CRREL REPORT 88-9

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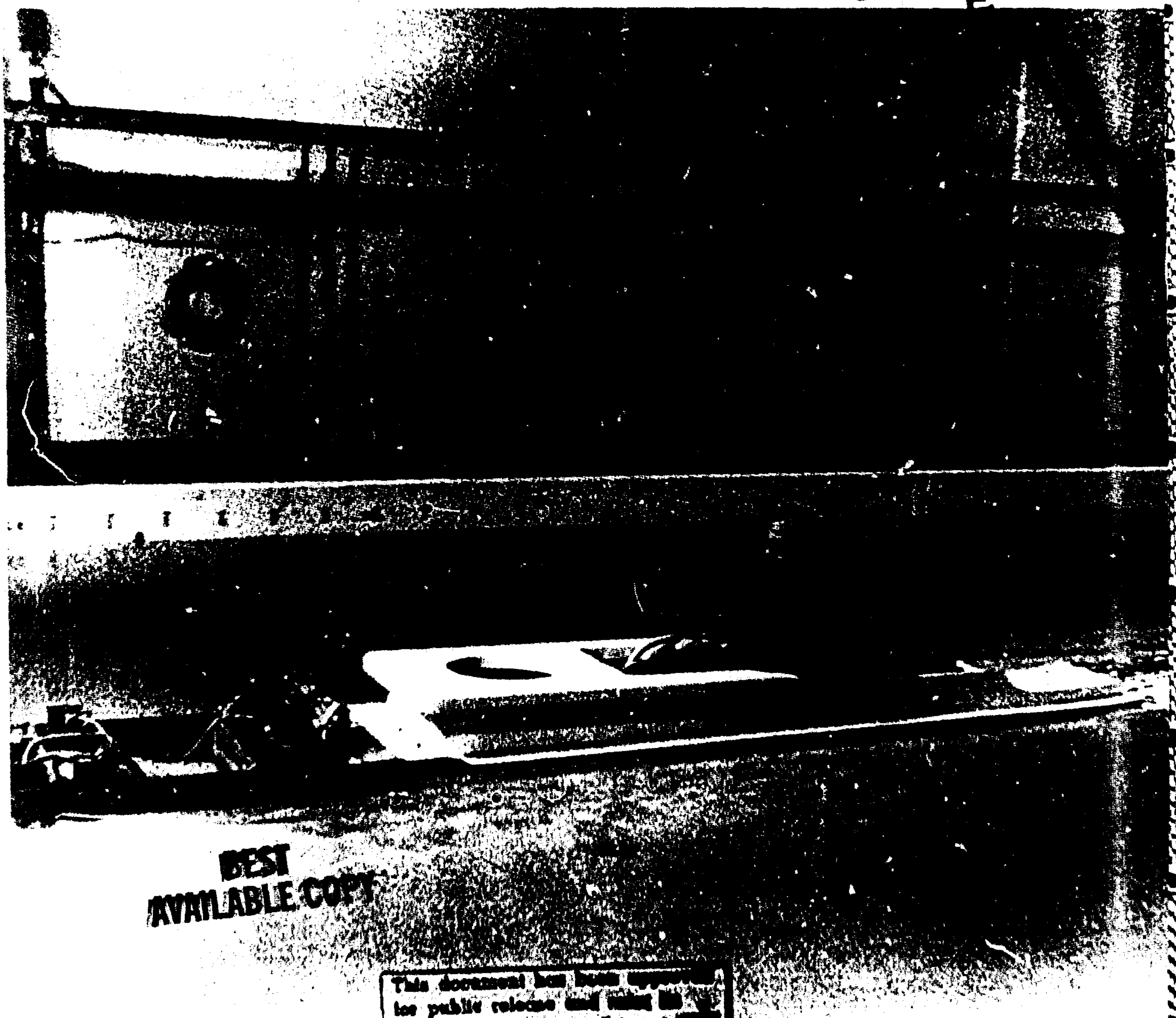
Development of a river ice prow



For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover: Model towboat used for testing ice prows.

CRREL Report 88-9

July 1988

Development of a river ice prow

Jean-Claude P. Tatinclaux and Carl R. Martinson

RIM
RIVER ICE MANAGEMENT

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

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This report describes the development of a river ice prow to be attached to a towboat for opening ice-free navigation channels or for ice management in the vicinity of the locks and dams on the northern rivers of the United States (Illinois, Ohio and Upper Mississippi Rivers). Following a literature survey, the basic concept of the prow was selected to minimize construction and maintenance costs. Three successive models were constructed and tested in level ice in the CRREL Test Basin to optimize the prow's performance from the points of view of resistance and maneuverability in level ice. Test results are presented and discussed.

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PREFACE

This report was prepared by Dr. Jean-Claude P. Tatinclaux, Research Hydraulic Engineer, and Carl R. Martinson, Mechanical Engineering Technician, both of the Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided under CWIS 32288, *Ice Prow*. This report was prepared as part of the River Ice Management Program (RIM), which is being conducted by CRREL under the direction of the Office of the Chief of Engineers, Washington, D.C., and supported by Civil Works Operations and Maintenance appropriations.

The manuscript of this report was technically reviewed by John Rand and Jon Zufelt. The authors express their gratitude to Calvin Ackerman for building and modifying on short notice the various ice prow models, and Charles Clark, Stephen DenHartog, Edward Foltyn and all the members of IERB who helped in one capacity or another during the laboratory tests. Many thanks are due to the Corps of Engineers Marine Design Center personnel, whose comments on the initial design of the field prow led in part to the last laboratory model.

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CARL R. MARTINSON

INTRODUCTION

The research and development program for ice problems in the navigable rivers of the northern United States was begun by the U.S. Army Corps of Engineers to facilitate operation of the locks and dams, decrease potential damage, and improve navigation during the winter season. The efforts of this River Ice Management (RIM) program have been concentrated primarily on the Illinois and Ohio rivers and their main tributaries. One of the objectives of RIM was the development and laboratory and field testing of an auxiliary icebreaking and ice clearing device, capable of creating ice-free, or nearly so, channels in level ice and brash ice. Such a device could be used to keep the approach to the locks relatively free of ice, to minimize the amount of brash ice entrained into the lock chamber by incoming tows, and to create channels between the upstream lock approach and the abutting dam where brash ice could be diverted and flushed over the dam.

The idea of an auxiliary icebreaking and ice clearing device is certainly not new, and a great many concepts for such devices have been proposed and patented or both. Many of the proposed devices have remained as concepts, some have been designed but never tested, some have been model tested, and only a few have been actually put into operation. The first section of this report is a literature survey of existing and proposed ice clearing devices. The second part describes the concept retained and the model testing program, and the third part presents the results of the tests.

The RIM program was periodically monitored by a field review group composed of representatives from the Office of the Chief of Engineers and various Corps Districts and Divisions affected by the program. The ice prow research program was modified to reflect the recommendations of the field review group.

LITERATURE SURVEY

Auxiliary icebreaking and ice clearing devices can be broadly divided into two main categories: passive devices that do not participate directly in the icebreaking or ice clearing processes but may make these processes easier for the vessel to which they are fitted (e.g., special hull coatings, air bubbler and water flusher systems), and active devices, which either weaken the ice to be broken by the main vessel or actually break the ice ahead of the main vessel. The literature search conducted for the present study was limited to reports and articles that described investigations and evaluations of existing and proposed icebreaking concepts. It was further concentrated on those active devices that either were not included in previous studies but might be applicable to river ice problems, or that have been tested through laboratory model studies or field experiments since 1970, or both. A rather extensive bibliography on auxiliary icebreaking devices can be found in Smith et. al. (1981). As a final note, some rather bizarre concepts were encountered during the literature search and are not presented in the following.

Wagner and Cappel (1971) conducted a study for the U.S. Coast Guard on developing a river icebreaking and ice clearing device capable of creating a 12-m-wide channel in 60-cm-thick level ice. The study reviewed various methods for weakening, breaking or otherwise removing ice, namely: water jets to cut grooves in the ice, projectiles to drive holes through the ice, thermal melting of slots or grooves in the ice, steam jet nozzles to cut grooves in the ice, chemical melting, saws to cut slots in the ice, and mechanical scoring of the ice underside. Based on this initial survey, on theoretical calculations, and on limited laboratory experiments to determine the energy required by some of the methods, they developed an icebreaker concept composed of: 1) mechanical impactors to fracture the ice ahead of the vessel, 2) a downward sloping bow and conveyor belts to carry the broken ice upward and aft, and 3) lateral ice chutes with water flushers to deposit the broken ice on top of the remaining ice cover. This device (dubbed UMR for Upper Mississippi River device) was to be pushed by a tow boat. Detailed engineering designs of the various components were presented, and construction and operational costs were estimated.

Lecourt et al. (1973) and Lewis et al. (1973) presented the design of a Mechanical Ice Cutter (MIC), a 1/6th scale model of which was built and tested in 5 to 13 cm of ice in a freshwater lake. The full-scale requirements for the MIC were to clear a 15-m-wide channel in 60-cm-thick ice at speeds of 4 to 5 kn (7 to 9 km/h). The MIC was composed of: 1) three circular saws mounted ahead of the bow to cut narrow slots in the ice, 2) a downward sloping bow to break the resulting cantilever beams in bending, and 3) underwater skegs or deflectors mounted on the bottom of the vessel to force the broken ice floes sideways underneath the remaining ice cover (Fig. 1).

From the field tests with the MIC model, the authors concluded that the MIC concept is a viable method for creating a practically ice-free channel, and that the circular saws were efficient machines for cutting the ice. They estimated that a self-propelled MIC capable of achieving the design requirements would require a total power of 3600 kW as compared to 5100 kW for a conventional icebreaker performing the same task. The authors did not address the performance of a MIC in brash ice or its repeated use in refrozen channels. It should be noted that, while the authors considered the MIC to be a self-propelled vessel, an ice prow along the same concept could be mounted to a towboat.

Worthing (1975) was awarded a patent for an icebreaking device in the form of a self-propelled vessel carrying outboard extensible booms that could swing out horizontally. One boom is mounted at the bow, the second, shorter one at the stern, and both can be positioned vertically from above the water to under the ice. These booms are equipped with high pressure water nozzles discharging upward for cutting the ice from beneath. The author claims the following advantages of the device over a conventional icebreaker: the main hull of the vessel need not be reinforced or heavily powered since the ice ahead of it is cut, the channel cut can be considerably wider than the beam of the vessel, and the device can be constructed and operated economically. No model of the device has been constructed and tested to verify its viability. Furthermore, it is doubtful that such a device could be used in brash ice.

Voelker and Kim (1978), for the Maritime Administration, designed, tested and evaluated six ice transiting bow forms for Great Lakes bulk carriers. A series of model tests in open water and level ice was carried out. Their main conclusions were:

1. Development of an ice transiting bow form should be based on a minimum or zero reduction in open water performance.

2. The best bow form in open water also gave the lowest broken ice resistance. Tests in level ice and refrozen broken ice showed that improved ice transiting capability can best be achieved with a sloping bow and a low-friction hull coating.

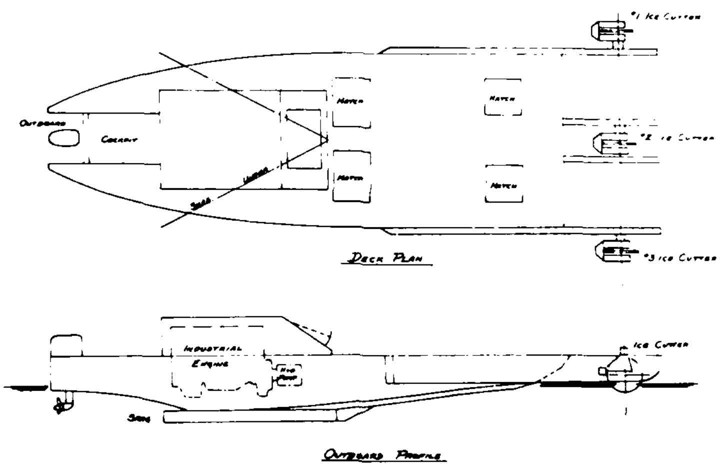


Figure 1. Sketch of mechanical ice cutter (MIC) (from Lewis et al. 1973).

3. For an 11-month operating season, the best transiting bow form can be expected to make one more round-trip voyage than can bow forms designed only for open water performance.

4. Based on full-scale observations and a limited number of model maneuvering tests, it appeared that changes in bow shape will have little or no effect on improving the ability of the ship to negotiate turns in ice-covered rivers.

Buck and Pritchett (1978) and Buck et al. (1978) presented the results of field tests conducted during the winter of 1977–1978 to demonstrate and evaluate the icebreaking capabilities of Air Cushion Vehicles (ACV). The tests were conducted on the Illinois River near Peoria with a barge-type ACV (the *River Guardian*) that was not self-propelled, but was pushed by the C.G. Cutter *Sumac*, and on the Kankakee River with the LACV-30, a self-propelled ACV. The main conclusions of the project are quoted as follows (Buck et al. 1978, pp. 86–87):

- The air cushion vehicles did break ice in the river environment. Plate ice of uniform thickness was easier to break than brash ice.
- The ACV's had little or no effect on clearing the channel of thick brash and heavy slush ice for facilitating towboat traffic. Ice clearance appeared to be as great a problem in the river ice environment as icebreaking. Once the ice was broken it had no place to go and remained in the channel.
- The self-propelled ACV was effective in breaking ice to reduce the potential for river flooding.
- The nonself-propelled ACV reduces the resistance of the pusher vessel by breaking the ice, reducing the size of the ice floes, and air lubricating the hull. The pusher vessel then partially clears the channel of broken ice and slush by pushing it aside with its displacement hull and propwash. All of this acts to facilitate the transit of a towboat immediately following the ACV/pusher combination.
- High noise levels from gas turbine propelled ACV's pose a potential problem for local residents. Such high noise levels are inherent to turbo-prop propulsion systems but may be controlled by future designs of ACV propellers.
- The Coast Guard can operate and maintain air cushion vehicles with only a minimal amount of additional personnel training. Operation of self-propelled ACV's is the area where most of the training would be required.

It is well known that ACVs are quite capable of breaking ice, but they are not efficient at clearing the navigation channel of the resulting ice floes. Maintenance can also become a serious problem. Indeed, both craft tested in the above field program had extensive periods of downtime for maintenance, 35 days out of 87 days of testing for the *River Guardian*, and 27 out of 63 days for the LACV-30. Frequent repairs to the skirts of the *River Guardian* were required because of ice damage. Preventive maintenance on the LACV-30 was necessary to assure effective operation of its comparatively complicated propulsion system. Finally, icing of the ACVs' propellers or other parts of the propulsion system can lead to serious difficulties during cold weather operations.

Vinogradov et al. (1979) describe a proposed icebreaking, lever type mechanism to be mounted at the bow of an icebreaker as follows (p. 1070):

> The concept is easily understood from Figure [2] where a sketch of the device, mounted on a ship's bow, is shown. This lever mechanism operates as follows: The forward moving ship causes the jaws of the device to engage with a sheet of ice when the resulting horizontal ice pressure on the lower jaw or arm 1 is transferred to the vertical force acting on the ice sheet from the upper jaw 2. The ship will then increasingly rise out of the water as it continues to move forward. This will in turn result in increasing force being exerted downward on the ice while compressing the spring 3 in the upper jaw 2. At some point the force on the ice will become large enough to break the ice, just as with a conventional icebreaker. At the point of fracture, the compressor spring will tend to drive the segment of ice downward and out of the way of both ship and arm. The arm will then be free to swing forward and up, facilitated by a spring return at the main pivot, enabling it to take another "bite." The inclined lip of the upper jaw 2 also acts to raise the mechanism as fresh ice is engaged. The cycle could then repeat itself.

The authors made some simplistic experiments that they claim showed the proposed system to require less horizontal force to break ice than a conventional icebreaker bow. It can be safely assumed that, even if the proposed device would prove effective in level ice, it would be far less so in brash ice. Furthermore, the device, while possibly improving the ice-breaking capabilities of the vessel to which it is mounted, does not resolve the problem of clearing the broken ice out of the channel created by the icebreaking vessel.

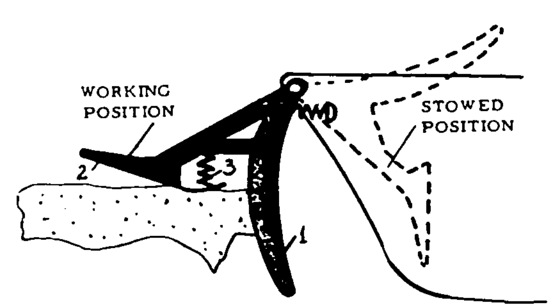


Figure 2. Conceptual sketch of icebreaking jaws (from Vinogradov et al. 1979).

Possibly the most comprehensive survey of potential auxiliary icebreaking devices or systems was compiled by Smith et al. (1981) for the U.S. Coast Guard. The authors analyzed 18 auxiliary devices that could be retrofitted on an existing icebreaker such as the 140-ft WTGB to improve its performance in icebreaking and channel ice clearing. The "devices" considered were: low friction hull coating, water hull lubricating system, bubbler system, hydroflushing equipment, stem knife, bilge keels, bow ramp, pitch inducing system, mechanical ice cutting, mechanical impact device, explosive icebreaking, mechanical saws, archimedes screw vehicle, Alexbow barge, air cushion bow, Upper Mississippi Icebreaker (UMR), waterjets and lasers. Four functions or missions were defined for an icebreaking vessel: channel breaking and clearing, river operation (control of ice jams), response to emergencies, and vessel breakout (assistance to vessels stuck in ice). Included in the analysis were 14 operational parameters such as speed, turning diameter, ice thickness in continuous icebreaking mode and in ramming mode, fuel consumption, endurance, cargo capacity, etc. The impact, whether positive or negative when compared to the existing icebreaker performance, of each device on each operational parameter for the four missions selected was estimated. In addition, 13 U.S. Coast Guard officers with icebreaking experience were interviewed and their responses to variations in the operational performance of the icebreaker were evaluated. The conclusions of the report read (p. 45):

> The results of this study indicate that there is little practical difference between any of the auxiliary devices when all the factors involved are considered. Only one system was clearly superior to the others. This was the Pitching System in which a set of rotating weights is used to induce a pitching motion to the hull while ice-breaking. This is a well proven system which has been used in Germany for many years. However, the cost of retrofitting existing Coast Guard vessels would be high. A further study of the application of Pitching Systems to Coast Guard vessels is recommended.

For obvious reasons, the U.S.S.R. is the most advanced country in winter navigation, especially navigation in inland waterways. The Soviet engineers have developed icebreaking and ice clearing devices (which go by the acronyms LLP and LPS) to be mounted ahead of a tug boat or conventional icebreaker. The available articles on these devices and their operation (Puzlevskii and Miasnikov 1972, Tronin et al. 1978, Tronin et al. 1984) give only scant physical descriptions of the devices, but elaborate at some length on their operation. However, a short film clip shown by one Soviet delegate at the IAHR (International Association for Hydraulic Research) Ice Symposium '84 in Hamburg showed a model of the LLP, a barge type vessel equipped with ice knives at the bow and deflector vanes along a gently sloping bottom, and demonstrated an icebreaker–LLP combination operating in an ice-covered river. The LPS device is similar to the LLP but is equipped with a horizontally pivoting axis at the stern that allows greater pitching of the device, especially in level ice. From the available literature, it appears, however, that of the two, the LLP is the favored device and is used most. The Soviets claim that both devices are successful in creating ice-free channels, as quoted verbatim from Tronin et al. (1978, pp. 73–75):

> Recently, trains of serial pushers and icebreaker attachments have been successfully used for breaking channels. Two types of attachments are used: with swinging installations and without them (LPS and LLP type attachments). The latter are characterized by the simplicity of construction, reliability and are not expensive. With their icebreaking quality they are slightly inferior to attachments with swinging installations but are considerably superior to ordinary icebreakers when advancing in level ice of lakes and reservoirs. Besides, attachments of the given type permit to break the channel with smooth edges, stable width and it is not obstucted by brash ice. None of the existing icebreaking means can give such quality of the channel.... In winter 1974–1975 and 1975–1976 full scale tests on providing navigable channels by means of the ice-breaking attachments LPS-14 took place on the Rybinsk water reservoir. A channel 6 km long was broken at the end of December and was maintained up to March. Observations show that even at an air temperature 30°C below zero it is possible to clean the channel from a new forming ice breccia within 2–3 days with the train motion velocity 3–ɔ km/hr ..... In the course of full-scale tests the optimum velocity of cleaning has been found near 5 km/hr. At the same time the increase or decrease of the train velocity gives poor results of the channel cleaning.

Tronin et al. (1984, p. 257) write:

> These years in a number of river basins of the USSR icebreaking removing devices of LPS and LLP type have shown good results in operation. They are of simple design, having no power plants and mechanisms, but stringer-knives and a bottom shoulder to separate ice and keep it apart. These devices and series pusher tugs together enable to make an ice channel with smooth edges and little brash in it. These ice breaking trains are capable to cut and make wider ice channels in level solid ice, move through hummocky areas of a storage basins and up a river, assist transport vessels or take them out when they are trapped in ice.

Figure 3. Tugboat Captain Krutov *equipped with LLP device (courtesy of V. Tronin).*

a. Cut by icebreaker working alone. *b. Cut by icebreaker equipped with LLP device.*

Figure 4. Views of channels in level ice (from Tronin et al. 1984).

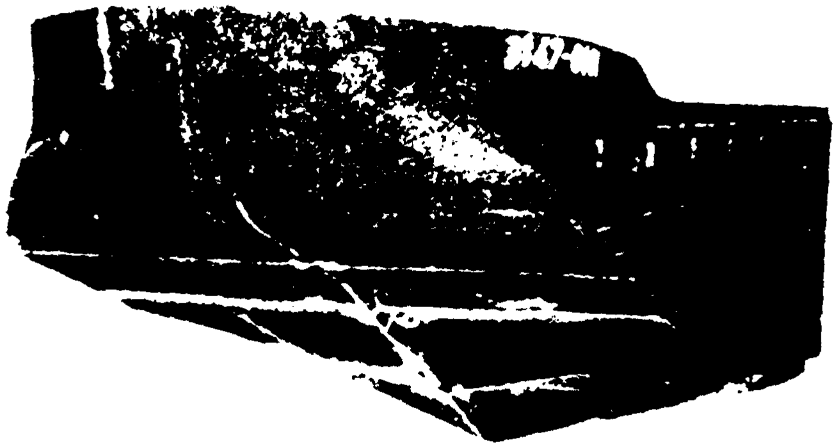
Figure 3 shows an icebreaker equipped with an LLP device. Figure 4a shows the track left by a conventional icebreaker working alone and Figure 4b shows the track left by the same icebreaker equipped with an LLP device.

For the past decade, a novel bow for ice-going icebreakers first proposed and patented by Waas (1976) has been developed and extensively tested in Germany both in the laboratory and at sea (Freitas 1981, 1982; Hellmann 1982; Schwarz 1986; Freitas and Nishizaki 1986). From the original concept, and the initial experimental prototype (Fig. 5), the Waas bow, as it is known, has evolved into radically new shapes shown in Figure 6. Basically, the Waas bow has square shoulders, a very low stem angle at the waterline, and an initially flat bottom that evolves into a slight wedge. During icebreaking it shears the ice at the shoulders, then breaks the resulting cantilever beams by downward bending into pairs of regularly shaped ice floes. These floes are deflected outwards under the remaining ice sheet. According to its developers, the main advantages of the Waas bow over conventional icebreaker bows are: 1) more efficient ice breaking, i.e., reduced resistance and required power in level ice, 2) bet-

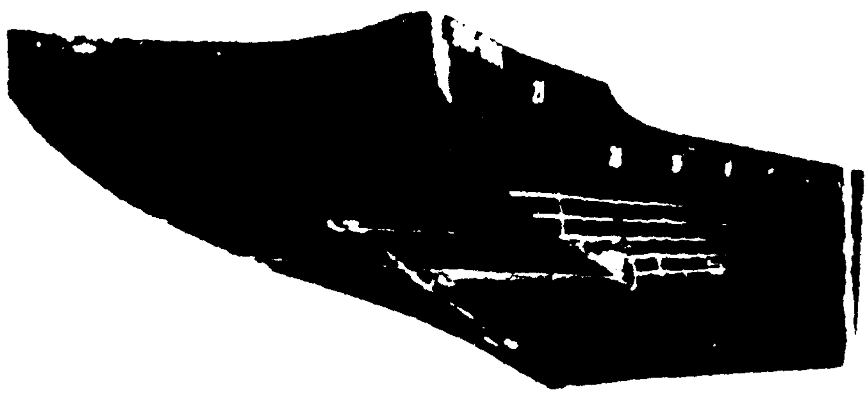
a. Front view of bow.

b. View of channel cut in level ice.

Figure 5. Experimental Waas bow mounted on icebreaker Max Waldeck *(from Freitas 1982).*



a. Round bow.



b. Cat bow.

Figure 6. Recent developments of the Waas-Thyssen bow (from Transactions of the ASME, Journal of Energy Resources, *A. Freitas and R.S. Nishizaki, June 1986).*

ter maneuverability in ice, and 3) the creation of a nearly ice-free channel for speeds up to 4–5 kn (7–9 km/hr) (Fig. 5b). The effects of a Waas bow on a vessel's seakeeping capabilities, performance in waves, and performance in ice ridges remain a subject of controversy. In spite of the efforts of its developers, the Waas bow has not yet been widely accepted; however, a Soviet icebreaker has been recently retrofitted with such a bow, and the U.S. Coast Guard has started a program to evaluate its performance potential. Furthermore, it is the understanding of these writers that the Waas bow developers are also attempting to adapt the bow to a shallow-draft icebreaker for operation in estuaries and rivers.

Even more recently, an innovative, experimental icebreaking bow has been designed and tested both in the laboratory and in the field in Finland (Enkvist and Mustamaki 1986). This bow, shown in Figure 7, has a small stem angle, circular waterlines and a plow or deflector vanes to deflect the ice floes outwards. The model and full-scale tests showed a significant decrease in icebreaking resistance over a conventional bow, no essential improvement of performance in ridges, old broken channels or in maneuvering, but an increase in open water resistance and in slamming during transit in head seas. Therefore, the authors did not recommend this innovative bow for vessels operating primarily in open water or in ice

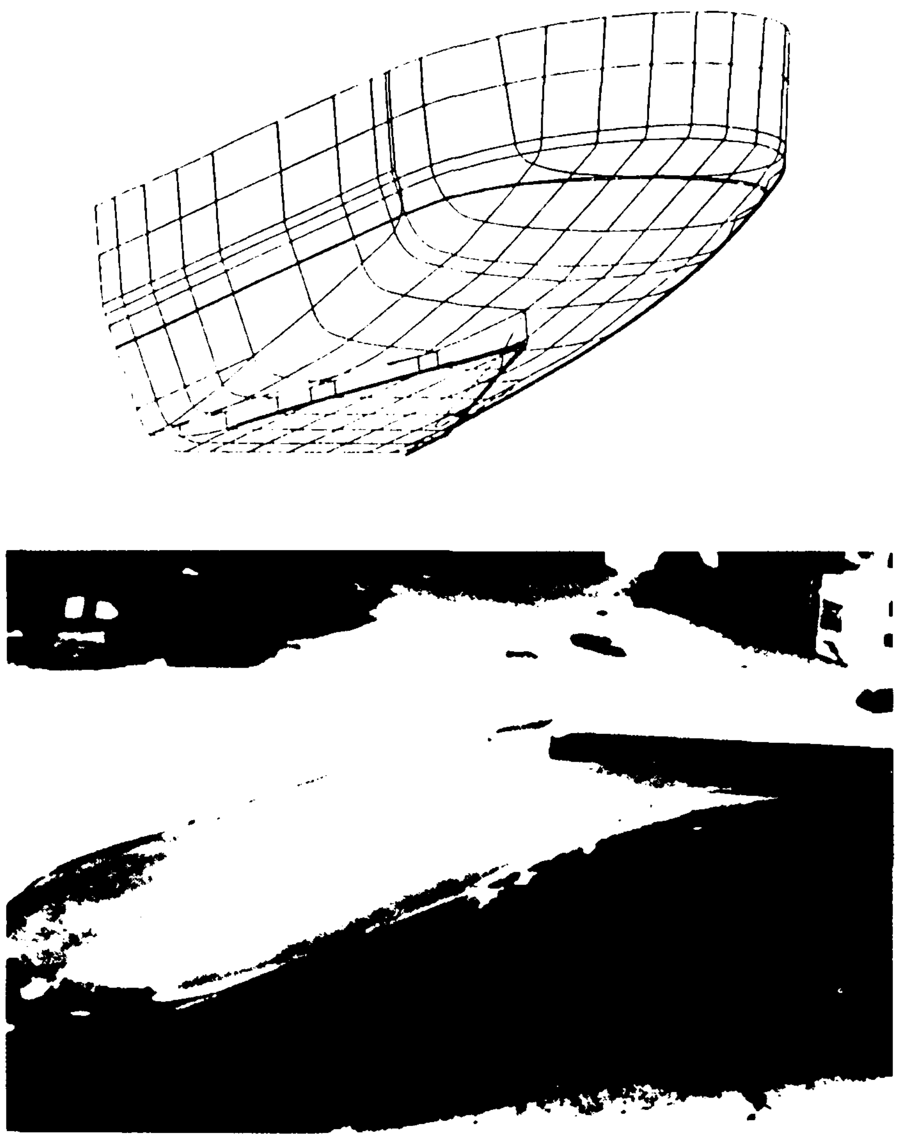


Figure 7. Innovative icebreaker bow developed by Wartsila (from Enkvist and Mustamaki 1986).

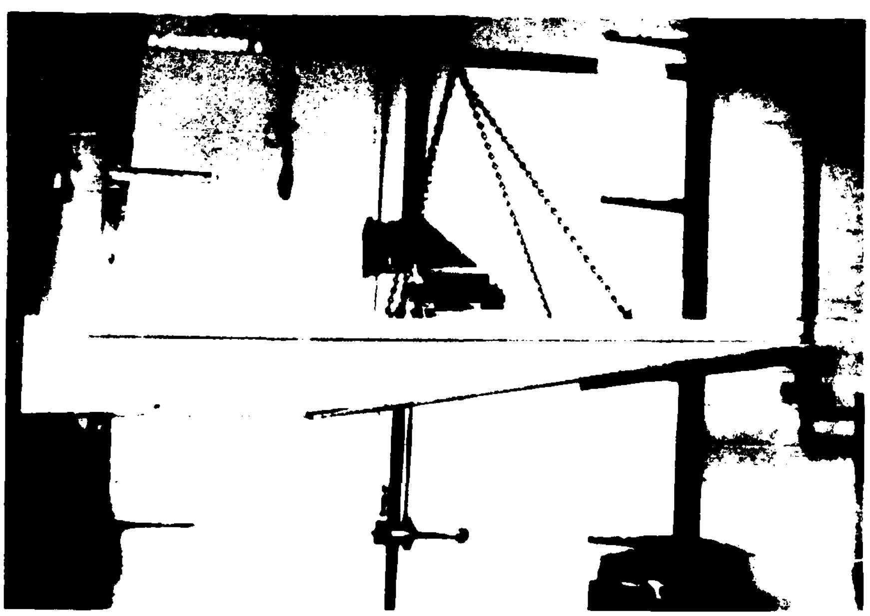
ridges or rubble ice. They considered that the usefulness of the bow was limited to areas of thick level ice such as in rivers, lakes or sheltered areas along a sea coast. However, during the presentation of their paper at the 1986 General Meeting of the Society of Naval Architects and Marine Engineers, the authors did mention that the experimental bow mounted on a towboat was used at the end of the 1985–1986 winter to open the Saima canal to navigation. They reported that the channel created was nearly free of ice, and that the navigation channel was open in less than one day. In previous years it had taken several days for a towboat working alone to open a channel that still contained a large amount of brash ice.

SELECTED PROW CONFIGURATION AND TEST PROGRAM

The period of severe navigation and lock and dam operation problems attributable to ice on the Illinois and Ohio rivers is relatively short. When it does occur, it extends at most from late December or early January to late February. For an ice prow to be [illegible]ally justifiable, the hull shape has to be relativel[illegible] [illegible]inimize construction cost, and it must be ea[illegible]y [illegible] [illegible]nd maintain without extensive training of Corps [illegible]. The initial schedule of the RIM program called [illegible] a [illegible]ield demonstration for the winter of 1986–1987, which required that the model tests be completed by the first quarter of Fiscal Year 1986. Final design and construction drawings of the field prow were due by the second or third quarter of Fiscal Year 1986, and the demonstration prow was to be constructed and delivered at the field test site by the end of the first quarter of Fiscal Year 1987. These constraints led to the initial decision that the ice prow to be tested in the laboratory should contain no moving parts such as conveyor belts as in the UMR, or circular saws as in the MIC. This would eliminate potential operational and maintenance difficulties because of icing of such components by water entrainment, and water splash or spray. Because of the reported success of the MIC model, the Russian LLP and LPS devices, and the Waas bow, the selected basic configuration of the ice prow was based on these devices. A rectangular, barge-type hull that is not self-propelled, it has a gently sloping bottom mounted with one or more deflector vanes, and is equipped with ice knives mounted at the bow. The prow is to be attached to the bow of a pusher for operation.

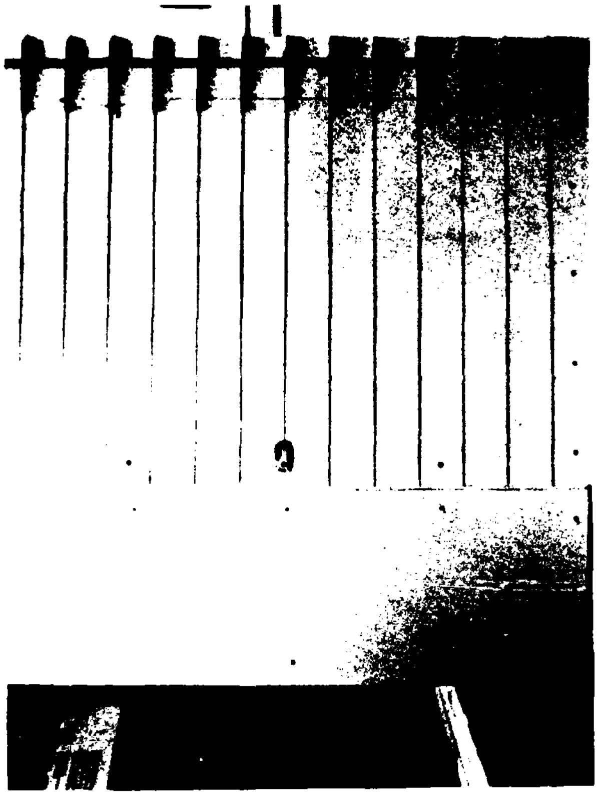
At the outset of the study, one of the requirements was that the ice prow be capable of opening a two-barge-width channel for potential use by the towboat industry. The first prow model built at a 1:15 scale was 142 cm wide at the bow, 178 cm long at the waterline, and had a 16-cm maximum draft, corresponding to full-scale values of 21 m in width, 26.5 m in length, and 2.4 m in draft. Fifteen ice knives, 10 cm apart (1.5 m at full scale), were mounted at the bow. The bottom slope was approximately 7°. The prow stern was raked so that ice floes present in the channel would not seriously interfere with attaching the prow to a pusher. This first prow model (model I) was used primarily to investigate the deflector vanes to be mounted on the bottom of the prow. Three vane configurations, shown in Figure 8, were tested in approximately 2.5-cm-thick (37.5 cm full scale) level ice, with flexural strength of about 50–60 kPa (750 to 900 kPa full scale) and in a double layer of brash ice. In addition to the ice prow model, a towboat model was acquired by CRREL to conduct self-propulsion tests with prow model I and any further models. These self-propulsion tests were qualitative in nature and aimed at complementing the resistance tests, at investigating the maneuverability of the towboat–prow configuration, at studying the possible re-entrainment by the propwash of ice floes in the broken channel, and at conducting tests in a shallow, temporary ice tank without a towing carriage.

However, the mission of the Corps of Engineers is primarily to maintain and operate the navigation locks and dams and their approach areas on the navigable rivers, and a large ice-prow was deemed unnecessary. Furthermore, the initial field demonstration program planned for the winter 1986–1987 was to be carried out with an existing Corps workboat with very limited power. So a sec-

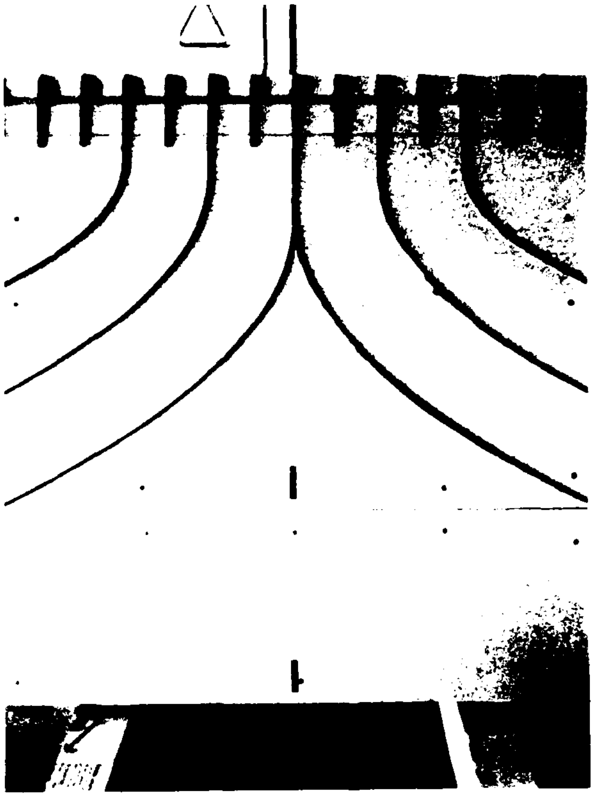


a. Side view.

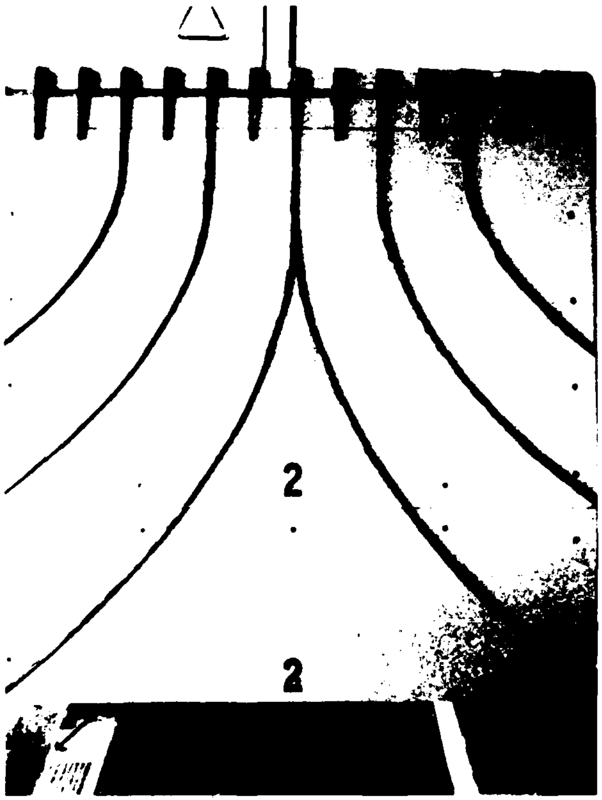
Figure 8. CRREL ice prow model I.



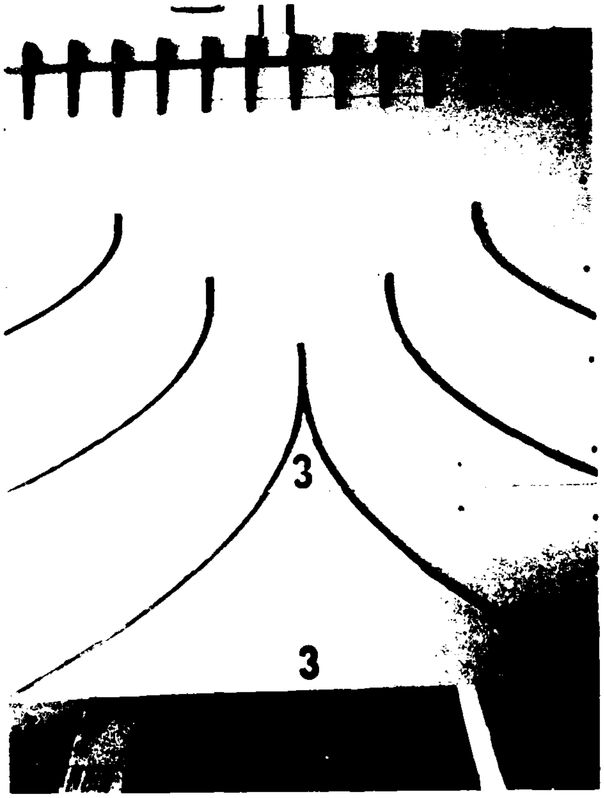
b. No deflector vanes.



c. Deflector vane configuration 1.

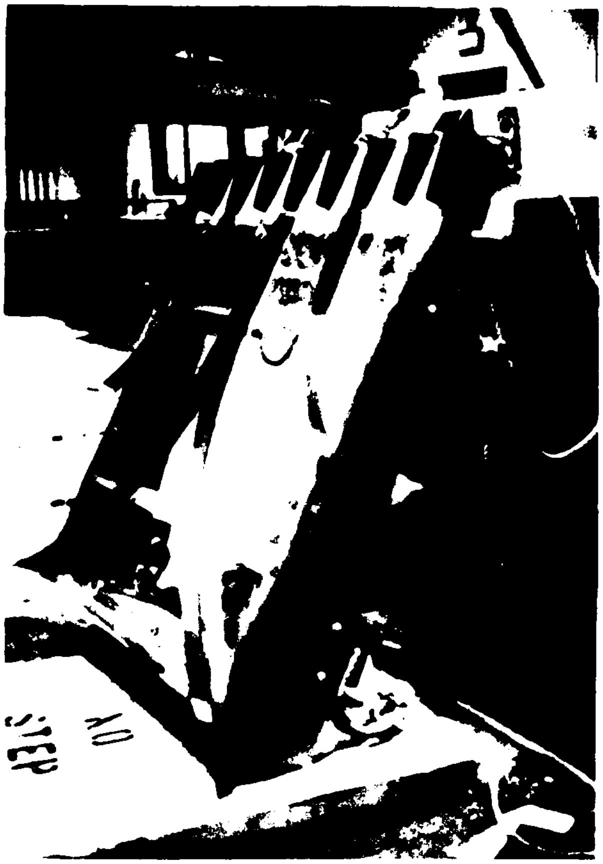


d. Deflector vane configuration 2.

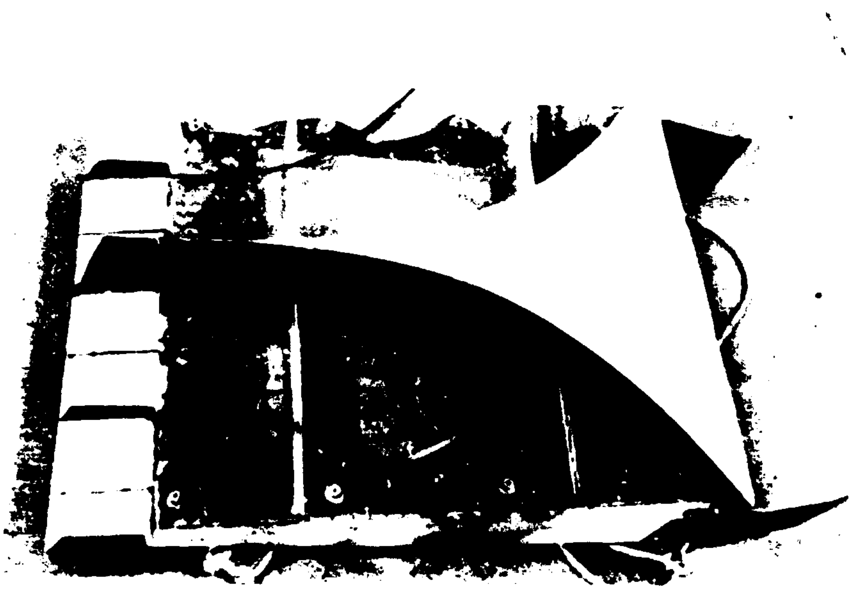


e. Deflector vane configuration 3.

Figure 8 (cont'd). CRREL ice prow model I.



a. Model II-1.



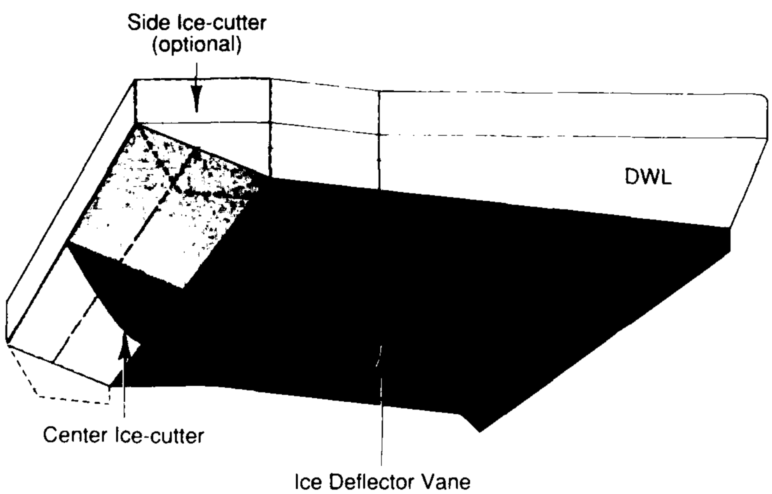
b. Model II-2.

Figure 9. Views of CRREL ice prow model II.

ond, smaller model (model II) was constructed also at a scale of 1:15. This model was 76 cm wide (11.4 m full scale), 89 cm long at the waterline (approximately 13.5 m at full scale), and had a draft of 14 cm (2.1 m full scale). Because of the smaller size of this prow, the number of ice knives was at first reduced to nine to keep the spacing at approximately 10 cm. The bottom slope was increased from 7 to 9° and only two ice deflector vanes were mounted on the prow bottom (model II-1, Fig. 9a). The number of ice knives was later reduced to five, and the outer deflector vanes were removed (model II-2, Fig. 9b). Also, in model II-2 the remaining vanes were extended to full draft through their total length, and the space between them was filled with styrofoam to increase the model (and projected prototype) buoyancy.

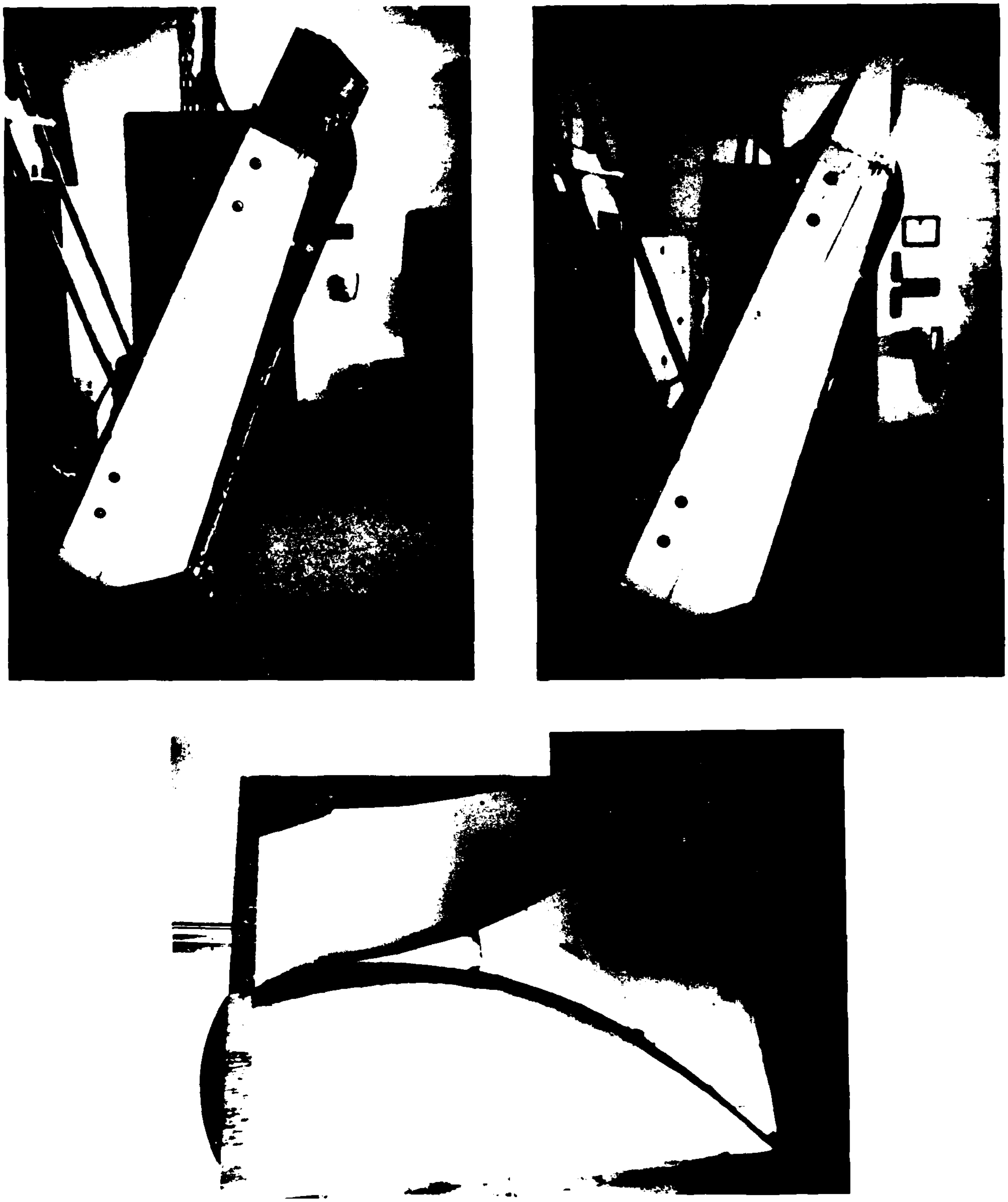
Following the test program with prow model II-2, the Corps of Engineers Marine Design Center was contracted to design a prototype of the ice prow following closely the lines of model II-2. This prototype was to be 5 m wide and 7.9 m long with a draft of 0.91 m. It was to be mounted to the *Pekin*, a Corps of Engineers workboat that has an overall length of 12.8 m, a beam of 3.7 m, and a maximum draft of 1.2 m. The *Pekin* is powered by two 123-kW diesel engines driving two three-bladed propellers that are 1 m in diameter. It should be mentioned that this so-called prototype was in fact a half scale model of an ice prow capable of opening a one-barge width channel. In the course of the design, it became apparent that the small angle of the prow bottom and the corresponding unbalanced weight distribution could create stability problems during operation and increase the risk of losing the prow should the hull be damaged by ice. Furthermore, in a private conversation with the first author at the IAHR Ice Symposium '86, in Iowa City, Iowa, Dr. Tronin of the USSR indicated that the intermediate ice knives (see Fig. 9b) may not be necessary and confirmed that only a single, central pair of deflector vanes was required. Since the RIM Field Review group suggested that field tests of a prow prototype might not be necessary and should be postponed until a final decision by the Office of the Chief of Engineers, the planned field prow was not built. Instead a third model (model III) was constructed to improve the weight distribution and investigate the effect of removing not only the intermediate ice knives but also the edge knives. This last model, shown in Figure 10, has a 20° slope at the bow that then changes to a 7° slope to give a better volume and weight distribution.

The following section presents and discusses the results of the laboratory tests conducted with the various prow models.



a. Conceptual sketch.

Figure 10. Views of CRREL ice prow model III.



b. Photographs of model.

Figure 10. (cont'd).

MODEL TEST RESULTS AND DISCUSSION

It is seldom that two ice sheets in which resistance tests are performed have exactly the same properties—thickness (h) and flexural strength (σ) in particular. It is therefore customary to compare experimental data obtained in various test series in dimensionless form. In dimensional analysis of ship resistance in ice, the most common dimensionless form of the resistance, R, the dependent variable, is $R/\gamma Bh^2$, where γ is the specific weight of water, and B is the ship beam. Another possible form is $R/\sigma h^2$. The primary dimensionless independent variables are usually the Froude number based on ice thickness, namely $V/\sqrt{gh}$, where V is the vessel velocity and g the acceleration of gravity, and the dimensionless ice strength, $\sigma/\gamma h$. The only requirement in calculating the numerical values of the dimensionless parameters is that all dimensional variables, R, h, σ, V, g and γ, be measured in a consistent system of units.

Tests with model I

As mentioned earlier, resistance tests in level ice were conducted with model I to select the best deflector vane configuration of the three shown in Figure 8. The model labeled 0 in Figure 8 had no deflector vanes and was used to establish a resistance baseline. Another model, labeled 2A (not shown here) was also tested. It differed from model 2 only in that the bottom of the prow stern section was sloping instead of horizontal. These tests with model I also allowed adjustment of the shape and height of the ice knives. In these preliminary resistance tests, the model was rigidly attached to the towing carriage of the ice tank so that it was totally restrained except in roll. The test results are listed in Table 1 and presented graphically in Figures 11a and b as the dimensionless resistance $R/\gamma Bh^2$ vs Froude number $V/\sqrt{gh}$. Figure 11a shows the results in level ice and Figure 11b shows the results in brash ice. From Figure 11a, it is apparent that the prow resistance in level ice is varying linearly with velocity (or Froude number), that is

$$\frac{R}{\gamma Bh^2} = \frac{R_o}{\gamma Bh^2} + k\left(\frac{V}{\sqrt{gh}}\right) \quad (1)$$

where R_o is the icebreaking component of the total resistance R, and k is the rate of increase of R with velocity and depends upon the vane configuration. R_o is usually assumed to be only a function of ice thickness h and ice strength σ, that is $R_o/\gamma Bh^2$ is only a function of the parameter $\sigma/\gamma h$. Since the bow characteristics of the prow

Table 1. Results of resistance tests with model I.

Vane no.	*Test type*	*Test no.*	h_i *(cm)*	σ *(kPa)*	V *(cm/s)*	R *(N)*
0	Level ice	31	2.7	54	13.0	107
		35	2.7	54	26.4	176
		32	2.7	54	26.4	179
		33	2.7	54	40.0	195
		34	2.7	54	54.0	232
1	Open water	101	–	–	12.9	1
		102	–	–	26.2	3
		103	–	–	39.6	7
		104	–	–	53.5	13
	Level ice	111	2.4	28	13.3	99
		112	2.4	28	26.4	171
		113	2.4	28	40.1	222
		114	2.4	28	54.0	289
	Brash ice	151	4	–	13.0	28
		152	4	–	26.3	46
		153	4	–	39.8	62
		154	4	–	54.0	83
2	Open water	201	–	–	12.9	1
		202	–	–	26.2	3
		203	–	–	39.8	7
		204	–	–	53.6	13
	Level ice	211	2.2	43	12.9	74
		212	2.2	43	27.2	142
		213	2.2	43	40.3	157
		214	2.2	43	54.0	178
	Brash ice	251	4.5	–	12.9	24
		252	4.5	–	27.2	44
		253	4.5	–	40.5	60
		254	4.5	–	54.0	59
2A	Open water	206	–	–	13.2	2
		207	–	–	26.7	5
		208	–	–	40.1	12
		209	–	–	54.0	20
	Level ice	221	2.9	69	13.0	142
		222	2.9	69	27.6	236
		223	2.9	69	40.4	243
		224	2.9	69	54.0	297
	Brash ice	261	5.5	–	12.9	52
		262	5.5	–	27.5	57
		263	5.5	–	40.2	82
		264	5.5	–	53.9	11

Table 1 (cont'd).

Vane no.	*Test type*	*Test no.*	h_i *(cm)*	σ *(kPa)*	V *(cm/s)*	R *(N)*
		301	–	–	13.1	1
		302	–	–	26.6	5
	Open water	303	–	–	40.0	9
		304	–	–	53.8	16
		311	2.9	69	13.1	189
		312	2.9	69	26.3	337
3	Level ice	313	2.9	69	39.8	402
		314	2.9	69	53.9	408
		352	5.5	–	26.3	67
	Brash ice	353	5.5	–	40.6	89
		254	4.5	–	54.0	59

models were the same for all the vane configurations, it is logical to assume that the icebreaking resistance component is the same for all prow models tested. Under these assumptions, a regression analysis of the test results was made, which led to the following equation

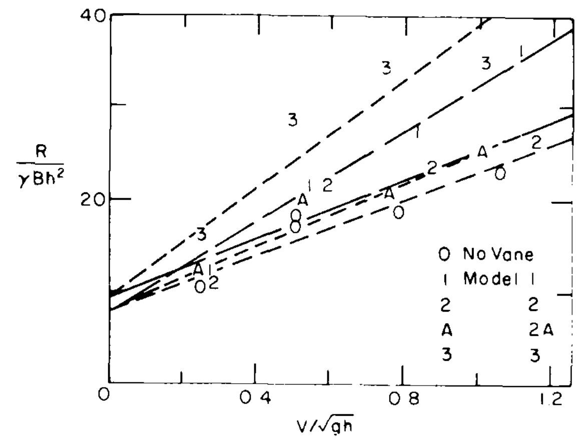
$$\frac{R}{\gamma \, Bh^2} = 0.0387\left(\frac{\sigma}{\gamma \, h}\right) + k\left(\frac{V}{\sqrt{gh}}\right) \qquad (2)$$

with $k = 15.2$ for the no vane case, $k = 24.8$ for vane 1, $k = 17.4$ for vane 2, $k = 16.0$ for vane 2A, and $k = 29.4$ for vane 3, with a regression coefficient $r = 0.96$. The resistance in level ice for the four models tested as predicted by eq 2 for the particular case of $h = 2.5$ cm and $\sigma = 50$ kPa (corresponding to full scale values of 38 cm and 750 kPa respectively) is shown in Figure 11c.

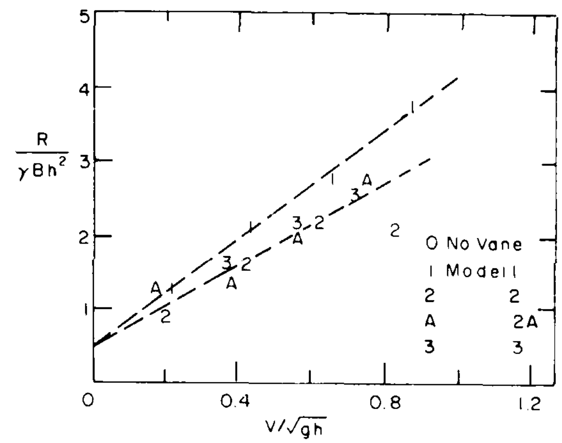
As was anticipated from Figure 11a, confirmed by the results of the regression analysis and illustrated in Figure 11c, vane configurations 2 or 2A are equivalent and have the least resistance in level ice. Figure 11b also shows that vane configurations 2 or 2A yield the lowest resistance in brash ice. The mathematical description of this vane is given by

$$Y = Y_o + A\,X^{2.5}$$

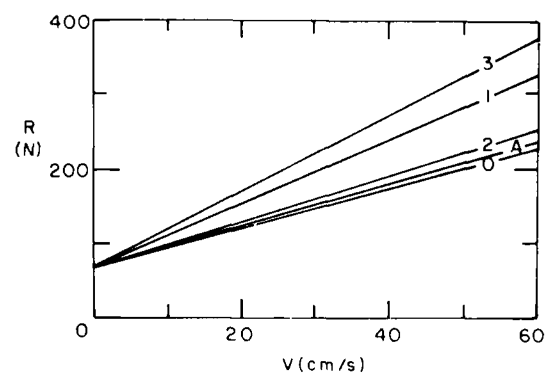
where Y is the prow ordinate measured from the prow centerline, Y_o is the initial ordinate at the bow, X is the abscissa measured from the bow along the centerline, and A is a coefficient adjusted so that the vane reaches the edge of the prow at a prescribed distance from the bowline.



a. In level ice.



b. In brash ice.

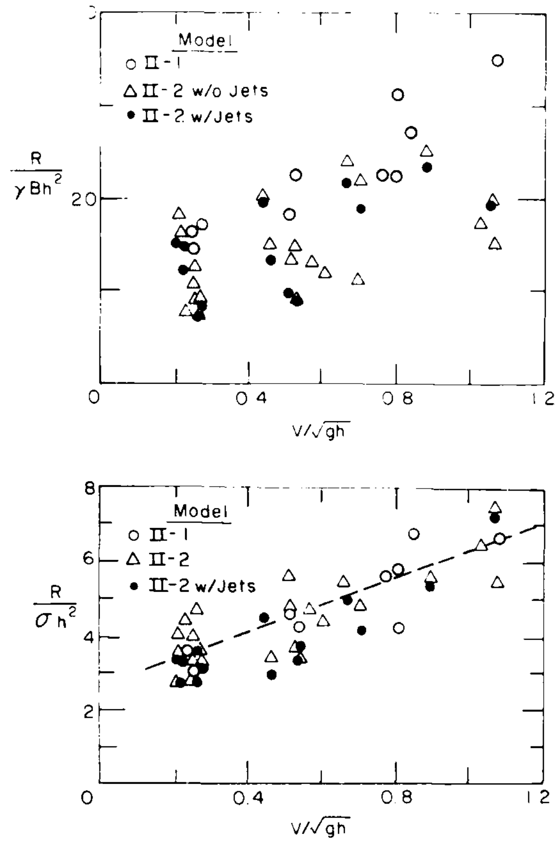


c. Predicted resistance for h *= 2.5 cm and* σ *= 50 kPa.*

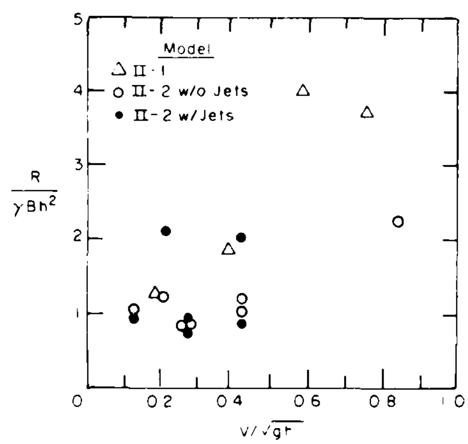
Figure 11. Resistance test results with model I.

Table 2. Resistance in level ice of prow model II.

Model no.	*Test no.*	h (*cm*)	σ (*kPa*)	V (*cm/s*)	R (*N*)
	401	2.7	30	39.7	122
	402	"	"	43.2	148
	403	"	"	26.2	100
	404	"	"	12.8	79
II-1	421	2.5	40	39.8	146
	422	"	"	53.3	166
	423	"	"	12.3	77
	424	"	"	26.4	105
	425	"	"	39.7	105
	426	"	"	12.9	81
	501	3.3	20	13.0	65
	502	"	"	39.6	92
	503	"	"	34.4	96
	504	2.5	20	12.9	36
	505	"	"	52.8	68
	506	"	"	26.0	46
	511	2.5	20	13.0	43
	512	"	"	28.2	60
	526	2.7	20	12.7	58
	527	"	"	26.1	71
II-2	529	"	"	52.7	93
no	701	2.5	20	12.7	59
water	702	"	"	25.9	70
jets	704	"	"	52.5	94
	705	"	"	12.8	45
	706	"	"	26.3	44
	711	3.3	34	12.8	166
	712	"	"	26.2	126
	713	"	"	39.8	181
	715	"	"	12.7	131
	720	3.6	33	12.5	177
	721	"	"	39.3	235
	725	"	"	25.9	198
	726	"	"	52.7	242
	701-J	2.5	20	12.8	41
	702-J	"	"	25.9	46
	704-J	"	"	52.5	91
	705-J	"	"	12.8	35
	706-J	"	"	26.3	42
II-2	711-J	3.3	34	12.8	119
with	712-J	"	"	26.2	110
water	713-J	"	"	39.7	155
jets	715-J	"	"	12.8	102
	720-J	3.6	33	12.5	144
	721-J	"	"	39.5	209
	725-J	"	"	25.9	194
	726-J	"	"	52.9	229



a. In level ice.



b. In brash ice.

Figure 12. Resistance test results with model II.

Table 3. Resistance in brash ice of prow model II.

Model no.	*Test no.*	h_i *(cm)*	V *(cm/s)*	R *(N)*
	411	5	40.4	75
	412	5	53.3	69
II-1	413	5	26.5	35
	414	5	35.0	24
	611	4	12.9	15
	612	4	26.2	14
II-2	614	4	52.6	27
no	750	9	25.9	50
water	751	9	39.3	58
jets	752	10	13.1	77
	753	10	26.1	63
	601	4	13.0	25
II-2	602	4	26.2	24
with	750-J	9	25.9	48
water	751-J	9	39.4	55
jets	752-J	10	13.1	71
	753-J	10	26.0	72

a. In level ice.

b. Resulting channel.

Figure 13. Views of towboat and model II-2 assembly.

Tests with model II

By the time model II was constructed, and equipped with deflector vanes similar to vane 2 for model I, the towboat model had been delivered. Model II was then attached to the towboat model by means of two force blocks. Resistance tests were conducted by pulling the prow model and towboat train in 2.5-cm-thick-level ice and in approximately 5-cm-thick brash ice.

Model II-2 was later equipped with vertically discharging water jets at the bow near the waterline to investigate the potential of such jets in reducing the prow resistance. Fourteen 3-mm holes were drilled 5 cm apart at the bow and connected to a common manifold fed by a pump. The pump intake was connected to a 5-cm hole drilled in the prow bottom near the stern. The jet velocity was about 1 m/s.

The level ice test results are listed in Table 2, and presented in Figure 12a, while those of the tests in brash ice are listed in Table 3 and shown in Figure 12b. Additional qualitative tests were made to further evaluate model II-2's towboat and ice prow combination as far as maneuverability and effect of shallow water draft were concerned. These tests were made both with the model towboat being self-propelled (Fig. 13), and with it being towed after problems developed in its propulsion system. The main results of the overall test program with model II can be summarized as follows:

1. The results obtained with model II are quite comparable to those obtained with model I equipped with deflector vane no. 2. This indicates that there was no net penalty for reducing the number of vanes and knives or increasing the prow bottom slope. Also, both model II-1 and model II-2 (without water jets) have comparable resistance, both in level and brash ice, as shown in Figure 12. Thus it appears that removing the outer vanes and every other ice cutter compensated for the expected increase in water drag when the depth of the remaining vanes was increased to full draft.

2. The prow is capable of opening a nearly ice-free channel in uniform level ice as shown in Figure 13. The broken ice floes are deflected under the surrounding ice sheet to a distance approximately equal to the prow width. The level ice thickness that can be broken by the prow will obviously depend upon the propulsion performance of the pusher to which it is attached.

3. Figure 14 presents the ratio of the resistance of model II-2 with and without water jets, respectively. It indicates that the addition of jets resulted in neither gain nor loss in the prow's performance in brash ice. On the other hand it did decrease somewhat the level ice resistance, particularly at low speed. However, it is doubtful that the drop in resistance would be sufficient to justify the power required to drive the pump.

4. It was found to be quite easy to widen a channel previously cut into level ice by making several parallel passes. However, it is better to widen the channel by half a prow width at a time to avoid deflecting ice floes into the previously cut channel.

5. The prow can also open nearly ice-free channels in brash ice, provided that the forward speed is sufficient for the prow to ride up over the ice. At low speed, the ice is merely pushed ahead by the prow without being submerged and deflected by the vanes. The risk then exists that ice will accumulate and thicken to the point where no forward progress is possible.

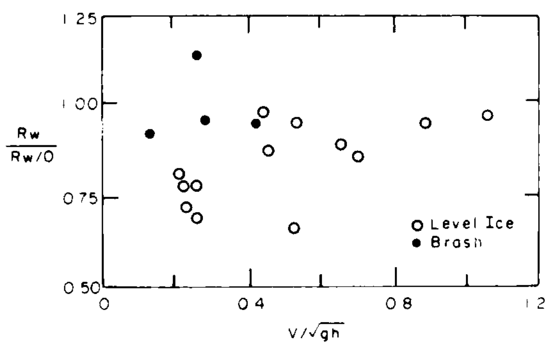


Figure 14. Ratio of resistance of model II-2 with water jets to that without jets.

6. Maneuverability in ice is poor. When attempts at leaving a previously cut channel were made, the side cutters hit the edge of the channel and forced the prow back into the channel.

7. No significant difference in the performance of the prow was observed between the tests in shallow water and those in deep water. Because of time and physical constraints, it was not possible during the shallow water tests to investigate the effect on prow performance of partially filled under-ice areas or of repeated passages. Obviously, since the prow deflects the broken ice floes underneath the surrounding remaining level ice, the prow's usefulness will be limited by the available storage area at any particular site.

Tests with model III

While the overall dimensions of model III were nearly identical to those of model II-2, the main modifications made to the design were to increase the bow angle to 20° and consequently to decrease the angle of the prow bottom to 7°. In a first stage the intermediate ice cutters were

Table 4. Resistance in level ice of prow model III.

Test series	*Test no.*	h *(cm)*	σ *(kPa)*	V *(cm/s)*	R *(N)*
With three ice cutters	1	3.0	29	20.0	89
	2	3.0	29	53.0	89
	3	3.0	29	37.0	81
	4	3.9	52	20.0	287
	5	3.9	52	53.0	340
	7	3.9	45	37.0	225
	8	3.9	45	53.0	219
	9	3.9	45	20.0	194
	10	3.2	50	53.0	141
	11	3.2	50	37.0	120
	12	3.2	50	20.0	131
Single ice cutter	13	3.3	28	51.0	138
	14	3.3	28	36.0	128
	15	3.3	28	21.0	117
	16	3.3	28	36.0	123
	17	3.1	51	21.0	99
	18	3.1	51	36.0	144
	19	3.1	51	51.0	136
	20	3.1	51	36.0	124
	21	3.5	49	21.0	198
	25	3.0	38	21.0	111
	26	3.0	38	36.0	109
	27	3.0	38	51.0	105
	28	3.0	38	36.0	83
	29	2.8	38	21.0	91
	30	2.8	38	36.0	63
	31	2.8	38	51.0	67
	32	2.8	38	36.0	55

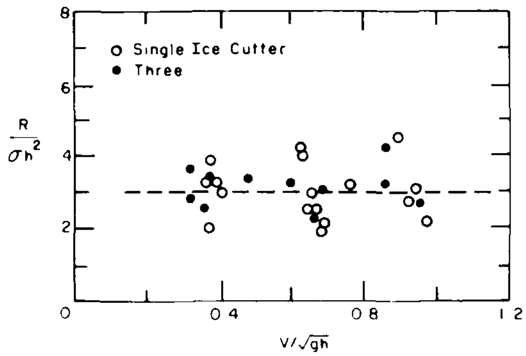


Figure 15. Results of resistance tests in level ice with model III.

Figure 16. View of channel created by prow model III in level ice.

eliminated, keeping only the center and side cutters. The side cutters were also later removed to leave only the center one. Only tests in level ice were carried out with model III, the results of which are listed in Table 4, and presented graphically in Figure 15. In addition to resistance tests made by towing the towboat and prow assembly in the test basin, qualitative maneuverablity tests were made with extensive video documentation.

The conclusions of the tests with model III are:

1. Surprisingly, the resistance in level ice of this prow design appears to be independent of velocity, at least in the tested speed range.

2. As shown in Figure 15, removal of the side cutters had on the average no significant effect on the prow resistance. However, it appears that the scatter in the data is greater when there were no side cutters. With no side cutters, even slight rolling motion of the prow influences how the edges of the prow bow contact and shear the ice, thereby possibly affecting the resistance. In the model tests where a person was sitting in the towboat to steer it, the overall center of gravity is exaggeratedly high, leading to increased roll motion from even a small shift in the driver's position. Such effects are expected to be of much lesser magnitude at full scale.

3. Comparison between Figure 15 and Figure 12a shows that model III has a lower resistance than model II-2 over the whole speed range investigated.

4. Model III, with or without side ice cutters, created nearly ice-free channels, with clearly defined straight edges, and widening a previously cut channel presented no difficulty (Fig. 16).

5. Removal of the side ice cutters greatly improved the maneuvering capabilities of the prow. The prow was no longer prevented from leaving the channel; however, in a one-prow-width channel, when the towboat attempted to turn, its stern would hit the channel edge, forcing the towboat and prow assembly back into the ice channel. As soon as the stern had some room into which to move, the prow could leave the initial channel without difficulty.

CONCLUSIONS

Successive laboratory tests led to modifications in the original concept of the ice prow, which, on the basis of the test results, resulted in significant improvements in the prow performance, both with regard to resistance and maneuverability. However, field tests with a full-scale prototype are needed to confirm the validity of the laboratory studies and to evaluate the usefulness of such a prow in managing ice in the vicinity of the Corps locks and dams.

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