



A laboratory investigation of river shore-line ice jam forces  
by Douglas Malcolm Stewart

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE  
in Civil Engineering  
Montana State University  
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**Abstract:**

This thesis presents the experimental results of a laboratory project to construct a measurement system in a refrigerated, hydraulic flume to measure the normal and tangential forces transmitted to a river shoreline due to a floating, fragmented ice cover. Two materials were used to model the floating, fragmented ice cover; real ice and a commercially available polyethylene with the same specific gravity as ice. Two block sizes of each material were used. The experimental results of the thrust exerted by the model ice covers on a floating retention structure, called a boom, are also presented.

The results of the studies of the boom thrust show that the boom thrust attains a maximum value when the length to width ratio of the ice cover reaches a certain value. This relationship is of the form (Formula not captured by OCR) The normal and shear force exerted by the ice cover on the shoreline was shown to generally have maximum values at the downstream edge of the cover and decrease in the upstream direction. The normal force was in the range of two times the shear force at all conditions tested. The normal and shear forces exerted on the shoreline, at any one point, were normally less than the thrust exerted on the boom.

The two model materials, ice and plastic, showed slightly different results. The real ice data always had much more experimental scatter. The forces developed by the plastic blocks were generally larger than for the ice blocks under the same testing conditions. It is theorized that this is due to differences in surface tension effects of the two materials. Friction coefficients were found for the jams consisting of the two model materials against the river shoreline. The friction coefficient for the jams consisting of plastic blocks was an order of magnitude higher than for jams consisting of real ice blocks.

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Date May 27, 1980

A LABORATORY INVESTIGATION OF  
RIVER SHORELINE ICE JAM FORCES

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DOUGLAS MALCOLM STEWART

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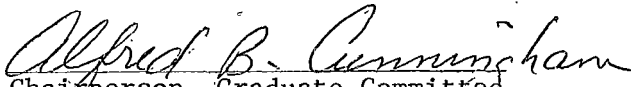
of

MASTER OF SCIENCE

in

Civil Engineering

Approved:

  
Chairperson, Graduate Committee

  
Head, Major Department

  
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MONTANA STATE UNIVERSITY  
Bozeman, Montana

May, 1980

## ACKNOWLEDGEMENTS

The author would like to thank the professional staff of the Ice Engineering Research Branch of the U.S. Army Cold Regions Research and Engineering Laboratory at Hanover, New Hampshire for their assistance and support in the research in this thesis. The author expresses sincere thanks to Mr. Steven Daly, Dr. Devinder Sodhi, and Mr. Darryl Calkins for their assistance and encouragement throughout the project.

The assistance of Dr. Albert Cunningham, Dr. Richard Brustkern, and Professor Theodore Williams at Montana State University in proof-reading the draft is gratefully acknowledged. The help of Sandra Johnson for the drawings and the patience of Evelyn Richard in typing the thesis is greatly appreciated.

This project was funded under DA Project 4A161101A91D, In House Laboratory Independent Research, Shoreline Distributed Ice Forces.

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## ABSTRACT

This thesis presents the experimental results of a laboratory project to construct a measurement system in a refrigerated, hydraulic flume to measure the normal and tangential forces transmitted to a river shoreline due to a floating, fragmented ice cover. Two materials were used to model the floating, fragmented ice cover; real ice and a commercially available polyethylene with the same specific gravity as ice. Two block sizes of each material were used. The experimental results of the thrust exerted by the model ice covers on a floating retention structure, called a boom, are also presented.

The results of the studies of the boom thrust show that the boom thrust attains a maximum value when the length to width ratio of the ice cover reaches a certain value. This relationship is of the form

$$F_B = C \left( 1 - C_0 e^{-\frac{L}{B}} \right).$$

The normal and shear force exerted by the ice cover on the shoreline was shown to generally have maximum values at the downstream edge of the cover and decrease in the upstream direction. The normal force was in the range of two times the shear force at all conditions tested. The normal and shear forces exerted on the shoreline, at any one point, were normally less than the thrust exerted on the boom.

The two model materials, ice and plastic, showed slightly different results. The real ice data always had much more experimental scatter. The forces developed by the plastic blocks were generally larger than for the ice blocks under the same testing conditions. It is theorized that this is due to differences in surface tension effects of the two materials. Friction coefficients were found for the jams consisting of the two model materials against the river shoreline. The friction coefficient for the jams consisting of plastic blocks was an order of magnitude higher than for jams consisting of real ice blocks.

## Chapter 1

### INTRODUCTION

In northern climates, ice jams in rivers have been historical events. However, it has only been in recent years that the study of the mechanics and hydraulics of river ice jams has been undertaken. Although various theories on the mechanics of river ice jams have been proposed and analogies with theories from other fields have been drawn, very few field or laboratory investigations have been undertaken in this area and quantitative data is very scarce.

Hydraulic engineering projects on rivers are playing an ever-increasing role in our expanding technological society. Ice jams are an extremely important feature of river engineering in cold regions. It is well to recall when defining the geographical limits of cold regions such events as the ice jam in 1899 in the Mississippi River at New Orleans! (Gerard, 1980) Design engineers for hydraulic structures seriously lack the data with which to evaluate the effect of forces exerted by river ice jams. Quantitative measurements of forces exerted by river ice jams are almost non-existent, due mainly to the difficulty of obtaining such measurements in the field. Recent literature has shown a beginning in the area of measurement of river ice jam forces through attempts at instrumenting bridge piers and piles in northern rivers which experience ice jams. However, much additional work needs to be done in order to provide information needed for cost effective design and operation of civil works projects.

Ice jams and ice accumulations may take many forms but there are fundamentally three basic modes of the accumulation process. In relatively low velocity flow the first mode of accumulation occurs. Under this condition the ice jam progresses upstream by mere juxtapositioning of ice floes. As the velocity in the reach of the jam formation is increased the ice jam thickens. The second mode of accumulation occurs in a "hydraulically narrow" river section, defined as the hydraulic reach in which the ice cover thickens by floe entrapment under the jam from underturning of the ice floes at the leading edge of the cover. This thickening will continue until the head loss created by the deposition of the entrapped floes raises the upstream water level to the point at which the velocity becomes low enough to allow a new upstream progression of the ice cover.

A "hydraulically wide" river section, in which the third type of accumulation will occur, is defined as the hydraulic reach in which the jam thickens when the thrust on the cover exceeds the internal strength of the ice cover. A folding or collapsing of the jam occurs which thickens the jam until the internal strength can resist the external forces applied, namely the shear force of the flow applied to the jam on the undersurface of the cover and the gravity component of the weight of the ice in the streamwise direction. When a new equilibrium is restored the upstream progression of the cover will continue.

Each of the modes of the accumulation process are dynamic.

A given river reach may during the course of the formation of a jam act as either hydraulically wide, hydraulically narrow, or juxtapositioning of the ice floes may occur, depending upon the changing hydraulic conditions and the integrity of the ice floes.

## Objectives

When a fragmented ice cover comes to rest within a given river reach the hydrodynamic forces exerted on the cover are either absorbed internally in a crushing failure of the cover or are transmitted to the shoreline throughout the length of the cover. The river shoreline will see this force in three components, a force normal to the bank face, a force tangential to the bank face, or a force which is in the vertical plane of the bank face. The objectives of this thesis are to present the results of a laboratory project to construct a measurement system in a refrigerated, hydraulic flume to measure the normal and tangential forces transmitted to a river shoreline due to a floating, fragmented ice cover and to present the results of a limited number of experiments conducted with this measurement system using two materials to model the floating, fragmented ice cover: real ice and a commercially available polyethylene with the same specific gravity as ice.

## Chapter 2

### LITERATURE REVIEW

The objective of this section of the thesis is to present a brief overview of the theoretical and experimental studies that have been conducted on the forces exerted on river ice jams. All of the river ice jam theories presented include a postulation of the stress distribution within the fragmented cover. A brief description of the assumptions involved in each is presented. A summarization of the laboratory and field investigations of the forces exerted by a floating, fragmented cover on a floating retention structure, normally called a boom, is also presented. To the knowledge of this author, this study is the first attempt at the measurement of the forces exerted by an ice jam on a river shoreline.

Many of the accepted theories of the distribution of stresses in a fragmented ice accumulation have stemmed from analogies with gravity flow of granular media through two dimensional hoppers and bins and from the theories of pressure distribution in granular soils. A floating, fragmented ice cover is assumed to act as a granular material with respect to the interaction of the particles in the mass, in all the present theories.

Pariset and Hausser (1961) have formulated a theory for the formation of ice covers and ice jams in rivers based on Janssen's (1895) theory for grain pressure in a silo. Michel (1970) has followed Caquot's (1956) theory from the field of soil mechanics

which assumes that the total thrust on the granular mass is transmitted to the edges by an arching action of the material.

Sodhi and Weeks (1979) have developed a one-dimensional theory governing ice pressure in a straight channel for a stationary fragmented ice cover based on Cowin's (1977) derivation of static loads in bins.

Uzuner and Kennedy (1976) have developed a theoretical model of a river ice jam in a straight, rectangular channel using an eulerian control volume approach and assuming that the stress within the ice cover is distributed to the banks according to the coulomb friction law.

Tatinclaux (1977) has presented a theoretical model similar to that of Uzuner and Kennedy and correlated this with a large number of flume experiments conducted with plastic and ice blocks. Tatinclaux's model concentrates on the equilibrium thickness of the jam accumulation and avoids the hydraulically wide river case.

Several experimental investigations have been conducted on the thrust developed on a boom by a floating, fragmented accumulation. Latyshenkov (1946) conducted a study in a small natural channel, 1.6 m wide, with a single layer cover of ice floes. Refer to Figure 1. The thrust exerted on the boom by the ice cover was shown to attain a maximum when the cover length was 2.5 to 3.0 times the channel width. Figure 1 plots the boom thrust normalized by the maximum

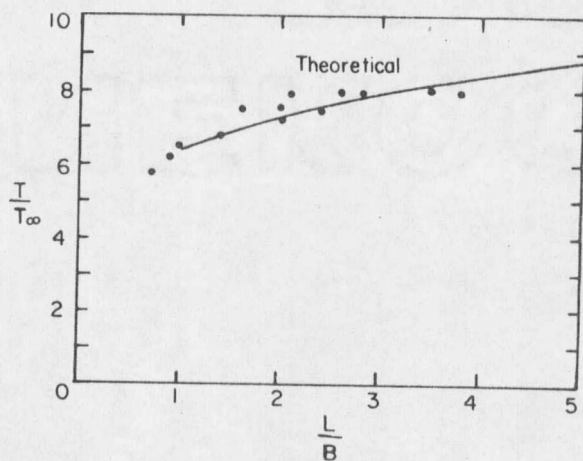


FIGURE 1. Results of tests with ice floes.  
Latyshenkov (1948)

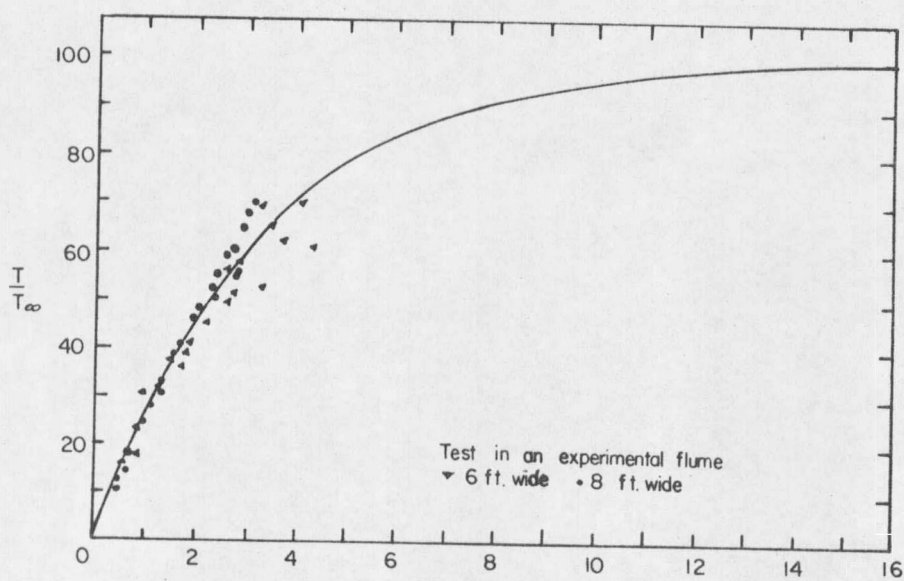


Figure 2. Forces on a boom caused by a model log jam.  
Kennedy (1956)

thrust seen on the boom against the length to width ratio ( $\frac{L}{B}$ ).

Figure 2 shows the results of flume tests conducted by Kennedy (1956) with model wooden logs. Kennedy's data is plotted in the same form as Latyshenkov's data. The experimental data was limited due to model length at the length to width ratio ( $\frac{L}{B}$ ) equal to 4.0. The correlation between model results using wooden logs and ice jam behavior may be of questionable value, due to differences in the material interaction and differences in material shapes.

Delagrave (1966) conducted tests in a 2 meter wide flume with polyethylene pieces used to model ice floes. Refer to Figure 3. Thick covers were modeled in these tests, simulating river ice jam conditions. The jam thickness to flow depth ratio ( $h/Y$ ) ranged from 0.2 to 0.3. The boom thrust is plotted against  $\frac{L}{B}$  showing the leveling off of the boom thrust as the ice jam is increased.

This study will extend the experimental work conducted on forces exerted by river ice jams. This is the first attempt to investigate the forces exerted on a river shoreline by an ice jam. Further experiments measuring the thrust on a boom from a river ice jam covering a wider range of conditions will be presented. Two model materials will be used to model the ice jams and resulting forces. It has not been shown in the literature that polyethylene can be successfully substituted for real ice in force model. Comparative data for the two materials will be presented. Data will be presented for the evaluation of

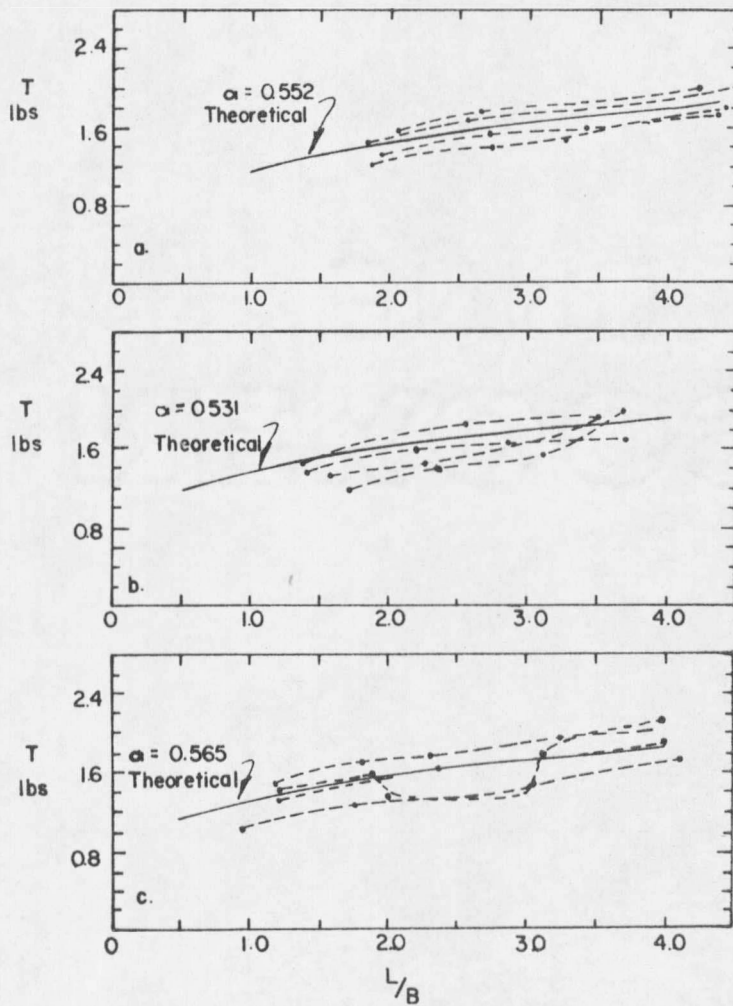


FIGURE 3. THRUST MEASURED ON A SCALE MODEL WITH SIMULATED ICE. DELAGRAVE (1966)

the stress distribution of the forces exerted on a model ice jam.

## Chapter 3

### EXPERIMENTAL APPARATUS AND PROCEDURE

#### Experimental Apparatus

The work reported herein was conducted in the refrigerated flume facility of the Ice Engineering Research Branch of the U.S. Army Cold Regions Research and Engineering Laboratory in Hanover, N.H. A measurement system was constructed which consisted of an instrumented river bank and ice boom located in the flume, and a computer controlled data collection system. Refer to Figure 4 for a schematic drawing of the test setup in the flume.

Instrumented river bank elements comprised the river shoreline between which the fragmented ice cover floated. The instrumented boom was placed at the downstream end of the test section to constrain the cover. A false wall extended below the river bank elements to form the channel into a rectangular shape. The length of the instrumented section was five times the test section width.

The hydraulic flume used for this project, shown in Figure 5 is 120 ft. long, 4 ft. wide, and 2 ft. deep. It can be tilted with a variable slope range from  $-0.009$  ft./ft. to  $0.018$  ft./ft. by an automatic coordinated jacking system. The flow capacity is variable from 0 to 14 CFS and is monitored with magnetic flow meters. The water level in the flume can be controlled with either a submersible headgate, tailgate or a series of adjustable vertical louver gates located in the tailbox.

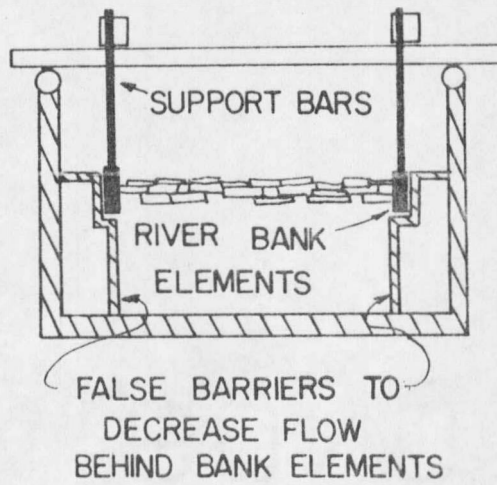
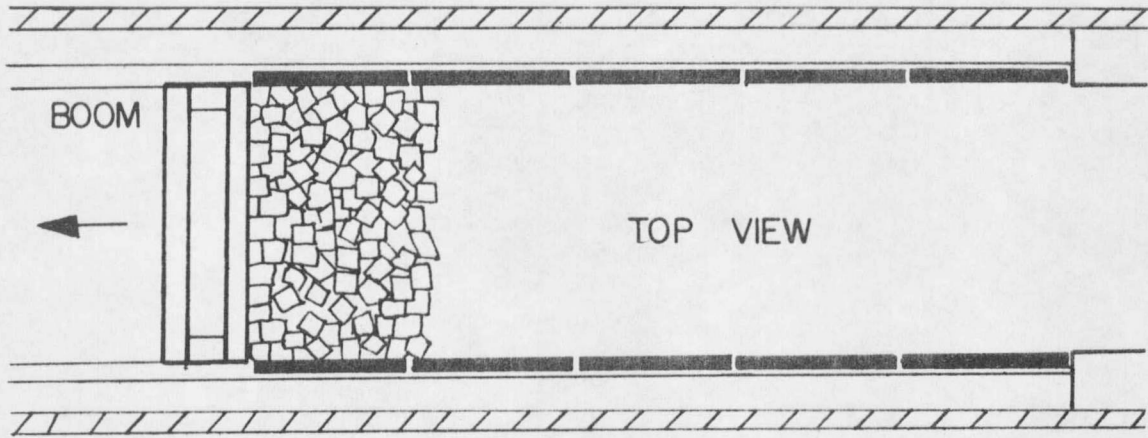


FIGURE 4

The flume is located in a room that can be refrigerated with a variable range down to  $-20^{\circ}$  F. The flume bottom can be refrigerated to  $0^{\circ}$  F and the test water used in the flume can be chilled to  $32^{\circ}$  F prior to entering the flume body. The sides of the flume are composed of 2 ft. by 6 ft. sections of tempered glass, supported with 2 in. by 4-1/2 in. aluminum channels with rubber isolation gaskets between the glass at all supports. The Manning roughness coefficient  $n$  for the flume bottom is in the range of 0.010 and 0.011, which corresponds to a Darcy-Weisbach friction factor  $f$  of 0.015 to 0.018.

The instrumented shoreline panels consisted of ten 3-feet long by 1/2-foot high, each suspended parallel with the flume walls by a 3/4 inch diameter strain gaged aluminum rod, five on each side of the flume. Refer to Figure 6. Each panel was bolted vertically through its center point to a support rod. The support rods were bolted to a rigid overhead frame, which was secured to the flume body.

Appendix A details the instrumented rod and strain gage positioning. Each support rod had a milled down section located one foot above the panel. The milled sections contained four flat vertical faces on which two pair of linear displacement strain gages were mounted. Movement of the panel in the horizontal plane would be transmitted to the strain gages through the movement of the rod. After calibration of the support rod and panel an unknown load could be measured by observing the readings from the strain gages on each rod.

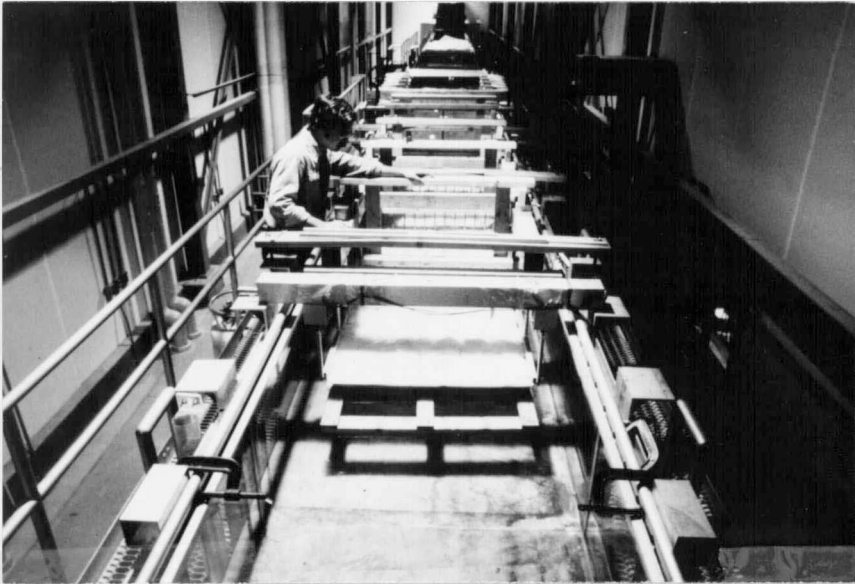


Figure 5. Photographs of Hydraulic Flume.

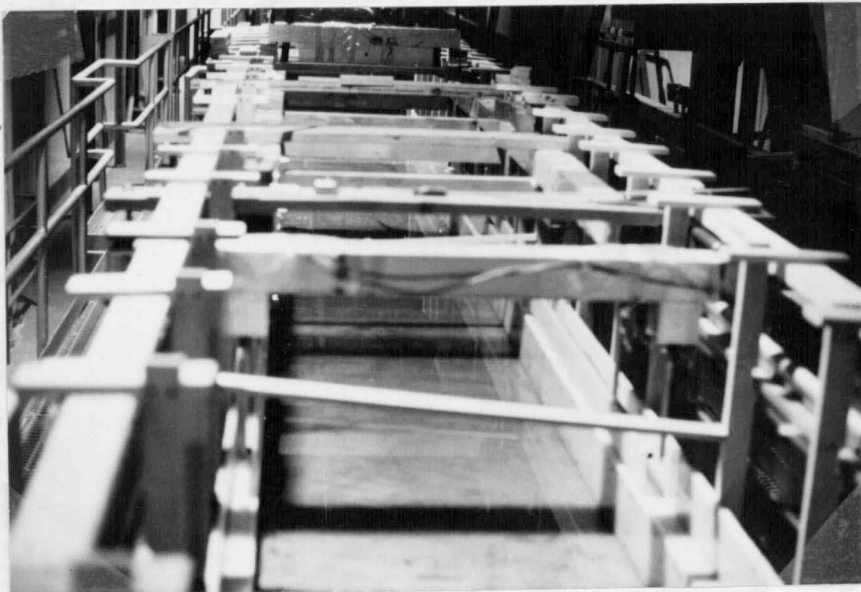


Figure 6. Photographs of Shoreline Panels and Instrumented Force Rods.

and comparing with the calibration matrix for each corresponding system. Refer to Appendix A for calibration principles and procedures.

The strain gaged rods were mounted in the support frame such that one pair of gages was oriented in the direction of water flow and the other pair was located transverse to the flow. The shoreline panels were positioned in the same plane as the streamwise pair of gages. In this configuration, one pair of strain gages measured the movement of the panel in the streamwise direction, analogous to the tangential force, and the transversely mounted gages measured the movement normal to the panel face, the normal force. The moment created due to an eccentric loading on the shoreline panel, with respect to the support rod, could not be read by the strain gages as the axis of the moment was coincident with the neutral axis of the bar.

Each pair of strain gages was wired into a NEFF series 300 amplifier and signal conditioner as a two active arm wheatstone bridge. Appendix A details the strain gage circuit. The NEFF signal conditioner was used to complete the Wheatstone bridge and to provide signal conditioning for interfacing with an HP 9845 digital computer. The purpose of signal conditioning is to prepare the transducer output for amplification and conversion to digital code for subsequent recording or direct processing. Refer to Appendix B for additional information on the NEFF signal conditioner.

The HP 9845 computer served as the controller for the NEFF system

and provided data storage via flexible disc memory units. Several programs were written for the HP computer to control the NEFF system, for calibration of the bar and panel systems, monitoring drift in the NEFF system, for controlling data acquisition, storage and reduction. These programs are listed in Appendix D.

### Experimental Procedure

A limited number of experiments were conducted in this apparatus in the time period allowed for this project. Polyethylene parallelepedes and real ice pieces of nearly identical size and shape were used to simulate floating, fragmented ice covers. Two block sizes were used with each material, 51 mm X 51 mm and 102 mm X 102 mm. The results of these experiments are reported herein.

The testing pattern followed is shown in Table I.

TABLE I

Q $\frac{m^3}{sec}$	PLASTIC BLOCKS		ICE BLOCKS	
	<u>51 mm</u>	<u>102 mm</u>	<u>51 mm</u>	<u>102 mm</u>
.0252	x	x	x	xx
.0316	xx	xx	x	x
.0379	xx	xx	x	x
.0442	-	-	x	x
.0473	xx	xx	x	xx

Each x denotes a separate testing event.

The ice jam thicknesses ranged from 6 mm to 150 mm and were relatively uniform along their lengths. These values are tabulated in Appendix E. The jam thicknesses were measured by inserting a rule vertically through the jam along the centerline of the flume and observing the readings at the top and bottom of the jam through the glass walls of the flume. Thickness measurements were taken at the midpoint of each panel section.

The plastic blocks were cut from commercially available polyethylene sheets with a band saw. All the plastic blocks had a thickness of 6 mm. The polyethylene had a density of 0.92, very similar to freshwater ice.

The ice blocks were frozen in trays near the headbox of the flume and placed in the flow at that point. The planar dimensions of the ice blocks were also 51 mm X 51 mm and 102 mm X 102 mm. The thickness of the ice blocks varied slightly due to the method of construction but on the average were the same as the plastic blocks. The thickness values for the ice blocks are tabulated in Appendix E.

A typical test procedure was as follows: The water discharge through the flume was set and the water elevation through the test section obtained. Force readings on the river bank elements were taken without the boom in place. The ice boom was then attached to its two support rods and another set of force readings obtained. A difference in the force readings on the shoreline was found, caused by

the backwater effect of the boom.

The model ice, either plastic or ice, was then placed in the flume upstream of the instrumented sections and allowed to float into position behind the instrumented boom. The floating cover was allowed to thicken until it came to its equilibrium thickness. Rakes, or dividers, were then introduced into the jam at the panel intervals and the jam was broken up into segments, with the length equal to the channel width. Refer to Figure 7. A floating sheet of polyethylene was then placed immediately upstream of the jam to act as an extension of the cover length to develop the proper shear stress underneath the cover within the instrumented length of the jam. The polyethylene sheet was held so that its weight did not contribute to the force within the jam.

Force readings were then taken, incrementing the cover length by removing the rakes. Typically the jam length was longer than the measured section. In this case the boom forces induced from the total length of the jam were measured but the bank forces could only be measured in the instrumented section, the first five river widths.

After all the rakes had been removed from the jam and the force readings were completed, the boom was removed and the model floes were released from the measurement section. On several tests these dynamic forces were measured, as the jam released and floated downstream. After the jam had cleared itself of the test section force readings were again

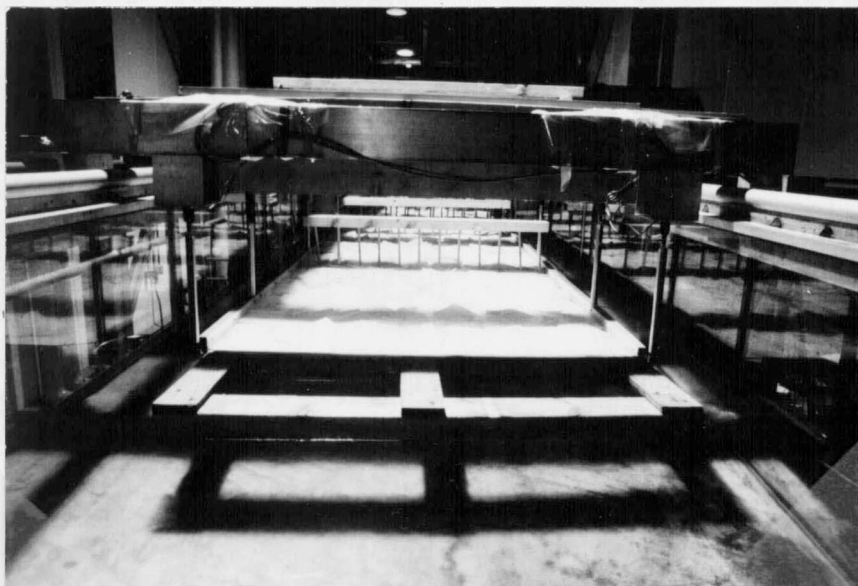
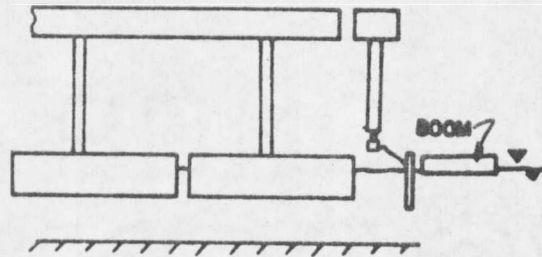
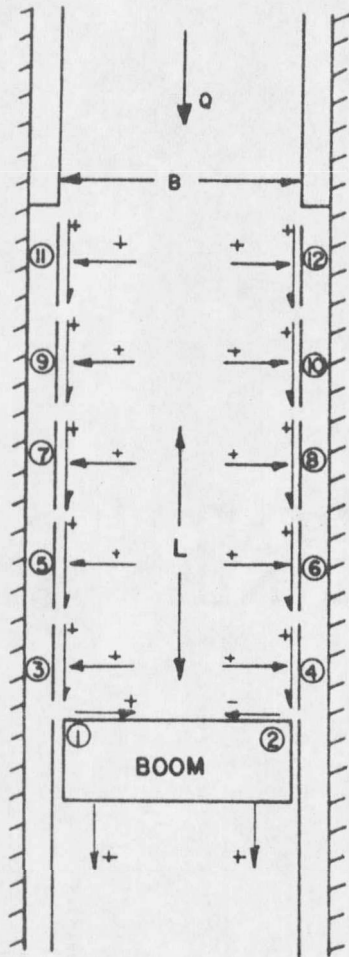


Figure 7. Photograph of Rakes and Experimental Apparatus.

taken, to measure any offsets and drift in the measurement system.

For each test sequence, the water level, flow velocity, jam thickness along its centerline, ambient air temperature, water temperature, and jam length were measured. When the ice blocks were used, the thickness of the blocks at the start and end of the test was measured to determine the amount of melting that occurred. In most instances, this was slight. The force readings and accompanying data for each test run are tabulated in Appendix F. Special care was taken in monitoring the room temperature and the flume water temperature with the ice tests to insure that the blocks were not freezing together in the jam. Forces induced from adhesion caused by freezing of the blocks to each other were not modeled in these tests.

The sign convention and numbering of the panels used in reporting the force values are shown in Figure 8.



BOOM WAS ATTACHED  
WITH STRINGS TO  
TWO RODS

FIGURE 8

## Chapter 4

### RESULTS AND DISCUSSION

The experimental conditions investigated, the model jam characteristics, and resultant force measurements are summarized in Appendix D.

In the Literature Review (pp. 7-8), a summarization of the previous studies of forces exerted on booms by floating, fragmented covers was presented. The data from the experiments reported herein will be presented in similar form for comparison. Alternative formats of viewing the data will also be used. In each series of plots shown, the tests with the plastic blocks and the tests with the ice blocks can be compared. The boom force data and results and the experimental results of the shear and normal force measurements on the river bank elements will be presented. In addition to the graphical format of the data presented in the main body of the thesis, the data is listed and summarized in tabular form in Appendix F.

It was not known at the outset of this investigation whether the hydrodynamics of the polyethylene blocks would be significantly different from the ice blocks thus affecting the modeling of forces with the simulated jams. Tatinclaux (1977) discussed the effect of surface tension on materials preferentially and non-preferentially wet by a water meniscus and the effects of this on the modeling of the incipient critical submergence velocity of model ice floes. Refer to

Figure 9 for a schematic drawing of the meniscus on each material.

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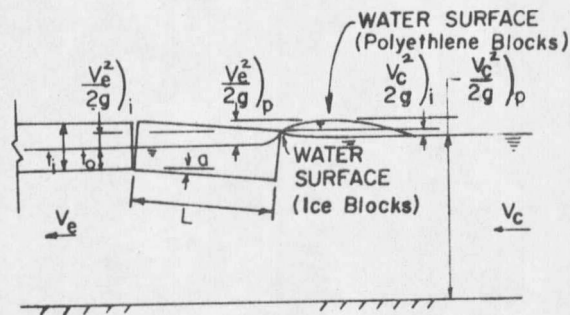


FIGURE 9.

Tatinclaux found the effect of surface tension between the plastic and the water to be significant when small blocks of the material were used in the laboratory experiments to simulate ice floes. This conclusion was based upon comparisons of the critical submergence velocities for polyethylene blocks and real ice blocks of similar dimensions. The polyethylene blocks, preferentially wet by the air meniscus, were found to have submergence velocities 40 to 50 percent higher than for the real ice floes, preferentially wet by the water meniscus. The polyethylene blocks were coated with an oxidizing agent to reduce the surface tension and the results were found to compare quite closely between the two materials. Although the

oxidizing agent gave good results, it was not practical for laboratory use as it wore off the blocks very rapidly.

At the outset of this study it was assumed that the surface tension of the blocks was not an important parameter as the method for the deposition of the jam was not being modeled, just the forces exerted on the boom and shoreline once the jam was in place. It will be shown that the forces developed with the plastic blocks and the ice blocks do not agree very closely. This is thought to be due only in part to the surface tension effect on the two model materials. The effect of the interaction of the two materials with the smooth shoreline is thought to be more significant. When melting ice is in contact with another surface there is a small water layer developed between the two surfaces. On a smooth boundary such as used in this experiment, this slight water layer will significantly change the coefficient of friction between the two surfaces. The plastic blocks tended to show an attraction to the shoreline due to the adhesive force from the surface tension effect. The ice blocks, due to water layer around them and a different surface tension tended to slip along the shoreline and each other, in comparison with the plastic. It is believed that a shoreline with a higher roughness would tend to minimize this difference in surface tension effect, being more resistant to motion along its surface. There would still be the effect of surface tension on the blocks between each other, the plastic attracting the air meniscus

and the ice attracting the water meniscus, but the differences would be minimized.

The boom force data are plotted in the following four formats:

1.  $F_B$  vs.  $L/B$                       Figures 10 - 14
2.  $[F_B/F_{B_{\max}}]$  vs.  $L/B$               Figures 15 - 18
3.  $[F_B/\rho \frac{AV^2}{g}]$  vs.  $L/B$               Figures 19 - 22
4.  $[F_B/\bar{\zeta}B^2]$  vs.  $L/B$                   Figures 23 - 26

where  $F_B$  = the resultant force exerted on the boom by the jam.

$F_{B_{\max}}$  = the maximum resultant boom force observed in each test.

$\rho$  = the specific density of the model ice pieces - 0.92.

$A$  = the average area of the ice cover in contact with the boom face.

$B$  = the channel width = 0.9 m.

$L$  = the model jam length.

$V$  = the average flow velocity under the cover.

$\bar{\zeta}$  = the average shear force exerted under the ice cover by the flow.

$\bar{t}$  = the average thickness of the jam.

In all of the following plots the convention of labeling the ordinate axis versus the abscissa axis was chosen. The numbers shown next to each line of data are the respective test numbers. The test numbers on the plots correlate with the test numbers used in the Appendices where additional data is available for each test.

J.  $F_B$  vs  $L/B$  (Figures 10 - 14).

From these plots, in general, it can be said that the boom force exerted by the plastic block ice jams levels off as the cover length reaches three to four times the river width ( $L/B = 3$  to  $4$ ). The real ice floes did not exhibit this phenomena. For the low velocity cases, refer to Appendix E, the ice block test data levels off but as the velocity was increased, the measured force pattern deviated from this leveling off trend.

The plastic blocks, at every velocity tested, developed a higher friction force with the shoreline panels than the ice blocks did. This is illustrated in the section of this thesis that discusses the shear versus normal force plots, Figures 27 to 30. Thus, for the same longitudinal forces exerted within the jam, a proportionally greater amount of the longitudinal force would be transmitted to the boom through the ice cover than through the plastic cover. There appears to be a direct relationship between the friction developed between the jam and the river shoreline and shape of the  $F_B$  vs.  $L/B$  plots, also the normalized boom forces versus  $L/B$  plots. When there is little friction developed between the ice jam and the river shoreline, as was the case with the real ice floes, the boom force will attain a maximum value at a much higher ice jam length than when a greater amount of friction is created, as was the case with the plastic floes. In the tests conducted with the real ice floes, less friction

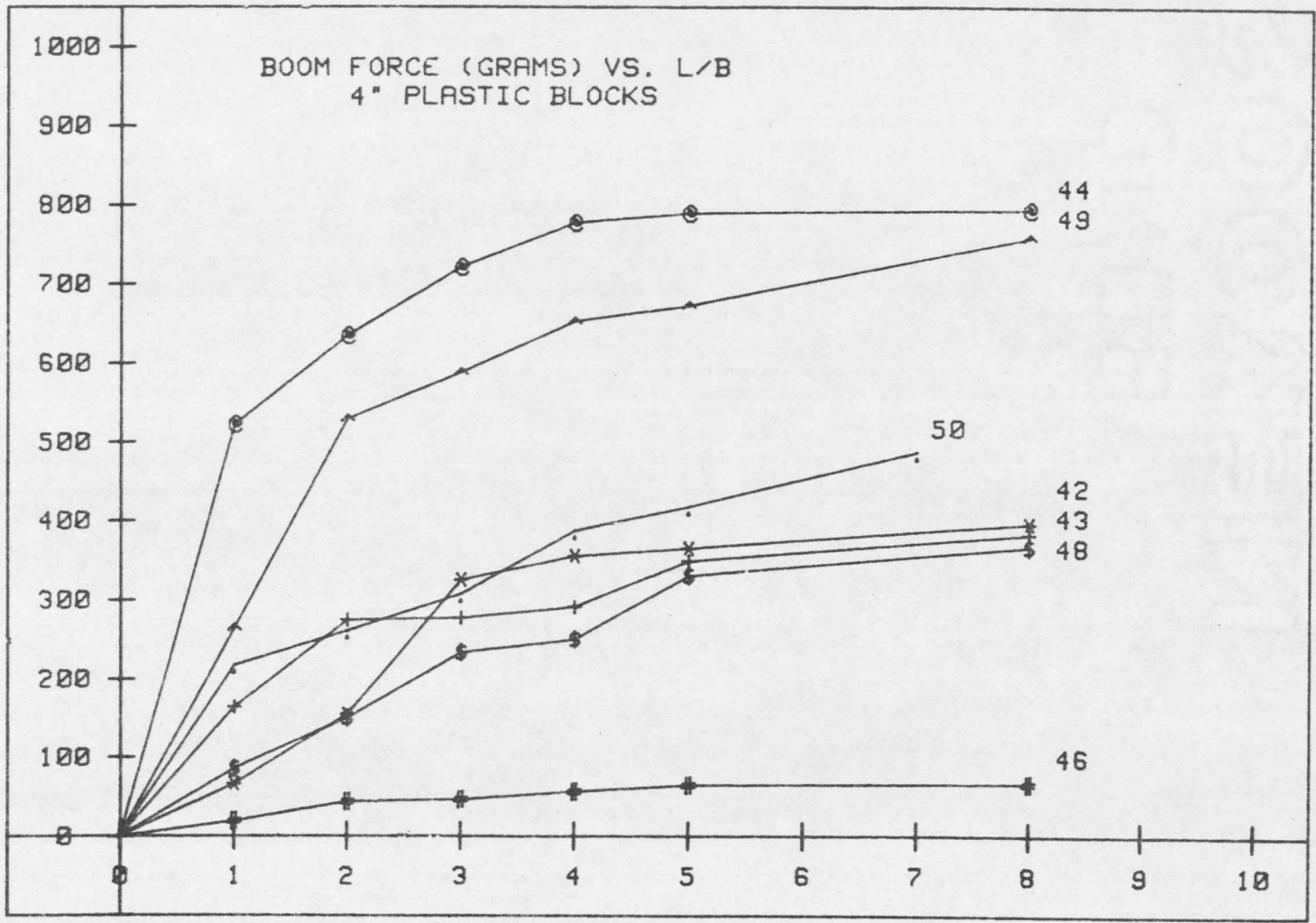


Figure 10.  $[F_B]$  vs L/B - 4" Plastic Blocks.

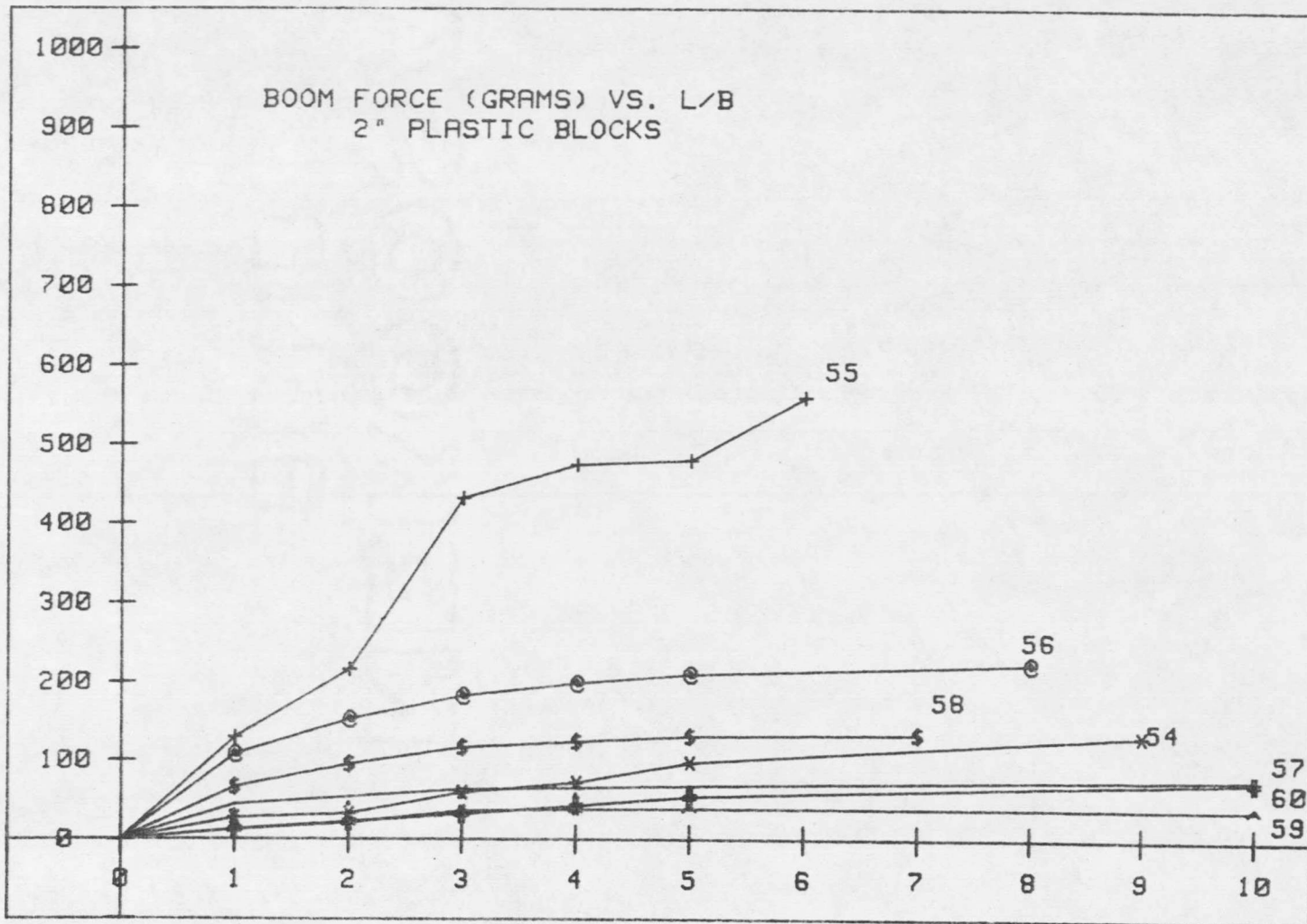


Figure 11.  $[F_B]$  vs L/B - 2" Plastic Blocks.

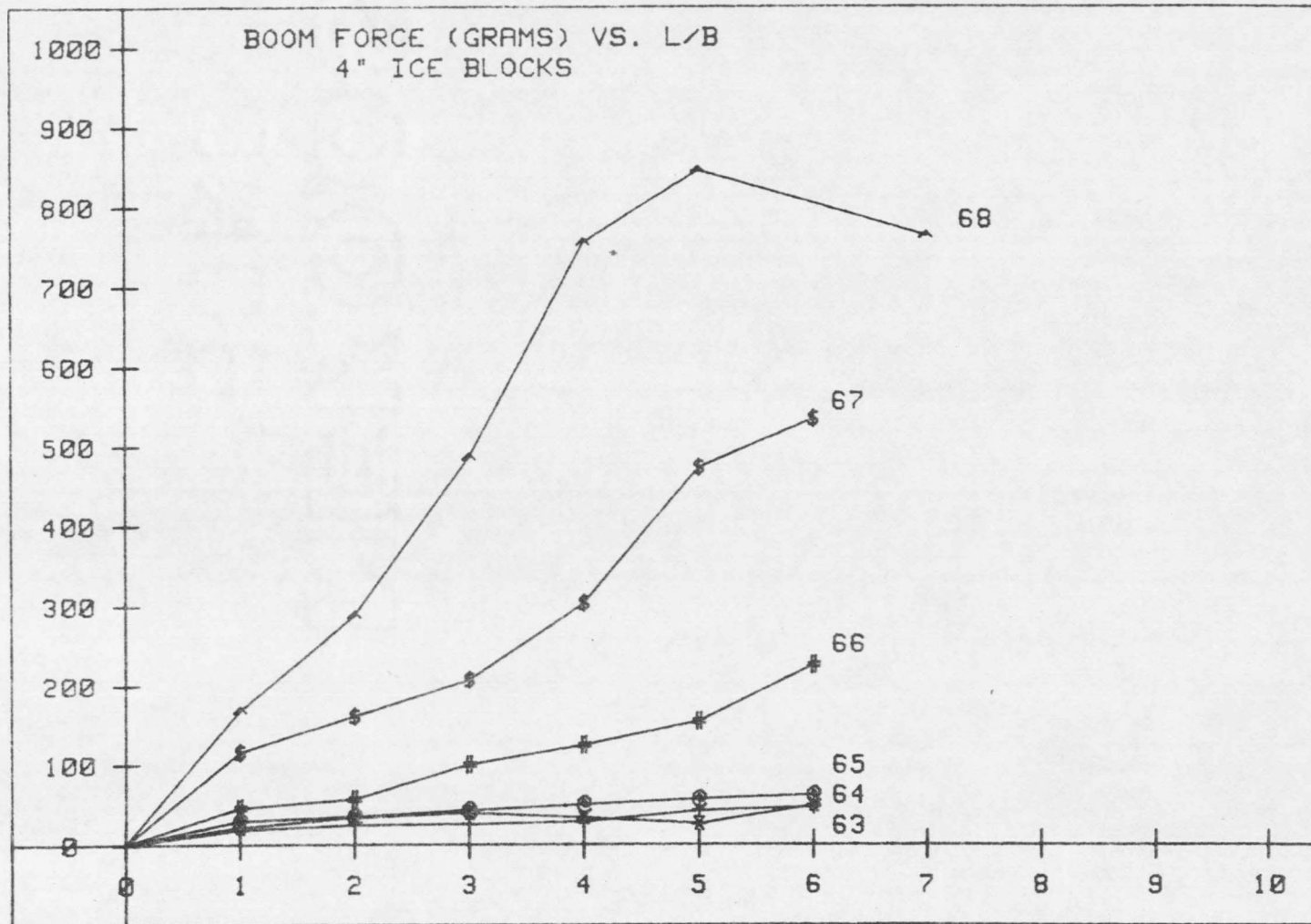


Figure 12.  $[F_B]$  vs L/B - 4" Ice Blocks.

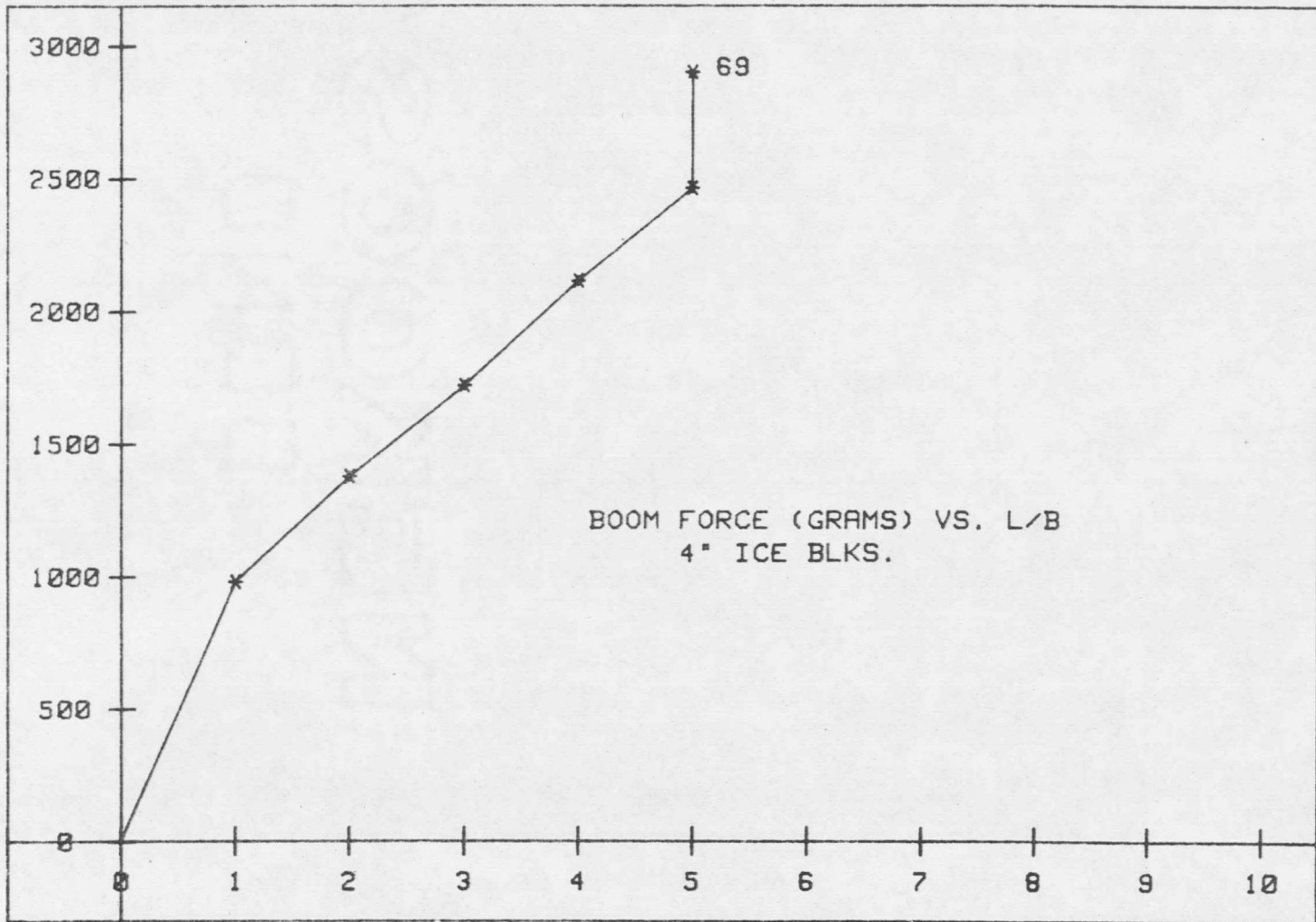


Figure 13.  $[F_B]$  vs L/B - 4" Ice Blocks (Test 69).



























































































































































































































































































