Draft Final Report
Research Project T9903, Task 3, Subtask 8
Ferry Wake Study

FERRY WAKE STUDY: FINAL REPORT

DRAFT

by

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This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

This report describes the findings of an extensive literature search on the impact of alternative ship designs on the wake and wash generated by high speed passenger ferries. Also included in the report are bibliographic citings of reports and articles describing the environmental impacts of various size and shape waves.

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SUMMARY

The purpose of this study was to locate reports, papers, conference proceedings, and other relevant publications on the subjects of high-speed vessel wakes, vessel designs that generate wash, and the environmental impact that vessel traffic has on erosion and the shoreline.

The research approach for this study included the following activities:

- contacting former employees of the now-defunct Advanced Marine Systems Associates;
- contacting the David Taylor Naval Research Center;
- conducting an on-line literature search at the Washington State Department of Transportation Library in Olympia. Established key words were used to locate relevant reports, studies, conference proceedings, and other related publications on ferry wakes, vessel designs, and erosion impact to the environment;
- investigating available resources at the University of Washington Library System; and
- contacting individuals and their respective local, national, and international companies and organizations for their expertise on ferry wakes, vessel designs, and their influence on erosion and the environment.

The conclusions established from this work include the following.

- The wake-wash a vessel generates is determined by several factors, including vessel design and vessel weight.
- Long, slender hulls produce less wash than vessels with short, wide hulls.
- Vessels that are designed with a high length to beam ratio produce less wash.
- The speed of the vessel as it travels through the waterway can determine how much wake-wash it will generate.
- The worst waves are those that emanate from the bow and then spread out diagonally.

Erosion from the wake-wash of a vessel can be caused by one or more of the following factors:

- the speed of the vessel,
- the distance of the vessel from the shoreline,
- the existing currents and waves of the waterway, and
- the depth of the water.

CHAPTER 1

INTRODUCTION

The purpose of this study was to locate reports, papers, conference proceedings and theses on the subject of high-speed vessel wakes. The Washington State Department of Transportation (WSDOT) wants to know how high-speed boats create wake-wash damage.

It wants information on how vessels of different designs, traveling at different speeds, create wakes of varying sizes and shapes, and how the resulting wake-wash causes damage along the shoreline. Additionally, WSDOT wants to know the kinds of boats and/or wakes that cause the most environmental damage.

Chapter 2 discusses the relationship between ferry vessel designs and the amount of wash generated.

Chapter 3 is devoted to the environmental issues of ferries and the impact their traffic has on the shorelines, including erosion.

Chapter 4 lists the individuals who were contacted during this study.

The Bibliography is a compilation of the reports, articles, and studies that were used to produce this report.

The information presented in this report does not represent the full spectrum of information that may exist on this topic. This report only represents an overview of material that was located in the allotted time for this study.

CHAPTER 2

FERRY VESSEL DESIGNS AND WAKE WASH

An October 1991 issue of "The Motor Ship" reported that "annual sales of fast ferries has rapidly grown from 1986 to 1990." "The Motor Ship" also reported that orders for catamarans had averaged 60 craft over the past five years (see Exhibit 2.1). "High-speed craft ordered or delivered during 1990 totaled 146 vessels."

As the growth of the fast ferry market develops, shipbuilders will be faced with the task of designing bigger and faster vessels to meet the increased demand of waterborne passenger ferries on a domestic and international basis. Additionally, they will need to design vessels that provide amenities such as comfort and stability for the passengers, and at the same time, vessels that produce low wash and are economical to maintain. Vessels that produce low wash as they travel along the waterways also provide a more comfortable ride for the passengers, and at the same time, produce less damaging wave action along the shoreline.

Designing a vessel that produces low wash becomes a challenge for any shipbuilder or naval architect. This engineering task is especially important for the 100- to 200-passenger catamaran, monohull, hydrofoil, and the surface-effect ship (SES).

The literature on the design aspect of a vessel and its relation to wake-wash generation consistently mentions several factors that affect the wash a vessel produces as it travels in the water:

- the displacement and length of the vessel beam—the higher the length-to-beam ratio, the lower the amount of wash generated,
- the length of the vessel, and
- the length and width of the vessel hull—long, slender hulls produce less wash than vessels with shorter, wider hulls.

Unfortunately, little information is available on ways to predict the size and nature of the wash that a specific boat or boat design will generate. However, engineers do know that the

worst waves are those waves that emanate from the bow and then spread out diagonally. Waves that flow diagonally from the stern of the boat are the next worst waves and are less damaging than the waves from the bow. The transverse waves that follow in the path of the vessel are the least harmful. Engineers know that a short, fat, heavy craft will create more wash than a thin, light craft.

In 1961, the Soviets built the Zaria Water Bus. It is still considered to have one of the lowest full-load displacements of a commercial craft in use. The Zaria is designed as a waterjet-propelled vessel with a ram-air lift. Apparently, the ram-air lift helps to reduce the cruising displacement/length ratio. This displacement ratio in turn reduces the wash the vessel produces.

In 1968, tests were conducted on six model ships at the University of California, Berkeley. These tests found that the water depth and the speed of the ship were important factors in determining the size of waves the ship generated. The design of the vessel's hull played a role in wave production. Smaller vessels produced waves comparable in height to those of a larger vessel, and at a slower speed (see Exhibit 2.2). Exhibit 2.3 demonstrates that the greater was the "fineness" of the ship, the less amount of wave action the vessel produced.

Gold Coast Yachts, Inc., in the U.S. Virgin Islands, has found that the surface-effect ships (SES) produce as little wake as a catamaran. Gold Coast Yachts has also found during its vessel test runs that the SWATH, or small water-plane area, twin hulls vessel, also produces low wake activity in the water. The drawback to the SWATH is that it is an expensive vessel to manufacture.

A low-wake, high-speed version of the SWATH is being developed by Navatek Ships in Honolulu, Hawaii. According to Eric Schiff of Navatek, the wash test results have not been completed.

Robert Trillo, a consultant for Advanced Marine Transport Concepts and Amphibious Vehicles in Hampshire, England, has patented a successful hull design for catamarans in river use. Trillo's design concept is to use very long and slender hulls in the catamaran in order to reduce wash from the vessel. Trillo's design ideas were incorporated into the "River Cat"

passenger boats that run in Australia. Two of Trillo's catamaran designs run on the Thames River. Little wash has been reported from these catamarans.

Trillo expanded on his design ideas in a paper he presented at the September 1988 annual conference of the International Transit Marine Association in Boston. The title of his paper was "The RTL Hydrocat—A Minimum-Wash River, Lake and Harbour Craft Concept." According to Trillo, wash is determined by the design of the hull and the weight of the vessel. In Trillo's hydrodynamic terms, "If wave drag and wave wash are to be minimized, you need a hull form with a resistance coefficient that does not increase with the Froude number."

Trillo further stated in his paper that the wash height is determined by these additional factors:

- displacement and length of the vessel beam,
- the length of the vessel,
- the amount of resistance the vessel encounters as it passes through a water surface; the waves will correspond to the amount of resistance encountered,
- the state of the naturally occurring wind waves,
- the distance of the vessel from the shoreline, and
- the existing speed restrictions.

Exhibit 2.4, Figure 3 from Trillo's paper, shows that vessels with hulls that have very high length beam ratios will experience little if any "hump drag" in the resistance versus speed curve. Trillo also suggested using light-weight construction materials in the manufacture of the vessel and economically priced gas-turbine engines (see Exhibit 2.5 to 2.16).

Kvaerner Fjellstrand of Norway has come up with its version of high-speed foilborne vessels. The FoilCat can accommodate as many as 450 passengers in a 40-meter length vessel. It is powered by twin waterjets with General Electric gas turbines. It is described as a "low flying catamaran supported by foils, combining dynamic lift and displacement." This stabilizing system allows the FoilCat to travel at 50 knots with a wave action that is less than the traditional catamaran.

Japan has been manufacturing several low-wash craft. In 1991, over 200 fast ferries operated in Japanese waters. NKK of Japan developed a V-Cat design to use in its fast ferry operations. This catamaran design, capable of transporting 400 passengers, utilizes aluminum alloy, v-shaped displacement hulls. The thin side struts, which are located and joined at the lower and upper hulls, helps to alleviate wave action.

In 1962, Mitsui of Japan was building several types of hovercrafts. In 1989, Mitsui's small waterplane area twin hull SWATH catamarans began running between Tokyo and the island of Oshima.

FBM Commercial of England is one of the leaders in designing and manufacturing vessels with low wash capabilities. FBM has spent over five years researching vessel designs that are "environmentally friendly" (see Exhibit 2.17 to 2.19).

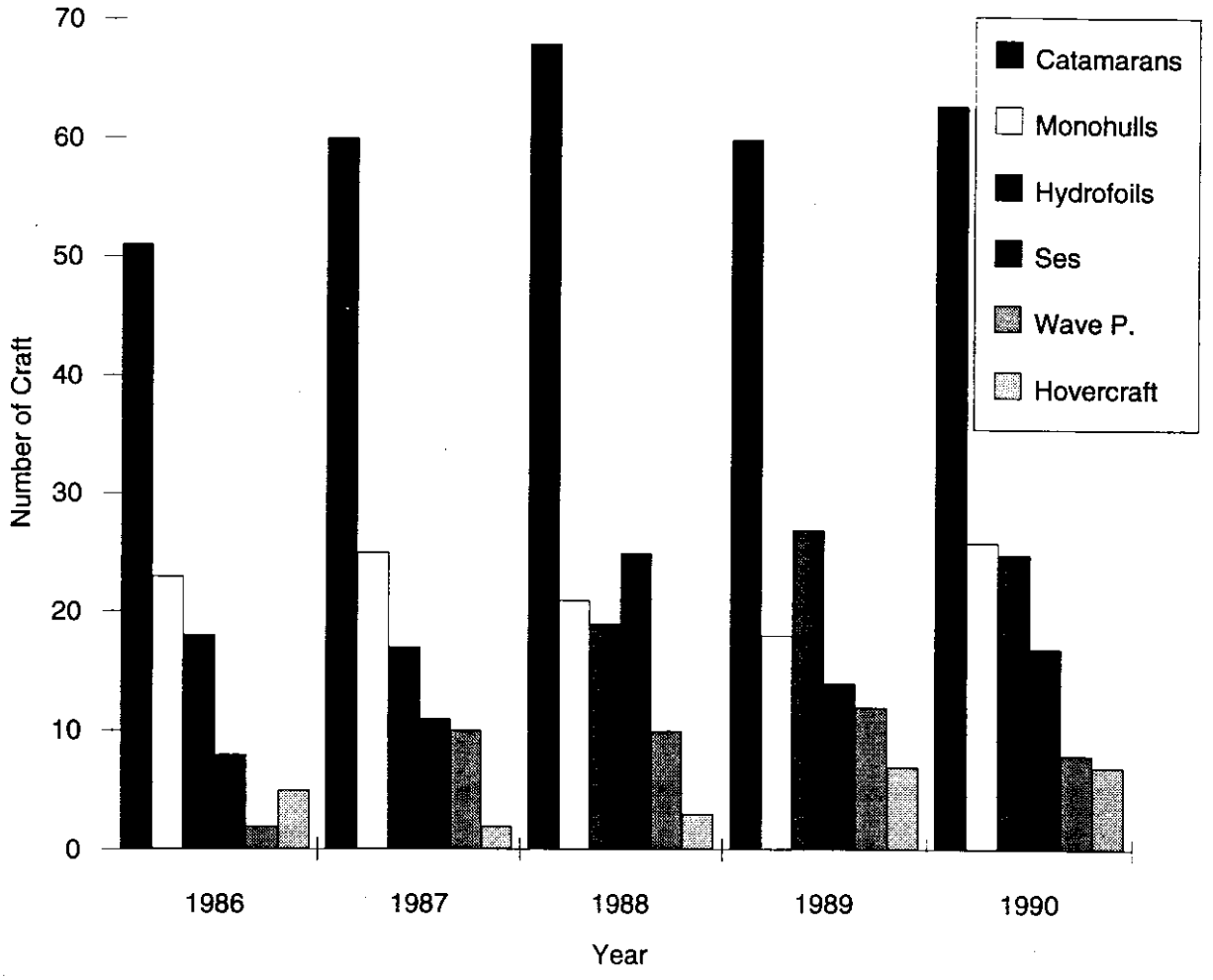
FBM has concluded that the wash of a vessel is determined mainly by the displacement/length ratio of the vessel. FBM has found that using light-weight materials in the construction of vessels helps to reduce wash production. A long, slender hull is another characteristic of vessels that produce little wash.

FBM has designed "ultra low-wash" craft and "low-wash craft." Both of these crafts were designed with a long, slender hull. An example of the ultra low-wash craft is the Thames Class Catamaran. It is 23 to 30 meters long, capable of transporting 60 to 140 passengers at one time. The low-wash craft designed by FBM is the Solent Class Catamaran, 30 to 45 meters long, with a carrying capacity of 120 to 360 passengers.

Other examples of FBM designs that produce low wash are the Canary Wharf II and the Executive Launch. The Canary Wharf is a 23-meter catamaran ferry that is part of the Thames River Bus Service. The 15-meter Executive Launch, with a passenger load of 12, is a monohull constructed of hard chine material. It has a displacement load of 8.0.

The displacement and length of the vessel beam, the size and length of the vessel's hulls, and a minimum frontal hull area are the best known and proven factors that affect the height of wake-wash that a small craft, or passenger carrying vessel or ferry will produce.

Exhibit 2.1



Fast Ferry Sales 1986 to 1990

Source: "The Motor Ship." October 1991.

Exhibit 2.2

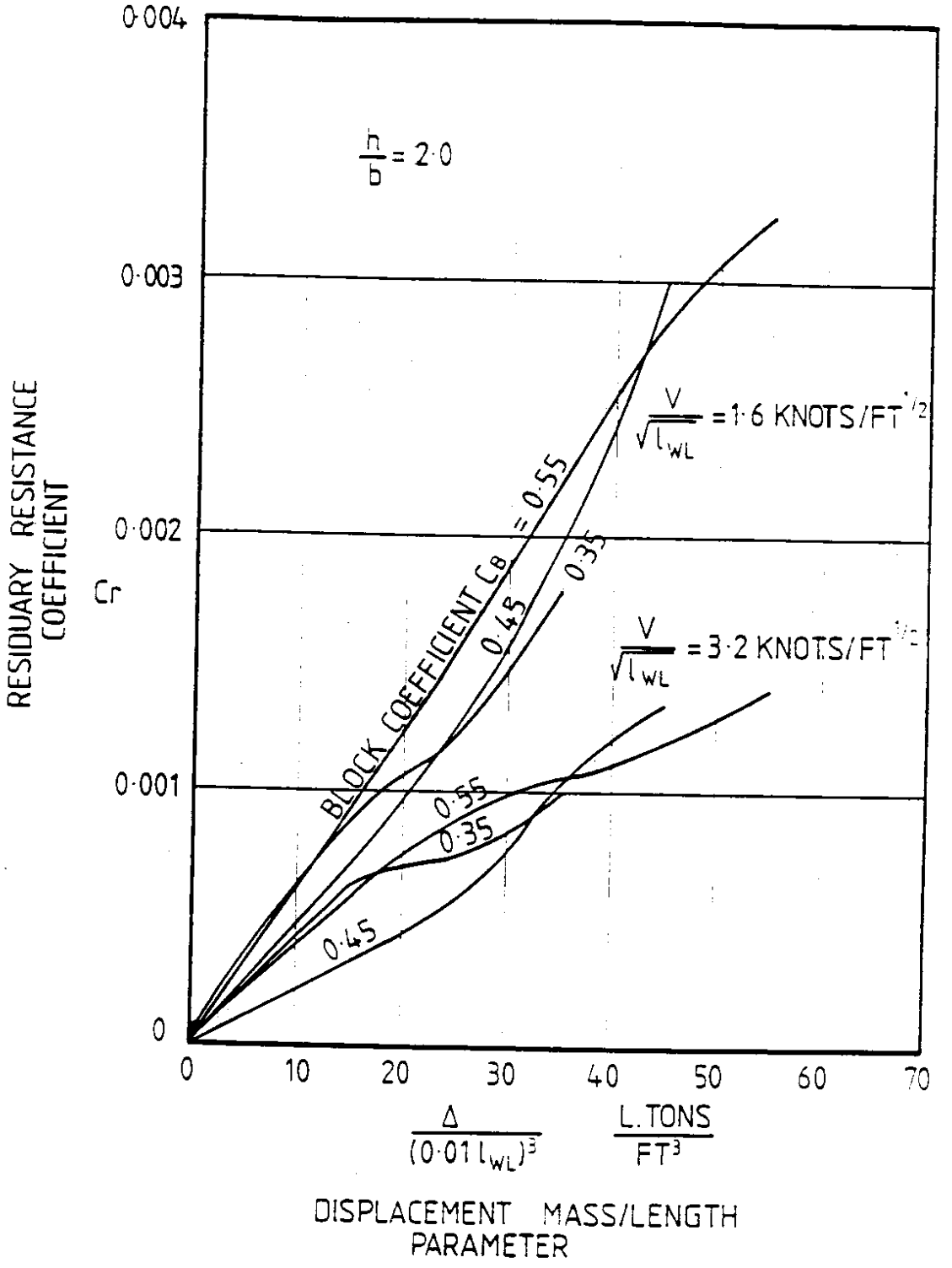


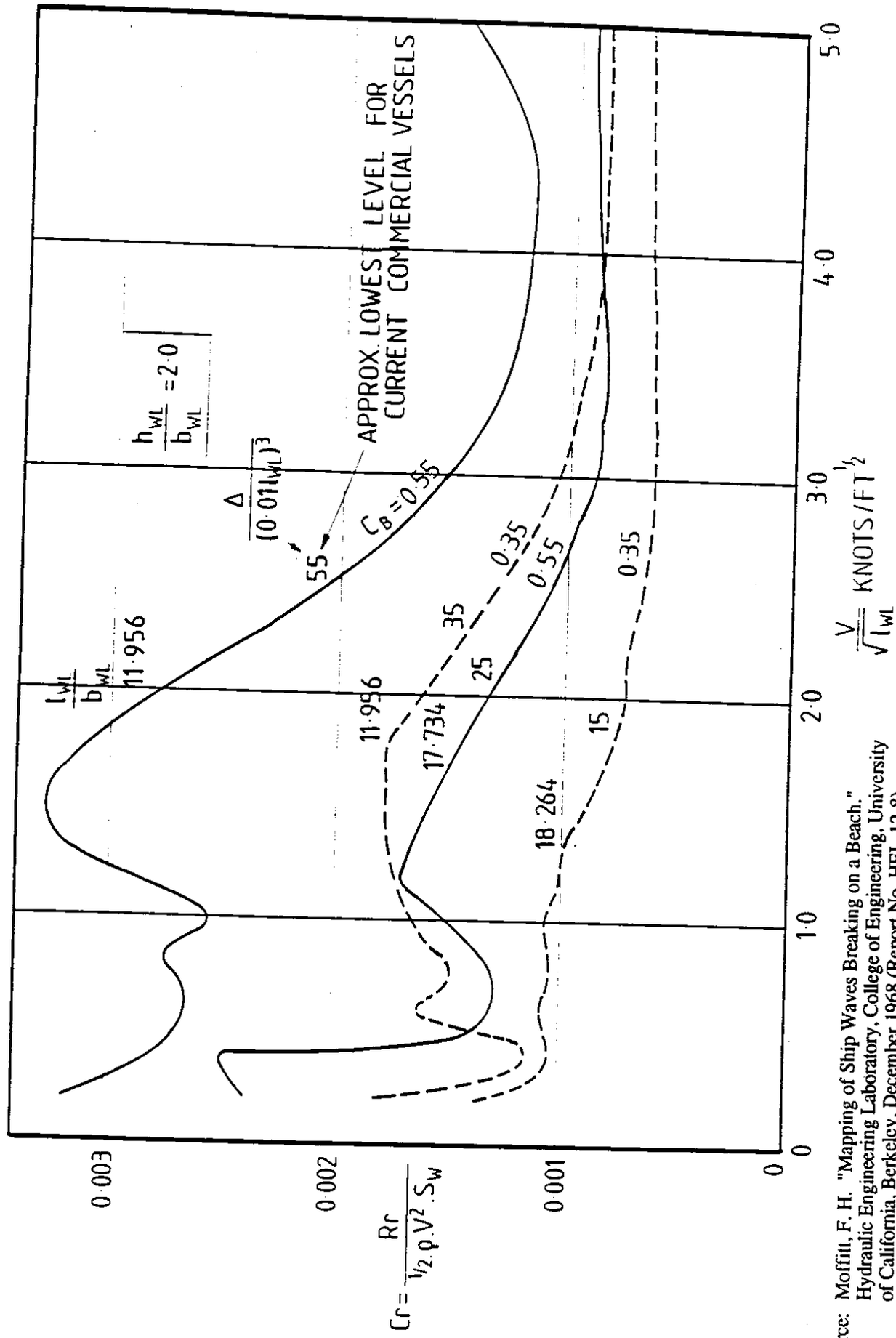
Figure 9

RESIDUARY RESISTANCE COEFFICIENT VARIATION WITH THE DISPLACEMENT/LENGTH PARAMETER

$$\frac{\Delta}{(0{\cdot}01\, l_{WL})^3}$$

Source: Moffitt, F. H. "Mapping of Ship Waves Breaking on a Beach." Hydraulic Engineering Laboratory, College of Engineering, University of California, Berkeley, December 1968 (Report No. HEL-12-8).

Exhibit 2.3



Source: Moffitt, F. H. "Mapping of Ship Waves Breaking on a Beach." Hydraulic Engineering Laboratory, College of Engineering, University of California, Berkeley, December 1968 (Report No. HEL-12-8).

Figure 10

RESIDUARY RESISTANCE COEFFICIENT VS. SPEED/LENGTH RATIO

Exhibit 2.4

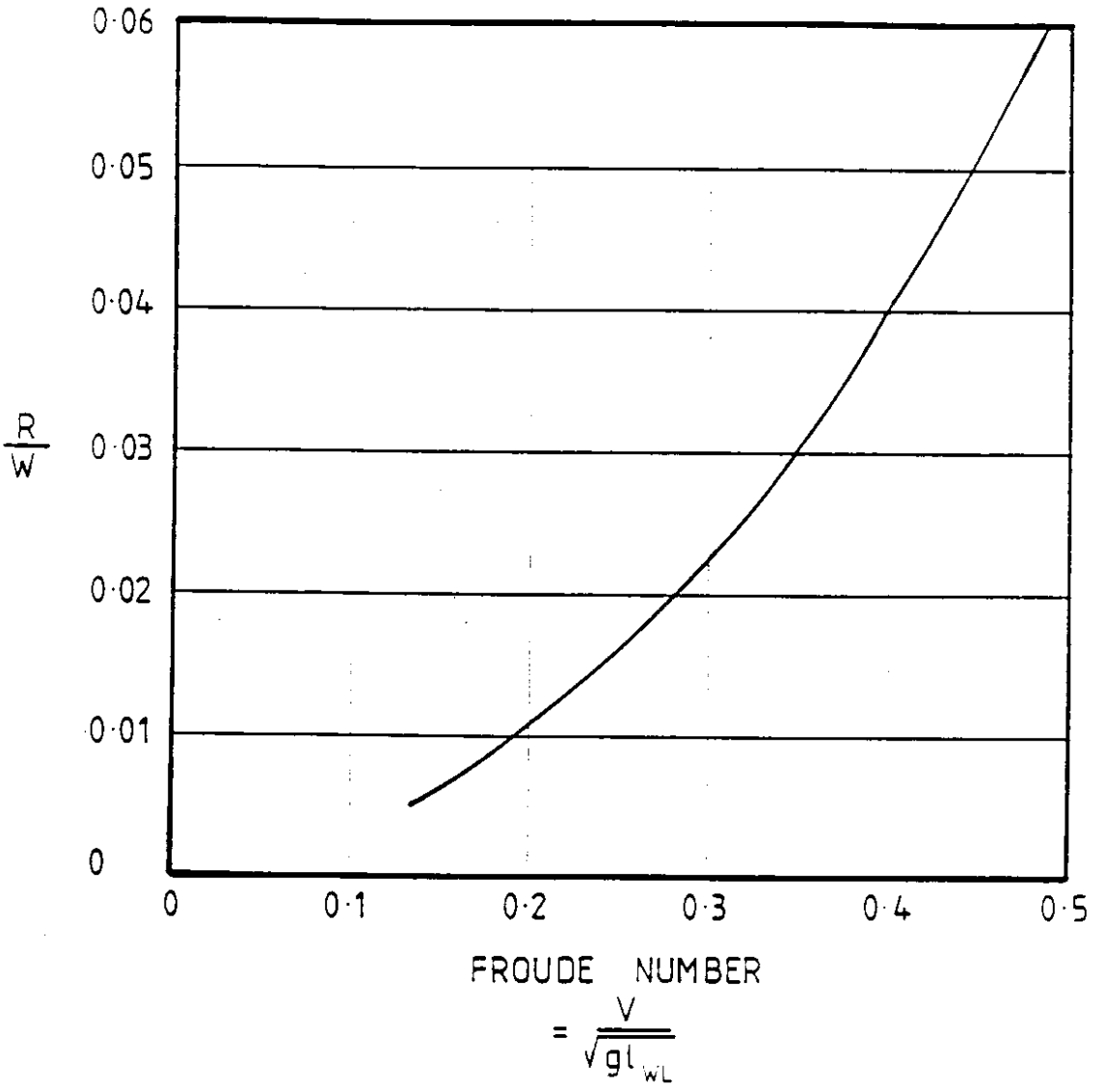


Figure 3

RESISTANE / WEIGHT RATIO FOR A TYPICAL ROWING 8 SCULL

LENGTH/ BEAM = 30·4

Source for Exhibit 4 to 16: "The RTL Hydrocat. A Minimum-Wash River, Lake, and Harbour Craft Concept." By Robert L. Trillo. Presented at the International Marine Transit Association Annual Conferece. Boston, Massachusetts, September 19-22, 1988.

Exhibit 2.5

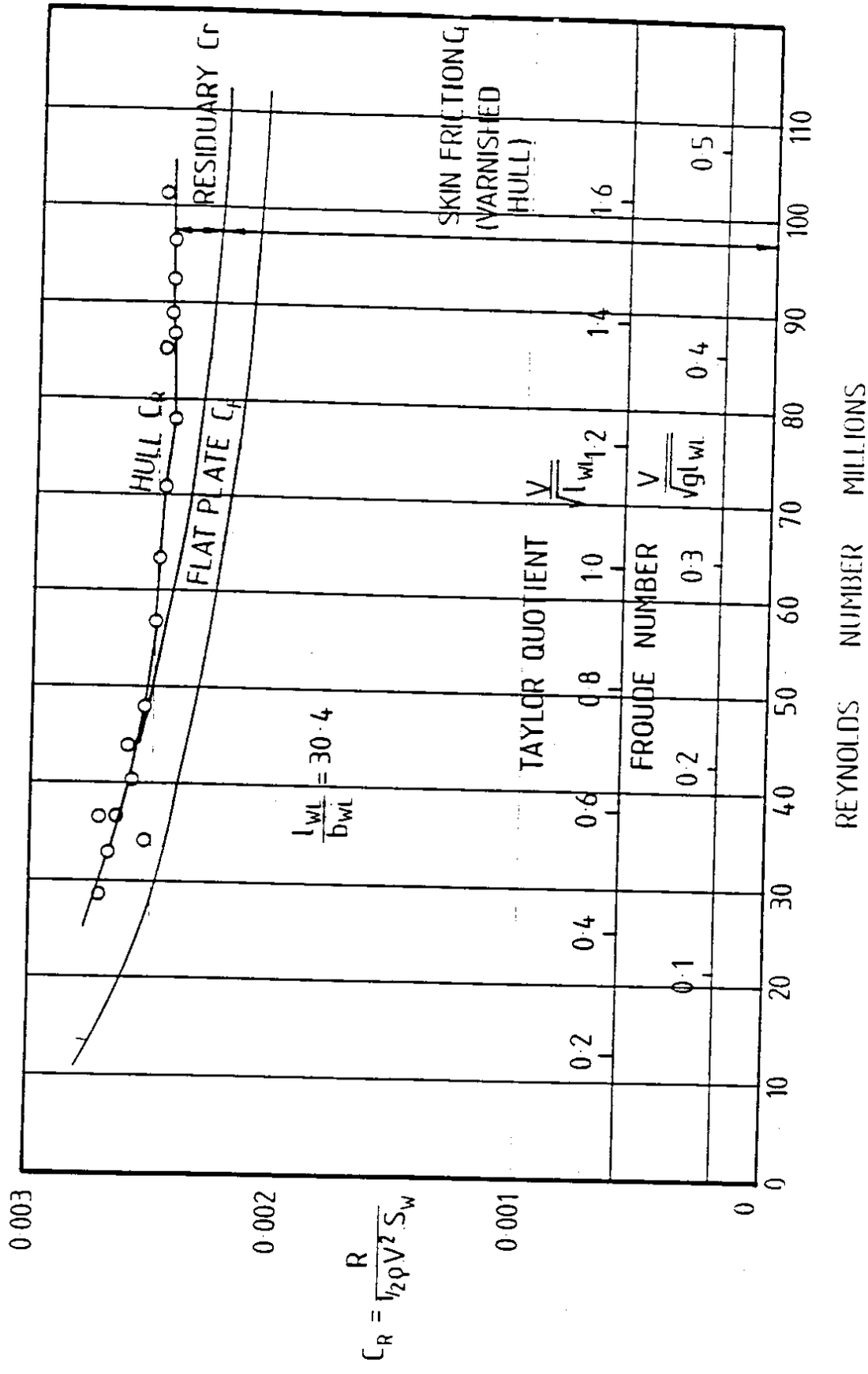


Figure 4

RESISTANCE COMPONETS OF A VERY HIGH LENGTH /BEAM RATIO HULL (ROWING SCULL)

Exhibit 2.6

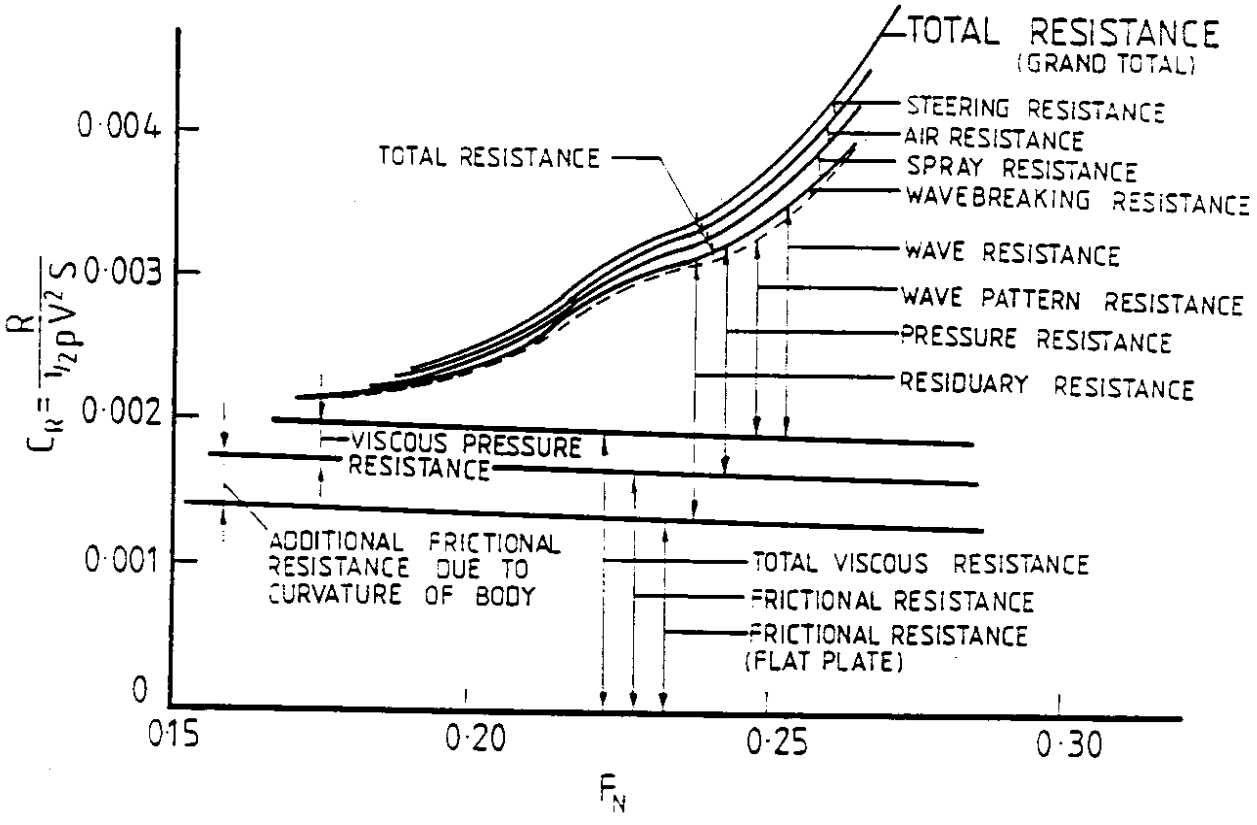


Figure 5

COMPONENTS OF THE RESISTANCE COEFFICIENT
OF CONVENTIONAL VESSELS (REF 1)

Exhibit 2.7

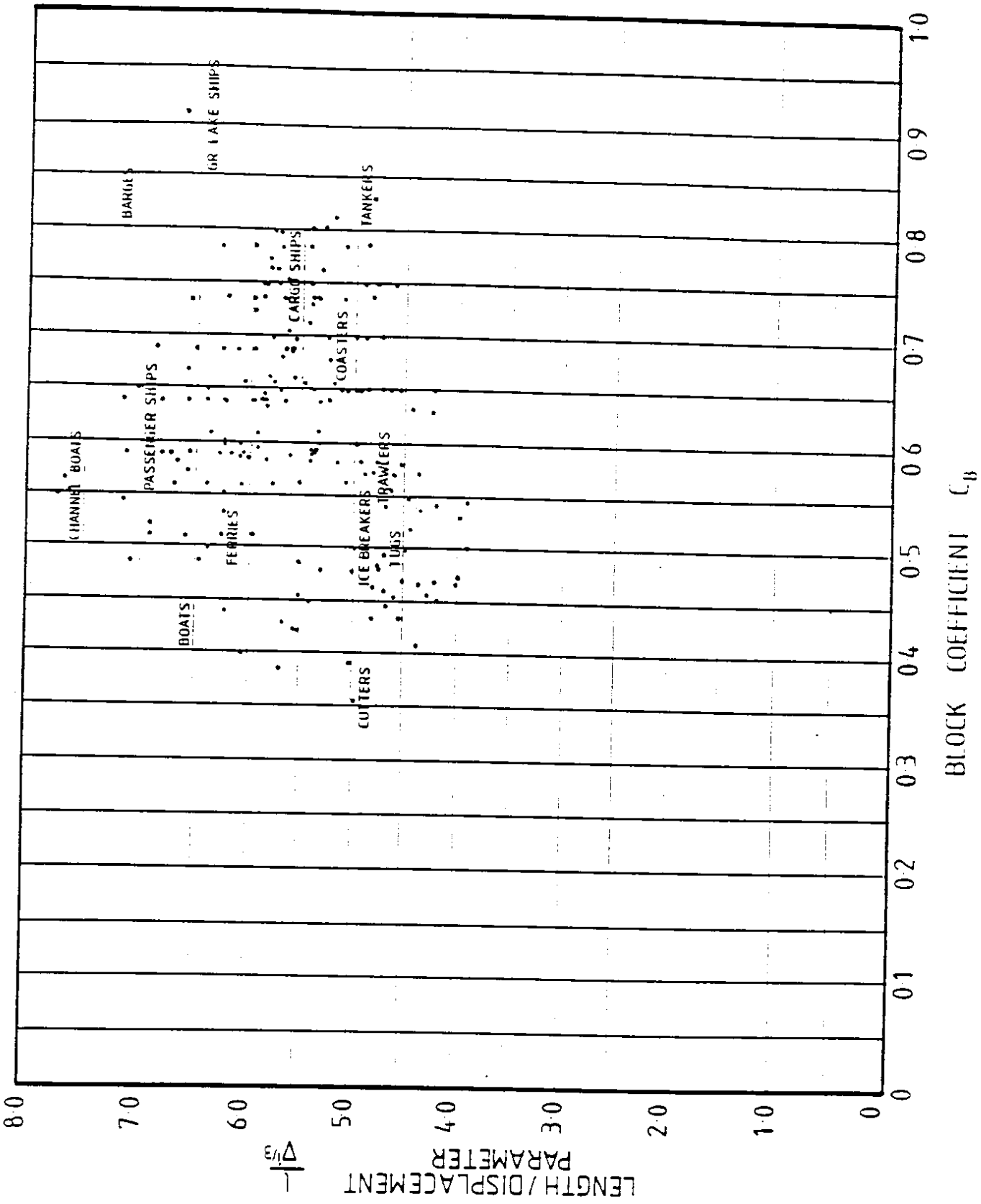


Figure 6

COMBINATIONS OF LENGTH/DISPLACEMENT PARAMETER $\frac{L}{\nabla^{1/3}}$ AND BLOCK COEFFICIENT C_B FOR TYPICAL COMMERCIAL VESSELS

(Based on Fig. 4.8.2. of Ref. 1)

Exhibit 2.8

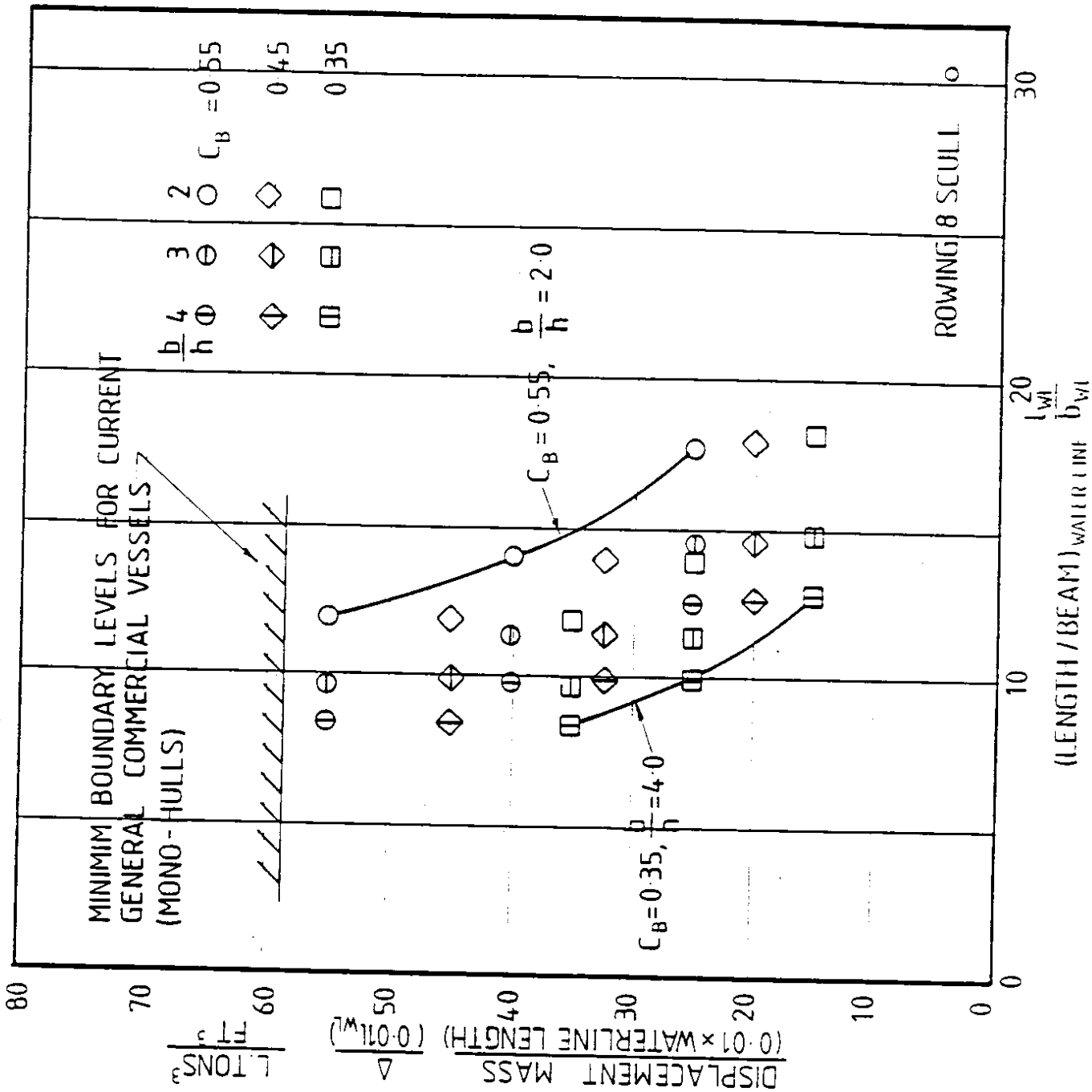


Figure 7

COMBINATIONS OF DISPLACEMENT LENGTH PARAMETER AND LENGTH/BEAM RATIO FOR 64 SERIES MONO-HULLS (REF 3)

Exhibit 2.9

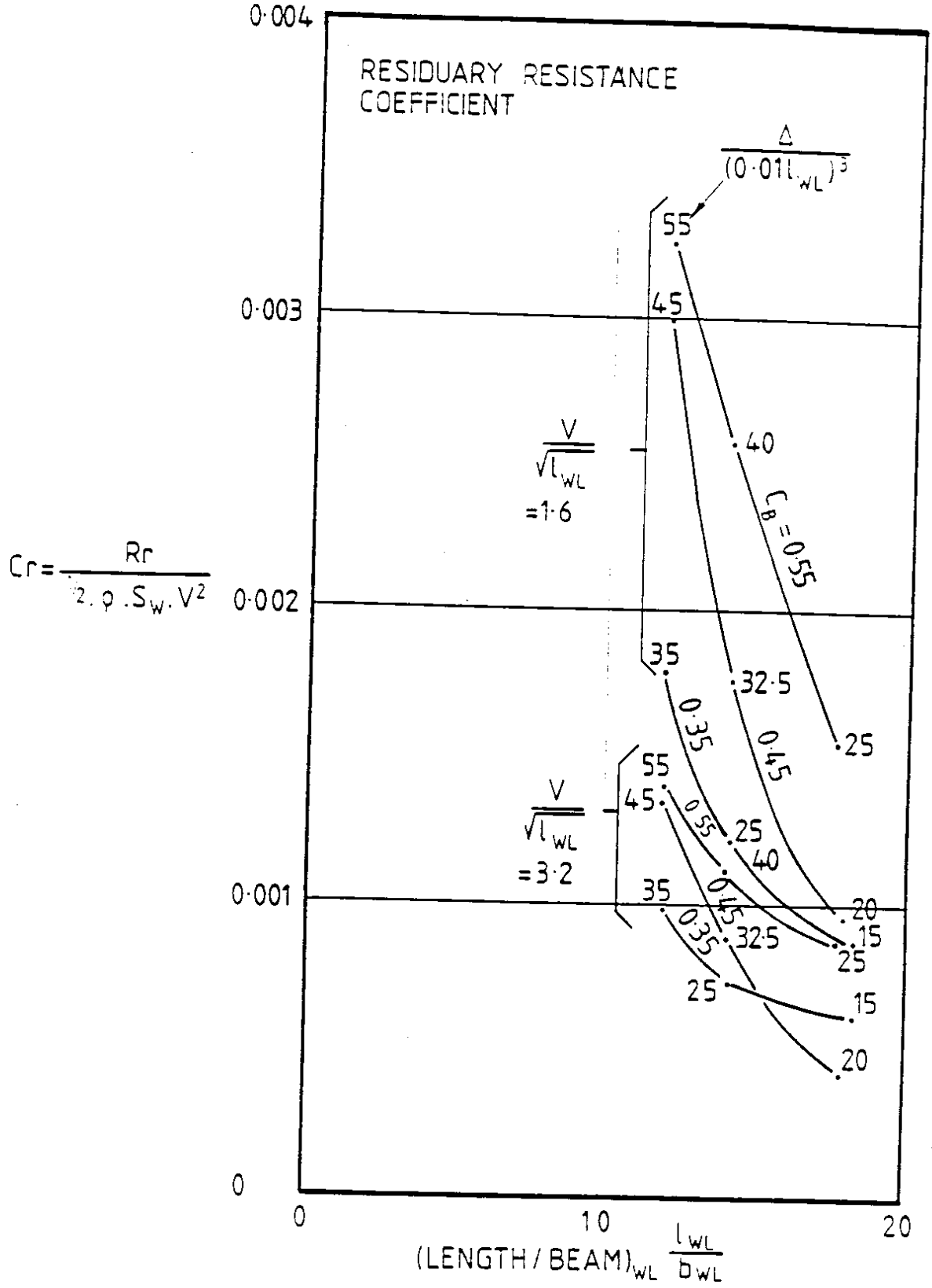


Figure 8

EFFECT OF LENGTH / BEAM RATIO ON RESIDUARY RESISTANCE COEFFICIENT

Exhibit 2.10

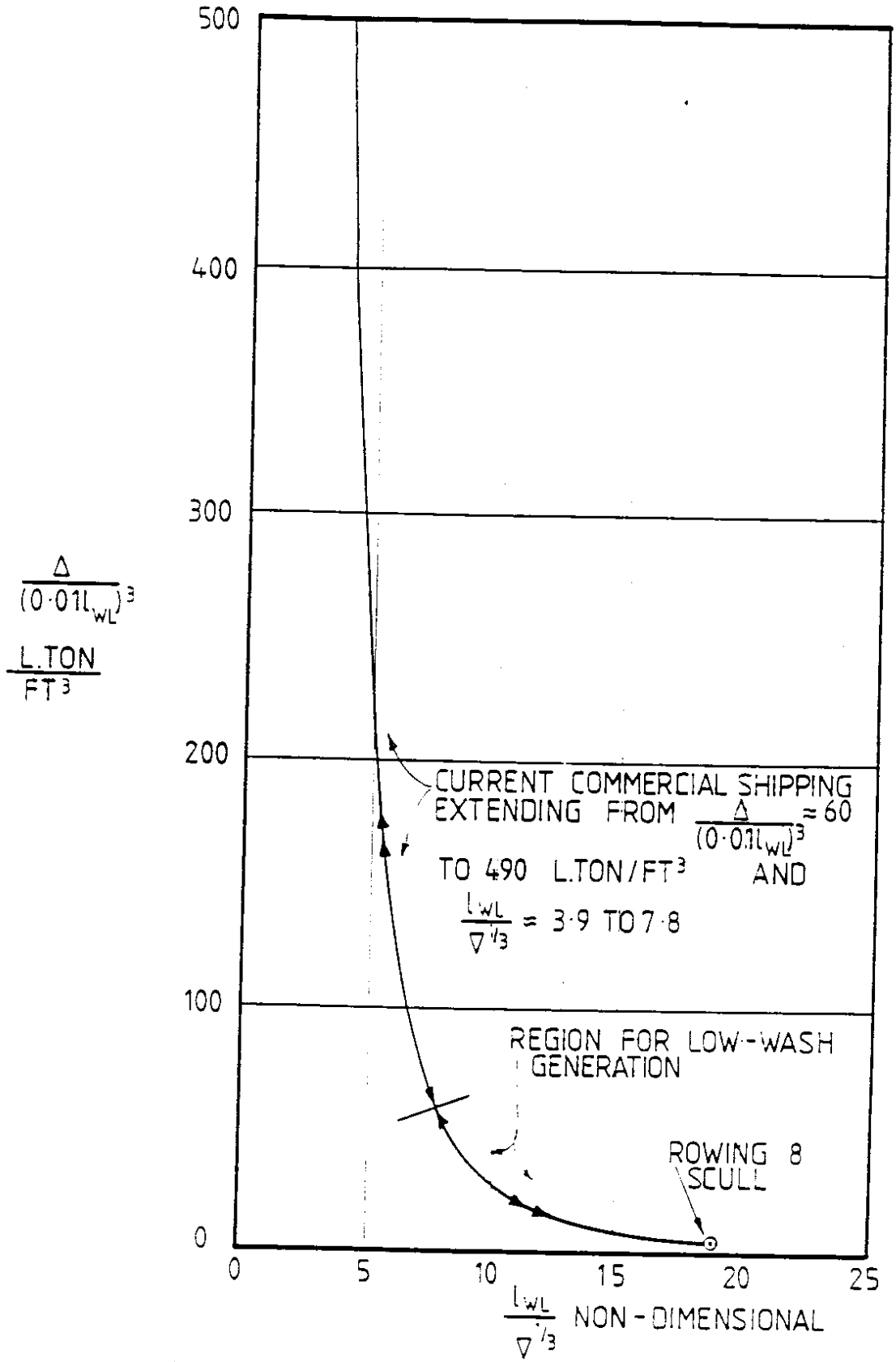


Figure 11

RELATIONSHIP OF DISPLACEMENT WEIGHT PARAMETERS

Exhibit 2.11

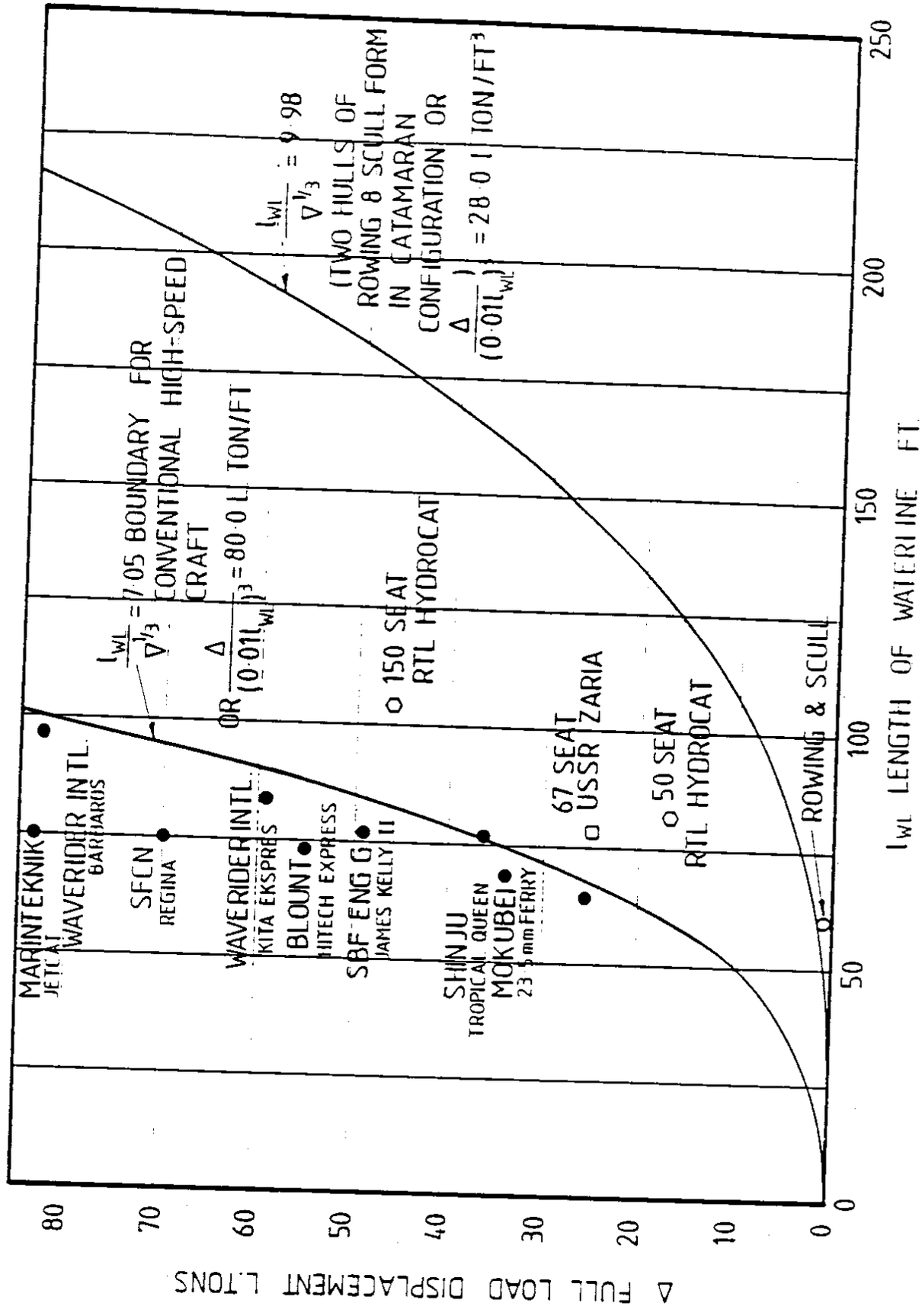
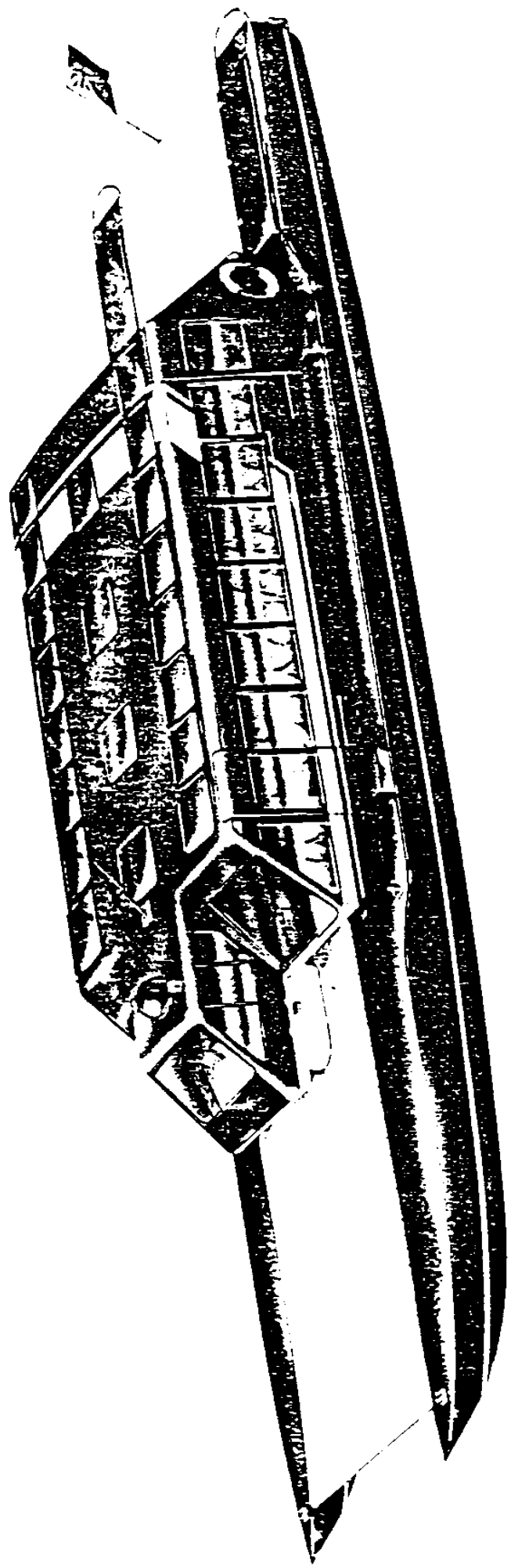


Figure 12

DISPLACEMENT/WATERLINE LENGTH RELATIONSHIPS FOR HIGH SPEED FERRIES

Exhibit 2.12

Figure 13. The Russian Zaria 67-seat, 22 knot river craft with one of the highest length-displacement ratios in high-speed passenger craft service



FAIREY RTL HYDROCAT

Figure 14. The Fairey MarinTeknik (UK) Ltd. design for a 60-seat RTL Hydrocat

Exhibit 2.14

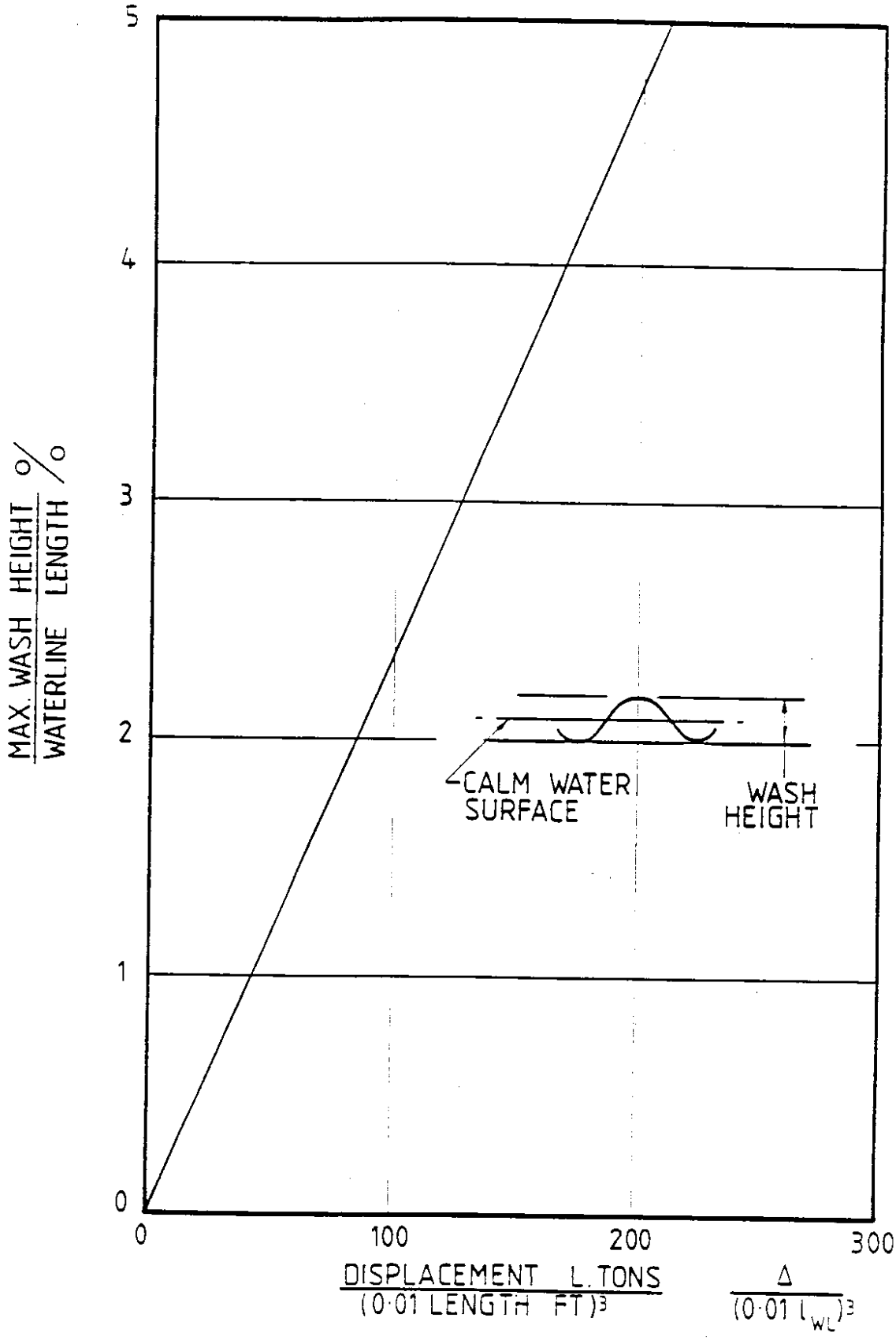


Figure 15

WASH HEIGHT FOR A PARTICULAR HULL FORM, SPEED, WATER DEPTH AND DISTANCE FROM VESSEL (REF 5)

(HEIGHT OF FIRST WAVE AND VESSEL ABOVE HUMP SPEED AT A DISTANCE OF ONE BOAT LENGTH.)

Exhibit 2.15

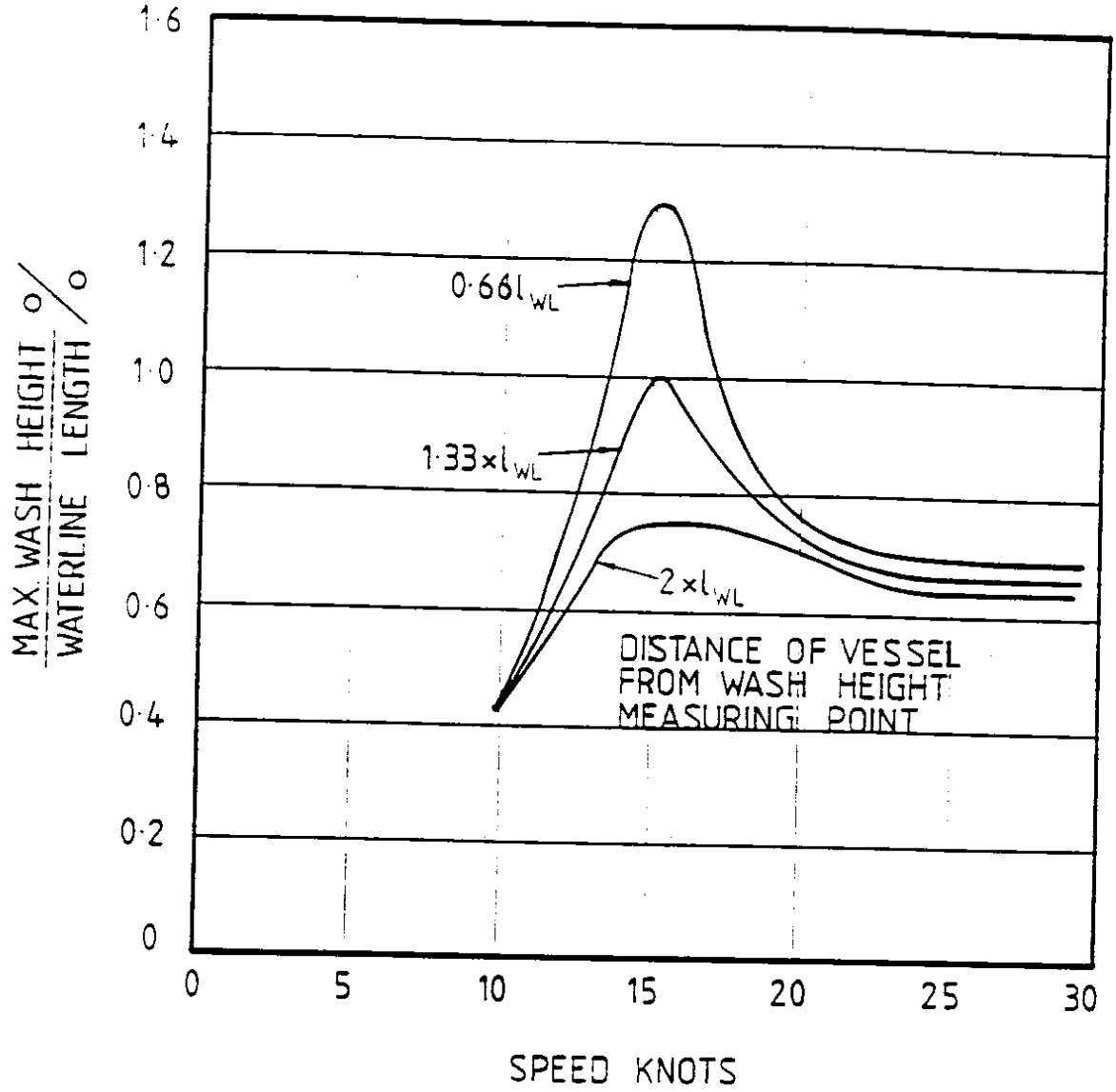


Figure 16

EXAMPLE OF WASH HEIGHT CHARACTERISTIC VARIATION WITH SPEED

CATAMARAN WITH VERY HIGH LENGTH/BEAM RATIO HULLS

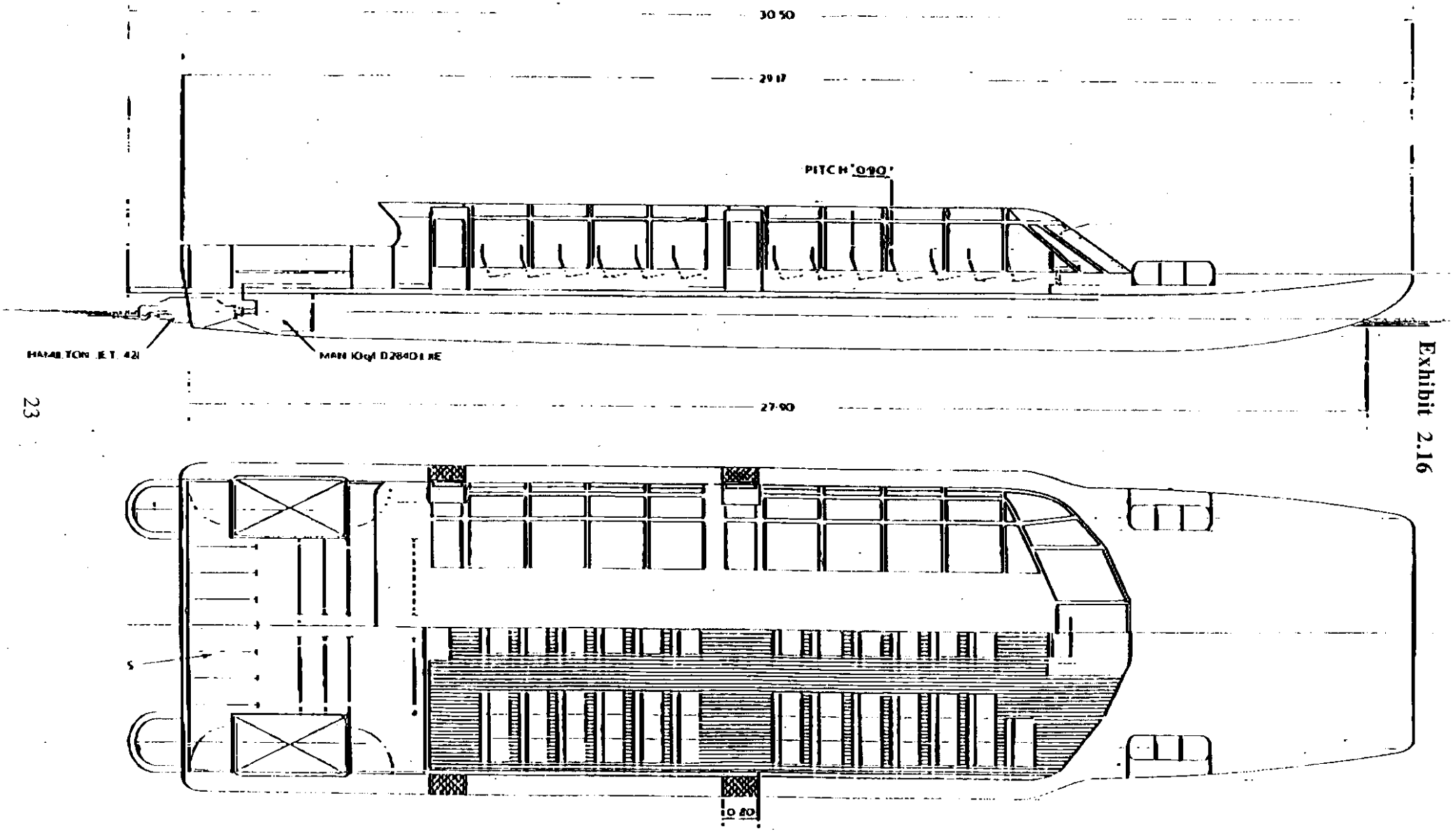
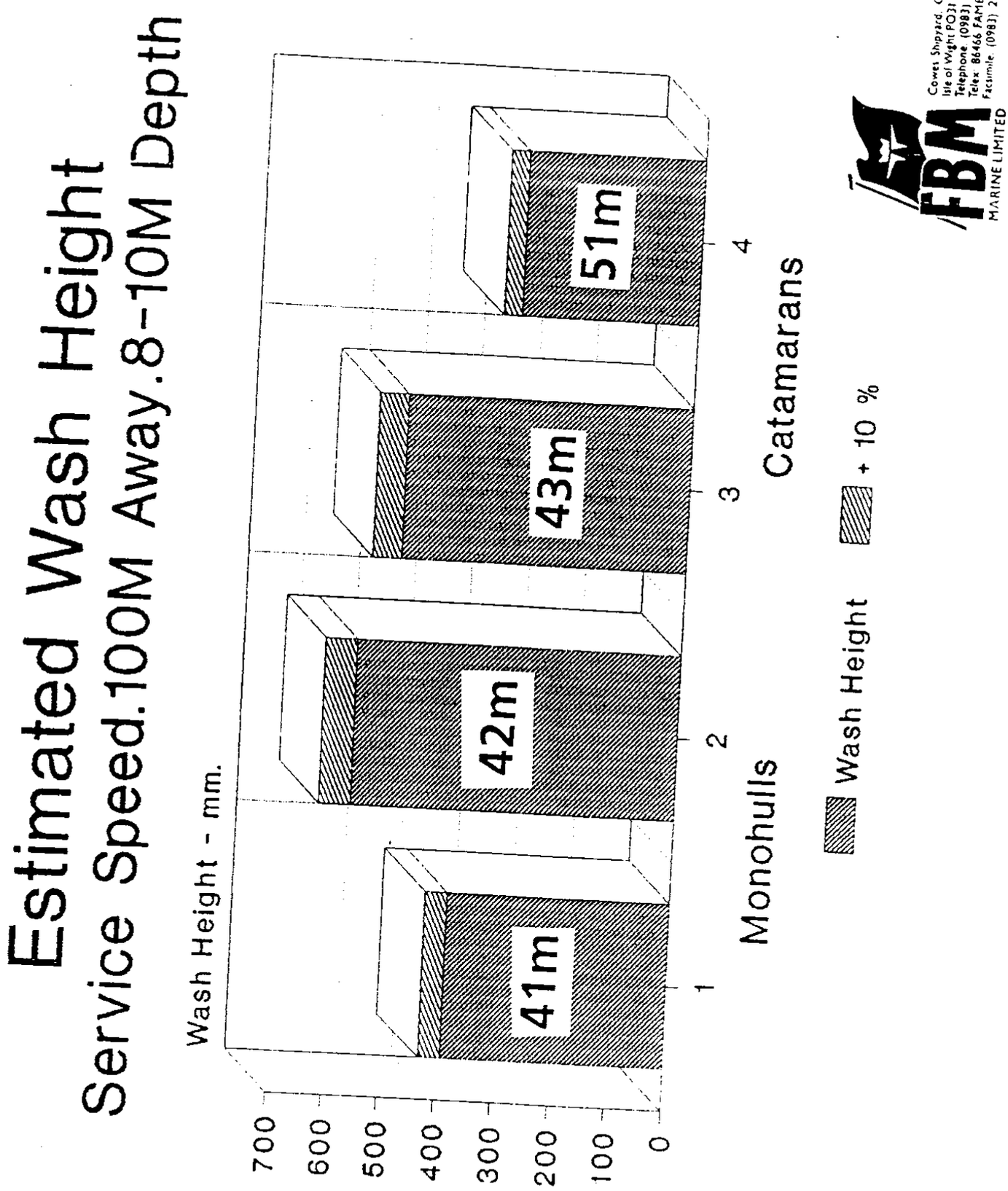


Figure 17. RTL preliminary design for a 100-seat Hydrocat
(Dimensions in metres)

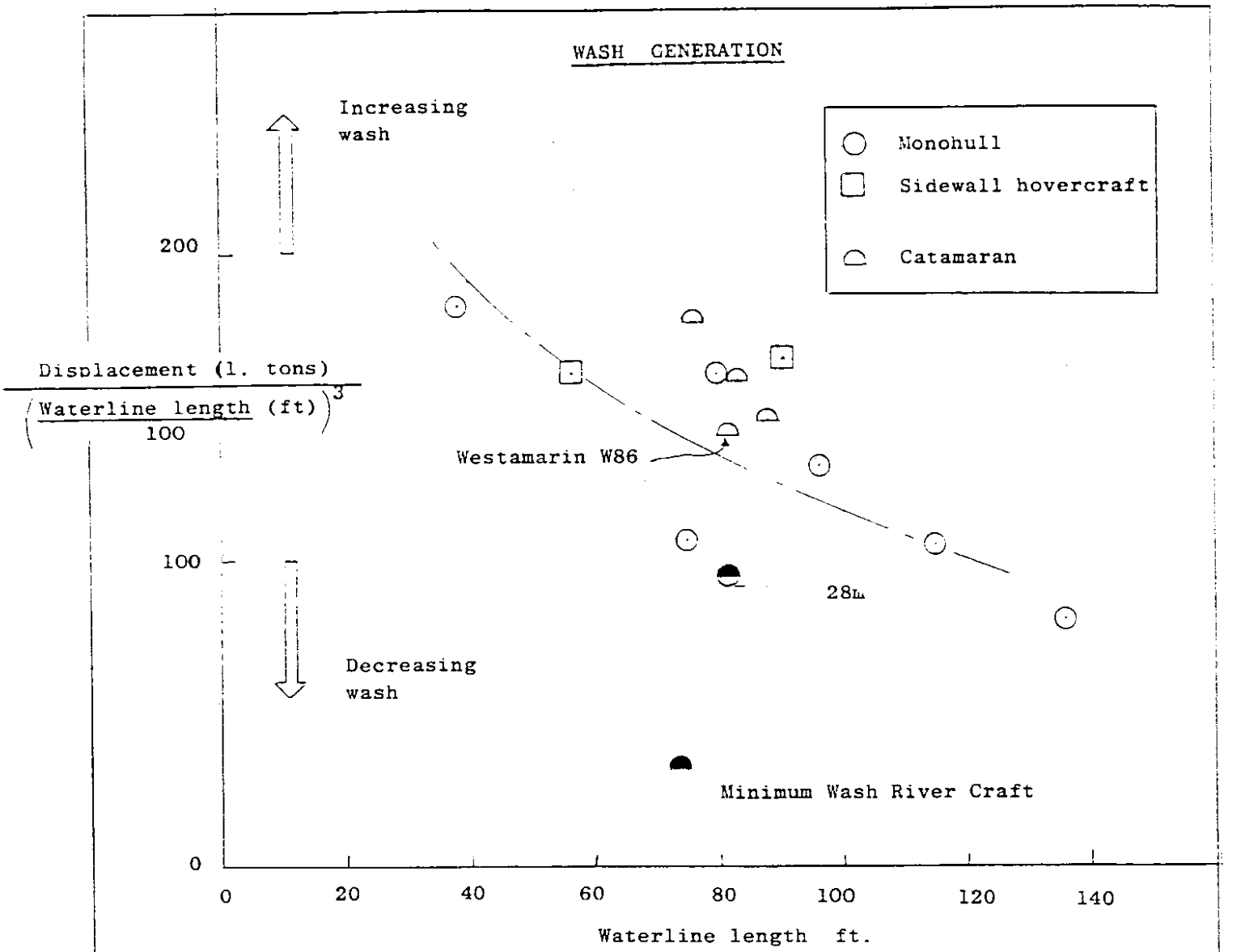
Exhibit 2.16

Exhibit 2.17



FBM MARINE LIMITED
Cowes Shipyard, Cowes
Isle of Wight PO31 7DL UK
Telephone. (0983) 297111
Telex: 86466 FAMBRO G
Facsimile. (0983) 299642

Exhibit 2.18



Cowes Shipyard, Cowes

Exhibit 2.19

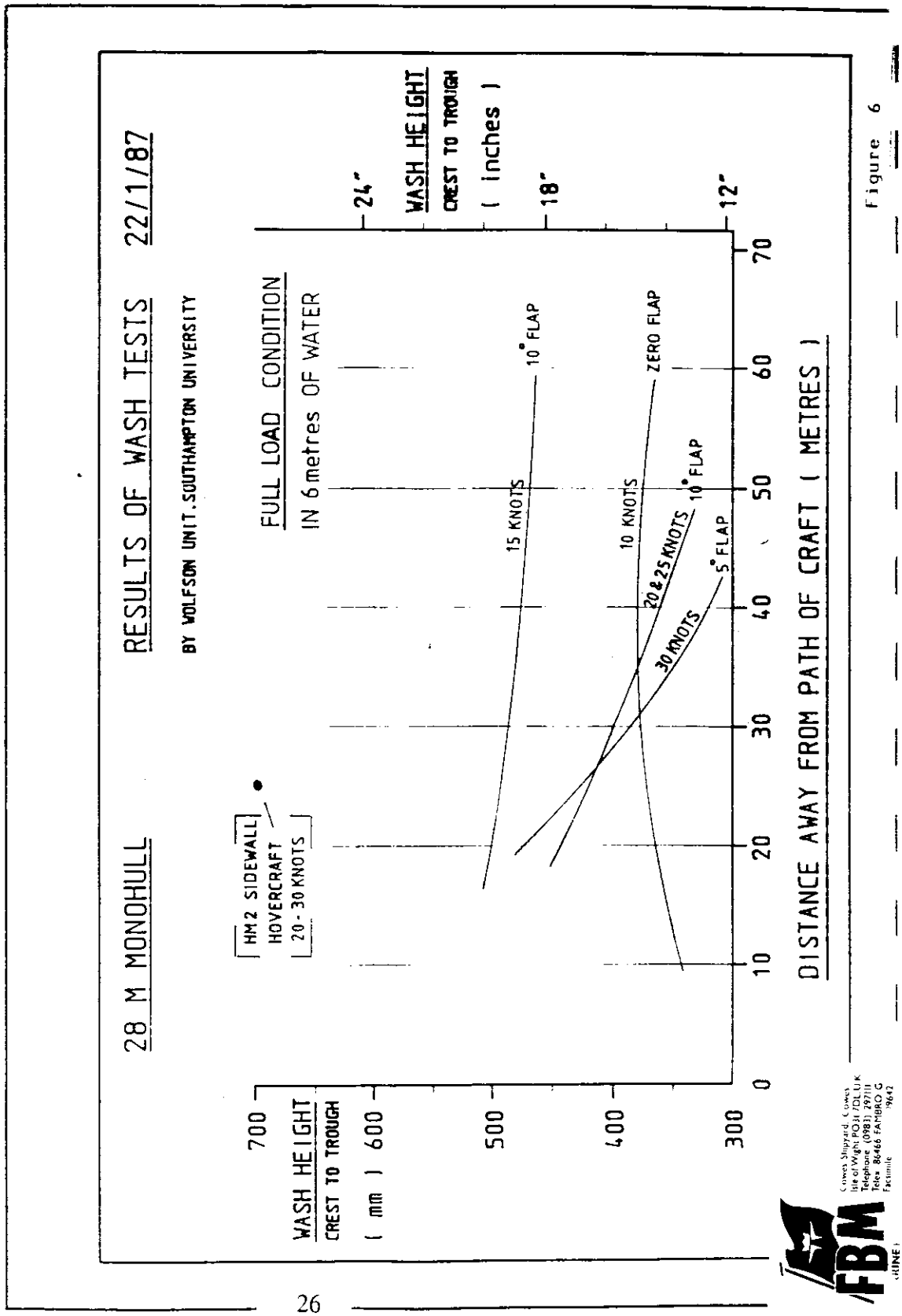


Figure 6

CHAPTER 3

SHORELINE EROSION

This chapter discusses the impact, if any, passenger ferries and vessels may have on shoreline erosion.

In the early 1970s, the Marine Engineering Division of the Department of Public Works, Ottawa, Canada, published several studies on river traffic and erosion. "Shore Erosion—Ship & Wind Waves—St. Clair, Detroit & St. Lawrence Rivers," (Report #21) published in March 1970, evaluated wind and cruiser waves along these rivers. This report provided an objective basis for calculating the amount of shore erosion that was caused by ice break-up in the spring, wind action on the banks, bank instability, and surface run-off. The study determined that wave height and the wave period increases with the speed of the vessel. According to this report, wave height is also dependent on the shape of the ship's hull and the distance of the vessel "from the measured point from the sailing line."

In May 1970, another report came out entitled "Shore Erosion—Ship & Wind Waves. Richelieu River" (Report #23). The purpose of this report was to document a study of erosion problems that had existed before the reconstruction of the St. Ours Dam on the Richelieu River. The water levels had been fluctuating in this area, and the Public Works Department needed to determine whether this fluctuation was due to wind or ship and cruiser waves prior to the dam's reconstruction. Exhibits 3.1 and 3.2 (Figures 16 and 18 from the report) illustrated that the total erosive damage caused by river navigation varied from 10 to 30 percent. The report stated that damage done by the St. Ours Dam was "no greater than 10 percent for a wind wave cut-off period that was measured at 1.5 seconds."

In June and July of 1973, the Department studied the north shore of the St. Lawrence River. Report #37 was entitled "Shore Erosion at Lanoraie, P.Q." Waves generated by both wind and ships were measured, as were the average recorded waves for each month of the year.

The conclusion of this report was that wind waves caused the greatest amount of natural erosion. Ships accounted "for less than half of the erosion that had occurred during the past five years."

In 1978, a project was funded by the U.S. Army Corps of Engineers to study bank erosion along the Ohio River. A 981-mile stretch of the Ohio River area was evaluated for conditions along the banks. From 1977 to 1983, 150 sites were investigated and they were re-evaluated in 1986. The study found that more than 700 miles of the river bank appeared less eroded in 1986 than they had in 1978. The study concluded that a change (increase) in river traffic had not significantly affected the erosion of the river banks. Instead, natural causes, such as waves caused by wind, affected the state of the banks.

In 1980, Frederick Camfield, Robert Ray, and James Eckert published a final report entitled "The Possible Impact of Vessel Wakes on Bank Erosion." The report addressed the impact of erosion by a vessel, driven by propeller jet, traveling too closely to a channel bank. Camfield, Ray, and Eckert concluded that wash can be caused by a propeller jet, especially in areas where barge tows pass. Robert Sorenson's graph, which appeared in the report (Exhibit 3.3), showed the magnitude of wave heights produced by six different model ships. Sorenson's graph illustrated the effect the speed of a ship and the depth of the water will have on the size and shape of the wave produced by the ship. This study indicated that there is no connection between a chosen hull shape and the occurrence of erosion. Other factors must be accounted for, such as waterway bends, changes in the cross section of the channel, areas near lock entrances, strong currents, and the steepness of the bank.

In 1986, the Danish Hydraulic Institute measured wave actions in the Port of Copenhagen. Measurements were taken at the Langelinie, Nordre Toldbod, and Ameliehaven Piers along the shipping route between September 22 and 24, 1986. The purpose of these tests was to determine the amount of wave action passing hydrofoil boats were generating in this area (see Exhibit 3.4 and 3.5). The report concluded that the wave action caused by the hydrofoil boats was the largest from 1000 to 1400 rpm. The largest wave heights were recorded between 1000 to 1500 rpm. At 1000 rpm, the wave period measured at 2 to 3 seconds, increasing to a

gradual rate of 4 to 5 seconds at 1400 to 1500 rpm. The wave period decreased to about 4 seconds at 1850 rpm.

In 1989, Nils Norrbin of the National Maritime Administration in Norrköping, Sweden, conducted a study entitled "Vessel Generated Water Movements in a Ferry Traffic Lane." The purpose of this study was to determine the effect that vessel traffic would have on a route that would run between Stockholm and Helsinki, Finland, across the Rödkobbsfjärden Strait (see Exhibit 3.6 to 3.8). Researchers studied the currents and wakes that car passenger ferries would generate in the strait. The vessel types ranged from an archipelago vessel of 36 meters to the larger, 200-meter Finland ferry. One of the significant findings of Norrbin's study was that expected wake height is *not* dependent on the vessel's size, only on the shape and speed of the vessel.

In 1991, Ingela Hammerfeldt and Magdalena Nohrborg of the Hydraulic Engineering Department for the Royal Institute of Technology, Stockholm, Sweden, performed field measurements at four sites in the Channel of Furusund. This study was undertaken to determine the effect ferries had on suction and suspended sediments in the channel. They observed that in channels of restricted width, waves from ferry traffic "attacked" the shoreline. They observed that the water level of the channel would rise as a large ship was approaching. However as the vessel was passing, the water level lowered, and the water flowed away from the shore until the stern had passed. Once this had occurred, the water flowed back toward the shoreline. Hammerfeldt and Nohrborg observed that the water level that flowed back toward the shoreline was higher than the level of the initial wave, created as the vessel entered the channel. Furthermore, their flow measurements of sediment levels indicated that "not much sediment was entrained into the water as the ferries passed."

An earlier study was undertaken by Daleke, Hedström, and Nissar for the Royal Institute of Technology, Stockholm, Sweden, in 1988. The purpose of this 1989 study, was to examine the relationship of erosion and ferry traffic in the Furusund Channel (see Exhibits 3.9 to 3.20). Daleke, Hedström, and Nissar found that the effects of vessel traffic were dependent upon

several factors: vessel speed, design of the vessel (vessel geometry), passage geometry, and the distance between the vessel and the shoreline. Additional factors contributing to erosion were the geotechnical qualities of the shoreline material, wakes from recreational vessels, fluctuating water levels, water turbulence, and rip-currents. Dalek, Hedström, and Nissar found that the shorter the distance was between the vessel and the shoreline, the greater were the damage and impact to the shoreline structure. Most of the sediment transport occurred during periods of high water levels, which in turn initiated appearance changes along the shoreline. The researchers' conclusion was that the ferry traffic was responsible for "severe erosion damage in Furusundsleden." The findings were based on comparisons between shorelines that were exposed to ferry traffic and shorelines that were not. Sediment particle sizes and their transport were also measured to determine erosion.

Erosion along the shoreline can be caused by naturally occurring wind waves, the geological make-up of the soil, changes in the water level, and the existing turbulence of the currents. Erosion caused by vessel and ship traffic can be determined by several factors, including the speed of the vessels, distance of the vessels from the shoreline, and the depth of water.

Exhibit 3.1

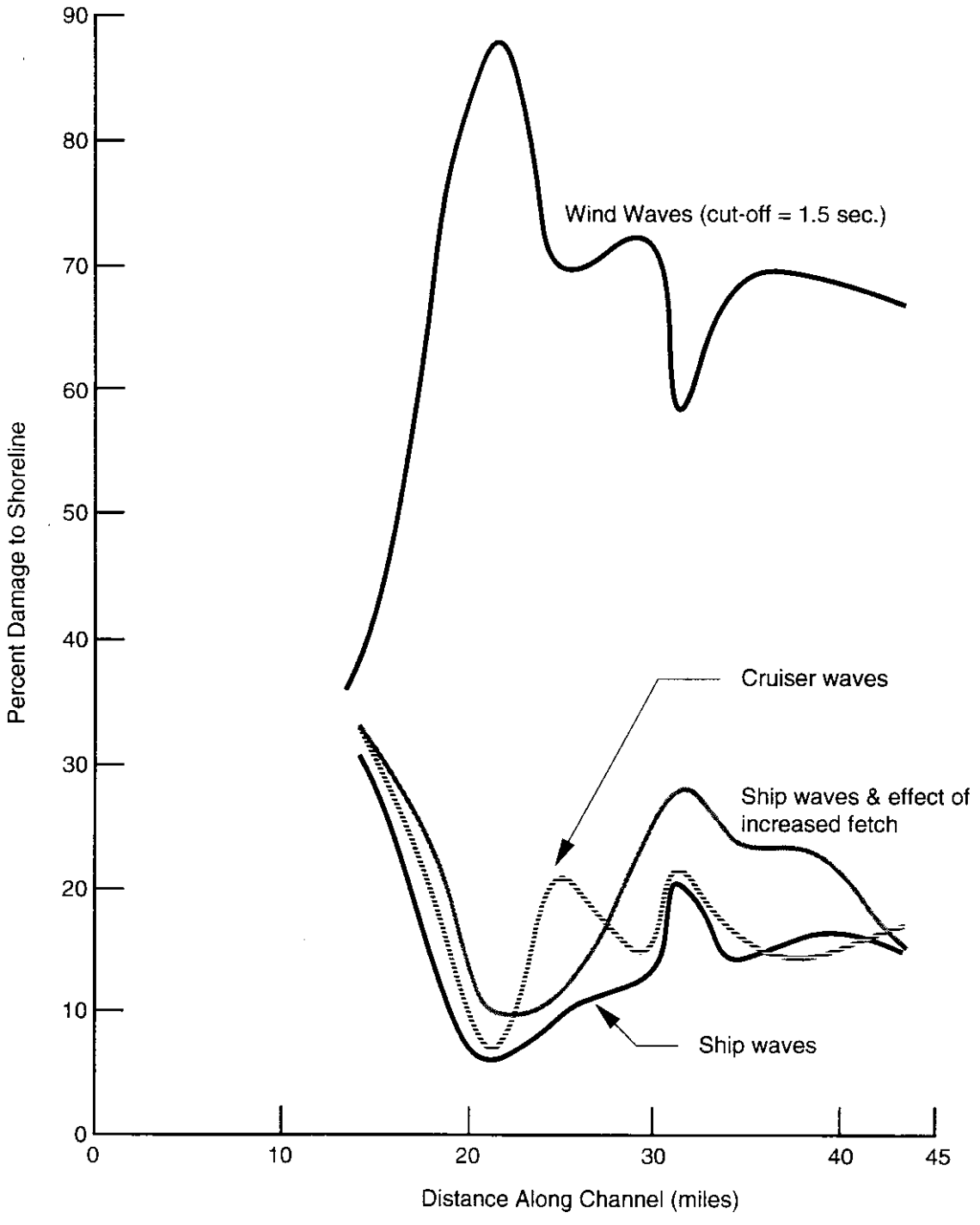


Figure 16. Relative Damage to West Shoreline Richelieu River

Source: "Shore Erosion – Ship & Wind Waves. Richelieu River." A.O. Offuya. Marine Engineering Division, Design Branch, Department of Public Works, Ottawa, Canada. Report #23, May 1970.

Exhibit 3.2

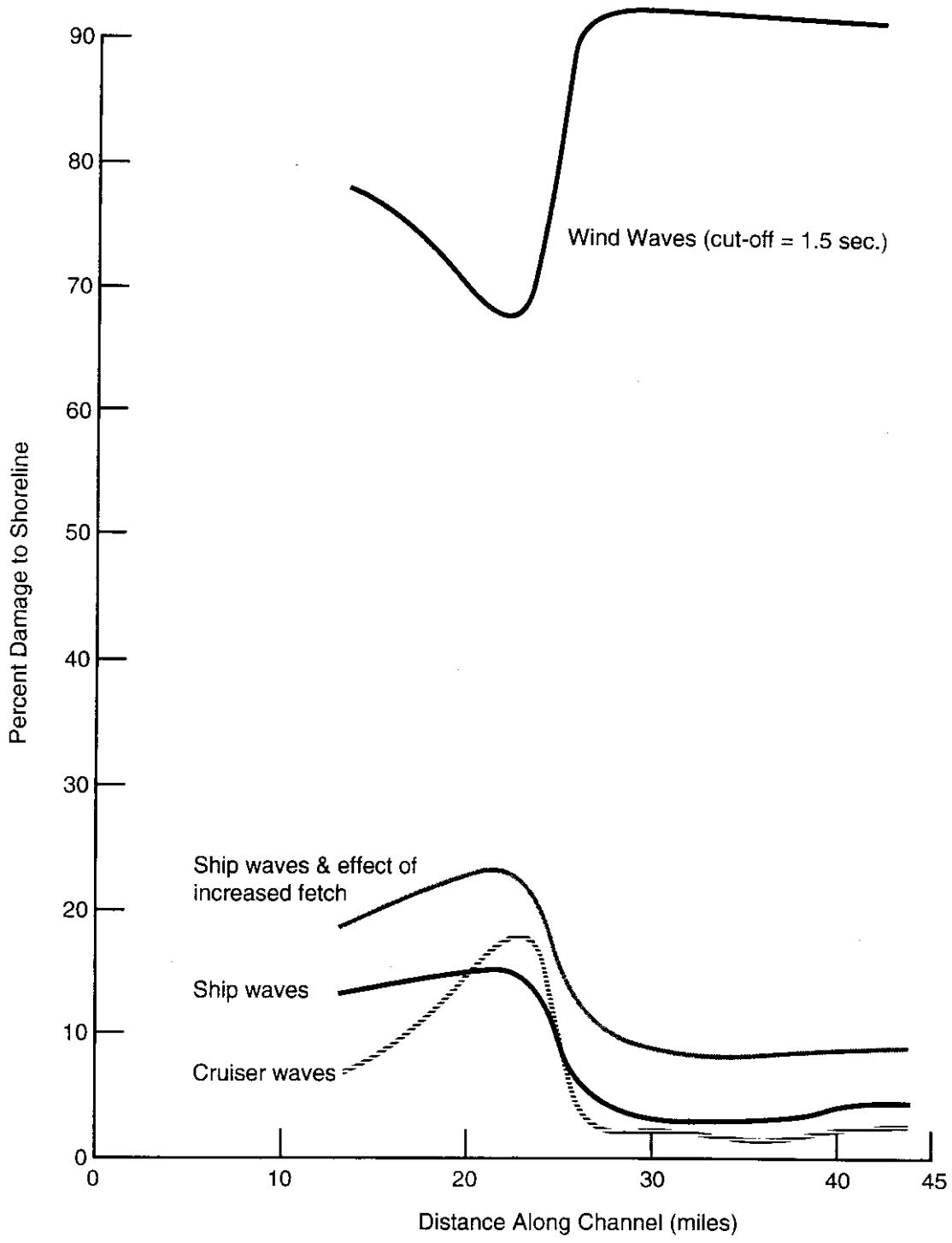


Figure 18. Relative Damage to East Shoreline Richelieu River

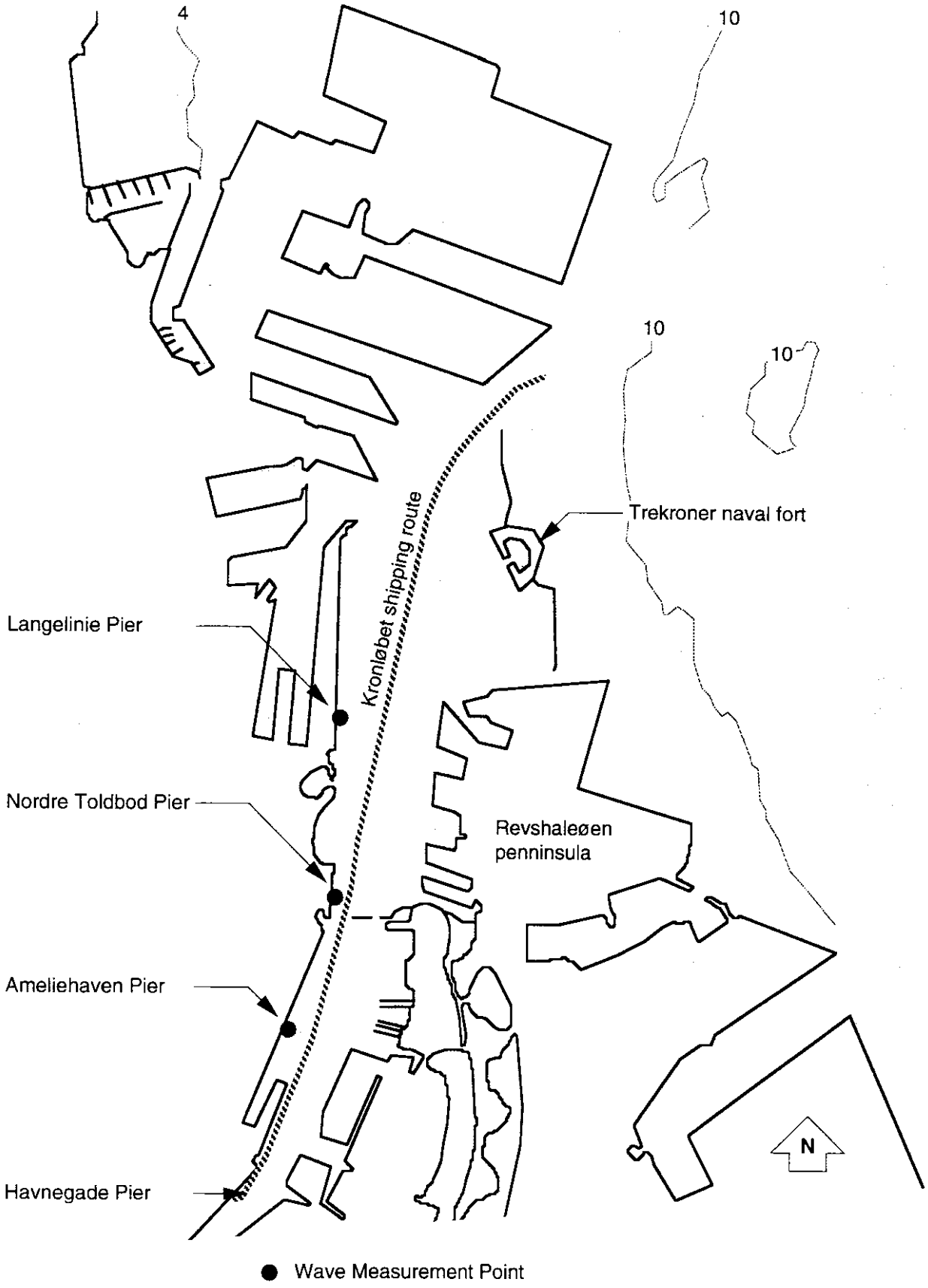
Source: "Shore Erosion – Ship & Wind Waves. Richelieu River." A.O. Offuya. Marine Engineering Division, Design Branch, Department of Public Works, Ottawa, Canada. Report #23, May 1970.

Selected Ship-generated Wave Heights (from Sorensen, 1973)

Vessel type	Length, in feet (meters)	Beam, in feet (meters)	Draft, in feet (meters)	Displacement, in tons (kilograms)	Water depth, in feet (meters)	Speed, in knots (meters per second)	Distance from Sailing Line, in feet (meters)		
							100 (30.5) H_{max} in feet (meters)	500 (152.4) H_{max} in feet (meters)	1000 (304.8) H_{max} in feet (meters)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Cabin Cruiser	23 (7.0)	8.3 (2.5)	1.7 (0.5)	3 (2,722)	40 (12.2)	6 (3.1) 10 (5.1)	0.7 (0.2) 1.2 (0.4)	0.4 (0.1) 0.8 (0.2)	
Coast Guard Cutter	40 (12.2)	10 (3.0)	3.5 (1.1)	10 (9,072)	38 (11.6)	6 (3.1) 10 (5.1) 14 (7.2)	0.6 (0.2) 1.5 (0.5) 2.4 (0.7)	1.0 (0.3)	
Tugboat	45 (13.7)	13 (4.0)	6 (1.1)	29 (26,309)	37 (11.3)	6 (3.1) 10 (5.1)	0.6 (0.2) 1.5 (0.5)	0.3 (0.1) 0.9 (0.3)	
Reconverted Air-Sea Rescue Vessel	64 (19.5)	12.8 (0.9)	3	35 (31,752)	40 (12.2)	6 (3.1) 10 (5.1) 14 (7.2)	0.3 (0.1) 1.4 (0.4) 2.0 (0.6)	0.8 (0.2) 1.1 (0.3)	
Fireboat (reconverted tug)	100 (30.5)	21 (1.5)	11 (3.4)	343 (311,170)	39 (11.9)	6 (3.1) 10 (5.1) 14 (7.2)	0.4 (0.1) 1.7 (0.5) 3.1 (0.9)	0.2 (0.1) 1.0 (0.3) 2.6 (0.8)	
Barge	263 (80.2)	55 (16.8)	14 (4.3)	5,420 (4,917,000)	42 (12.8)	10 (5.1)	1.4 (0.4)	0.7 (0.2)	0.3 (0.1)
Moore Dry Dock Tanker	504 (153.6)	66 (20.1)	21 (8.5)	18,800 (17.1×10^4)	56 (17.1)	14 (7.2) 11 (9.3)		1.5 (0.5) 5.2 (1.6)	1.1 (0.3) 4.7 (1.4)

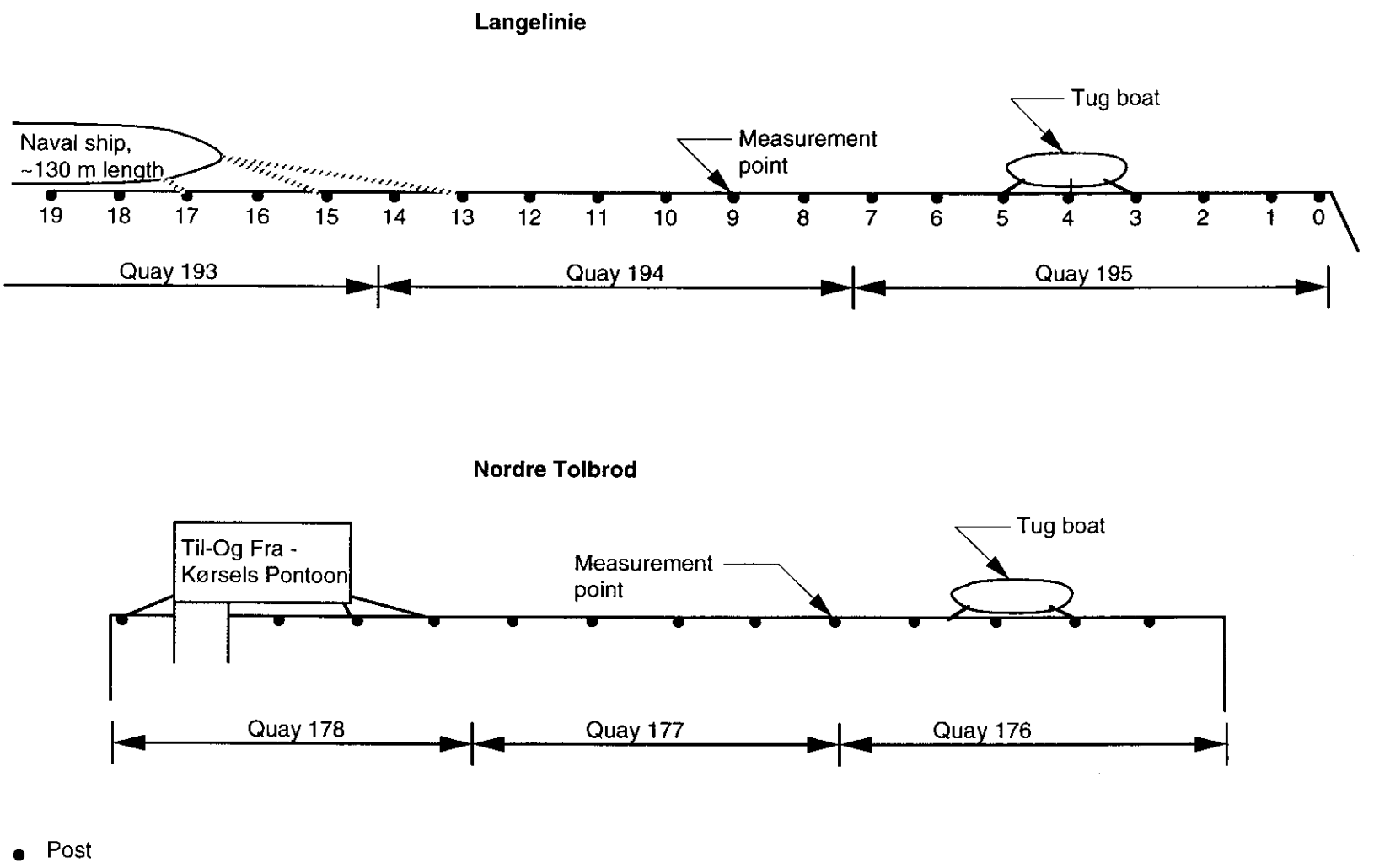
Source: Camfield, Frederick; Ray, Robert, and Eckert, James. "The Possible Impact of Vessel Wakes on Bank Erosion." Final Report. Prepared for the U.S. Department of Transportation, U.S. Coast Guard, Office of Research and Development. Washington, D.C. 1980.

Exhibit 3.4



Shipping Route of the Hydrofoil Boats
in the Port of Copenhagen

Source: "Measurements of Waves in The Port of Copenhagen." Danish Hydraulic Institute, 1986.



Measurement of Waves in the Port of Copenhagen

Source: "Measurements of Waves in The Port of Copenhagen." Danish Hydraulic Institute, 1986.

Exhibit 3.6

Table. Summary of the available measurements for the height of the top of the wake above the calm water elevation ($\}_+$) and for the wake height (from top to bottom, H_w) in the relevant speed areas; all refer to the maximum of any of the first four wakes. (The profiled section's distance from the sides was for the archipelago vessel 21 m, or 0.62*L, and for the Finland ferry 48 m or 0.27*L.)

Archipelago Vessel

Speed	V_s	knots	15	16.5	17.5	18.5
Froudes Number	F_{nL}	—	0.423	0.465	0.493	0.521
Wake elevation	$\}_+$	m	0.24	0.25	0.34	0.50
Wake height	H_w	m	0.37	0.58	0.72	0.82

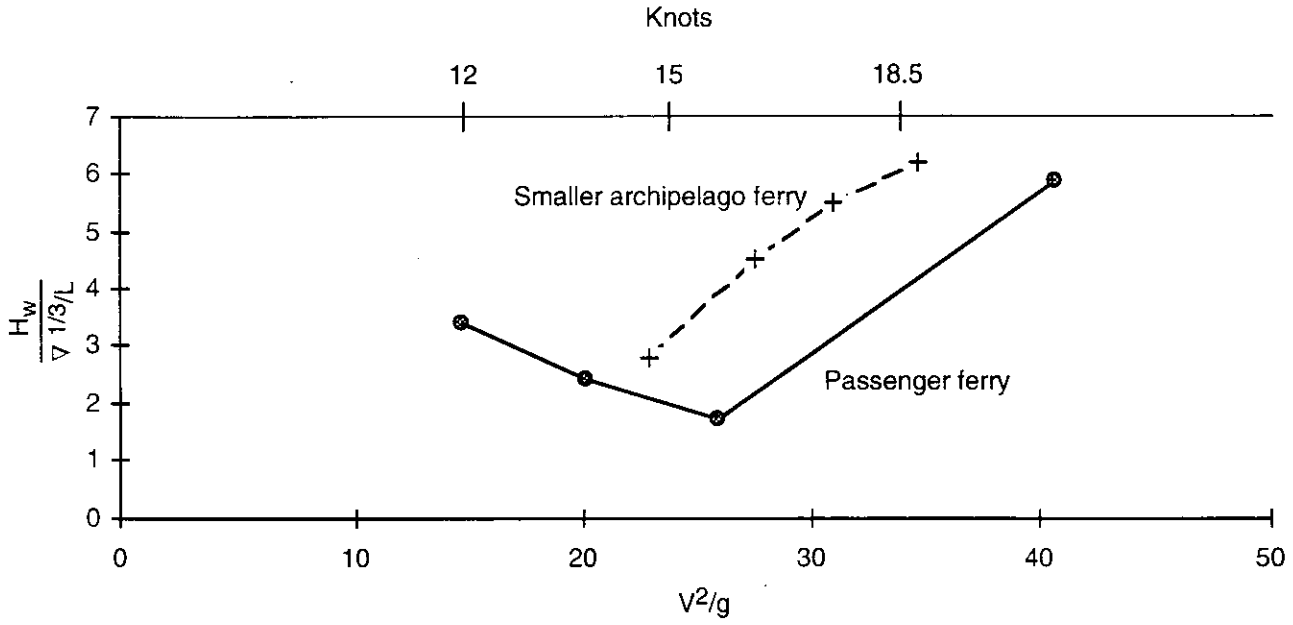
Finland Ferry

Speed	V_s	knots	12	15	16	17	18	20
Froudes Number	F_{nL}	—	0.146	0.183	—	0.207	0.220	—
Wake elevation	$\}_+$	m	0.55	0.35	—	0.41	0.54	—
Wake height	H_w	m	0.56	—	0.27	—	—	0.96

Source: "Vessel Generated Water Movements in a Ferry Traffic Lane". Norrbin, Nils H. National Maritime Administration, Norrkoping, Sweden. (EIS Study). 1989.

* Includes Figures 20 & 21 (SSPA Maritime Consulting).

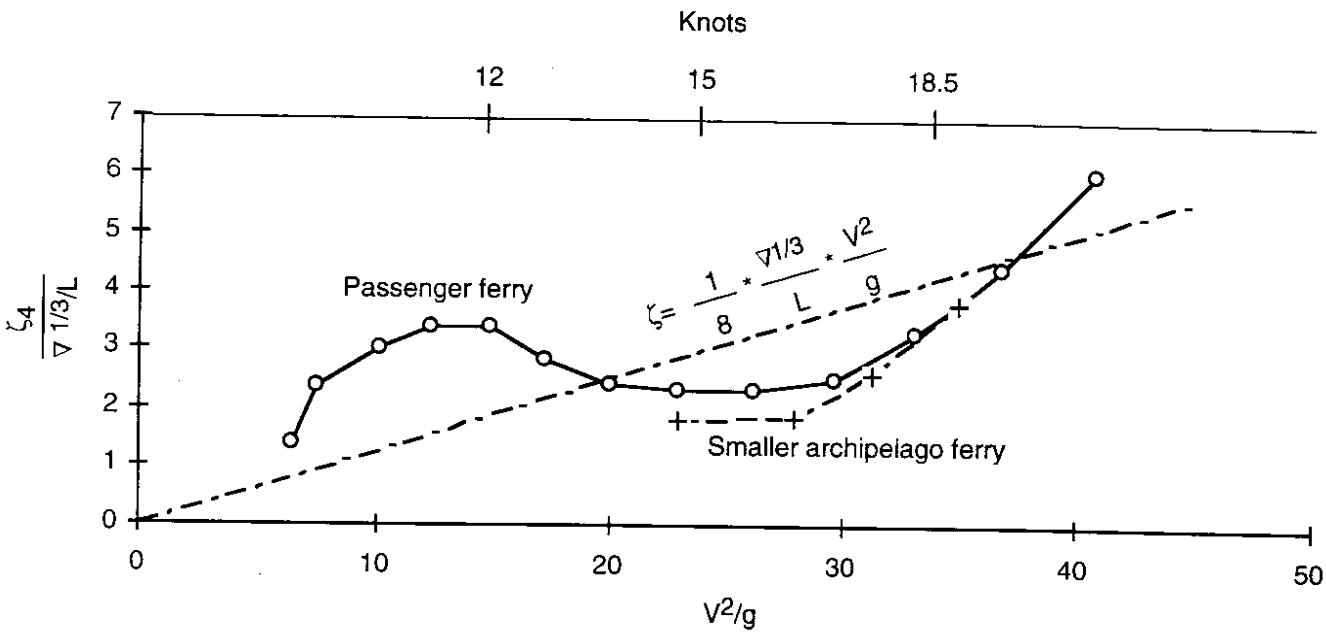
Exhibit 3.7



Source: "Vessel Generated Water Movements in a Ferry Traffic Lane." Norbin, Nils, H. National Maritime Administration. Norrkoping, Sweden. (EIS Study). 1989.

Wake heights from measurements during experiments with models of large passenger ferry and smaller archipelago vessel. A comparison with theoretical relations.

Exhibit 3.8



Maximum Wake Elevations in the First Four Divergent Wakes

Source: "Vessel Generated Water Movements in a Ferry Traffic Lane." Norbin, Nils, H. National Maritime Administration. Norrkoping, Sweden. (EIS Study). 1989.

Wake heights from measurements during experiments with models of large passenger ferry and smaller archipelago vessel. A comparison with theoretical relations.

Exhibit 3.9

Table 6.1.1. Wake Measurements at Stabo Udde, 6/8-6/9 (page 53)

Each mentioned vessel is a different ferry traveling either to Finland or Åland. The ferries are all large, but there is no specification of the size or design for any particular vessel—Translators note.

Vessel	Speed (knots)	Distance (m)	Wave length (m)	Wave period (s)	Wave height (cm)	Depression (cm)
Ånedin	13.3	169	8.5	2.8	30	5
Viking-Sally	12.6	167	6.3	2.4	25-30	5
Silja-Wellamo	12.4	148	8.0	2.8	45	13
Birka-Princess	13.0	189	7.7	2.5	35-40	0
Apollo 3	10.8	207	6.1	2.4	25-30	0
Viking-Sally	—	—	5.0	2.5	30	5
Silja-Wellamo	12.9	168	5.5	2.1	40	15
Viking-Rosella	14.3	154	6.9	2.4	25	5
Silja-Svea	13.0	147	8.1	2.8	30-35	10
Viking-Rosella	14.5	162	7.0	2.8	20	6
Silja-Svea	12.4	151	6.5	2.2	20	9
Birka-Princess	12.4	151	6.5	2.2	20	9
Apollo	12.5	160	7.5	2.4	20-25	0

Comments: The measurements are calculated from an average from the 5 largest wakes in the "wavetrain." The given distance is that between the vessel and the shoreline used for the study. The depression is the lowest level of the water below normal. In the part of the table where only Ånedin has been used as a name, the complete name is Ånedin Baltic Star.

Source for Table & Photographs:

"Environmental Effects of Vessel Traffic In The Archipelago - Shoreline Erosion." Daleke, Ola, Hedstrom, Henrik, & Nissar, Katarina. Department of Hydraulic Engineering, Royal Institute of Technology, Stockholm, Sweden. Diploma Work #303. 1989.

Exhibit 3.10

Photo 7.7. Small island protected from ferry traffic effects.

Exhibit 3.11

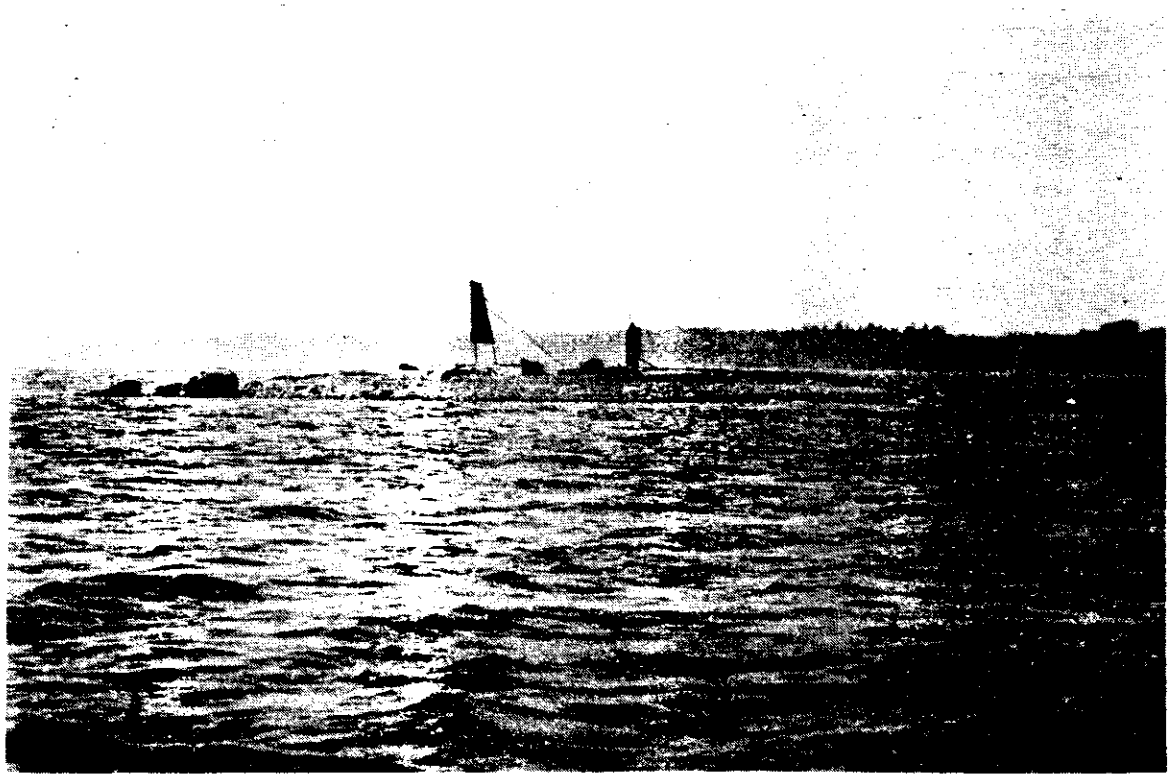


Photo 7.8. Small island heavily exposed to ferry traffic effects.

Exhibit 3.12

Photos 7.9 to 7.16 depict a vessel passing Stabo Udde.

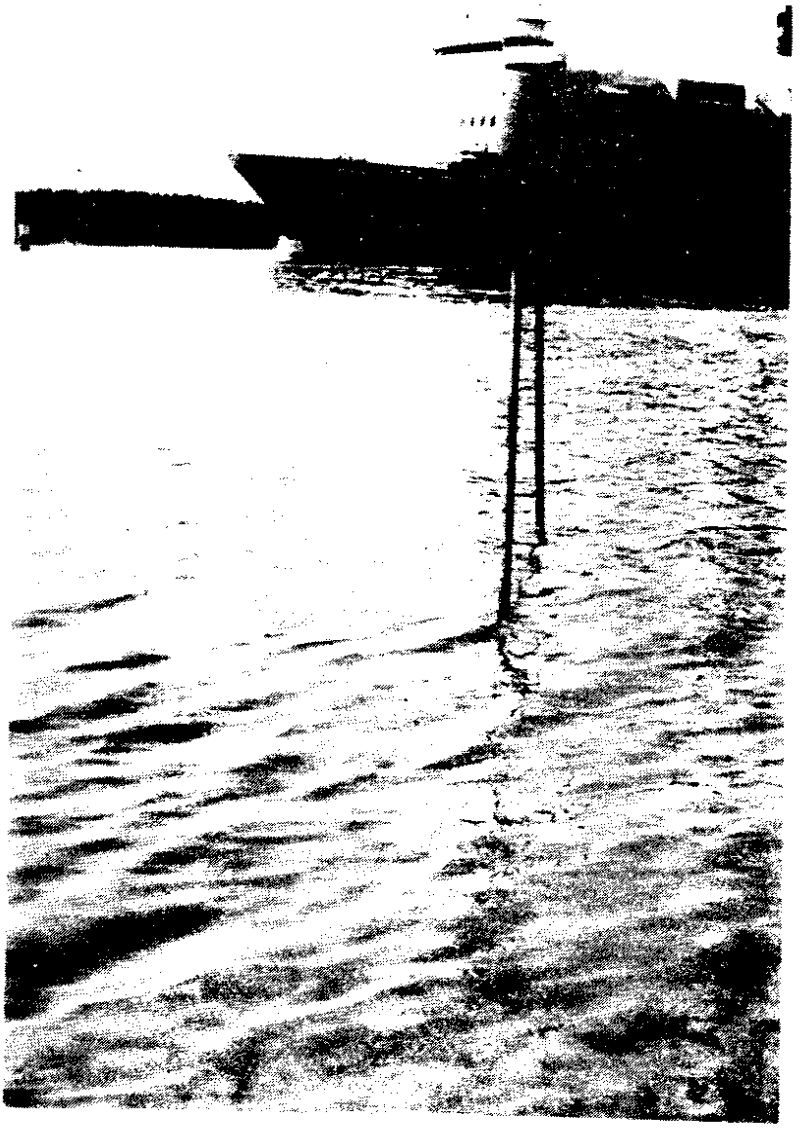


Photo 7.9. Water level has risen a few cm's and is now decreasing.

Exhibit 3.13

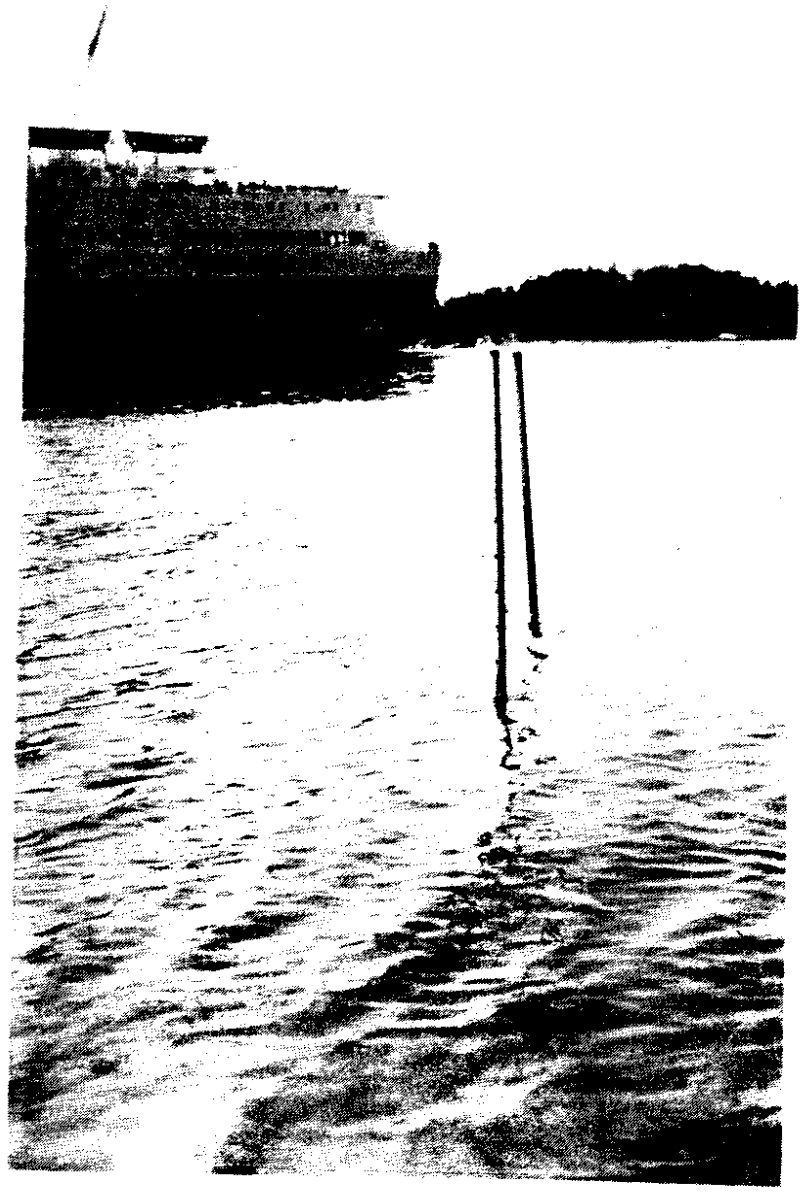


Photo 7.10. The vessel stem has now passed the measured cross-section, which is perpendicular to the direction of travel for the vessel. The water level continues to drop.

Exhibit 3.14

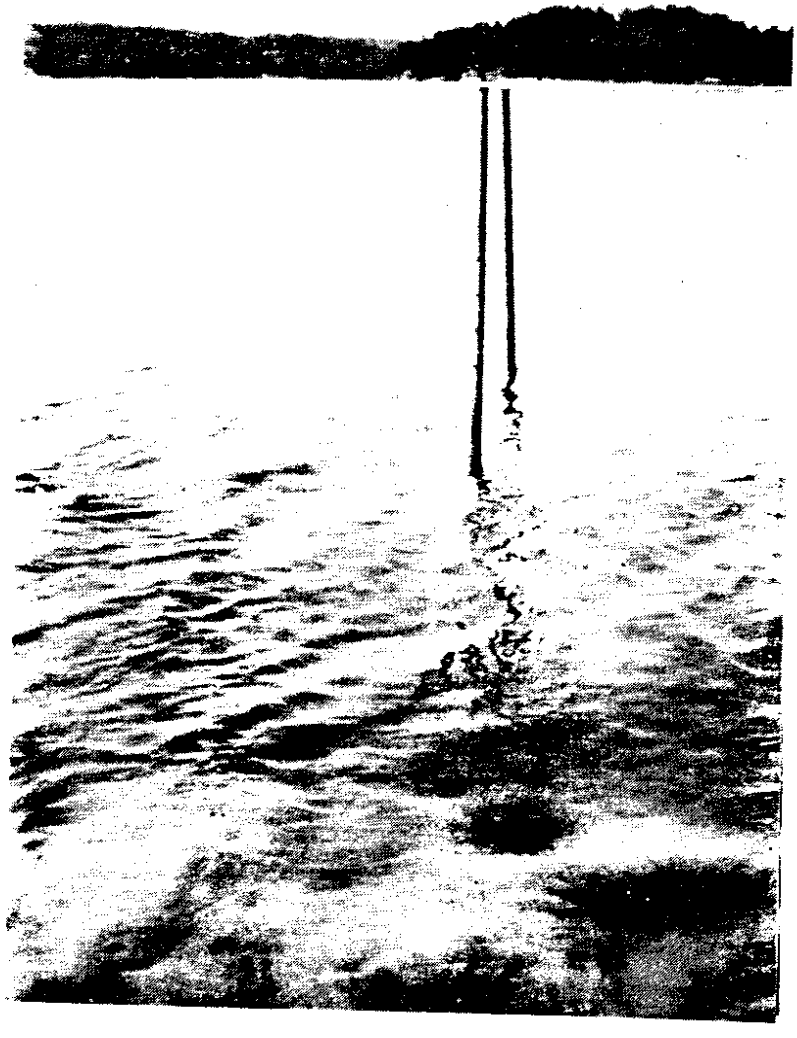


Photo 7.11. The vessel is now halfway across the cross-section. The water level has decreased about 15 cm and the water movements are now becoming more apparent.

Exhibit 3.15

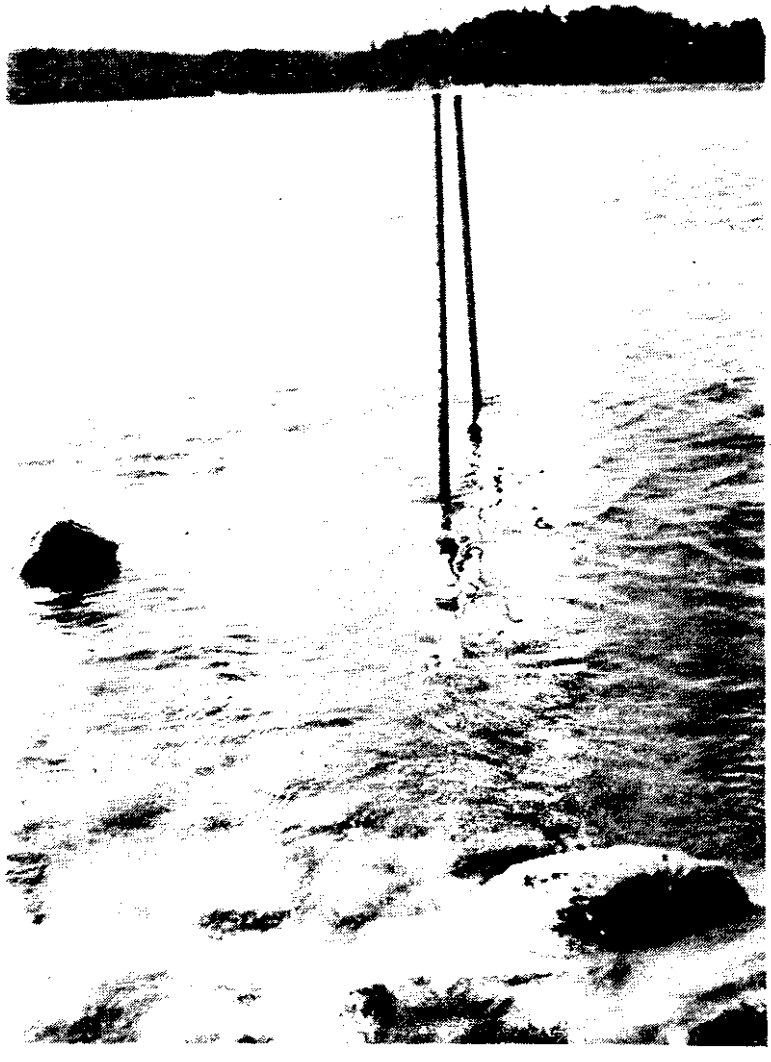


Photo 7.12. The water level has decreased about 20 cm and the water speed is approaching maximum. The vessel has passed 3/4 of the way.

Exhibit 3.16

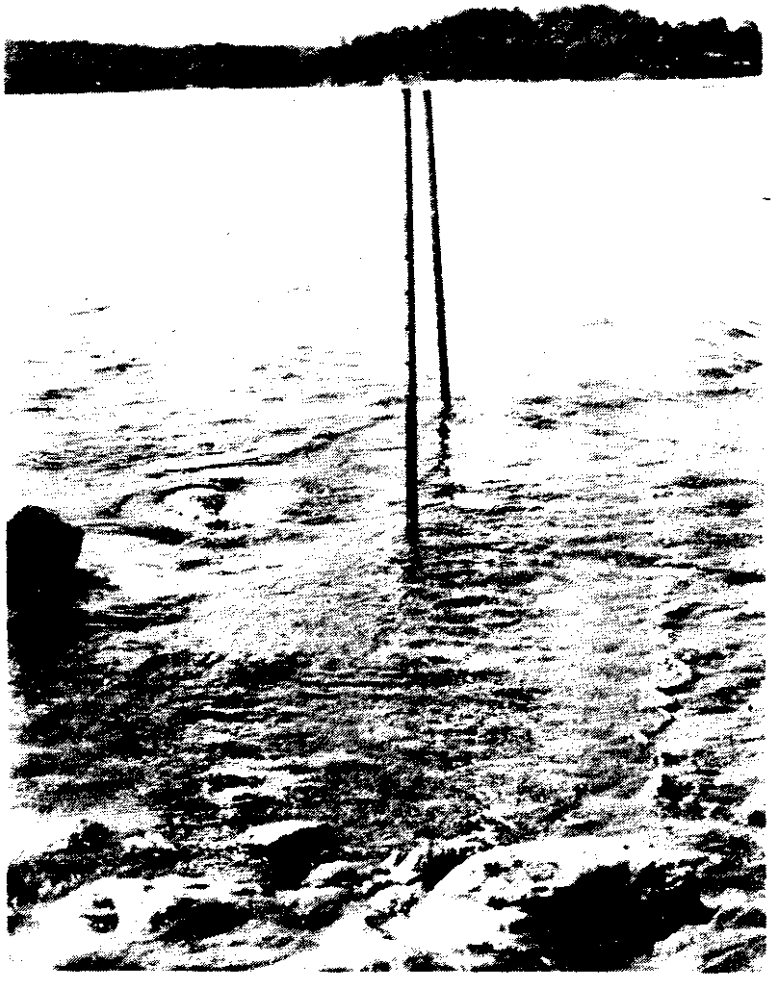


Photo 7.13. The vessel has passed entirely and the maximum decrease of the water has developed. It is about 30 cm.

Exhibit 3.17

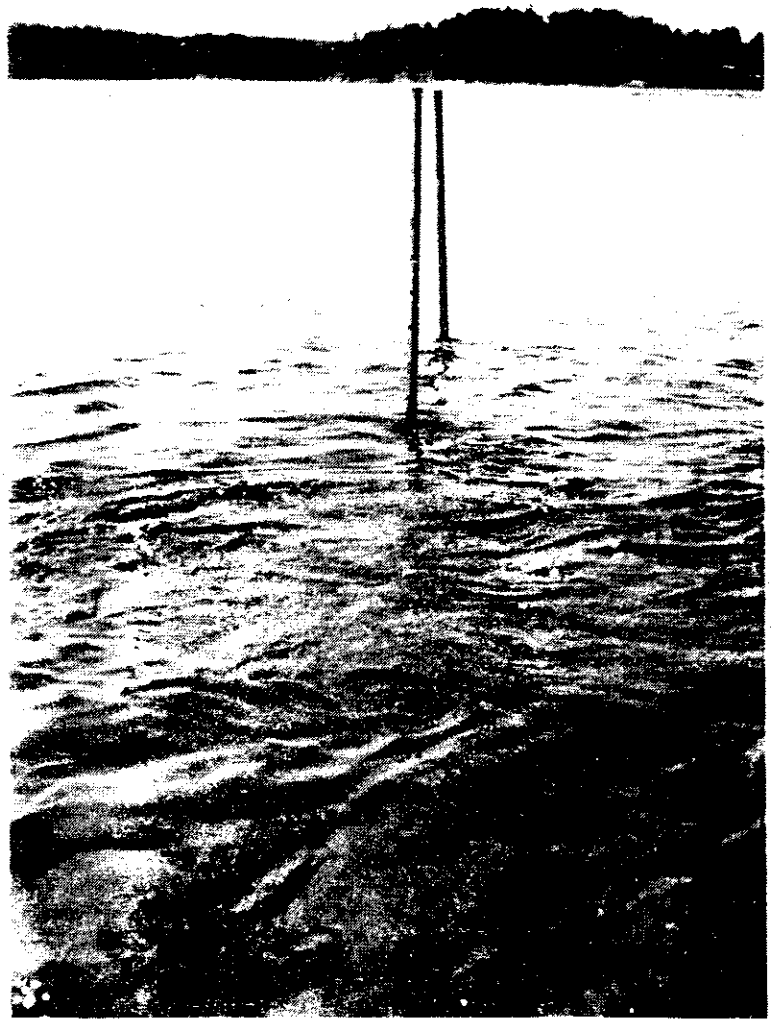


Photo 7.14. The water is quickly flowing back towards the shore.

Exhibit 3.18

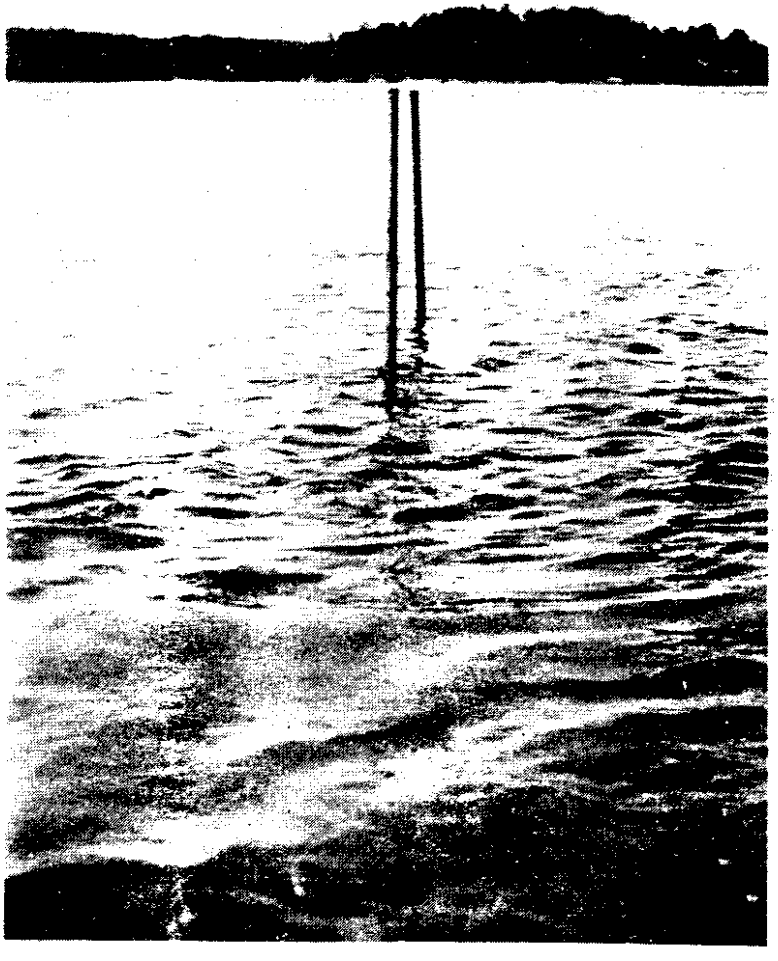


Photo 7.15. The water level reaches its highest level (about 15 cm above calm water level) shortly after the vessel has passed.

Exhibit 3.19

Photo 7.16. The wake washes are hitting the shore.

Exhibit 3.20

Photo 7.22. Wake washes at Marö becomes very large due to the high speed of the ferries at this location.

Exhibit 3.21

Table #. Waves Generated by Various Boats Operating at 10 Knots in the Oakland Estuary (depth = approx. 35')

Boat	Length (ft)	Beam (ft)	Draft (ft)	Displace-ment (tons)	Distance from sailing line			
					100 ft		500 ft	
					H_{max} (ft)	T/2 (sec)	H_{max} (ft)	T/2 (sec)
Cabin Cruiser	23	8.25	1.66	3	1.1	-	0.8	-
Coast Guard Cruiser	40	10	3.5	10	1.6	1.0	1.0	1.0
Tugboat	45	13	6	29	1.6	1.2	0.9	1.2
Fishing Boat	64	12.8	3	35	1.8	1.8	0.7	1.0
Fireboat	100	28	9-12	343	1.6	1.6	1.0	1.3

Source: Johnson, J.W. "Ship Waves in Shoaling Waters," Chapter 96. p. 1488 - 1498. Proceedings of the Eleventh Conference on Coastal Engineering; ASCE, London, Sept. 1968.

Exhibit 3.22

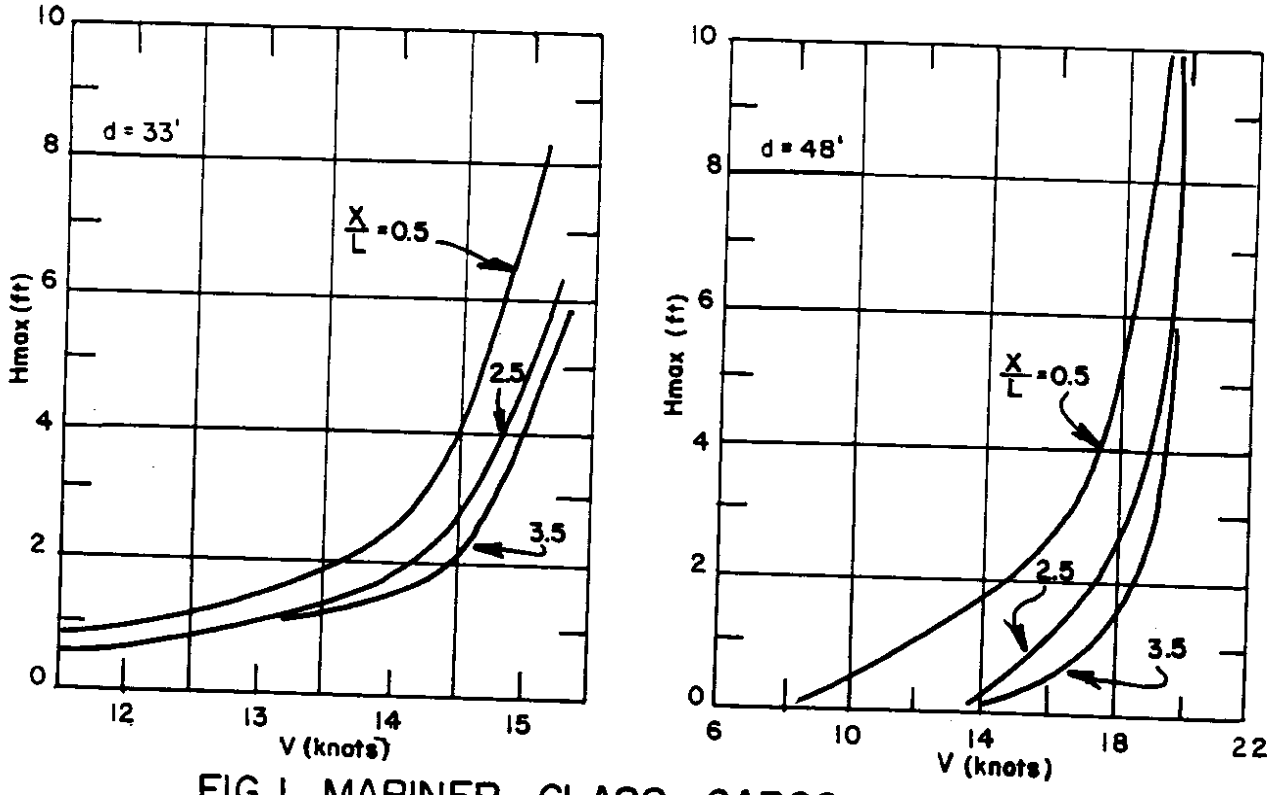


FIG 1. MARINER CLASS CARGO SHIP.
L=566' D=24'

Source: Hay, Duncan. "Ship Waves in Navigable Waterways." Proceedings of the Eleventh Conference on Coastal Engineering, ASCE, September 1968, Chapter 95, p. 1472-1485.

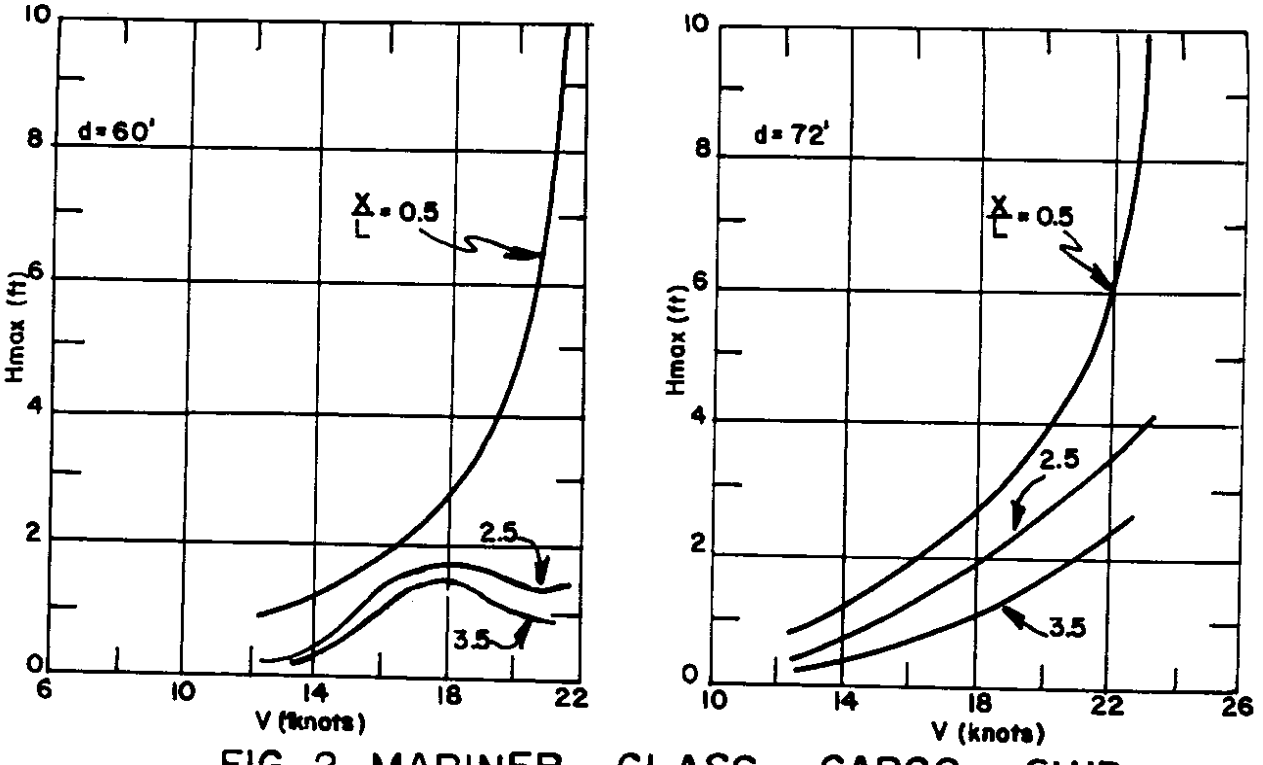


FIG 2. MARINER CLASS CARGO SHIP
L = 566' D = 24'

Exhibit 3.23

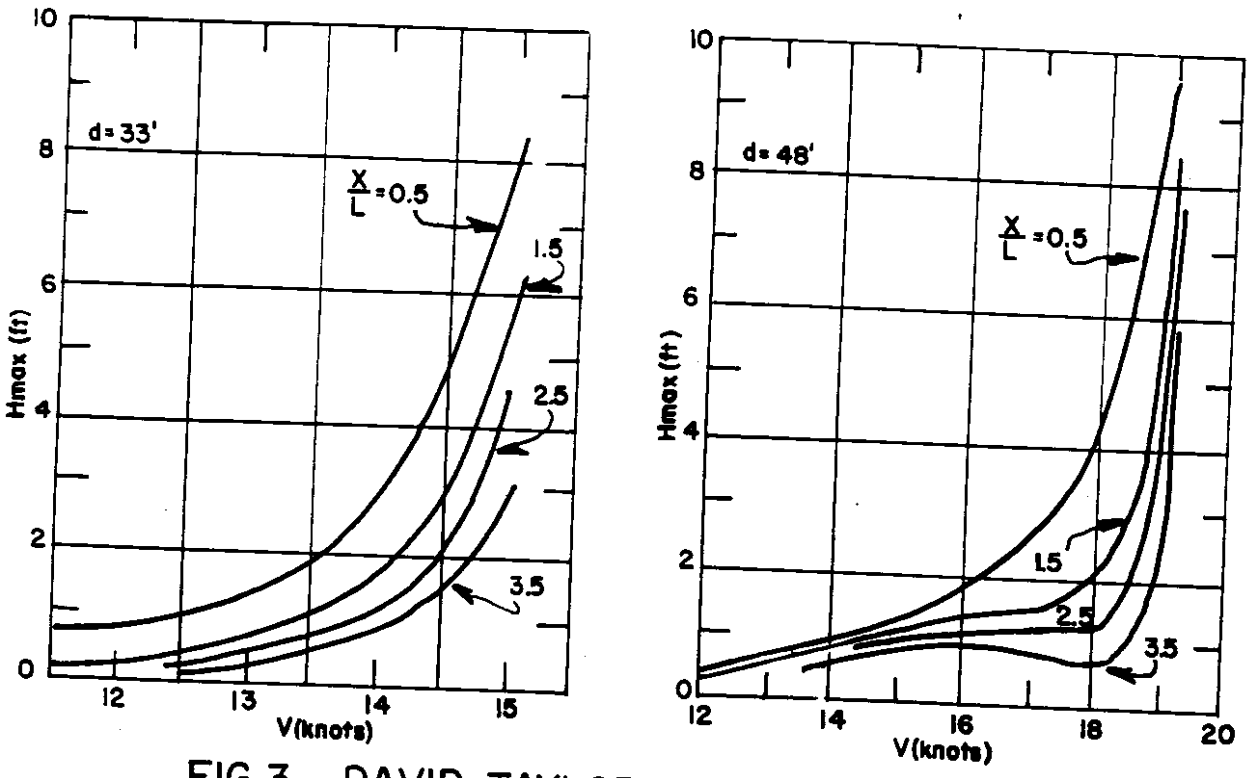


FIG 3. DAVID TAYLOR SERIES 60
L=505' D=24'

Source: Hay, Duncan. "Ship Waves in Navigable Waterways." Proceedings of the Eleventh Conference on Coastal Engineering, ASCE, September 1968, Chapter 95, p. 1472-1485.

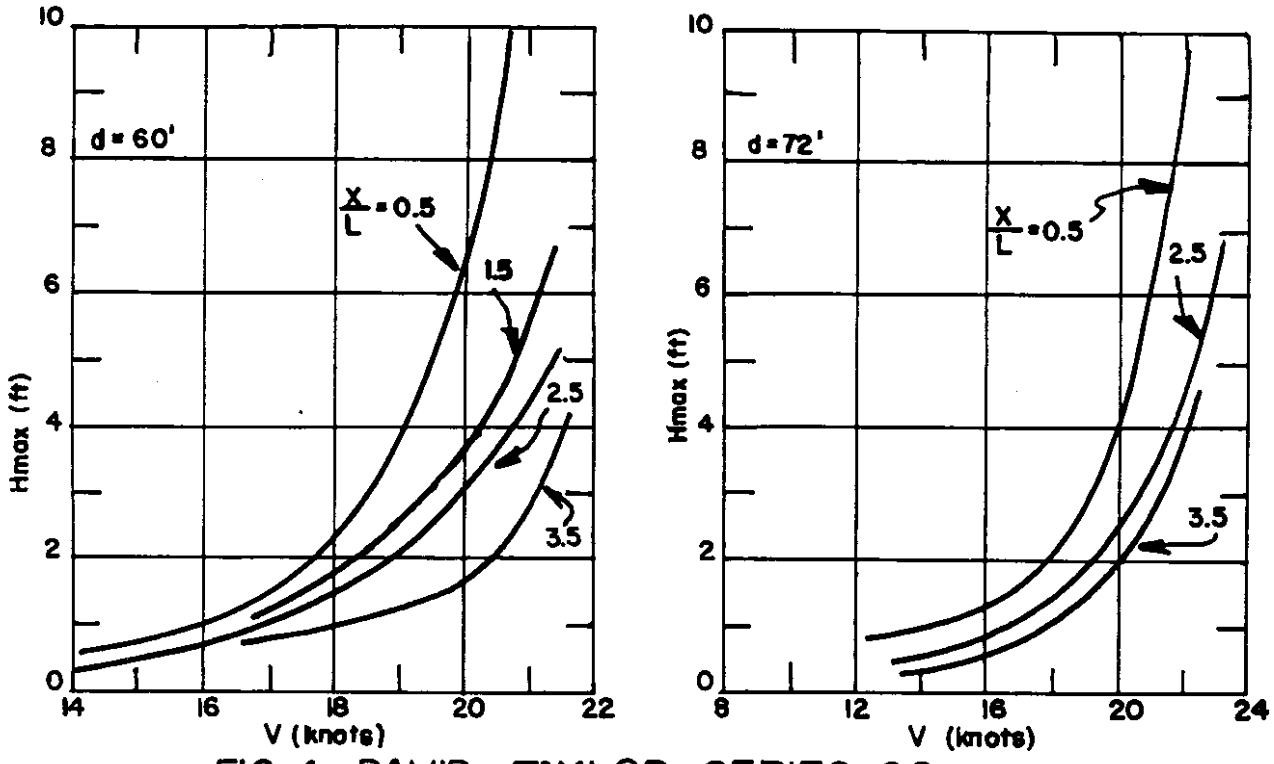


FIG 4. DAVID TAYLOR SERIES 60.
L=505' D=24'

Exhibit 3.24

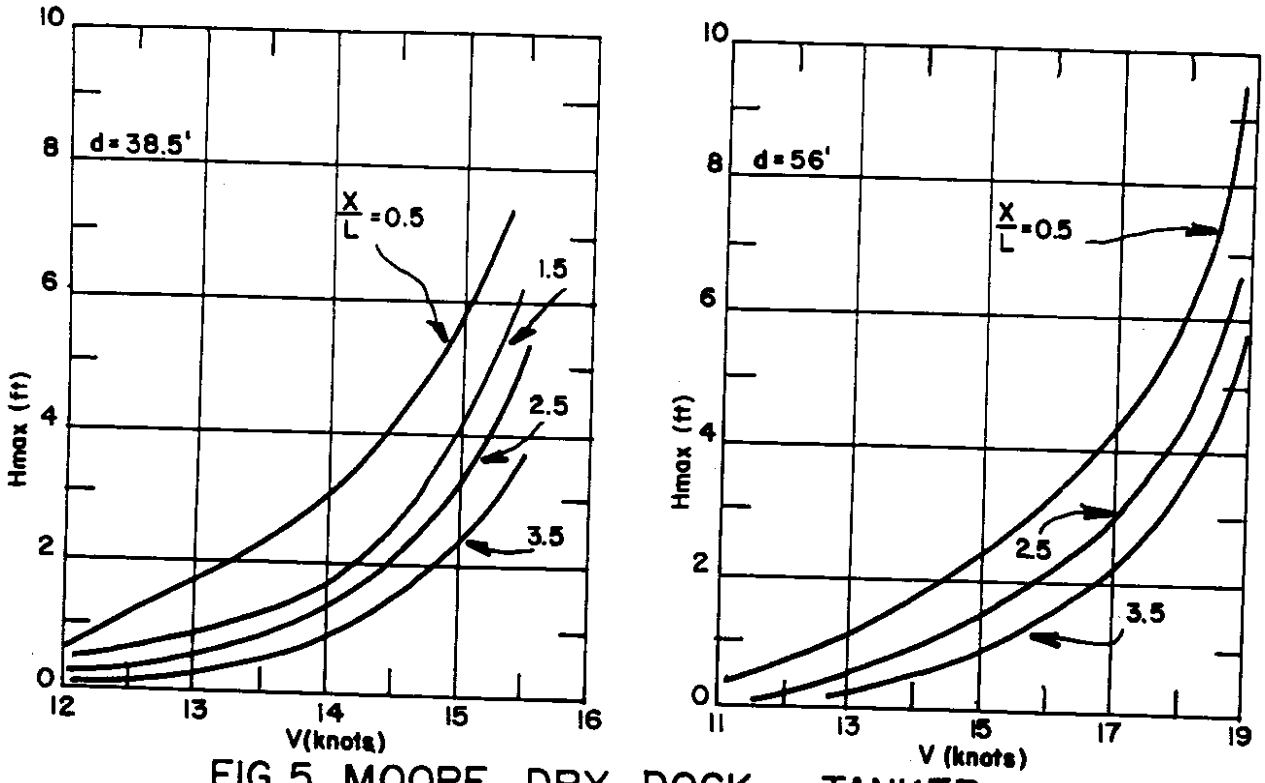


FIG 5. MOORE DRY DOCK - TANKER.
L = 504' D = 28'

Source: Hay, Duncan. "Ship Waves in Navigable Waterways." Proceedings of the Eleventh Conference on Coastal Engineering, ASCE, September 1968, Chapter 95, p. 1472-1485.

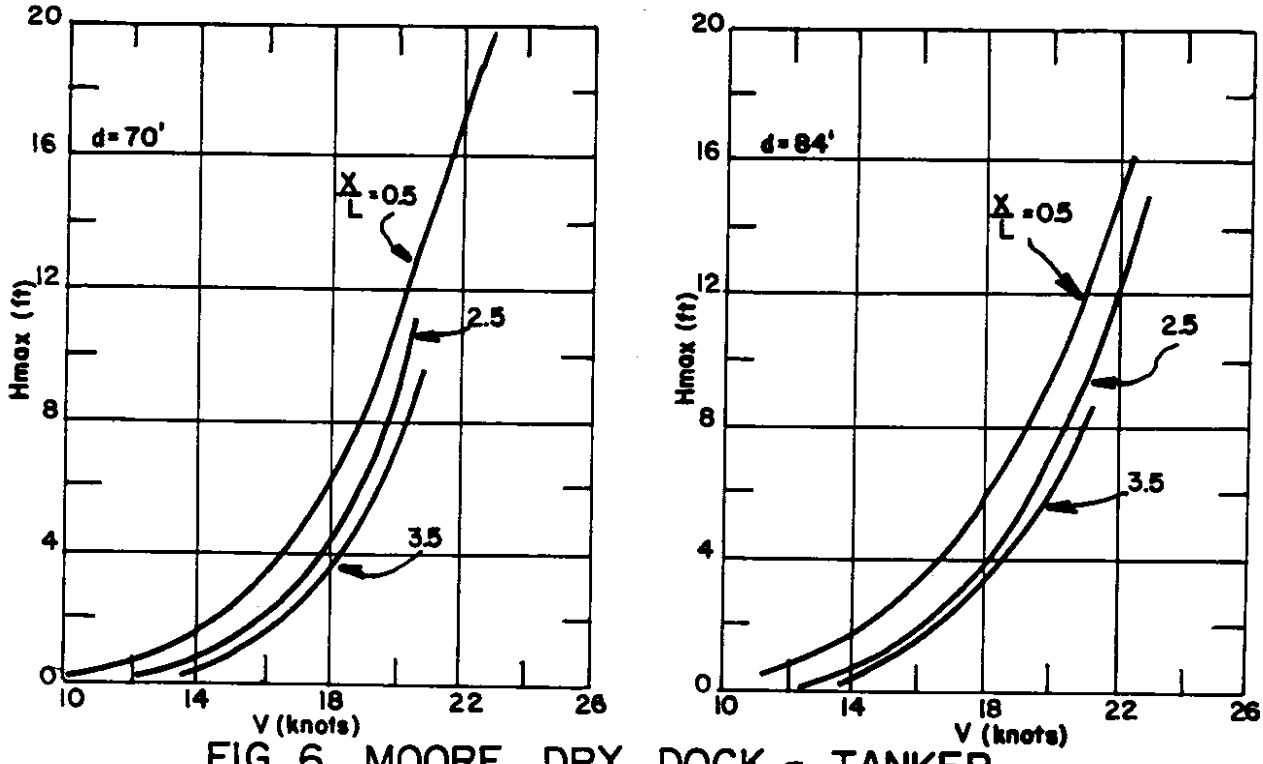


FIG 6. MOORE DRY DOCK - TANKER.
L = 504' D = 28'

Exhibit 3.25

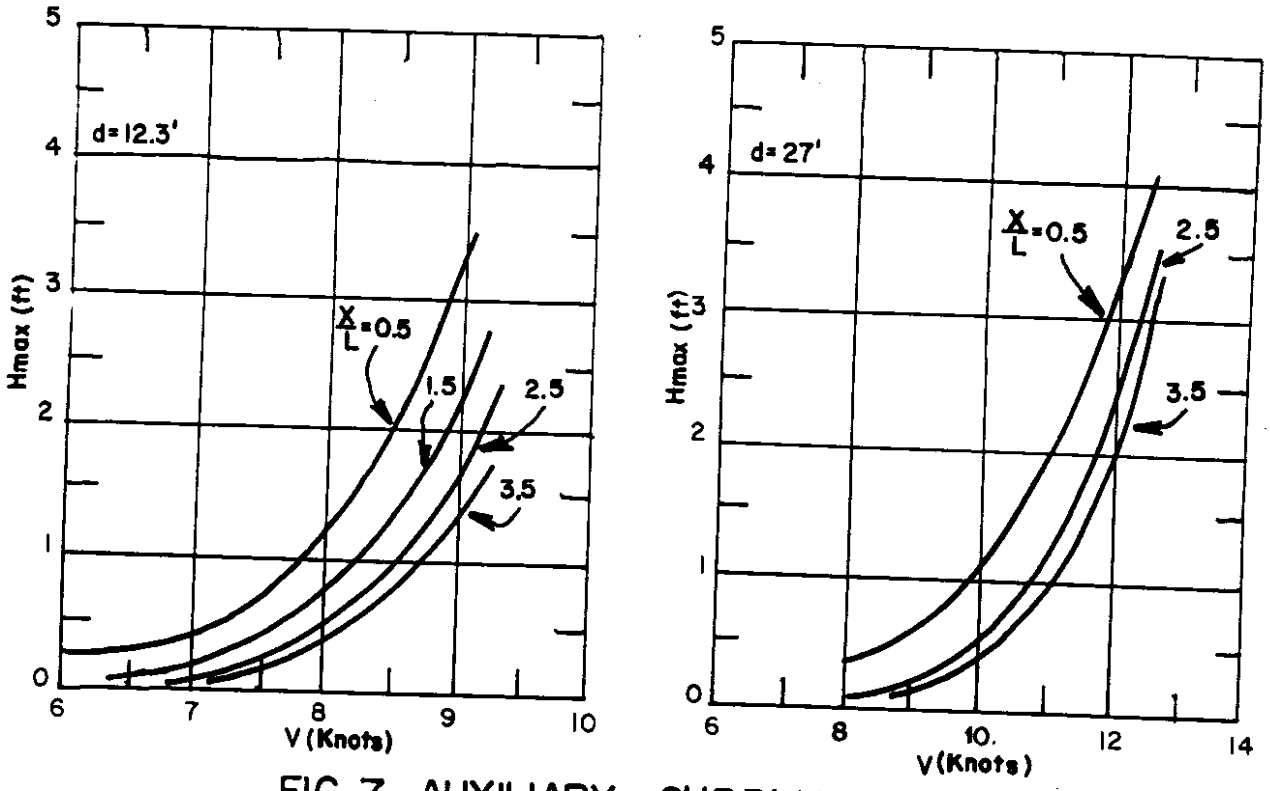


FIG 7. AUXILIARY SUPPLY VESSEL.
L=156' D=9'

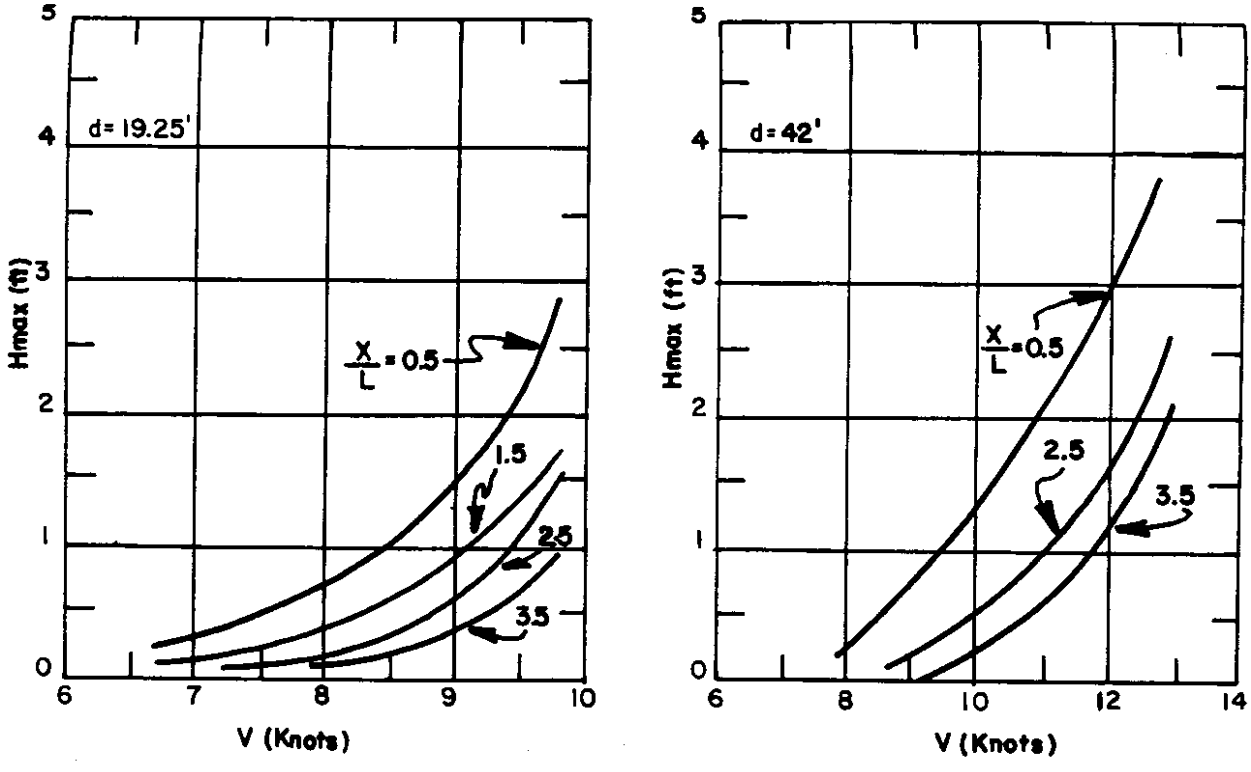


FIG 8. BARGE.
L=263.5' D=14'

Source: Hay, Duncan. "Ship Waves in Navigable Waterways." Proceedings of the Eleventh Conference on Coastal Engineering, ASCE, September 1968, Chapter 95, p. 1472-1485.

Exhibit 3.26

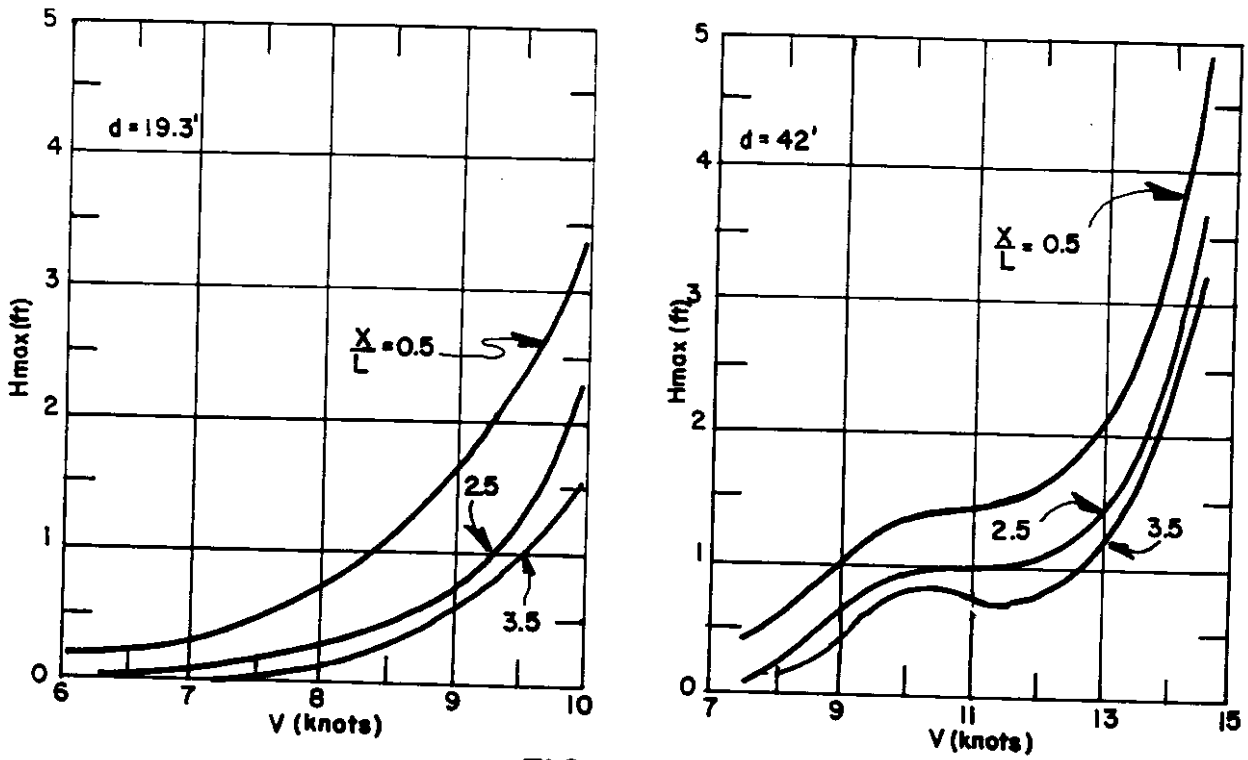


FIG 9. TUG

L = 153'. D = 14'.

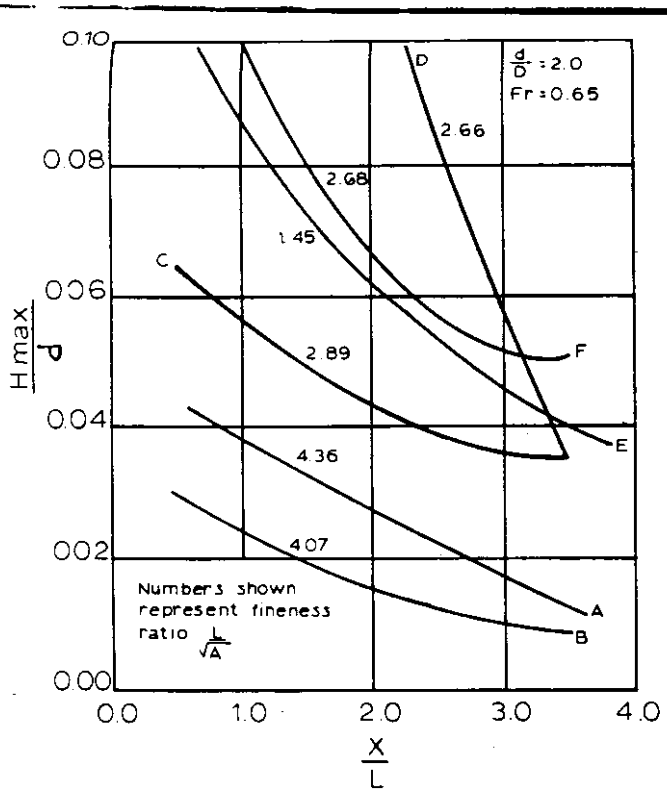


FIG 10 CROSS-PLOT OF $\frac{H_{max}}{d}$ VS $\frac{X}{L}$

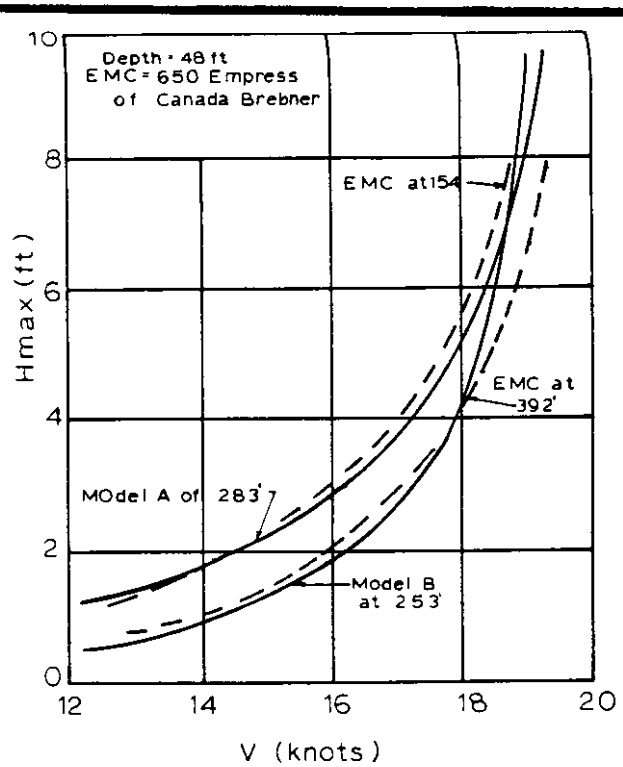


FIG 11 COMPARISON OF MODELS A & B WITH TESTS ON EMPRESS OF CANADA

Source: Hay, Duncan. "Ship Waves in Navigable Waterways." Proceedings of the Eleventh Conference on Coastal Engineering, ASCE, September 1968, Chapter 95, p. 1472-1485.

Exhibit 3.27

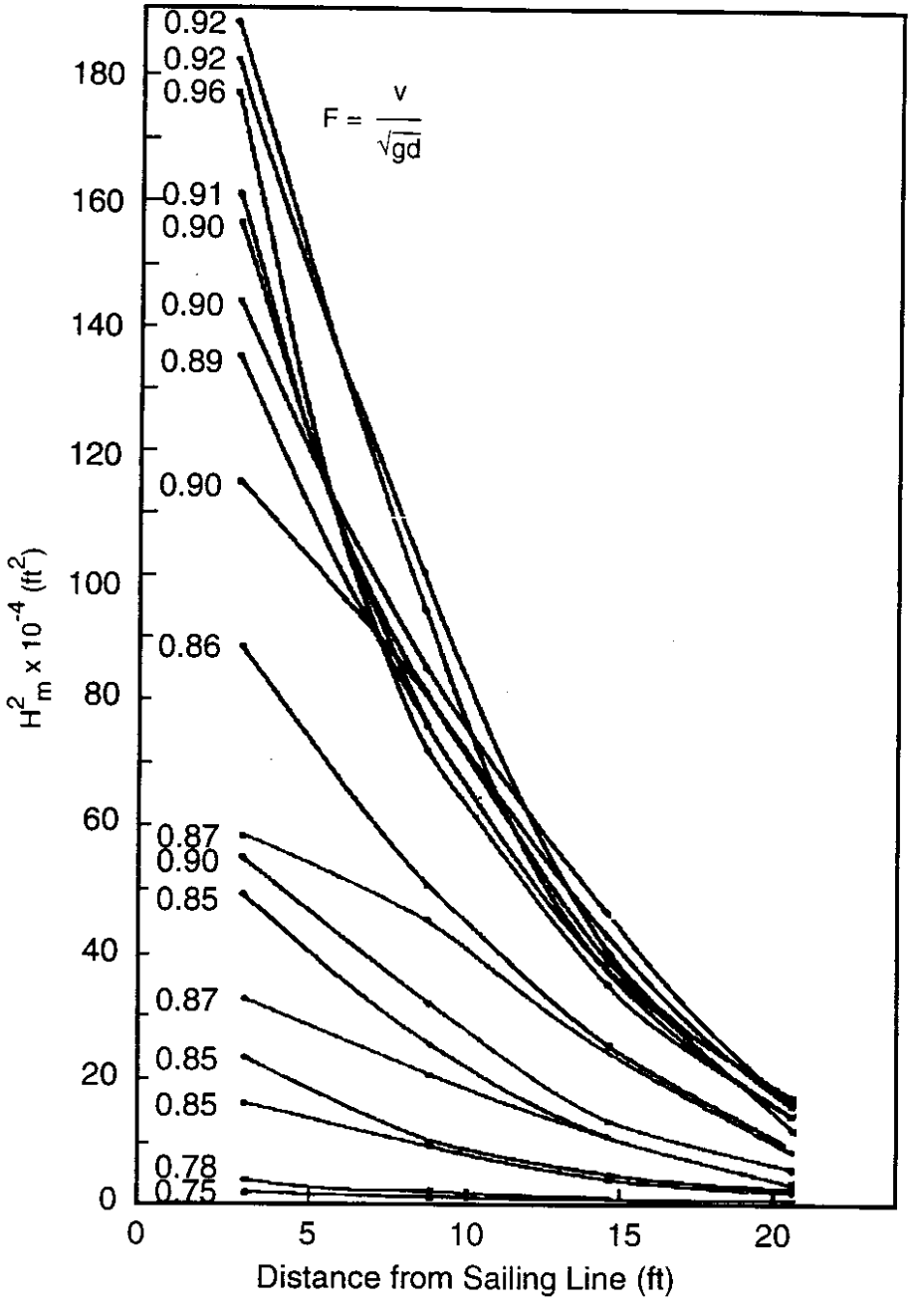


Figure #. H^2_m as a Function of Distance from Sailing Line with Froude Number as a Parameter for Cruiser Model in Shallow Water

Source: "Waves Generated By Large Ships and Small Boats." Das, M.M. & Johnson, J.W. Proceedings of the Twelfth Coastal Engineering Conference, ASCE. Washington, D.C., September 13-18, 1970. (Chapter 138, p. 2281-2285.

Exhibit 3.28

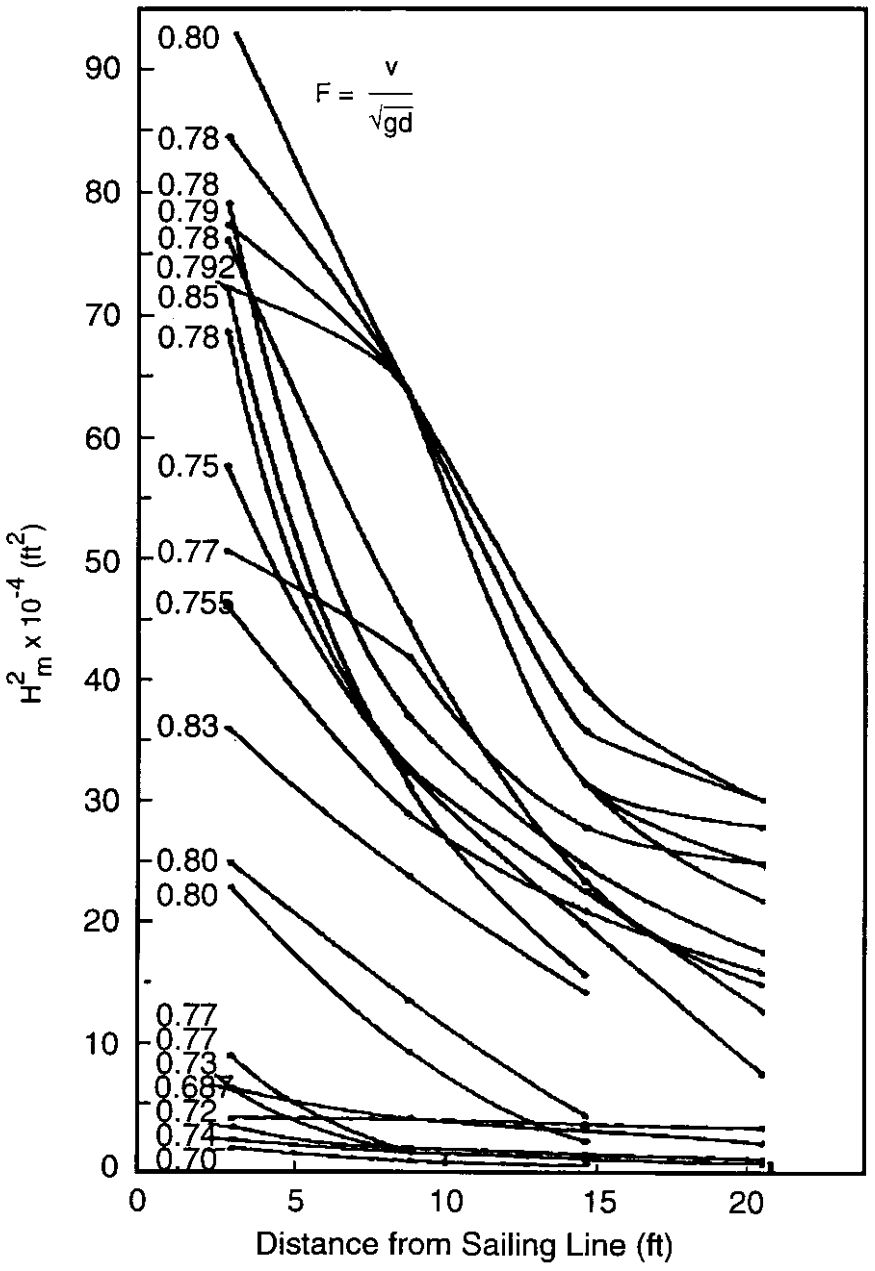


Figure #. H_m^2 as a Function of Distance from Sailing Line with Froude Number as a Parameter for Mariner Model in Shallow Water

SOURCE: "Waves Generated By Large Ships and Small Boats." Das, M.M. & Johnson, J.W.Proceedings of the Twelfth Coastal Engineering Conference, ASCE. Washington, D.C., September 13-18,1970. (Chapter 138, p.2281-2285.

Exhibit 3.29

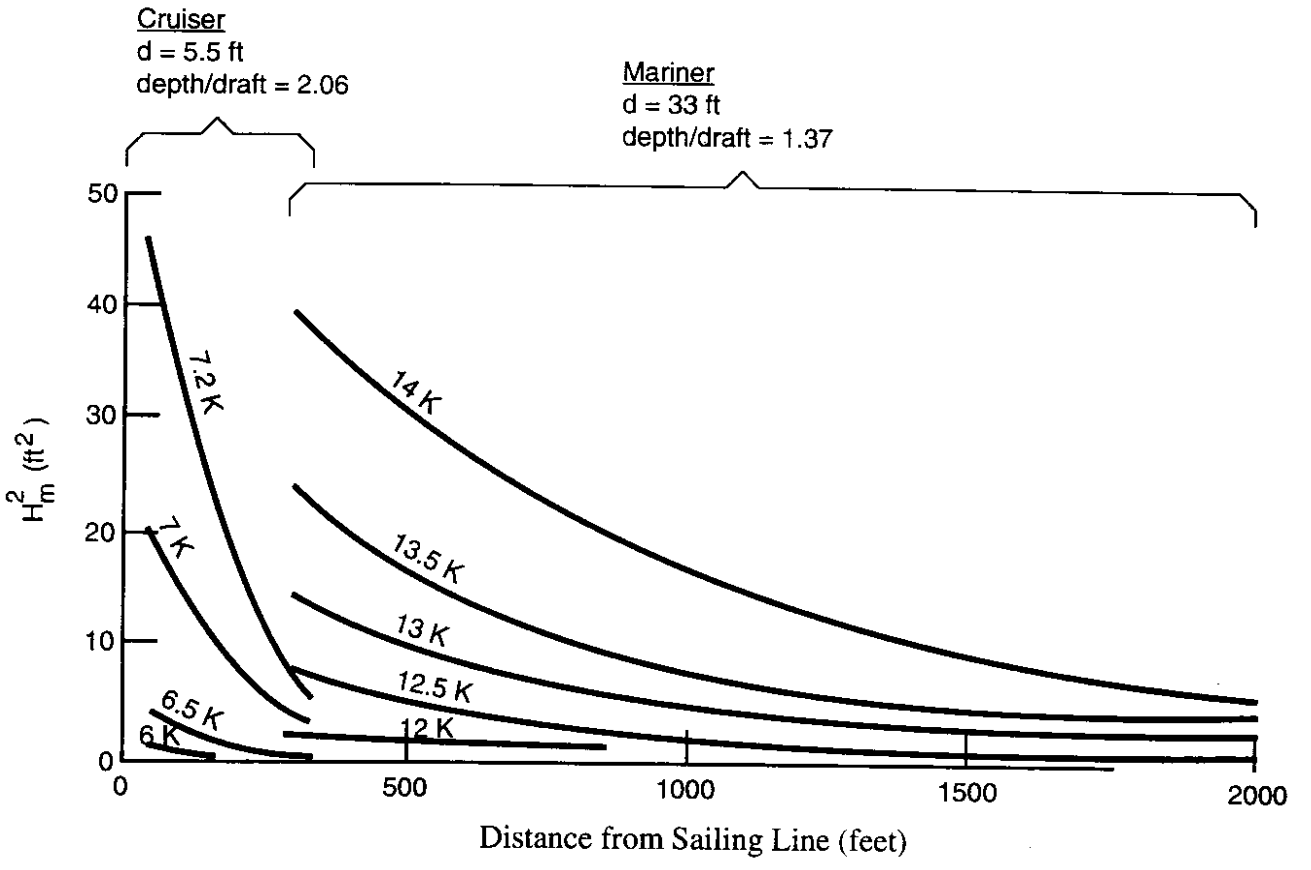


Figure #. Prototype Values of H_m^2 as a Function of Distance from the Sailing Line with Ship Speed in Knots as a Parameter for a Cargo Ship and a Cruiser Operating in Shallow Water

Source: "Waves Generated by Large Ships and Small Boats." Das, M.M. & Johnson, J.W. Proceedings of the Twelfth Coastal Engineering Conference, ASCE, Washington, D.C. Spetember 13-18, 1970.

CHAPTER 4

INDIVIDUALS AND COMPANIES WHO WERE CONTACTED FOR THIS STUDY

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