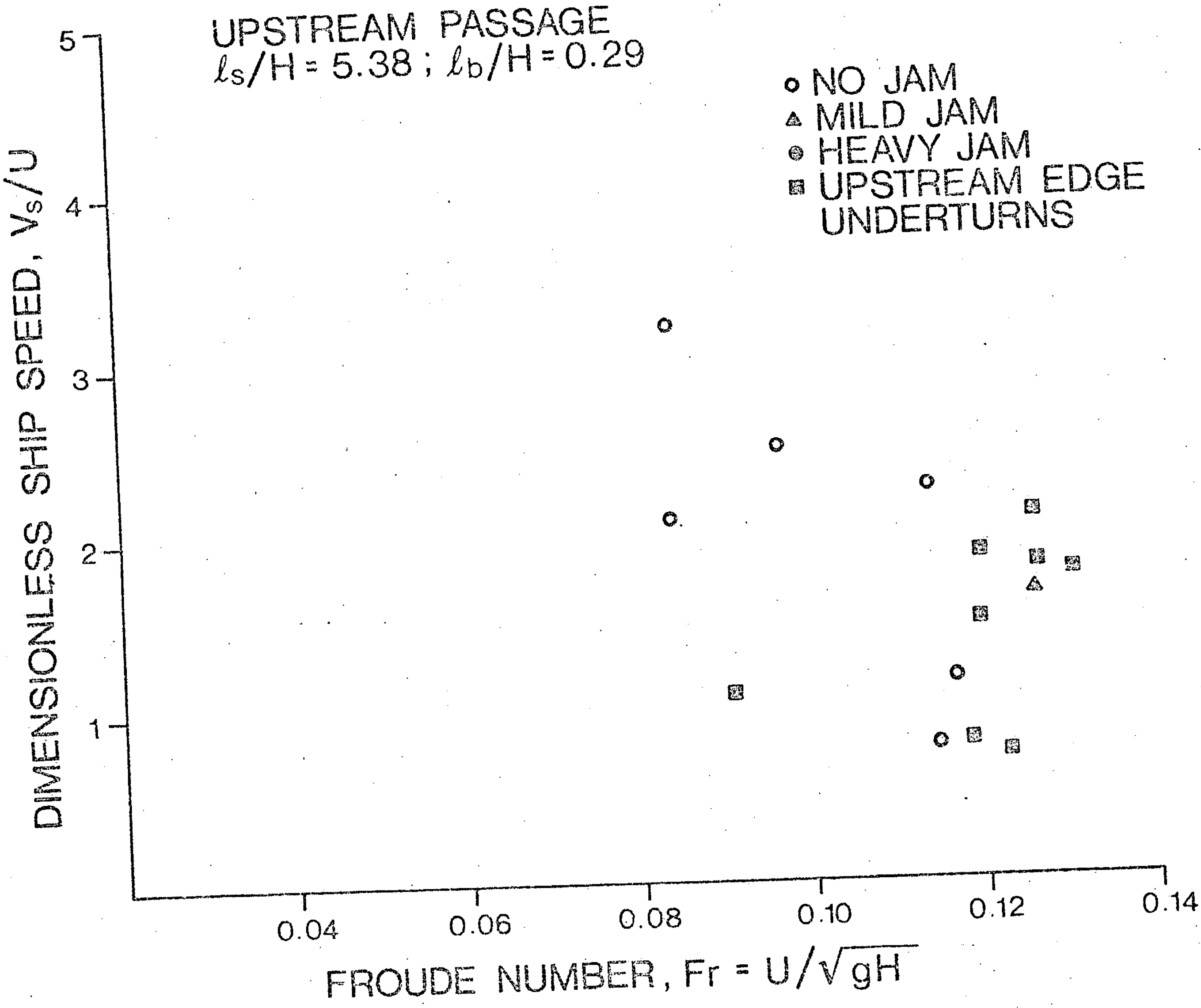


FIGURE 19 ICE JAM INITIATION FOR UPSTREAM SHIP PASSAGE (LARGE SHIP, SMALL ICE FLOES)

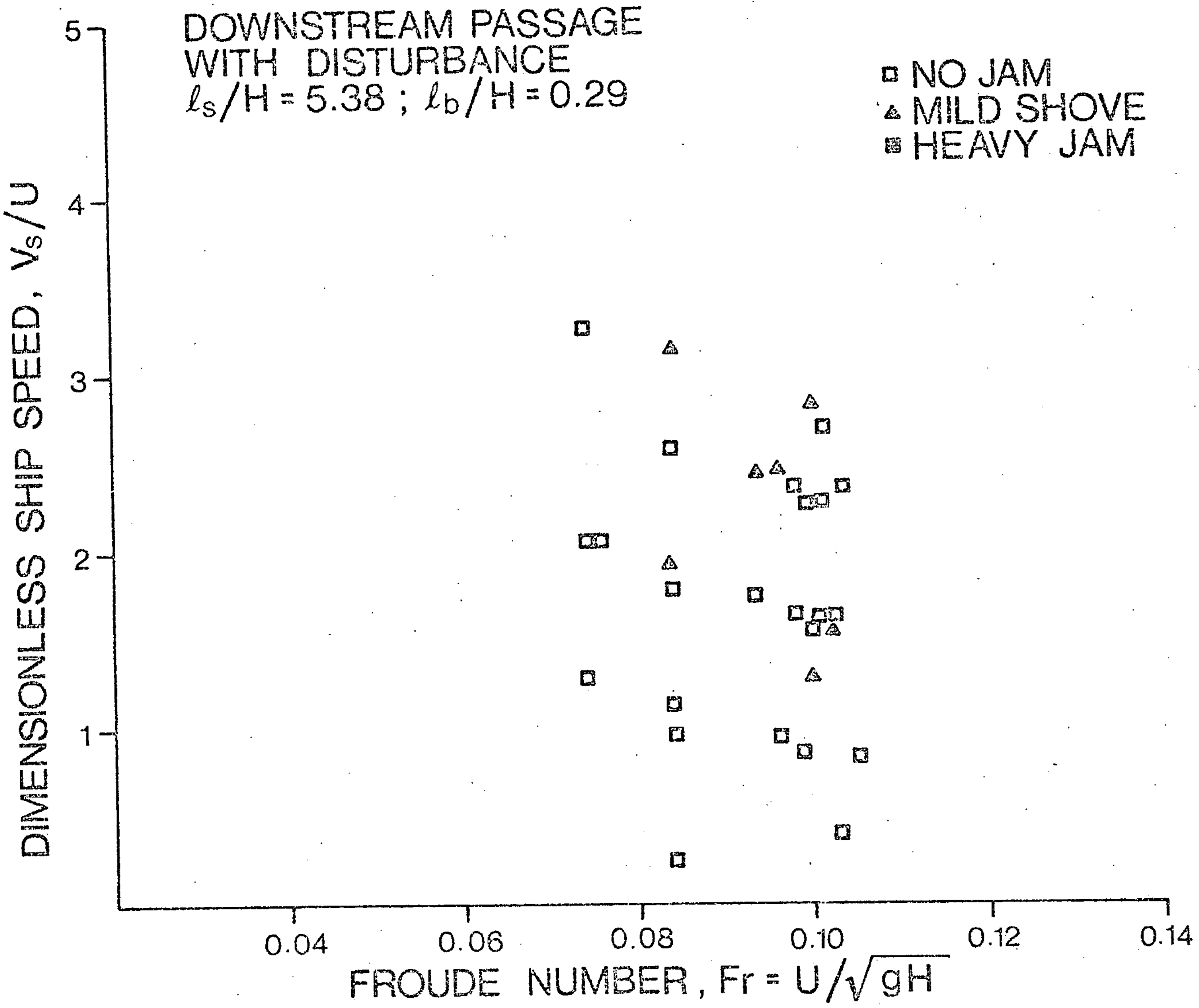


FIGURE 20 ICE JAM INITIATION FOR DOWNSTREAM SHIP PASSAGE WITH A DISTURBANCE (LARGE SHIP, SMALL ICE FLOES)

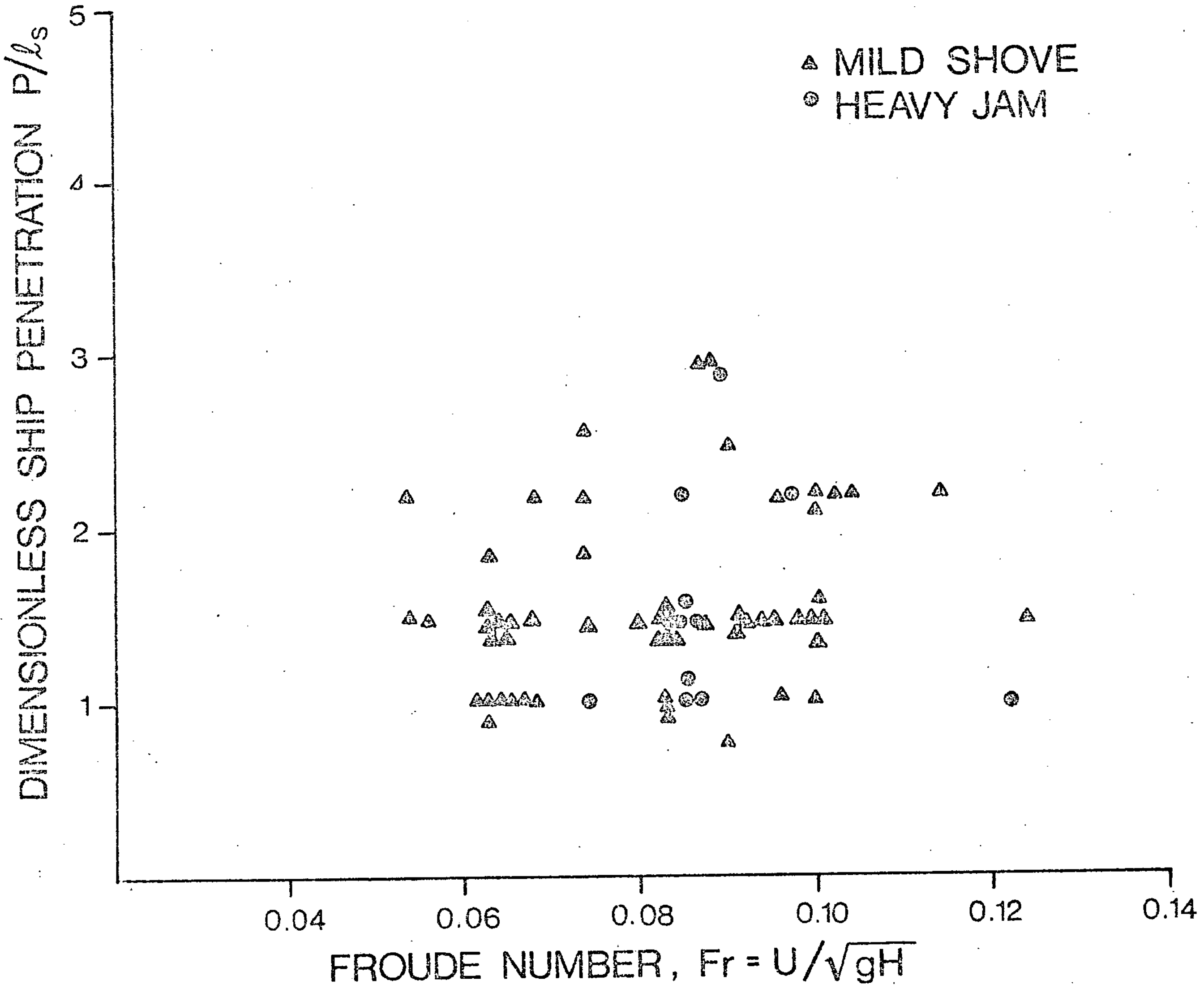


FIGURE 21 EFFECT OF FROUDE NUMBER ON DIMENSIONLESS SHIP PENETRATION, AT JAM INITIATION, DOWNSTREAM PASSAGE

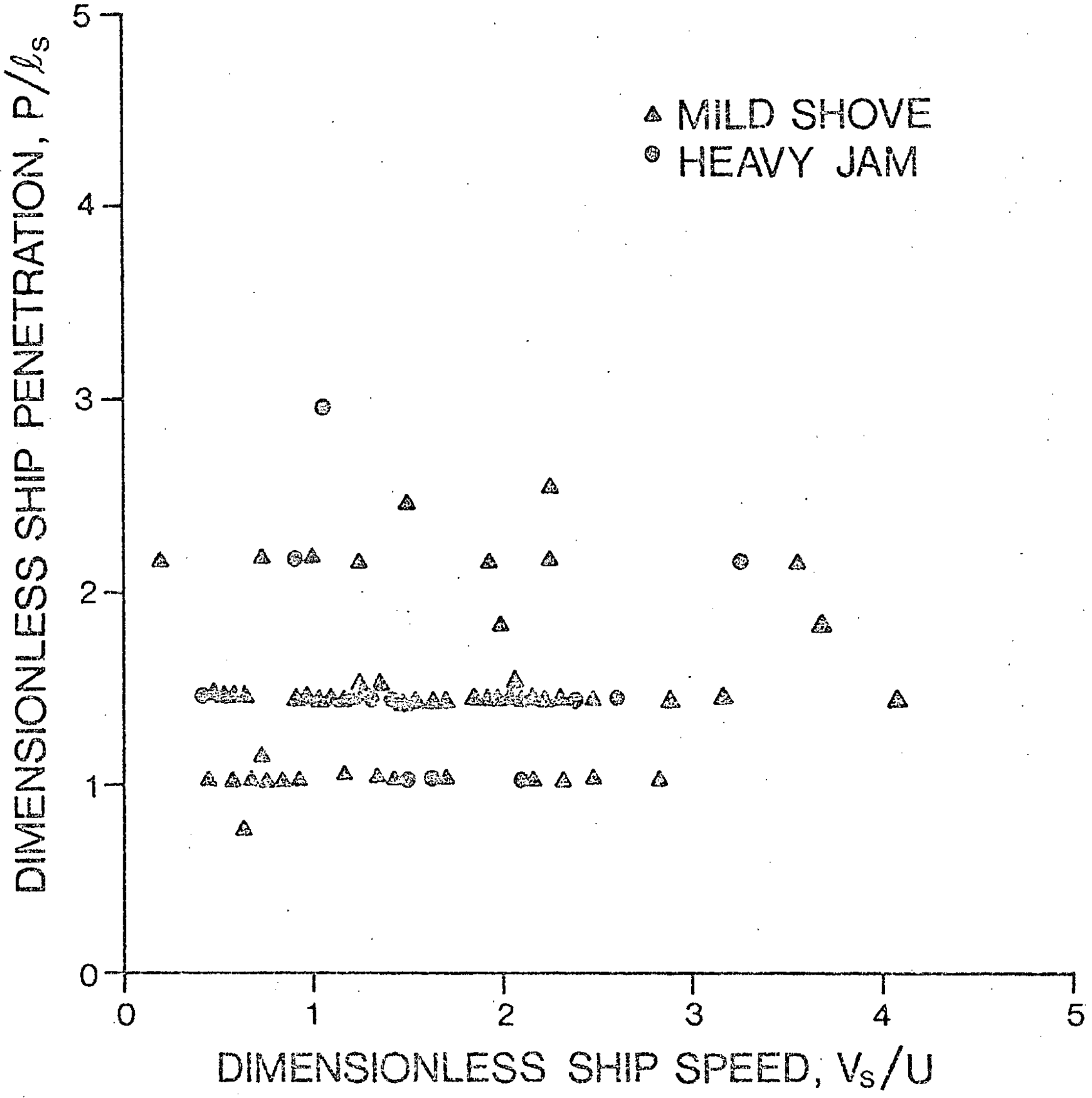


FIGURE 22 EFFECT OF DIMENSIONLESS SHIP SPEED ON DIMENSIONLESS SHIP PENETRATION, AT JAM INITIATION, DOWNSTREAM PASSAGE

APPENDIX C

TABULATED DATA

The letters and symbols in the column "Test Condition" represent the ship direction, ship model scale and ice floe sizes as outlined below:

d - downstream passage
u - upstream passage
1 - large scale ship
2 - small scale ship
s - small ice floes
l - large ice floes
* - denotes a test when a shock was delivered to the flume side walls.
ni - denotes a test when there was no border ice on the flume side walls.

Table C1

Ship Passage Ice Jam Data

Day 1

Test No.	Q (m^3/s)	H (m)	U (m/s)	Fr $U/\sqrt{gH}$	Vs (m/s)	$\frac{Vs}{U}$ (m/s)	P (m)	Jam Description (m)	Test Condition	Comments
1	.0076	.129	.098	.087	.100	1.02	2.03	medium	dls	Jammed ahead of the ship
2	.0073		.094	.084	.040	0.43	1.02	medium		Jammed ahead of the ship
3	.0076		.098	.087	.125	1.28	1.02	medium		Jammed ahead of the ship
4	.0063		.083	.074	.053	0.64	--	none		
5		.132	.087		.100	1.15	--	none		
6					.172	1.98	1.27	mild		Not a true jam-a mild shove
7					.128	1.47	0.69	heavy		
8					.089	1.02	--	none		
9					.122	1.40	--	none		
10					.128	1.47	--	none		
11					.147	1.69	--	none		
12					.172	1.98	--	none		
13					.192	2.21	1.02	mild		Not a true jam
14					.192	2.21	1.77	mild		Not a true jam
15					.192	2.21	1.52	medium		Not a true jam
16					.250	2.87	--	none		
17					.250	2.87	--	none		
18					.227	2.61	--	none		
19	.0072	.129	.090	.080	.034	0.38	--	none		
20					.098	1.09	--	none		
21	.0074		.096	.085	.128	1.39	0.69	heavy		
22					.143	1.49	0.69	heavy		
23					.154	1.60	0.69	heavy		
24					.200	2.08	1.02	heavy		
25					.250	2.60	1.52	heavy		
26					.313	3.26	?	heavy		
27					.333	3.47	1.02	medium		
28	.0073		.090	.080	.111	1.23		medium		

Table C2

Ship Passage Ice Jam Data

Day 2

Test No.	Q (m³/s)	H (m)	U (m/s)	Fr U/√g H	Vs (m/s)	Vs/U	P (m)	Jam Description (m)	Test Condition	Comments
29	.0057	.129	.075	.067	.036	0.48	0.69	mild	dls ni	No border ice-not a true jam
30	.0056		.072	.064	.036	0.50	1.02	heavy		Not a true jam
31	.0055				.104	1.44	0.69	mild		Not a true jam
32			.071	.063	.105	1.48	1.02	medium		Not a true jam
33					.082	1.15	1.02	medium		Not a true jam
34					.143	2.01	1.02	medium		Not a true jam
35					.200	2.82	0.69	mild		Not a true jam
36					.263	3.70	1.27	mild		Not a true jam
37					.042	0.59	0.69	mild		Not a true jam
38	.0056		.072	.064	.111	1.54	1.02	mild		Not a true jam
39					.208	2.89	1.02	mild		Not a true jam
40					.045	0.63	0.69	mild		Not a true jam

Table C3

Ship Passage Ice Jam Data

Day 3

Test No.	Q (m^3/s)	H (m)	U (m/s)	Fr $U/\sqrt{g H}$	Vs (m/s)	$\frac{Vs}{U}$	P (m)	Jam Description (m)	Test Condition	Comments
41	.0025	.129	.030	.029	.046	1.53	--	none	dls	
42					.128	4.27	--	none		
43					.208	6.93	--	none		
44	.0052		.070	.068	.052	0.74	0.69	mild		Not a true jam
45					.083	1.19	--	none		
46					.104	1.49	--	none		
47					.135	1.93	1.52	mild		Not a true jam
48					.167	2.39	1.02	medium		
49					.200	2.86	--	none		
50					.222	3.17	--	none		
51					.167	2.39	--	none		
52					.053	0.76	--	none		
53	.0056		.072	.063	.048	0.67	--	none		
54					.078	1.08	--	none		
55					.104	1.44	--	none		Almost jammed
56					.143	1.99	--	none		
57	.0057		.074	.066	.167	2.26	--	none		
58	.0056		.072	.063	.200	2.78	--	none		
59					.233	3.24	--	none		
60					.108	1.50	--	none		
61					.111	1.54	?	mild		Not a true jam
62					.056	0.78	0.69	mild		Not a true jam

Table C4

Ship Passage Ice Jam Data

Day 4

Test No.	Q (m³/s)	H (m)	U (m/s)	Fr $U/\sqrt{gH}$	Vs (m/s)	$\frac{V_s}{U}$	P (m)	Jam Description (m)	Test Condition	Comments
63	.0036	.142	.043	.037	.042	0.98	--	none	dls ni	No border ice
64					.132	3.07	--	none		
65					.204	4.74	?	mild		Not a true jam
66	.0051		.063	.054	.086	1.37	--	none	dls	Border ice has formed
67					.152	2.41	--	none		Compact ice cover
68					.222	3.52	1.52	mild		Not a true jam
69					.208	3.30	--	none		
70					.189	3.00	--	none		Ice cover compressed to side
71					.263	4.17	--	none		
72					.135	2.14	--	none		
73	.0081	.131	.105	.089	.018	0.17	--	none		
74	.0065		.083	.073	.055	0.66	--	none		
75					.086	1.04	--	none		
76					.109	1.31	1.02	mild		Not a true jam
77					.172	2.07	1.02	mild		Not a true jam
78					.238	2.87	--	none		
79					.196	0.79	--	none		
80	.0053	.130	.070	.062	.055	2.04	--	none		
81					.143	3.04	--	none		
82					.213	1.19	--	none		
83					.083	0.56	--	none		
84	.0074	.132	.094	.083	.053	0.95	--	none		
85					.089	1.52	--	none		
86					.143	1.83	1.02	none		
87					.172	2.17	1.02	mild		Not a true jam
88					.204			mild		Not a true jam

Table C5

Ship Passage Ice Jam Data

Day 5

Test No.	Q (m^3/s)	H (m)	U (m/s)	Fr $U/\sqrt{gH}$	Vs (m/s)	$\frac{Vs}{U}$	P (m)	Jam Description (m)	Test Condition	Comments
89	.0049	.129	.063	.057	.029	0.46	--	none	dls	
90					.071	1.13	--	none		
91					.067	1.06	--	none		
92	.0055		.071	.063	.035	0.49	--	none		
93					.065	0.92	--	none		
94	.0061	.131	.078	.067	.018	0.23	--	none		
95					.056	0.72	--	none		
96	.0067		.086	.076	.025	0.29	--	none		
97			.085	.075	.053	0.62	--	none		
98					.161	1.89	--	none		
99					.192	2.26	--	none		
100					.303	3.56	--	none		
101			.086	.076	.312	3.63	--	none		
102					.118	1.37	--	none		
103	.0073	.132	.092	.080	.019	0.21	--	none		
104					.062	0.67	--	none		
105					.161	1.75	--	none		
106					.204	2.22	--	none		Ice cover compressed to sides but re-expanded
107	.0078		.098	.087	.019	0.19	--	none		
108					.077	0.79	--	none		
109					.119	1.21	--	none		
110					.164	1.67	--	none		
111					.200	2.04	?	mild		Not a true jam

Table C6

Ship Passage Ice Jam Data

Day 6

Test No.	Q (m^3/s)	H (m)	U (m/s)	Fr $U/\sqrt{gH}$	Vs (m/s)	$\frac{V_s}{U}$	P (m)	Jam Description (m)	Test Condition	Comments
112	.0074	.129	.095	.083	.020	0.21	--	none	dls	
113					.063	0.66	--	none		
114					.109	1.15	--	none		
115					.156	1.64	0.69	mild		Not a true jam
116					.111	1.17	0.69	mild		Not a true jam
117					.192	2.02	1.02	mild		Not a true jam
118					.200	2.11	0.69	medium		Not a true jam
119					.263	2.77	--	none		
120					.385	4.05	1.02	mild		Not a true jam-just shoved to compact
121					.385	4.05	--	none		
122					.192	2.02	--	none		
123					.238	2.51	--	none		
124					.222	2.34	--	none		
125					.156	1.64	1.02	mild		Not a true jam
126	.0080	.130	.103	.090	.018	0.17	--	none		
127					.063	0.61	0.51	mild		Mild shove stopped before the ship passed
128					.074	0.72	--	none		
129					.156	1.51	--	none		
130					.156	1.51	--	none		
131					.192	1.86	--	none		
132					.227	2.20	--	none		
133					.278	2.70	--	none		
134	.0081		.104	.091	.156	1.50	1.70	mild		Not a true jam
135					.200	1.92	1.02	mild		Not a true jam
136					.256	2.46	--	none		
137					.192	1.85	--	none		

Table C7

Ship Passage Ice Jam Data

Day 7

Test No.	Q (m^3/s)	H (m)	U (m/s)	Fr $U/\sqrt{g H}$	Vs (m/s)	$\frac{Vs}{U}$	P (m)	Jam Description (m)	Test Condition	Comments
138	.0080	.129	.103	.092	.025	0.24	--	none	d1s	
139	.0079		.102	.091	.069	0.68	--	none		Cover compacted to sides
140					.102	1.00	--	none		
141					.147	1.44	--	none		Compact cover did not compres to flume walls
142					.182	1.78	--	none		
143					.278	2.73	--	none		
144					.357	3.50	--	none		
145					.192	1.88	--	none		
146					.167	1.64	1.02	mild		Almost stopped
147					.116	1.14	--	none		
148	.0084	.131	.107	.095	.018	0.17	--	none		Thick ice cover
149					.065	0.61	1.02	mild		Stop and start shove
150					.106	0.99	--	none		
151					.152	1.42	--	none		Ice pushed to the sides
152					.179	1.67	--	none		
153					.270	2.52	?	mild		Shoved
154					.313	2.93	--	none		
155					.357	3.34	--	none		
156					.250	2.34	--	none		
157					.208	1.94	?	mild		Not a true jam
158	.0068	.129	.088	.078	.192	2.18	--	none		
159					.156	1.77	--	none		
160					.104	1.18	--	none		
161					.250	2.84	--	none		

Table C8

Ship Passage Ice Jam Data

Day 8

Test No.	Q (m^3/s)	H (m)	U (m/s)	Fr $U/\sqrt{gH}$	Vs (m/s)	$\frac{Vs}{U}$	P (m)	Jam Description (m)	Test Condition	Comments
162	.0092	.135	.114	.102	.024	0.21	1.52	mild	dls	Not a true jam
163	.0090		.111	.098	.057	0.51	1.02	medium		
164	.0088		.109	.094	.102	0.94	0.69	mild		Not a true jam, upstream edge was unstable
165	.0090		.111	.097	.100	0.90	1.52	heavy		
166	.0089		.110	.096	.156	1.42	--	none		
167					.135	1.23	1.52	mild		Not a true jam
168	.0091	.134	.113	.099	.104	0.92	1.02	mild		Not a true jam
169	.0089		.111	.096	.143	1.29	--	none		
170	.0090		.112	.097	.175	1.56	--	none		
171					.200	1.79	--	none		
172	.0092		.114	.100	.227	1.99	1.02	mild		Mild shove
173					.263	2.31	0.69	mild		Mild shove
174					.385	3.38	?	mild		Mild shove
175					.321	2.82	?	medium	*	Mild shove
176					.263	2.31	1.02	mild		Mild shove
177					.208	1.82	--	none		
178					.175	1.54	--	none		
179					.175	1.54	--	none	*	
180					.139	1.22	1.02	mild	*	Not a true jam
181					.100	0.88	--	none		
182					.161	1.41	--	none		
183	.0098		.122	.105	.024	0.20	--	none		

Table C9

Ship Passage Ice Jam Data

Day 9

Test No.	Q (m^3/s)	H (m)	U (m/s)	Fr $U/\sqrt{g H}$	Vs (m/s)	$\frac{Vs}{U}$	P (m)	Jam Description (m)	Test Condition	Comments
184	.0061	.129	.079	.070	.015	0.19	--	none	d2s	Small ship does not displace ice like the larger model
185					.109	1.38	--	none		
186					.250	3.16	--	none		
187	.0073		.094	.083	.111	1.18	--	none		
188					.263	2.80	--	none		
189	.0078		.101	.090	.357	3.53	--	none		
190					.200	1.98	--	none		
191	.0086	.135	.106	.092	.024	0.23	--	none		
192					.098	0.92	--	none		
193					.185	1.75	--	none		
194					.185	1.75	--	none	*	
195					.263	2.48	--	none		
196					.263	2.48	1.02	mild	*	Stop and start shoving
197	.0095	.134	.118	.103	.025	0.21	--	none		
198					.100	0.85	--	none	*	
199					.100	0.85	--	none		
200					.278	2.36	--	none	*	
201					.278	2.36	--	none		
202					.189	1.60	--	none	*	
203	.0099	.140	.118	.101	.189	1.60	--	none		
204					.189	1.60	--	none	*	
205					.189	1.60	--	none	*	
206					.270	2.29	--	none		
207					.270	2.29	--	none	*	Started to shove and stopped
208					.096	0.81	--	none		
209	.0106	.140	.126	.107	.106	0.84	--	none		
210	.0108		.129	.103	.100	0.78	--	none	*	Ice was pushed to the sides

* denotes that a shock was delivered to the side of the flume

Table C10

Ship Passage Ice Jam Data

Day 10

Test No.	Q (m^3/s)	H (m)	U (m/s)	Fr $U/\sqrt{g H}$	Vs (m/s)	$\frac{Vs}{U}$	P (m)	Jam Description (m)	Test Condition	Comments
211	.0064	.129	.083	.074	.032	0.39	--	none	dls	
212					.106	1.28	--	none	*	
213					.106	1.28	--	none	*	
214					.172	2.07	--	none	*	
215					.172	2.07	--	none	*	
216					.270	3.25	--	none	*	
217	.0077	.133	.097	.084	.025	0.26	--	none	*	
218					.092	0.95	--	none	*	
219					.250	2.58	--	none	*	
220					.172	1.77	--	none	*	
221	.0089		.112	.098	.094	0.84	--	none	*	
222					.263	2.35	--	none	*	
223					.182	1.63	--	none	*	
224	.0072	.129	.093	.084	.103	1.11	--	none	*	
225					.294	3.16	--	none	uls *	
226					.294	3.16	1.02	mild	dls *	Not a true jam
227					.192	2.06	--	none	uls	
228					.178	1.91	?	mild	dls *	Not a true jam
229	.0079	.130	.101	.090	.111	1.10	?	mild	uls *	Upstream edge underturned as ship left the cover
230	.0086		.110	.096	.105	0.95	--	none	dls *	
231					.270	2.45	--	none	uls *	Compacted without jamming
232					.270	2.45	0.69	mild	dls *	Mild shove
233	.0098	.128	.128	.114	.092	0.72	--	none	uls	
234					.092	0.72	1.52	mild	dls	Mild shove
235	.0097		.126	.113	.279	2.21	--	none	uls	
236					.279	2.21	--	none	dls	
237	.0104		.135	.122	.100	0.74	?	mild	uls	Upstream edge failed
238					.096	0.71	0.69	heavy	dls	
239	.0108	.128	.141	.125	.250	1.77	--	mild	uls	Upstream edge underturned
240					.294	2.09	--	mild	uls	Upstream edge jammed
241	.0106	.128	.139	.124	.278	2.00	1.02	medium	dls	Off and on shove
242	.0108		.141	.125	.233	1.65	?	mild	uls	Ice moved past ship
243	.0107		.140	.124	.175	1.25	?	medium	dls	Ice pushed to side-a real jam

Cont'd...

Table C10

Ship Passage Ice Jam Data

Day10

Test No.	Q (m^3/s)	H (m)	U (m/s)	Fr $U/\sqrt{gH}$	Vs	$\frac{Vs}{U}$	P (m)	Jam Description (m)	Test Condition	Comments
244	.0108	.134	.134	.118	.103	0.77	?	mild	uls	Upstream edge failed
245	.0109		.136	.119	.256	1.88	?	mild	uls	Upstream edge folded
246					.200	1.47	?	mild	uls	Upstream edge broke away clogging the channel
247	.0107		.133	.116	.200	1.50	--	none	uls	
248	.0071	.129	.092	.083	.109	1.18	--	none	d1l	
249	.0088		.114	.102	.109	0.96	--	none	d1l	Ice "too large" to shove
250					.278	2.44	?	mild	d1l	Ice overlapped
251	.0081		.105	.094	.278	2.65	?	mild	d1l	Shoved a little
252					.100	0.95	1.02	mild	d1l	Mild shove
253	.0093		.120	.107	.109	0.91	1.02	mild	d1l	Not a true jam
254	.0088		.114	.100	.280	2.46	--	none	d1l	
255	.0103		.133	.118	.109	0.82	--	none	d1l	

Table C11

Ship Passage Ice Jam Data

Day 11

Test No.	Q (m^3/s)	H (m)	U (m/s)	Fr $U/\sqrt{gH}$	Vs (m/s)	$\frac{Vs}{U}$	P (m)	Jam Description (m)	Test Condition	Comments
256	.0150	.132	.114	.100	.103	0.90	1.52	mild	d1s *	Not a true jam
257						0.90	1.52	mild	d2s	Not a true jam
258	.0140	.132	.106	.093		0.97	1.02	mild	d1s	Not a true jam
259	.0138		.105	.092		0.98	0.51	mild	d2s	Not a true jam
260	.0133		.101	.089		1.02	--	none	d2s	Very local passage
261						1.02	1.02	mild	d1s	Not a true jam
262	.0118	.130	.091	.079		1.13	1.52	mild	d1s	Not a true jam
263		.131	.090	.080		1.14	--	mild	d2s	Not a true jam
264					.192	2.13	--	none	d2s	
265					.103	1.14	--	none		
266					.192	2.13	--	none		
267					.103	1.14	--	none	d1s	
268					.192	2.13	--	none		

Table C12 Data for Critical Froude Number for Ice Cover Stability without Ship Passage

Day	Q (m^3/s)	H (m)	U (m/s)	$Fr=U/\sqrt{gH}$	ℓc (m)	Ice Jam?	Upstream Edge Fails?	Percent Underturning	Jams When Distrubed?
1	0.0056	0.129	0.072	0.064	1.02	no	no	0	
	0.0066		0.085	0.076		no	no	0	
	0.0100		0.129	0.115		no	yes	40	
	0.0106		0.137	0.122		no	yes	80	
	0.0120		0.155	0.138		no	yes	40	yes
	0.0114		0.147	0.130		yes	yes	--	
	0.0124		0.160	0.142		yes	yes	100	
	0.0126		0.163	0.145		yes	yes	--	
	0.0059		0.076	0.068	3.05	no	no	20	
	0.0086		0.111	0.099		no	no	40	
	0.0106		0.137	0.122		no	yes	40	
	0.0109		0.141	0.125		no	yes	80	
	0.0116		0.150	0.133		yes	yes	60	
	0.0121		0.156	0.139		yes	yes	80	
	0.0124		0.160	0.142		yes	yes		
	0.0109		0.141	0.125		no	no		yes
	0.0121		0.156	0.133		yes	yes		
	0.0129	0.132	0.163	0.143		no	no		yes
	0.0058	0.129	0.075	0.067	5.10	no	no	0	
	0.0084		0.109	0.097		no	no	0	
	0.0102		0.132	0.117		no	no	0	
	0.0112		0.145	0.129		no	yes	80	
	0.0123		0.159	0.141		no	yes	40	
	0.0124		0.160	0.142		no	yes	60	
	0.0127	0.134	0.158	0.138		no	yes	80	
	0.0130		0.161	0.141		no	yes	80	
	0.0173		0.170	0.149		no	yes	100	
	0.0140	0.134	0.174	0.152	5.10	no	yes		
	0.0145	0.140	0.173	0.147		no	yes		
	0.0144		0.171	0.146		yes	yes		
	0.0147	0.139	0.176	0.151		no	yes		
	0.0156	0.140	0.186	0.159		yes	yes		
2	0.0118	0.129	0.153	0.136	1.02	yes	no		
	0.0109	0.131	0.139	0.122		yes	yes		
	0.0107	0.130	0.137	0.121	0.76	yes	yes		

Table C12 (cont'd) Data for Critical Froude Number for Ice Cover Stability without Ship Passage

Day	Q (m^3/s)	H (m)	U (m/s)	$Fr=U/\sqrt{gH}$	ℓc (m)	Ice Jam?	Upstream Edge Fails?	Percent Underturning	Jams When Distrubed?
	0.0105	0.129	0.136	0.121	1.02	no	no		yes
	0.0107		0.138	0.123	2.03	no	yes		yes
	0.098		0.128	0.114		no	yes		--
	0.0104		0.134	0.119		no	no		yes
	0.0079		0.102	0.091		no	no		--
	0.0094		0.121	0.108		no	no		no
	0.0097		0.125	0.111		no	no		yes
	0.0101		0.131	0.116		no	no		no
	0.0106		0.137	0.122		no	no		no
	0.0111		0.143	0.128		no	no		yes
	0.0102		0.132	0.117	3.55	no	no		yes
	0.0102		0.132	0.117	2.54	no	no		yes
3	0.0074		0.096	0.085	3.05	yes	--		--
4	0.0105		0.136	0.121		no	no		no
	0.0108	0.135	0.133	0.116		no	no		no
	0.0114	0.140	0.136	0.116		no	no		no
	0.0115	0.134	0.143	0.125		yes	--		--
	0.0114		0.142	0.124		no	no		yes
	0.0109		0.136	0.118		no	no		yes
	0.0102	0.133	0.128	0.113		yes	--		--
	0.0098	0.130	0.125	0.111		yes	no		--
5	0.0096	0.132	0.121	0.107		no	no		yes
	0.0094	0.133	0.118	0.103		no	no		yes
	0.0090	0.132	0.114	0.100		no	no		yes
	0.0090	0.133	0.113	0.099		no	no		yes
	0.0090	0.132	0.114	0.100		no	no		no
	0.0090		0.114	0.100		no	no		no
	0.0083		0.105	0.092		no	no		yes
	0.0084		0.106	0.093		no	no		no
6	0.0052	0.135	0.106	0.092		no	no		yes
	0.0059	0.140	0.118	0.101		no	no		yes
	0.0059	0.128	0.128	0.114		no	no		yes
	0.0064		0.140	0.124		no	no		yes

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