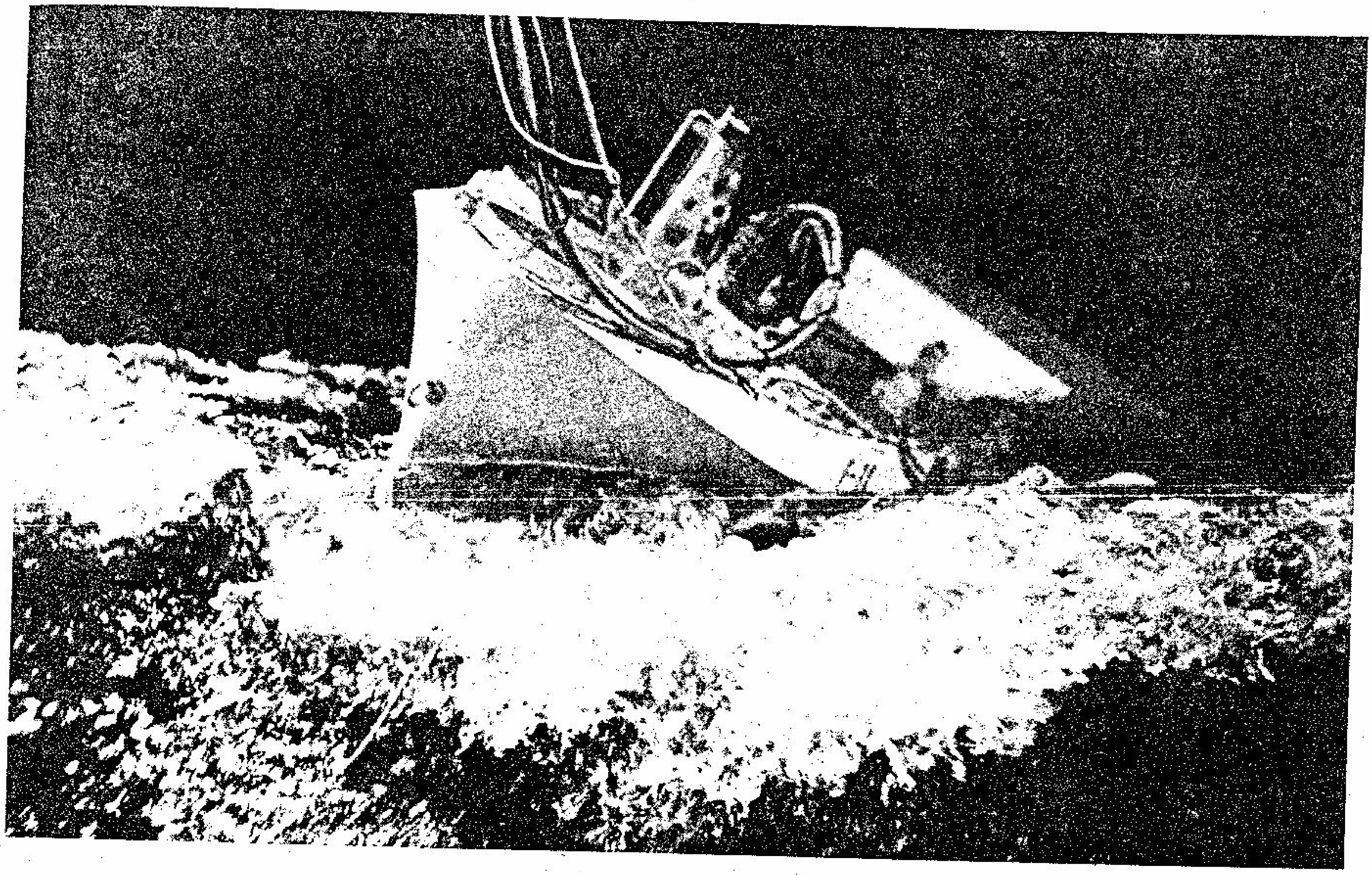

Development of Intact Stability Criteria for Towing and Fishing Vessels

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An experimental and analytical study was made of intact stability requirements for U. S. towing and fishing vessels. A literature survey determined what criteria are in use by various authorities, to judge the adequacy of intact stability of their fleets. The characteristics of the U. S. towing and fishing fleets in general were gathered, and 51 vessels were characterized in detail. Four models of representative vessels were built and tested in calm water and in regular waves. The calm-water tests studied towing vessels' tripping by their own power, and by the movement of their tow. The tests in waves took place in following, beam, and head waves, with the vessels running free or towing. The relationships between a vessel's power, handling, and proportions, and its probability of capsizing were studied. A set of stability criteria was formulated, and is presented for possible future use by the Coast Guard.

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The opinions expressed herein are those of the authors and are not necessarily those of the U. S. Coast Guard or HYDRONAUTICS, Incorporated. The contents do not constitute a standard, specification, or regulation of the U. S. Coast Guard.

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Introduction

MODERN intact stability regulations are not perfect. It is a fact that modern, fully equipped vessels which meet all the requirements of their Government's intact stability regulations are still being lost at sea. The exact cause of many of these accidents will never be known. Sometimes it is a case of a vessel leaving port under normal conditions, just as it has many times before, and never being heard from again. The British fishing trawler *Gaul*, a new, well-equipped vessel, was recently lost in heavy weather. There is no reason to doubt that she was being handled in normal fashion by her crew. Another apparently anomalous loss was the capsizing of the small Danish bulk carrier *Edith Terkol* [1].[4] This vessel, while in the ballast condition, capsized unexpectedly in following or quartering seas. In its loading condition at the time of the accident, it met all the intact stability requirements of the Intergovernmental Maritime Consultative Organization (IMCO). Other vessels capsize in less dramatic ways under a wide variety of circumstances. In one case, a 50-ft-long towing vessel was overturned when the barge it had in tow capsized. Not long ago, an 80-ft vessel towing a chip barge with a large sail area capsized in 30 to 40 knot winds in Alaskan waters. Because the wind was almost at a right angle to the towing vessel's course, the barge was considerably to leeward. A slight course change in the wrong direction was all that was needed to pull the towing vessel over.

These examples are a small sample of the total number of this type of accident. As the Government agency responsible for accident prevention, the U. S. Coast Guard must develop regulations governing the design and operation of a variety of types of vessels. The intact stability criteria in use today are largely the products of years of experience. These criteria have been modified from time to time as accident statistics have pointed to areas where they should be more stringent. Nowadays, with vessels of all types changing more rapidly than ever before, exclusive reliance on past experience may result in criteria whose applicability becomes less and less universal. Supply vessels are of relatively conventional form, and yet experience has shown that it is not always possible to ensure their safe operation using criteria developed and tested before the introduction of these vessels.

The subject of this paper is the intact stability of towing and fishing vessels. The scope of this research was restricted to these types of vessels because both have special problems, related to their size, which make them more vulnerable than most larger vessels. Towing vessels, when engaged in towing, must carefully manage their towline to prevent large overturning moments from being applied to themselves. They often have low freeboard to make line handling easier. Older towing vessels may be re-engined with more powerful engines. The increase in power can cause barely adequate original designs to become inadequate. Towing vessels are often called on to tow in exposed locations in poor weather conditions. There have been a number of losses in recent years which can reasonably be assumed to be intact stability accidents, for example, the *Theresa F.* loss [2] and the loss of the *Marjorie McAllister* [3].

Fishing vessels have been included because they often have hull forms which are very similar to those of towing vessels and they often carry heavy deck loads in poor weather conditions. Losses have been recorded which are very similar to towing vessels' tripping losses: a heavy net suspended on a boom has swung outboard when the vessel rolled and capsized the vessel almost instantly.

In addition to the broad concerns outlined in the foregoing, the Coast Guard has strong incentives for studying the intact stability requirements for towing, fishing, and supply vessels which arise from actions of international bodies. There are four actions of particular significance which should be mentioned. First, the 1966 International Load Line Convention (ILLC) came into effect in 1968. This convention was important with respect to the Coast Guard's regulation of towing vessels. Prior to 1968, the Coast Guard only reviewed the stability characteristics of those towing vessels subject to Coast Guard inspection regulations. Since most are motor vessels under 300 gross tons, they were not subject to inspection. The 1966 ILLC, by requiring all vessels over 79 ft (24 m) which are on an international voyage to have their stability analyzed, changed this. This requirement was also included in the load line regulations for vessels over 150 gross tons on coastwise voyages, so that now most towing vessels on offshore voyages were subject to a stability analysis. Second, in 1968 IMCO published intact stability standards for passenger and cargo ships under 328 ft (100 m) [4]. The Coast Guard's supply vessel stability criterion is very similar, with one important difference: the Coast Guard criterion does not require that the maximum righting arm occur between 30 and 40 deg of heel angle. IMCO is presently at work on a criterion specifically for offshore supply vessels. In addition to evaluating the Coast Guard's criterion, IMCO is investigating the stability of these vessels while towing. Third, and also in 1968, IMCO published a stability criterion for fishing vessels [5] based on Rahola's thesis, but when work began on a Construction and Equipment Code for Fishing Vessels, IMCO's member countries decided that the original criterion should be reevaluated in the light of recent papers contributed by the U.S.S.R. introducing the concept of the "pseudostatic angle of heel." This term refers to the nearly static heel angle about which a vessel with water trapped on deck will roll. (This occurrence was noted in the model test program which is the subject of this paper; see Fig. 8.) Fourth, an international fishing vessel convention under the auspices of IMCO is planned for the spring of 1977. This convention will include intact stability criteria for fishing vessels over 79 ft (24 m) in length.

Before describing the model testing and analytical work done in this research, it is useful to review briefly previous work in the general area of intact stability. A literature search produced a long list of papers whose relevance to the present work naturally varied from significant to negligible. References [6] and [7] list all of these papers. One general statement can be made after an examination of them: Most propose criteria or suggest better ways to calculate curves of stability; relatively few contain comprehensive experimental or full-scale data on which to base conclusions. Reference [8] is a recent summary of various approaches to determining adequate intact stability levels, and contains many European sources.

To conserve space, only papers which discuss work of a nature similar to this paper's will be considered here. The approach used herein was to determine, from model tests and theory, what the forces are that cause vessels to capsize. Therefore, the discussion that follows will describe the work of earlier investigators who performed model tests and of others who used theoretical means to quantify the forces on vessels. There appears to have been remarkably little of this kind of research. The literature search was limited to mainly American sources and well-known European sources. Reference [7] refers to relevant IMCO papers. There are probably many other publications on the subject, particularly from countries with large fishing vessel fleets like the U.S.S.R. and Japan.

Roach's 1955 paper [9] contains recommendations which were based on tests of actual Army Transportation Corps tugs. Getz and Bakke [10] first studied towing vessels' capsizings to determine if any of the vessels involved had extreme or unusual proportions. Their conclusion was that the vessels involved in accidents were somewhat narrower than average and had

[4] Numbers in brackets designate References at end of paper.

rather small freeboards—not surprising findings. Their next step was to perform a series of model tests in calm water to determine the worst towing point locations and operating conditions. Two models were tested. Sideways towing tests supplied data to determine "critical speeds," or speeds above which the ship would capsize. They found that once the deck edge is submerged the heeling moment increases very rapidly. Therefore, the critical speed could be defined as the speed which will result in the submergence of the deck edge if the vessel is towed sideways. They suggest that a stability criterion could be written whose goal would be to prevent the deck edge from going under.

For the dynamic case, where the overturning moment is suddenly applied, estimation of the forces becomes so difficult that only model tests can give accurate estimations. This is also true for the case of loads due to waves. Since towing and fishing vessels operate in all sorts of weather and sea conditions, it is desirable to carry out model tests in head, bow quartering, beam, stern quartering, and following waves. Coast Guard-sponsored research at the University of California on the motions of vessels in following and quartering waves [11] is very applicable to this problem. Models of two different vessels were tested in San Francisco Bay in sometimes extreme conditions. Results of this work were used to select test conditions, in the analysis of data, and when drawing up proposed criteria.

References [12] and [13] report model tests of trawlers in beam seas. In [12], freeboards, bulwark heights, freeing port areas, and deckhouse lengths were varied. The authors were impressed by the complexity of the phenomenon of a vessel capsizing in a beam sea when water on deck is involved. In [13], a side trawler was tested in irregular seas, giving an indication of the conditions in which capsizing will occur in beam seas. Capsizing did take place at metacentric heights less than that recommended by IMCO.

The main sections of this paper discuss our analysis of the U. S. towing and fishing vessel fleets which was used for the model selection, model test procedures and typical results, the formulation of a set of empirical intact stability criteria, and the potential impact of these criteria on the U. S. fleet.

Fleet analysis

Fleet census

After the literature search of existing criteria and model or full-scale experiments, a census and characterization of the U. S. offshore towing vessel and fishing fleets were carried out. The objective of this effort was to obtain definitive data on the size and characteristics of the U. S. towing and fishing vessel fleets. These data were required to guide the selection of models for the test program and to aid in the assessment of the impact of stability criteria on the fleet.

The primary source of information on towing vessels was in the form of computer cards made from the data tapes used in the preparation of the U. S. Coast Guard's "Merchant Vessels of the United States," CG-408. From this initial listing of all towing vessels, those engaged on the Great Lakes or inland operations were eliminated, which left a final sample of 2995 offshore towing vessels. The following data were placed in a file for each vessel: official number, gross tonnage, registered length, registered breadth, registered depth, type of construction, year of completion, installed horsepower, and number of flooding, foundering, or capsizing casualties the vessel had experienced.

The principal information on fishing vessels was supplied by the National Marine Fisheries Service in the form of a magnetic tape with additional information on the vessels added from "Merchant Vessels of the United States." Again, Great Lakes and inland waterway vessels were eliminated, leaving a sample of 12,670 offshore fishing vessels. The following data were placed in a file for each vessel: official number, gross tonnage, registered length, registered breadth, registered depth, type of construction, year of completion, installed horsepower, state and county of registry, fishing gear type, and number of casualties.

The casualty data were supplied by the U. S. Coast Guard and included floodings, founderings, and capsizings from fiscal years 1969 through 1972. The official number, case number, and type of casualty were punched onto computer cards and then stored in separate casualty files.

These data were analyzed to produce histograms showing trends in towing and fishing vessels based on gross tonnage, length, breadth, year of completion, and horsepower. Figure 1 depicts the upward trend in installed horsepower versus year of completion. Figures 2 and 3 show the trend in length/breadth ratio versus length for towing and fishing vessels, respectively. The circles and squares on the figures indicate the actual values for the 51 vessels described in the following. Other histograms were produced showing number of vessels versus horsepower, number of vessels versus gross tonnage, and number of vessels versus length. This effort produced a general picture of the towing and fishing vessels but was too general to permit any analysis of stability characteristics or causes of casualties. Thus, it was necessary to collect detailed data on a representative sample of the U. S. fleet.

Detailed characterization

Detailed characteristics were assembled on 51 vessels, including 29 fishing vessels, 20 conventional towing vessels, and 2 combination offshore supply towing vessels. The vessel design and loading data were obtained from the following sources:

- Nickum and Spaulding Associates, Seattle, Wash.
- HYDRONAUTICS, Incorporated, Laurel, Md.
- U. S. Coast Guard Headquarters, Washington, D. C.
- B. F. Jensen, Seattle, Wash.
- L. W. Glosten and Associates, Seattle, Wash.
- Marine Construction and Design, Co., Seattle, Wash.
- Maritime Shipbuilding Co., Tacoma, Wash.
- The Haney Co., Baltimore, Md.
- John Gilbert, Boston, Mass.
- Offshore Logistics Co., Lafayette, La.
- Canadian Ministry of Transport.

Table 1 lists by identification number the 51 vessels chosen for detailed analysis. Gaps in the numerical sequence are a result of deleting vessels for which complete data could not be obtained. For each vessel, a characteristics booklet was prepared showing the vessel's stability characteristics for two loading conditions, and compliance with 23 different stability criteria. Appendix 1 contains part of the characteristics booklet for vessel T-01. Loading condition 2 has been omitted to conserve space. Appendix 2 contains an index of the acronyms used in Appendix 1 and Appendix 3 lists the 23 stability criteria.

The curves of static and dynamic stability were prepared for calm water and for the vessel poised on a wave with crest amidships and a height of $1.1\sqrt{L_{BP}}$. The stability curves for the towing vessels were prepared using the constant trim moment method. For the fishing vessels, the stability curves in calm water were prepared using both the constant trim and constant trim moment methods.

Model selection

The fleet census could supply only limited data on vessels' geometric characteristics for use in model selection. Figures

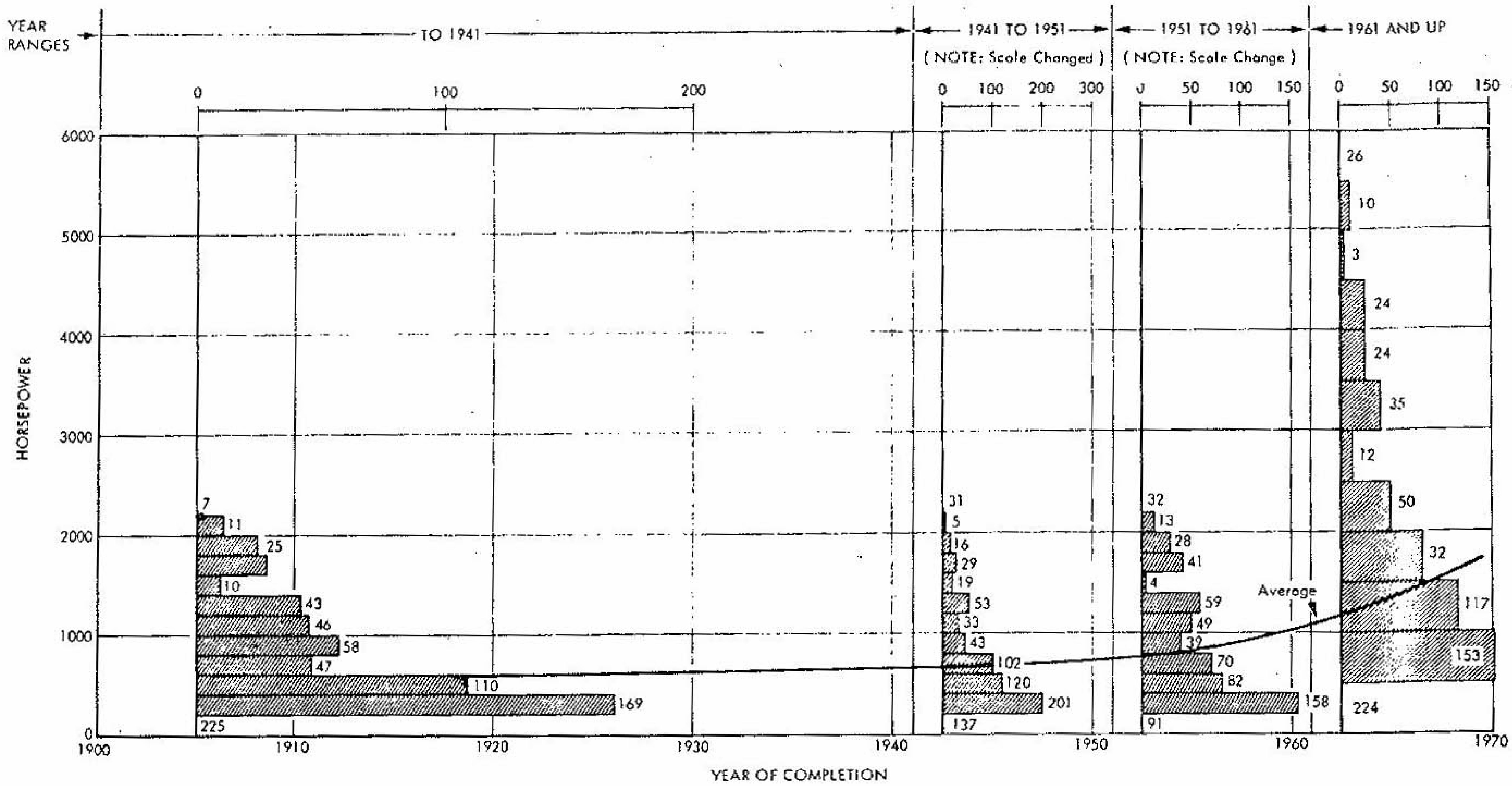

Fig. 1 All towing vessels; horsepower distribution within various year ranges

2 and 3 present the relationship between L/B and L for the fleet and the vessels listed in Table 1. (L stands for length overall, or registered length.) In general, the 20 towing vessels have a distribution of L/B which is similar to the fleet as a whole, while the selected fishing vessels have L/B values which are lower than the fleet-wide average. Several other observations could be made:

1. The towing vessels, typically, are representative of the newer vessels in the fleet.
2. The range of L/B of the 20 towing vessel sample covers the extremes of the fleet, with the exception of the smallest harbor tugs.
3. The fishing vessels typically have greater beam and more power than the fleet average. This is an indication that the sample vessels are newer than the fleet average.
4. The range of L/B values in the 29 fishing vessel sample is sufficient to cover the extremes of the fleet.

In addition, comparisons were made of some of the fundamental hull form geometric parameters within the 51-vessel sample. Figure 4 presents the displacement-length ratio, $\Delta/(0.01L)^3$, as a function of L/B. These two parameters are closely correlated and there are no notable differences between the towing vessels and fishing vessels. Breadth-depth ratio was also plotted as a function of L/B. Again, the towing vessels and fishing vessels were equally distributed within a narrow band about $B/D = 2.0$. Similarly, block coefficients and prismatic coefficients were plotted as a function of L/B for the towing and fishing vessels. The prismatic coefficients were closely grouped between values of 0.59 and 0.68. The towing vessels, on the average, have prismatic coefficient values which are about 3 points less than the fishing vessel average. The block coefficient values average about 0.52 for both towing and fishing vessels. The scatter in block coefficients is somewhat larger than that of the prismatic coefficients. Thus, the fundamental form parameters of the towing vessels and fishing vessels are very similar at equal values of L/B.

The scope of the project permitted the testing of four models. It was determined that the selected models should cover a reasonable range of the parameters L/B, C_B, C_W, and B/H (H = draft). In addition, consideration was given to their relative importance in the fleet and the probability of stability problems. It was decided not to attempt to model a casualty because of the lack of knowledge about the exact circumstances of the specific casualties in the 51-vessel sample.

The following models were selected for the model test program:

1. T-24, a round-hull ocean towing vessel.
2. S-04, a two-chine-hull offshore supply vessel.
3. F-34, a transom-stern crabber.
4. T-14, a low-L/B two-chine-hull towing vessel.

The characteristics of these models are given in Table 2, and profile views are presented in Fig. 5.

The rationale for the selection of the models was as follows:

Model 1: Vessel T-24, an Atlantic Coast towing vessel, was selected because it is a modern high-power twin-screw vessel employed in ocean towing, with lower stability than most towing vessels. In addition, it has a round hull form as opposed to the chine hull form of the other three models.

Model 2: Vessel S-04, a Gulf Coast offshore supply vessel, was selected because of the large number of these vessels in existence and their poor stability characteristics in following waves. These vessels are often used for towing; therefore, the model was tested as a towing vessel. Vessel S-04 was selected over vessel S-03 because its chine hull form is more common than the round form of S-03.

Model 3: Vessel F-34, a Pacific Coast crabber, was selected because there is a large number of these vessels and the data indicate they have poor stability in following waves. This vessel has a raised fo'c'sle and a wide transom stern. Except for a lower value of L/B and corresponding higher value of $\Delta/(0.01L)^3$, vessel F-34 is similar in hull form to the Atlantic Coast stern trawlers. Consideration was given to the possible trends in towing vessel design if regulations are made to apply to vessels down to 79 ft (24 m) in length. It is likely that some attempts will be made to produce ocean tugs just under this length limit. These vessels would necessarily have low values of L/B and high values of $\Delta/(0.01L)^3$. Vessel F-34 is repre-

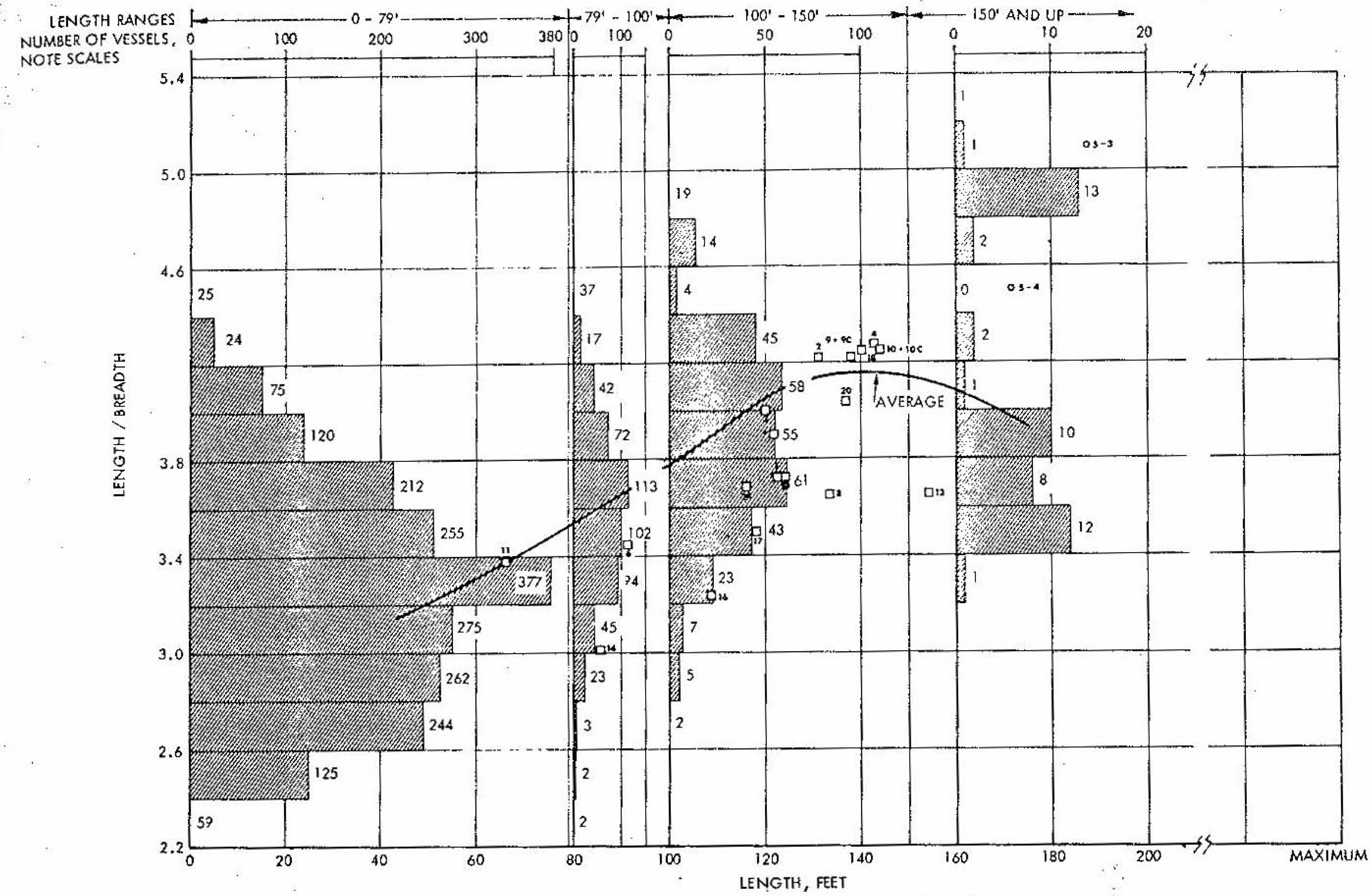

Fig. 2 Length-to-breadth distribution in various length ranges for all towing vessels

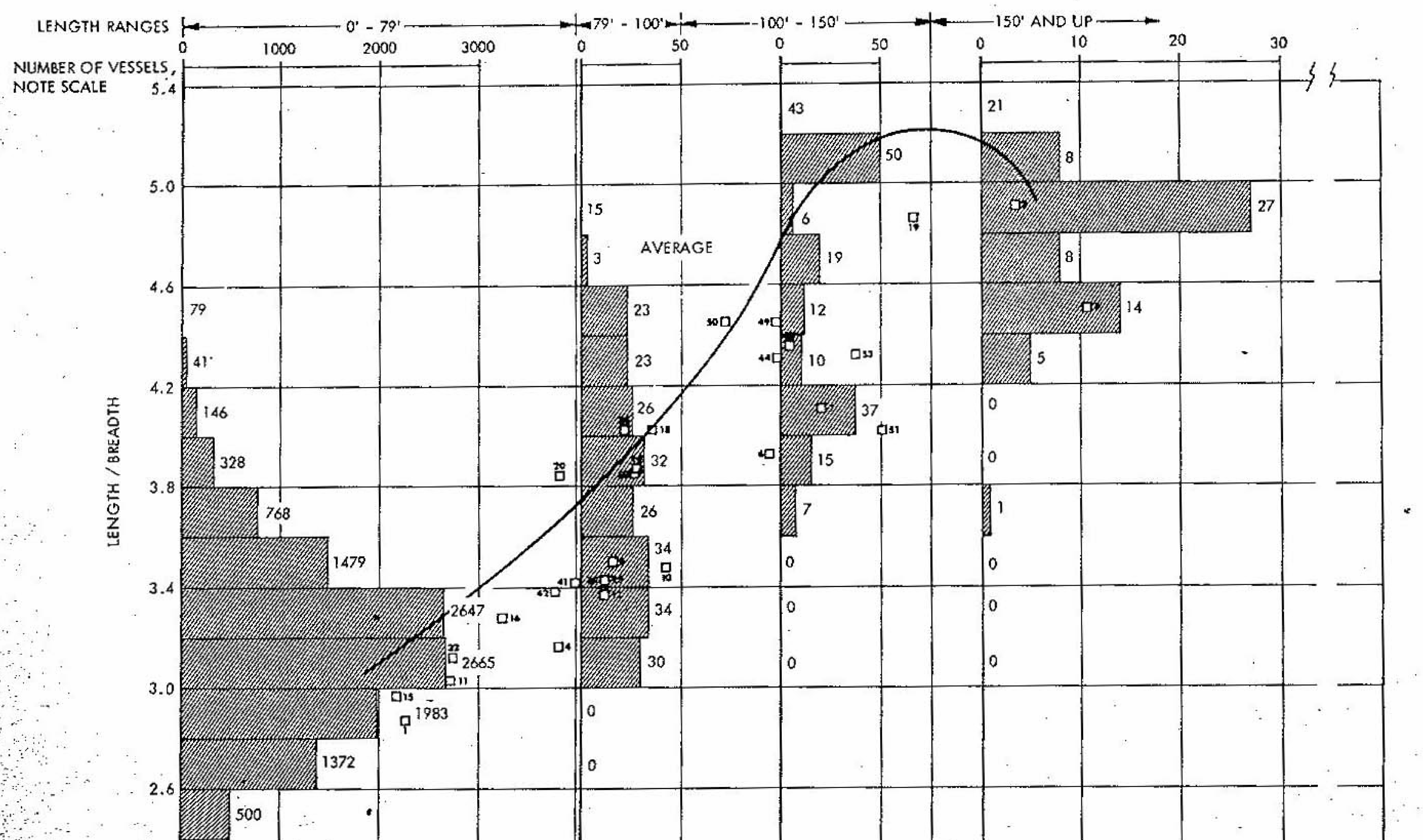

Fig. 3 Length-to-breadth distribution within various length ranges for all fishing vessels

Table 1 Index of vessels

Vessel	Coast	L_{BP}, ft	BHP	Hull form	Type
T-01	Gulf	116.7	3280	round	flush deck, ocean
T-02	Pacific	125.0	3300	round	flush deck, ocean
T-03[a]	Atlantic	111.5	3600	2-chine	flush deck, ocean
T-04[a]	Gulf	132.5	5000	round	raised fo'c'sle, ocean
T-06	Pacific	85.0	2150	2-chine	flush deck, ocean
T-07[a]	Pacific	114.25	2200	round	flush deck, ocean
T-08	Pacific	133.0	5750	round	flush deck, ocean
T-09	Gulf	126.67	1500	round	raised fo'c'sle, ocean
T-9C	Pacific	126.67	3300	round	raised fo'c'sle, ocean
T-10	Pacific	140.0	1175	round	flush deck, ocean
T-10C	Pacific	140.0	4850	round	flush deck, ocean
T-11	Atlantic	63.75	600	round	flush deck, harbor
T-13	Pacific	144.0	7420	round	raised fo'c'sle, ocean
T-14	Pacific	79.0	2000	2-chine	flush deck, harbor
T-16	Pacific	104.55	2900	1-chine	flush deck, ocean
T-17	Pacific	110.87	3000	round	raised fo'c'sle ocean
T-18	Pacific	138.54	2400	round	flush deck, ocean
T-19	Gulf	117.75	4200	2-chine	flush deck, ocean
T-20	Gulf	127.5	3700	2-chine	raised fo'c'sle, ocean
T-24	Atlantic	116.7	5750	round	flush deck, ocean
S-03	Gulf	189.0	5733	round	raised fo'c'sle, supply
S-04	Gulf	170.0	unknown	2-chine	raised fo'c'sle, supply
F-01[a]	Pacific	43.0	unknown	2-chine	raised fore-deck, crab-ber
F-02	Atlantic	167.5	unknown	2-chine	raised fo'c'sle, menhaden
F-04	Pacific	70.87	unknown	2-chine	raised fore-deck, crab-ber
F-06	Pacific	110.0	unknown	round	raised fo'c'sle, tunaseiner
F-07	Pacific	124.25	unknown	round	raised fo'c'sle, tunabait boat
F-08	Pacific	175.0	unknown	round	shelter deck, tunaseiner
F-09	Pacific	84.2	unknown	2-chine	raised fo'c'sle, crabber
F-10	Pacific	96.0	unknown	1-chine	raised fo'c'sle, crabber
F-11	Pacific	53.0	unknown	1-chine	raised fore-deck, seiner
F-12	Atlantic	79.0	unknown	2-chine	raised fo'c'sle, stern trawler
F-15[a]	Pacific	42.5	unknown	1-chine	raised fore-deck, seiner
F-16	Gulf	62.5	unknown	1-chine	flush deck, shrimp boat
F-18	Atlantic	93.33	unknown	2-chine	raised fo'c'sle, stern trawler
F-19	Atlantic	145.0	unknown	round	raised fo'c'sle, side trawler
F-20	Atlantic	75.0	unknown	1-chine	raised fore-deck, side trawler
F-28	Atlantic	87.5	unknown	2-chine	raised fo'c'sle, longline
F-29	Pacific	84.0	unknown	1-chine	raised fo'c'sle, crabber
F-32	Pacific	54.0	unknown	1-chine	raised fore-deck crab-ber
F-34	Pacific	85.0	unknown	1-chine	raised fo'c'sle, crabber
F-35	Atlantic	87.5	unknown	round	raised fo'c'sle, side trawler
F-41	Gulf	72.83	unknown	1-chine	flush deck, shrimp boat
F-42[a]	Atlantic	73.0	unknown	2-chine	raised fore-deck, seiner
F-44	Atlantic	110.0	unknown	round	raised fo'c'sle, stern trawler
F-45	Atlantic	80.0	unknown	round	raised fo'c'sle, crabber
F-47	Atlantic	110.0	unknown	round	flush deck, stern trawler
F-49	Atlantic	114.5	unknown	round	raised fo'c'sle, side trawler
F-50	Atlantic	104.99	unknown	round	raised fo'c'sle, side trawler
F-51	Atlantic	138.5	unknown	round	raised fo'c'sle, stern trawler
F-53	Atlantic	121.77	unknown	round	raised fo'c'sle, stern trawler

[a] Casualty

sentative of this trend. Accordingly, vessel F-34 was tested as a towing vessel as well as a fishing vessel.

Model 4: Vessl T-14, a Pacific Coast harbor tug, was selected because it has a low L/B ratio and is similar in hull form parameters to many of the smaller towing and fishing vessels. This vessel was considered to be representative of the smallest vessels which would be used offshore.

In the construction of the models, it was decided to incorporate provision for geometric variations during some of the tests. These included the ability to increase the freeboard on the model of F-34 for certain runs in the seakeeping tests. The bulwarks on all of the models were removable so that the influence of bulwarks on water on deck could be determined in the seakeeping tests. A final geometric variation was the provision of an aft house on Model F-34. This allowed the influence of a large aft house in following sea runs to be determined. This arrangement, with a raised fo'c'sle and aft house, is typical of a large number of Atlantic Coast vessels.

Testing program

The hull shapes selected for model testing were tested in the towing tank at HYDRONAUTICS, Incorporated. Both the roll and pitch angles were measured by a vertical gyro located in a waterproof can mounted on a forward bulkhead. Yaw, or heading angle, measurements were attempted using an intergrating yaw rate sensor. This was found to be unreliable and testing was continued without it. The towline force was measured by means of a two-inch block gage which connected the model and the towline. This gage was attached at the forward end of the open deck area, and the towline extended from it through the tow point fitting (whose location could be varied longitudinally) to the carriage. Rudder angle was measured using a potentiometer on the rudder actuator. Relative motion between the vessel and the water surface was measured by a capacitance wave probe attached to the model at midships. The first probe was too delicate and was damaged

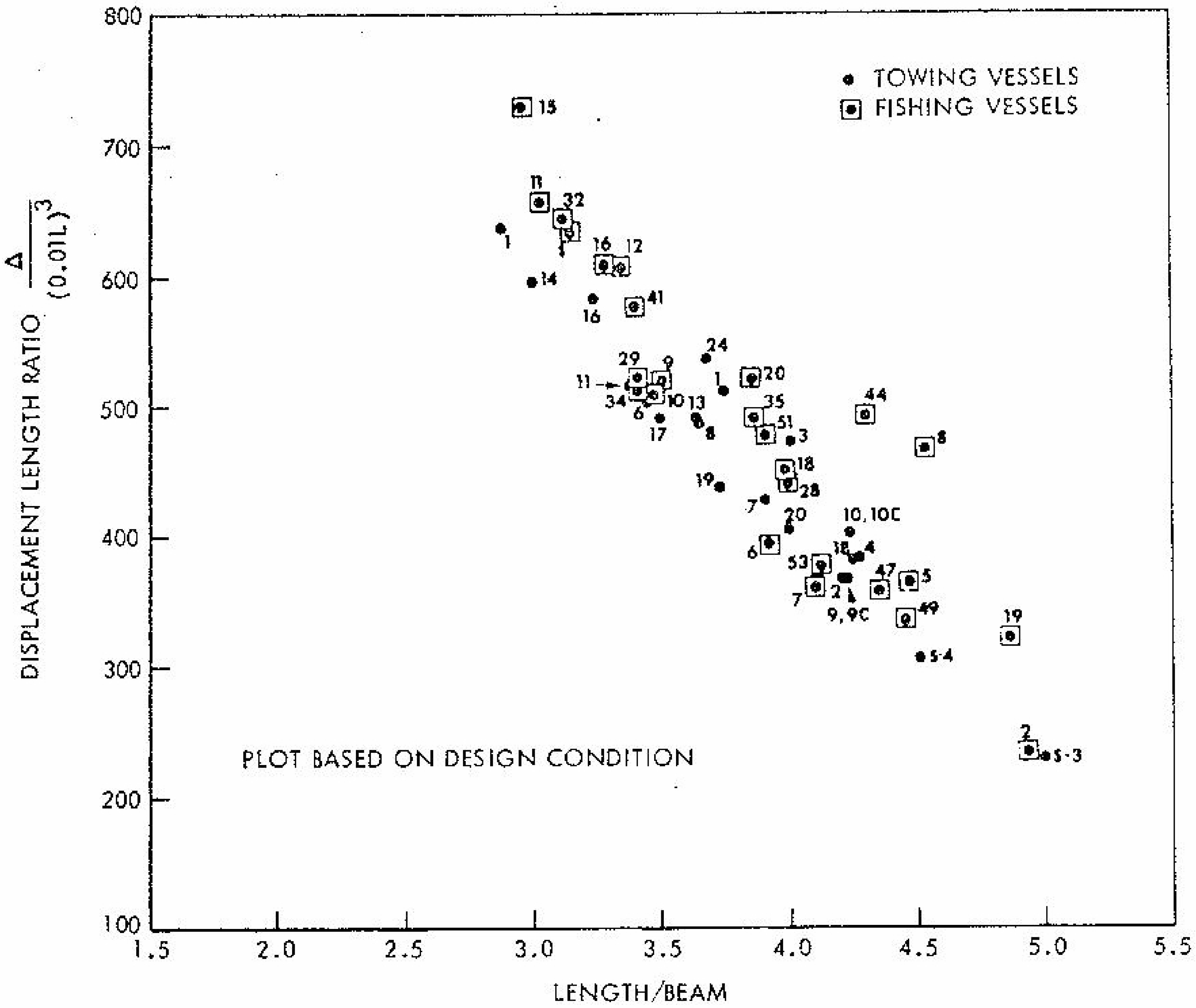

Fig. 4 Displacement length ratio versus length/beam ratio for towing and fishing vessels

because of its exposed location and the sometimes violent motion of the model. A guard and stronger probe solved the problem. The speed at which the towline was reeled in during some tests was determined by recording the pulses generated at each revolution of the towline-hauling winch's sheave. Since they were recorded as a function of time, the velocity of the line was easily determined. The towline angle relative to the vessel's centerline was measured using a potentiometer driven by a "finger" through which the towline passed. Angles up to 90 deg to each side could be measured. The speed of the model was determined by measuring the speed of the carriage. The carriage control circuit provide an analog voltage which was calibrated to speed in forward and reverse. Wave height, measured with a capacitance wave probe mounted on the carriage, was also recorded. Because of the models' surging during testing, it was not possible to determine the phase relationships between the motions and the waves. Three 35-mm still cameras were attached to the carriage and equipped so that they could be operated by foot pedal from the control station. They were connected to operate simultaneously at the rate of one frame per second. Each test run was recorded on video tape. A portable, tripod-mounted camera was used. The voice track of these tapes was used to list test conditions and the observations of the operator during the model run. A monitor in the carriage's control room allowed instant replaying of the previous test runs. This feature was very useful, because greater study could be made of the exact causes of a capsizing, the behavior of the model could be analyzed, and the test schedule changed if needed. Later, during analysis and report writing, this feature again proved its usefulness.

The signals from all the instrumentation were recorded on a 14-channel FM tape recorder. Eight channels could be displayed on a strip chart recorder.

Model test program procedures

There was a variety of test conditions covered in this research. Generally, all the tests performed were of one of two types: pure tripping in calm water or tests in waves. Tripping is defined as the capsizing of a vessel by the force of the towline on it. A vessel can be tripped by the forces developed by its own engines or by the movement of whatever it is towing. The first case is called self-tripping; the second is called tow-tripping. In the second category of tests, those done in waves, forces caused by waves which act on the vessel can cause it to capsize. Water on deck can also cause capsizing, even if the wave forces are not large enough to cause capsizing directly. The effects of both types of forces are, of course, combined when a vessel is towing in waves.

Before the start of testing the models were ballasted to the proper displacement and metacentric height (GM). The longitudinal radius of gyration was determined by swinging the model in air; the natural period in roll was found by oscillating the model in still water. The vessel's trim was checked and the electric bilge pump operated before each test run.

Table 2 Characteristics of selected models

PARAMETER	T-24	S-04	F-34	T-14
Overall length, ft	120.12	178.5	91.0	86.91
L/B	3.678	4.502	3.416	3.009
B/D	1.687	2.533	1.817	2.212
$\Delta/(0.01L)^a$	538.7	305.5	514.2	598.7
C_B	0.5069	0.6458	0.4377	0.4901
C_P	0.6182	0.7277	0.6492	0.5918
B/H	1.988	2.980	2.083	2.583
C_w	0.8299	0.8685	0.8157	0.7941
Propeller diameter/H	0.462	0.533	0.342	0.498
Number of propellers	2	2	1	2
Hull form	round	2-chine	2-chine	2-chine
Stern type	ship	transom	transom	transom
KG/D^a	0.752	0.857	0.813	0.699
Scale ratio	17.39	17.4	11.16	12.0

[a] Condition 1.

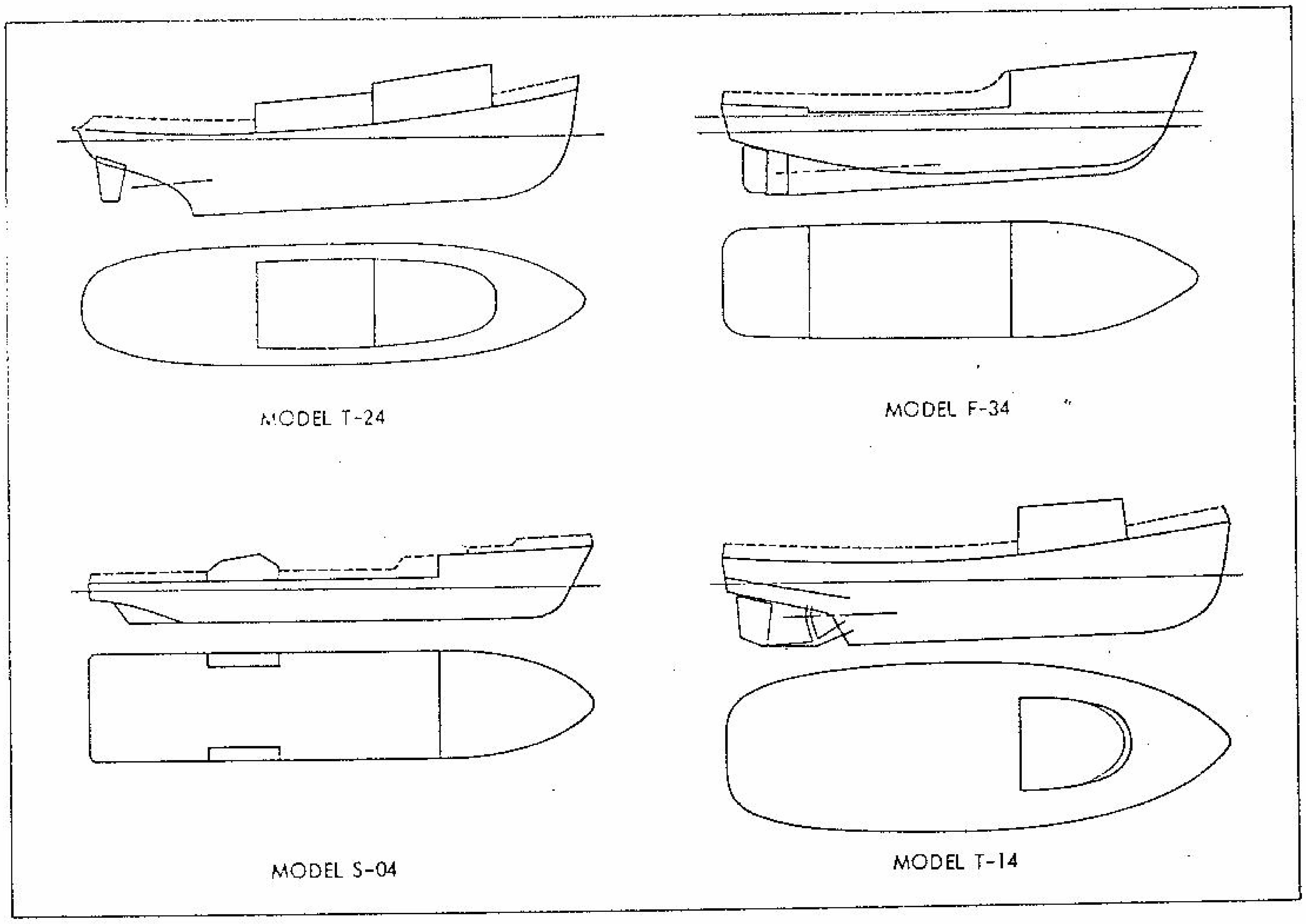

Fig. 5 Model profiles and deck plans

Self-tripping tests. In these tests, the model was connected to a towing line, power applied to the propeller, and various maneuvers executed by use of the rudder. In most cases, the tests were conducted at zero speed, that is, the carriage to which the towline was attached was stationary. All self-tripping tests were in calm water. In a typical test the model was maneuvered to the port side of the tank and held steady as it strained against the towline, the rudder was turned hard to starboard, and the vessel would head across the tank. As the towline's angle with the centerline of the vessel increased, the model would heel and sometimes capsize. Because the rudder could be controlled remotely, some runs investigated the effect of corrective rudder action to prevent capsizing. In general, the power level was varied until the point at which capsizing occurred was found. The towline attachment point was also varied longitudinally to evaluate its effect on capsizing. The models were ballasted to several *GM*'s during the program.

Tow-tripping tests. These tests were designed to simulate the case of a towing vessel being capsized by the movements of its tow. Two different conditions were tested. First, was the case of the towing vessel having no way on, and being dragged sideways by the tow. The model was positioned at right angles to the centerline of the tank, the towline was attached to the carriage, and the carriage was accelerated to a predetermined speed. The speed at which the model capsized was determined in this way. Various towing speeds and towing point locations were investigated, as well as different metacentric heights and displacements. As before, the effectiveness of various corrective rudder and power actions was checked.

Tow-tripping tests were also conducted with the model moving forward at different speeds. The intention in this series of tests was to duplicate the situation of a towed vessel sheering to one side, thus imposing an overturning moment on the towing vessel. An electric winch mounted on the carriage was used to haul in the towline and simulate the towed vessel's sheer; see Fig. 6. A typical test run might have gone as follows: model on course down the tank, moving slowly ahead as the carriage moves ahead. Once conditions were steady, the winch was activated and the effect on the model noted. Variables in this type of test were: towing point location, winch speed, model displacement, metacentric height, and power.

Tests in waves. An extensive series of tests was carried out in waves. There were runs in head, beam, and following regular waves. There were none in irregular waves. A variety of wave lengths and heights was used, with the intention of quickly finding the limits of survivability for each vessel condition. Waves with a height-to-length ratio of as high as 1/7 were used. The actual wave heights were as large as 24 in.

Tests in following waves. Models were tested in both the free-running and the towing condition. In the free-running case, the only connections between the model and carriage were the umbilical and slack safety lines which prevented collisions between the tank walls and the model if motions became very violent.

The runs were started with the model at the wavemaker end of the tank. For a free running test, the wavemaker was started and the model was held, by a safety line, straining toward the far end of the tank. After the first several waves had passed, the carriage was started and the model's motor rpm adjusted so that the model speed was the same as the carriage speed. The model was steered by remote control down the tank. The yawing and surging motions of the model were large in steep following waves. Tests were run with the waves directly astern and with quartering waves, produced by zigzagging the model down the tank. If capsizing occurred, the carriage was stopped and the model retrieved. If there was no capsizing, the carriage was stopped at the end of the tank; the model was stopped by safety lines. In some cases, the models capsized after only several waves had passed and before they had started down the tank. This was avoided by allowing the model to move slowly forward (about 0.5 fps) before the wavemaker was started. At the end of the run, the same tendency to capsize was noted for some models; the best solution was to minimize the number of wave encounters the model had to survive by turning off the wavemaker before the carriage reached the end of the tank.

Towing tests in following seas were run using similar procedures. The model towline was attached to a strut on the carriage with a section of shock cord inserted in the towline to give a realistic spring constant to the line. The model's propeller rpm was adjusted to give the proper bollard pull. Control problems were less in this case than for the free-running case because of the towline.

Speeds up to a speed-length ratio of 1.0 were used for the free-running tests; speeds up to a speed-length ratio of 0.5 were investigated in the simulated towing condition.

Beam sea tests. These test runs were conducted with the model at zero forward speed lying in the carriage's test bay. The model was positioned by fore and aft control lines which were kept as slack as possible. As the model drifted with the waves, the carriage was moved under manual control to keep it positioned in the bay. The runs were continued until the model capsized or until it was clear that it would not capsize. Wave height, wave length, freeing port area, model displacement, and model metacentric height were varied during this series of tests.

Head and bow sea tests. Both towing and free-running tests were conducted in head and bow seas. The models were started from the opposite end of the tank from the wavemaker, and accelerated to the test speed as the waves reached them. Motions were very severe and control was difficult. Straight and zigzag courses were used. Propeller rpm, forward speed, wave dimensions, and vessel loading conditions were varied.

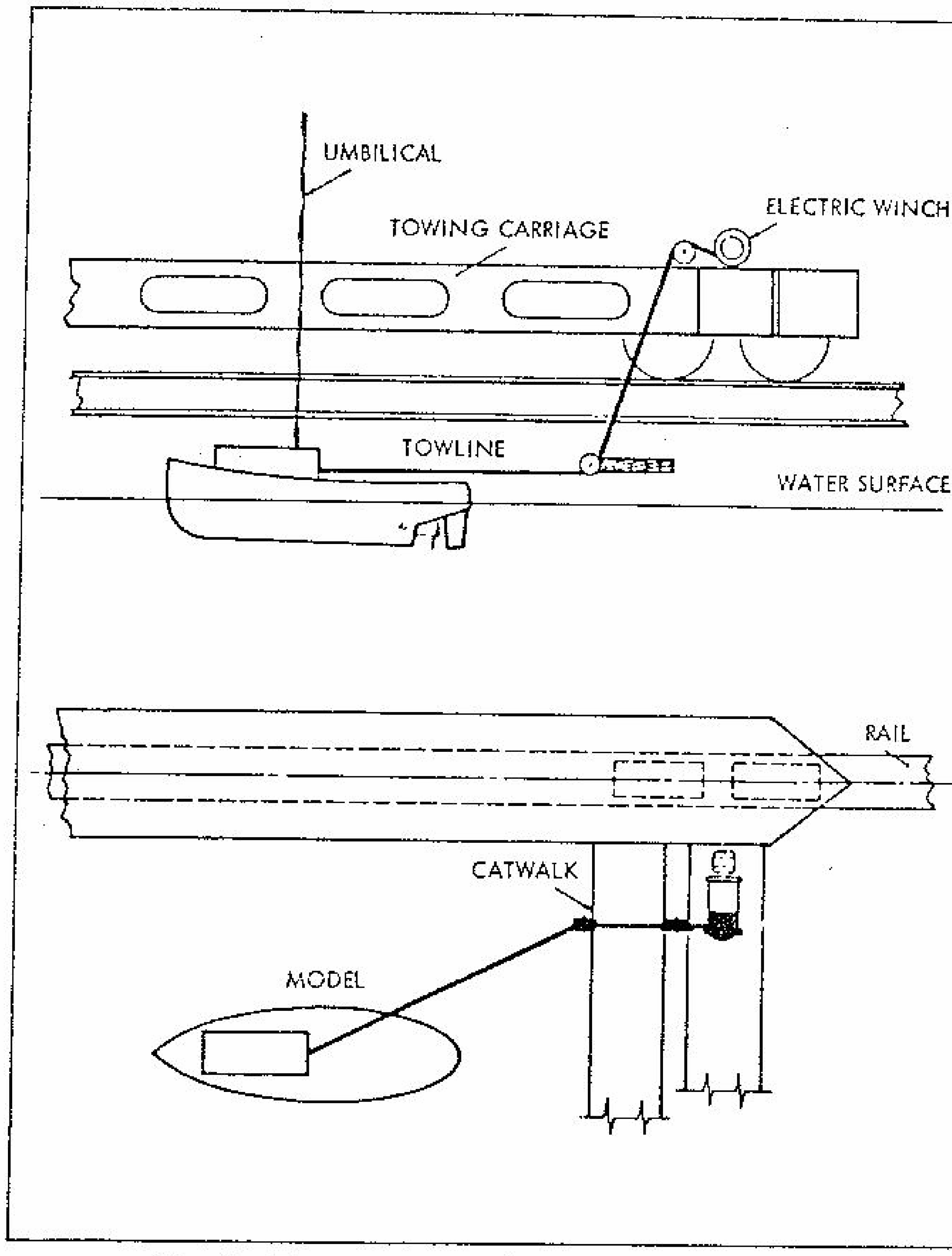

Fig. 6 Tripping test schematic arrangement

Experimental results

The results of the model tests are generally of several types: observations made during the testing, time histories of forces and motions recorded during the tests and reproduced as strip chart recordings, and tabulated or plotted data. Each major division on the horizontal axis of the strip chart tracings is equal to two seconds. A key to the loading condition of each model is given in Table 3.

Results of self-tripping tests. Table 4 lists the results of these tests. The test conditions used to obtain these results were: rapid application of rudder angle from zero to 45 deg in a typical case, and no subsequent corrective action. When a capsizing occurred, bollard thrusts and horsepowers were listed which existed at the time of capsizing. These figures, of course, have been converted to full-scale values. It was assumed that open propellers produced 25 lb of bollard thrust per horsepower and nozzle propellers produced 30 lb/hp. When a capsizing did not occur, the bollard thrust and horsepower listed are the maximum values reached.

In Table 4 the models in the conditions marked by asterisks exactly satisfy the Murphy criterion once used by the Coast Guard to safeguard against self-tripping capsizing. One of the variables in this criterion is the shaft horsepower of the vessel. The shaft horsepower figures used to determine the metacentric height of the models to exactly meet the criterion for T-24, F-34, and T-14 were 5635, 1200, and 1960, respectively. A vessel the size of S-04 would normally have about 5000 horsepower. As Table 4 shows, more power is required to cause capsizing then would normally be installed. For F-34, however, the margin is small.

It was observed in all cases that corrective actions, such as reducing power or returning the rudder to midships, would prevent capsizing. This was true even if the corrective action was taken when the model was on the verge of capsizing.

Results of tow-tripping tests. These were conducted at zero

Table 3 Test conditions

Model	Condition code	Draft, ft	Trim, ft	*GM*, ft
T-24	1-A	16.29	1.86	3.50
	1-B	16.29	1.86	2.17
	1-C	16.29	1.86	5.70
	2-A	13.36	0.0	2.17
S-04	1-A	12.61	0.19	6.00
	1-B	12.11	1.19	7.80
	1-C	12.11	1.19	6.00
	3-A	9.35	2.25	10.75
F-34	2-A	10.81	1.35	2.11
	2-B	10.81	1.35	2.65
	3-A	14.09	1.60	2.96
	3-B	14.09	1.60	1.97
	3-B-AH	same as above with aft house added		
	3-B-2FB	same as above with additional freeboard		
T-14	1-B	9.76	0.0	2.65
	1-C	9.76	0.0	4.00

Table 4 Results of self-tripping tests (full scale)

Model	Load condition	Displacement, tons	*GM*, ft	Capsize	Bollard thrust, tons	Approximate SHP
T-24	1-A[a]	889.9	3.30	yes	99	7425
	1-C	889.9	5.70	no	112	8400
	2-B	630	2.17	no	120	9000
S-04	1-A	1507	6.00	no	78	5850
F-34	3-A[a]	367	2.96	yes	17.9	1342
	3-B	367	1.97	yes	10.7	800
T-14	1-B[a]	308	2.65	no	33	2475

[a] These conditions exactly satisfy Murphy's criterion.

Table 5 Results of tow-tripping tests (full scale)

Model	Load condition	Displacement, tons	GM, ft	Capsize	Sideways towing speed at capsize, knots
T-24	1-A	889.9	3.30	yes	6.2
	1-C	889.9	5.7	yes	7.4
	2-B	630	2.17	yes	7.4
S-04	1-A[a]	1507	6.00	yes	4.9
F-34	3-A[a]	367	2.96	yes	3.9
	3-B	367	1.97	yes	2.9
T-14	1-B[a]	308	2.65	yes	4.75

[a] These conditions exactly satisfy Murphy's criterion.

speed and with the model underway. Table 5 lists the results. Sideways towing speeds were increased until the model capsized at the speed shown in the right-hand column. The data apply to the case of the towing point being located as designed. As might be expected, capsizing was less likely with the towing point located farther aft. In several tests, power and rudder action were used in an attempt to swing the stern under the towline and avert a capsizing. This action did not prevent the capsizing; in fact, it appeared to cause capsizing more quickly. This suggests that actions like these by the crew would be of no avail if capsizing is imminent.

The mechanism of a zero-speed tripping accident appears to be as follows: a steady buildup of water on deck caused by flow through the freeing ports and quick capsizing as soon as the water reaches the top of the bulwark. The initial buildup may happen slowly, making the actual capsizing a surprise.

The criterion proposed by Getz and Bakke [10] is based on the assumption that a towing vessel should be able to withstand a sideways towing speed of between 4 and 5 knots. As Table 5 shows, F-34 and T-14, ballasted to meet the Murphy criterion, cannot be towed over 4 and 5 knots, respectively, without capsizing.

Results of tests in waves. Figures 7 through 11 show sample results from model tests in waves. Some of these figures are strip chart records, others are plots on which boundaries have been drawn between apparently safe and apparently dangerous regions of wave conditions. In the latter type of figure, the dashed straight line represents the locus of waves with a length-to-height ratio of 8:1. A wave with this length-to-height ratio is about the steepest wave that is physically possible in deep water. The data points are represented by symbols whose shape corresponds to an observed amount of roll motion. The assignment of these symbols is, of course, a subjective process. In general, moderate rolling is defined as rolling which causes occasional immersion of the deck edge with some water on deck. Heavy rolling is defined as rolling which causes the deck to be continuously under water with large amounts of water on deck. Extreme rolling is rolling which puts the model in danger of capsizing, causes the deck edge to be well under water, and generally shows loss of stability. The capsizing conditions were chosen as the limiting conditions resulting in capsizing or near capsizing during the tests.

Free-running tests in following seas. The time history of a typical free-running following-sea test is shown in Fig. 7. In this example, Model T-24 in load condition 1-B is running in waves 11 ft long and 15 in. high. The model is being held stationary by the towline until several waves have passed under it. Since the towline is being used as a restraint, Channel 4 records a towline force. Channel 7 shows the carriage being accelerated to the test speed of 4.5 fps; the model also accelerates, and the towline force falls to zero. Channel 2 shows that the model begins immediately to roll at one-half the wave encounter frequency. The amplitude of the roll motion builds up rapidly and the model takes a bow-up trim as it capsizes.

In all the free-running tests in following seas, capsizings and extreme rolling were due to either a complete loss of stability with the model poised on the wave crest or to rolling at a period equal to twice the wave encounter period. Both of these phenomena are discussed in detail in [11]. In order for these types of rolling motion to occur, that is, for the necessary ratio of vessel roll period to wave encounter period to occur, a long encounter period and a long effective roll period were necessary. In no case did a model capsize in stern waves while running free at a low speed-length ratio. It was necessary to have waves which were long enough ($\lambda/L_{WL} = 1.5$) and a high enough model speed ($V/\sqrt{L_{WL}} \sim 1.0$) for the model to surf for some time with the wave crest amidships. For this reason, running in waves coming from directly astern was more dangerous than running in quartering waves. Another requirement for capsizing to occur was the presence of water on deck. This is the same as saying that the stability of the model had to be reduced and the roll period had to be longer than in calm water. It is interesting and informative to compare the behavior of Model S-04 (load condition 1-C) with that of Model T-14 (load condition 1-B). For the models in these conditions, their nondimensionalized curves of static stability (GZ/B versus heel angle) are very similar; their range of positive stability is about 45 deg. In spite of this similarity, Model S-04 capsized easily, but model T-14 did not for any of the wave conditions. The difference was due to the large amount of water which S-04 shipped. Several runs were made with the freeing port area doubled on Model S-04, but no significant difference in behavior was noted.

No models capsized by broaching. Several models showed broaching tendencies, but the results of these tendencies were unplanned collisions with the tank wall, not capsizing. In general, the models remained controllable even at high speeds in near breaking waves.

Towing tests in following seas. Model tests under these conditions were conducted in following waves at a speed-length ratio of 0.5. The propeller rpm was set to produce the scaled estimated bollard thrust of the prototype. In the case of Model F-34, a bollard thrust typical of a towing vessel of the same size was selected. The metacentric heights were the same as those used in the free-running tests. The test results for Models S-04 and F-34 are presented in Figs. 8 and 9. Model test results are not shown for T-14 because this model did not capsize when towing in following seas, at least for the two metacentric heights tested. Only limited following-seas towing tests were conducted with Model T-24 in load condition 1-A. In this case, with a λ/L_{WL} ratio of 2.1:1 and a wave height-to-length ratio of 0.225:1, the model did not capsize.

A typical following-sea towing test time history is presented in Fig. 10. The model, S-04, rolls to a certain angle, rolls to either side of this somewhat steady heel angle, and does not respond to its rudder. The roll motion becomes larger and the model suddenly capsizes. The large towline forces recorded on Channel 4 are a result of the waves washing over the model.

The sequence of events preceding capsizings when towing in following seas is very different from that in the high-speed free-running condition. In the towing case, with a relatively low model speed, water tended to collect on deck from overtaking waves which washed over the stern and sides. This water on deck caused a semisteady heel angle which either remained unchanged or increased, causing capsizing. The towline was an important contributing factor, since it would cause an initial heeling moment when led over the quarter. The towline also affected the likelihood of capsizing because its presence increased the amount of water on deck. It did this

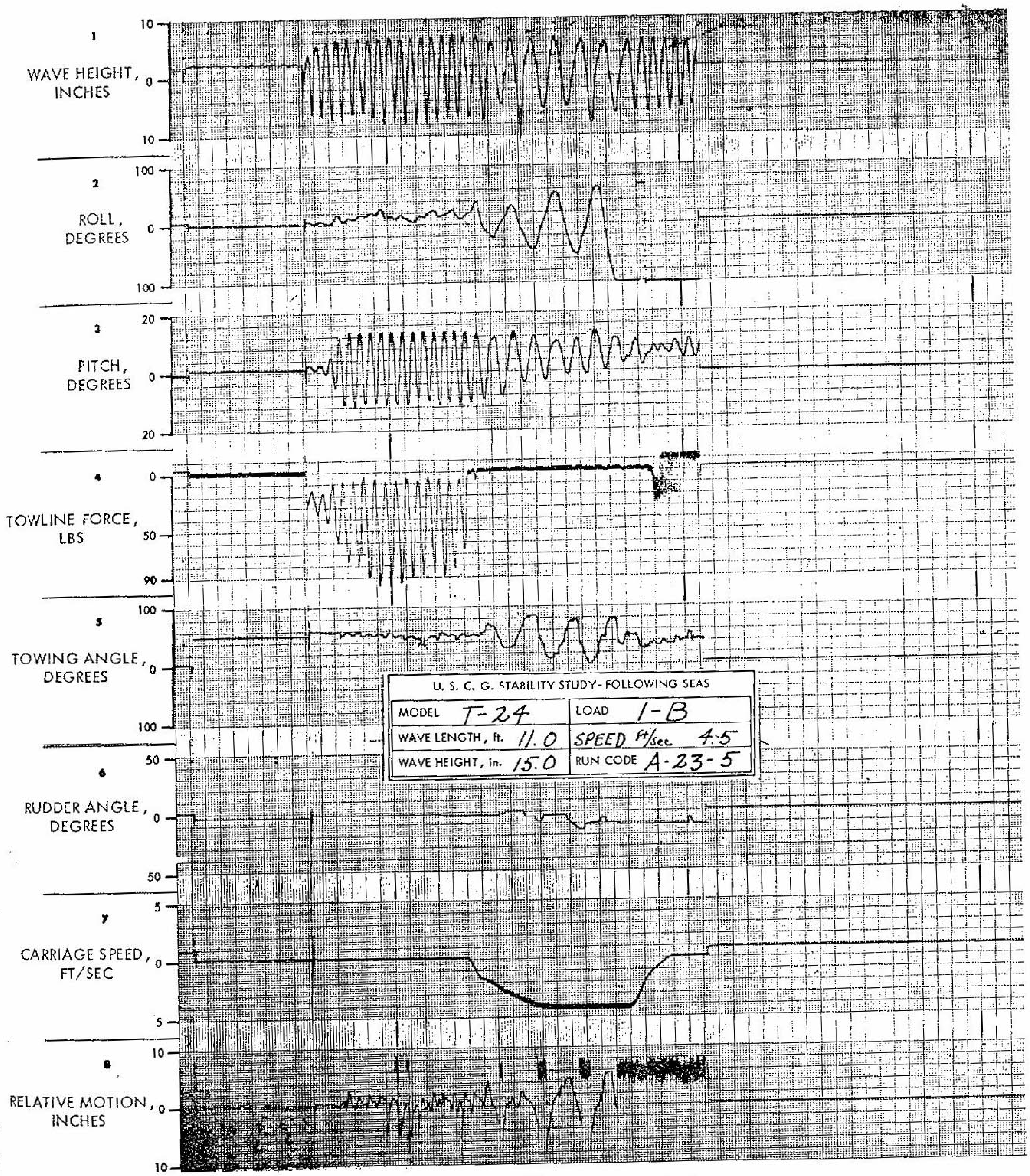

Fig. 7 Time history of typical free-running following-sea test

by reducing the model's surging and perhaps its pitching. It was noted that capsizing in the towing condition occurred in lower, shorter waves than capsizing in the free-running, higher-speed case. This occurred because water is more likely to collect on deck when the relative motions are large and the encounter period is short. Maneuverability when towing in stern seas was often very poor. It some cases a model would not respond to its rudder at all. In these cases, extreme rudder commands could contribute to capsizing.

Beam sea tests at zero speed. Under these conditions, capsizings sometimes occurred. Models T-24 (load 1-B) and F-34 (load 3-B) capsized. Water piled up on deck as short, steep waves broke on deck. The model slowly heeled into the waves with little rolling. Eight to twelve wave encounters were necessary for capsizing. Model T-24 would capsize only if it was held beam to the waves with safety lines, since it had a strong tendency to turn its bow into the waves. Model S-04 in load condition 1-C would assume a large, steady, heel angle into the waves in some beam sea conditions, but would not capsize. Various freeing port areas were tried on Models F-34 and S-04. When the area was increased to twice the IMCO required value, it was easier for water to get on deck. The result seemed

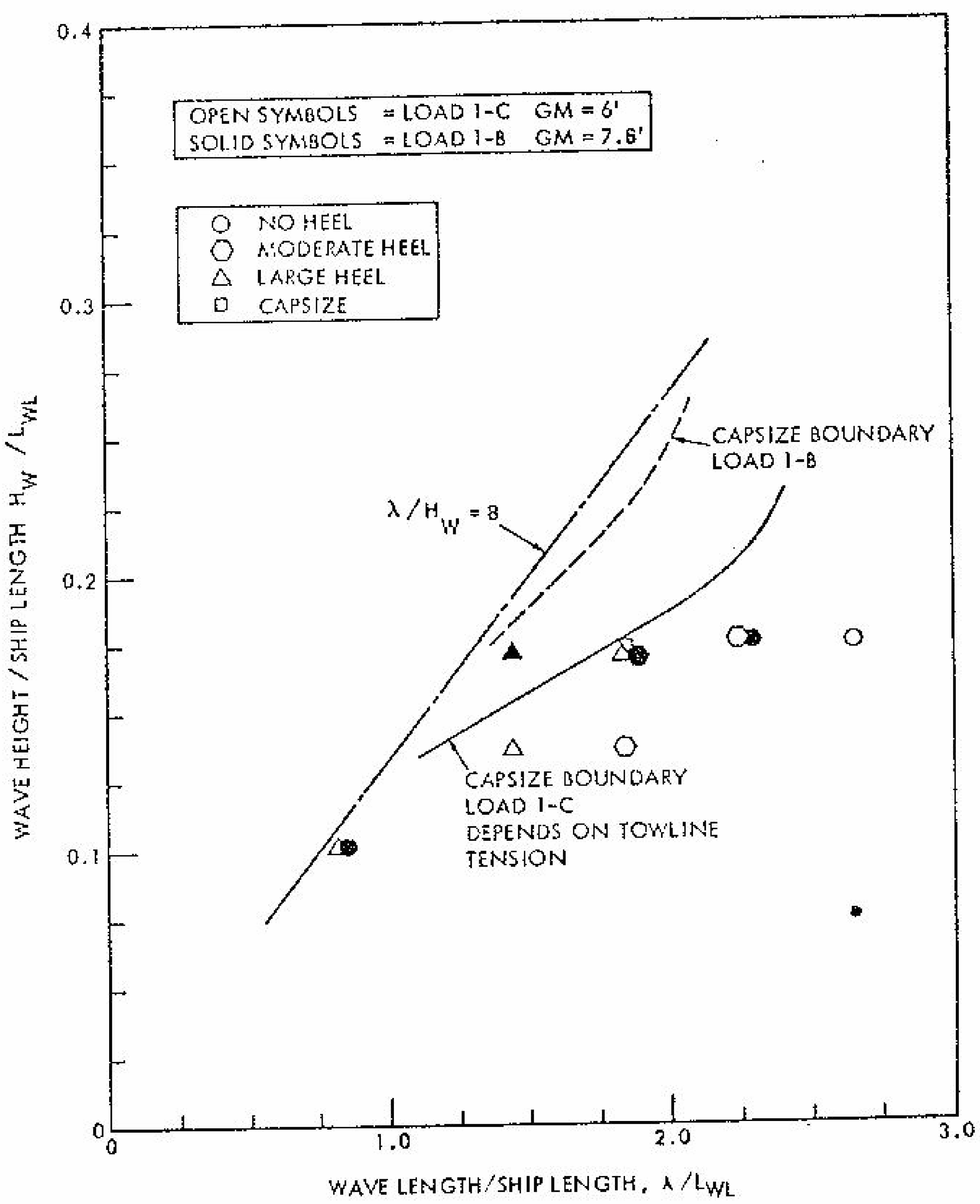

Fig. 8 Capsize boundary for S-04 towing in following seas

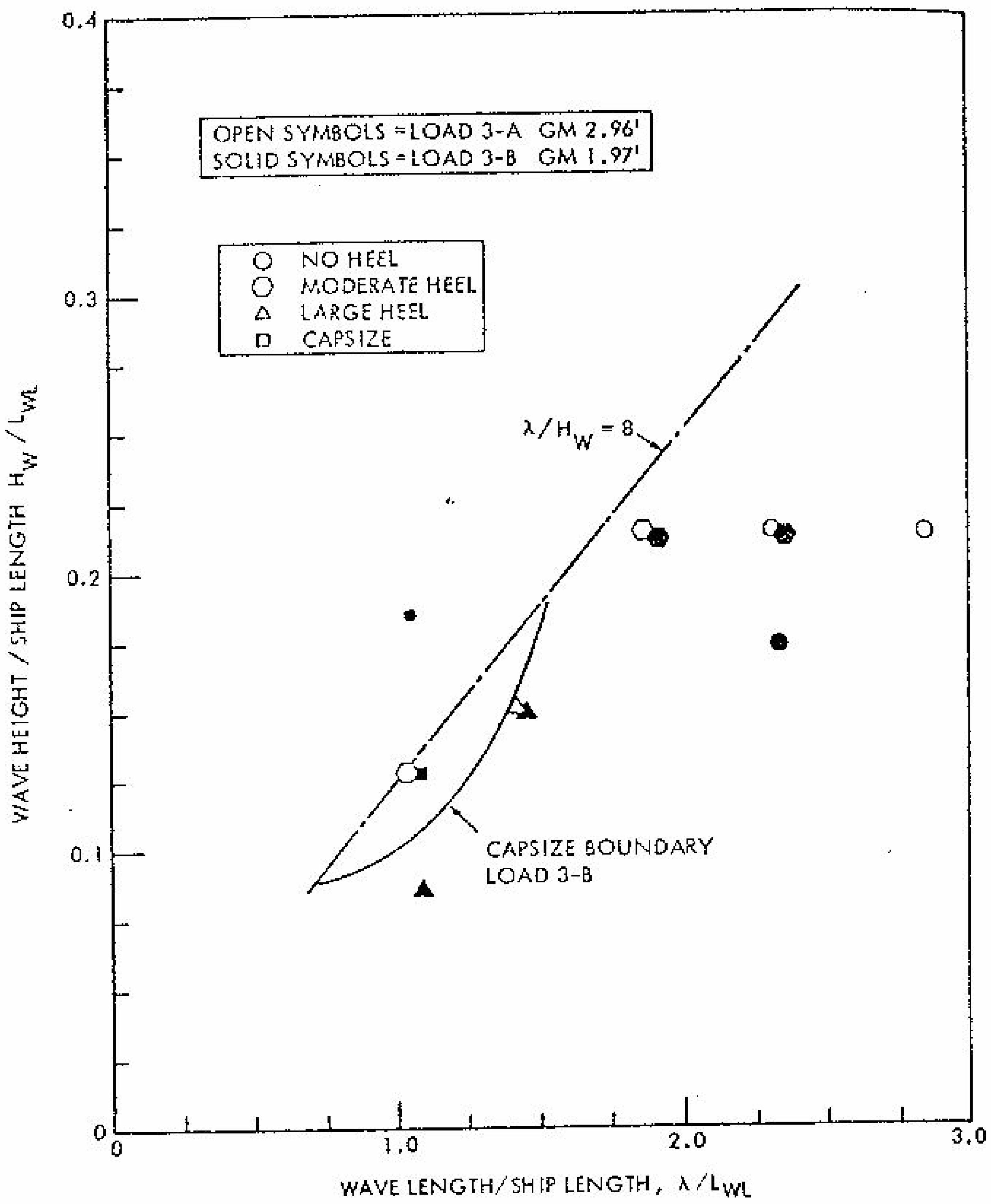

Fig. 9 Capsize boundary for F-34 towing in following waves

to be a larger steady heel angle or quicker capsizing.

Tests in head and bow waves. Tests on Models T-14, T-24, and S-04 were conducted. Model T-14 was tested the most extensively, and in both free-running and towing conditions. Figure 11 presents the results for Model T-14. Although it would not capsize in following or beam seas, capsizing in head seas was possible. Typically, there was a rapid buildup of water on deck from the waves breaking directly over the bow or over the port and starboard bows in rapid succession. This resulted in a rapidly increasing heel angle which could end in a capsizing. In cases where a capsizing ultimately occurred, as many as 30 to 50 waves were encountered, although the final large increase in heel which led to the capsizing would occur during about three encounters. In general, the towline would assist the capsizing by providing an initial heeling moment. On the other hand, for the shortest waves the towline tended to right the model. In many respects, the capsizing "mechanism" in head waves is similar to the capsizing mechanism during towing in following waves and in beam waves. A limited number of head wave tests were conducted with Models T-24 (load 1-A) and S-04 (load 1-C); no tendency toward capsizing was noted.

Criteria development

In undertaking the development of improved intact stability criteria for small vessels, the following steps were followed:

- The basic concepts for the types of criteria to be developed were defined.
- Guidelines and general assumptions for use in the criteria were established.
- The specific capsize hazards to be protected against were determined.
- Formulations for the criteria were established based on model test results and other analysis.

The results of the first three steps are briefly reviewed and followed by a description of the formulation of a set of intact stability criteria.

Types of criteria

There are two basic types of stability criteria which could be proposed. They are the general-type criterion and the specific-type criterion. The general criterion is an all-inclusive one which is based on data from the casualty history of a group of vessels. A measure of stability is chosen, such as the area under the righting arm curve, and the criterion is set by selecting a level of stability which exceeds that of the casualties. A specific criterion is one in which the measure and level of stability are defined to prevent a certain type of capsizing hazard under given environmental conditions. The relationship between the stability and the occurrence of a capsizing is determined by analysis of the phenomenon using full-scale, model, or theoretical information. Specific criteria must be presented as a complete set which includes all types of hazards that a particular vessel may be expected to encounter.

In the past, most stability criteria have been of the general type. However, it was decided to develop a set of specific criteria primarily because the types of hazards faced, the specific design features which influence the degree of hazard, and the applicable environmental conditions are defined.

Guidelines and assumptions

The guidelines and general assumption used in the development of specific criteria were as follows:

1. The criteria are only to apply to towing, fishing, and supply vessels which are of a size and form covered by the analysis or experiments that form the basis of the criteria.
2. Stability criteria which apply to operations at sea should result in a stability level which provides a vanishingly small probability of capsize for a properly handled vessel in a defined extreme sea condition (see Item 4).
3. Proper handling of the vessel includes compliance with

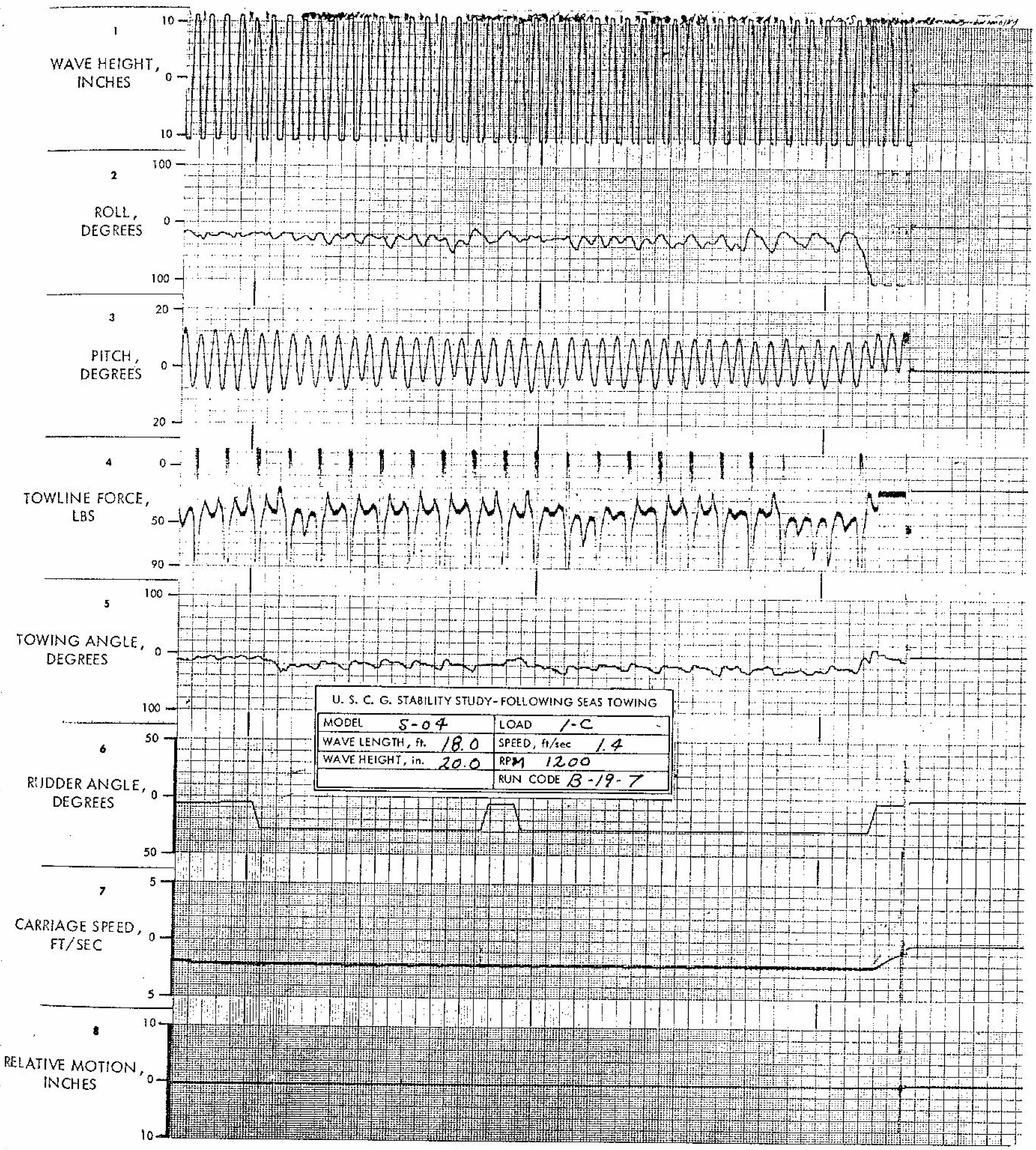

Fig. 10 Time history of typical following-sea towing test

conditions assumed in the stability calculations (that is, openings closed, tanks pressed up) and the avoidance of local areas where unusual conditions exist, such as over shoals or in surf.

4. Vanishingly small probability of capsizing implies that only hazard situations which logically exist together, such as high winds with large waves, need to be considered. A margin should be added, however, to the stability level predicted for capsizing in extreme conditions to account for uncertainties in the analysis.

5. Deterministic extreme sea conditions can be defined on the basis that, for wave lengths which are critical, the wave steepness is limited by wave breaking.

6. The use of extreme conditions and margins in the criteria supplies a reasonable allowance for crew error or equipment failure in less than the most extreme conditions.

7. Stability criteria which apply to normal operations, such as towing vessel tripping criteria, should prevent capsizing of a vessel which is not properly handled by its crew or which is subject to errors by others, up to arbitrarily defined limits.

8. The resulting criteria should not be so stringent that large segments of the fleet could not satisfy them and still operate economically.

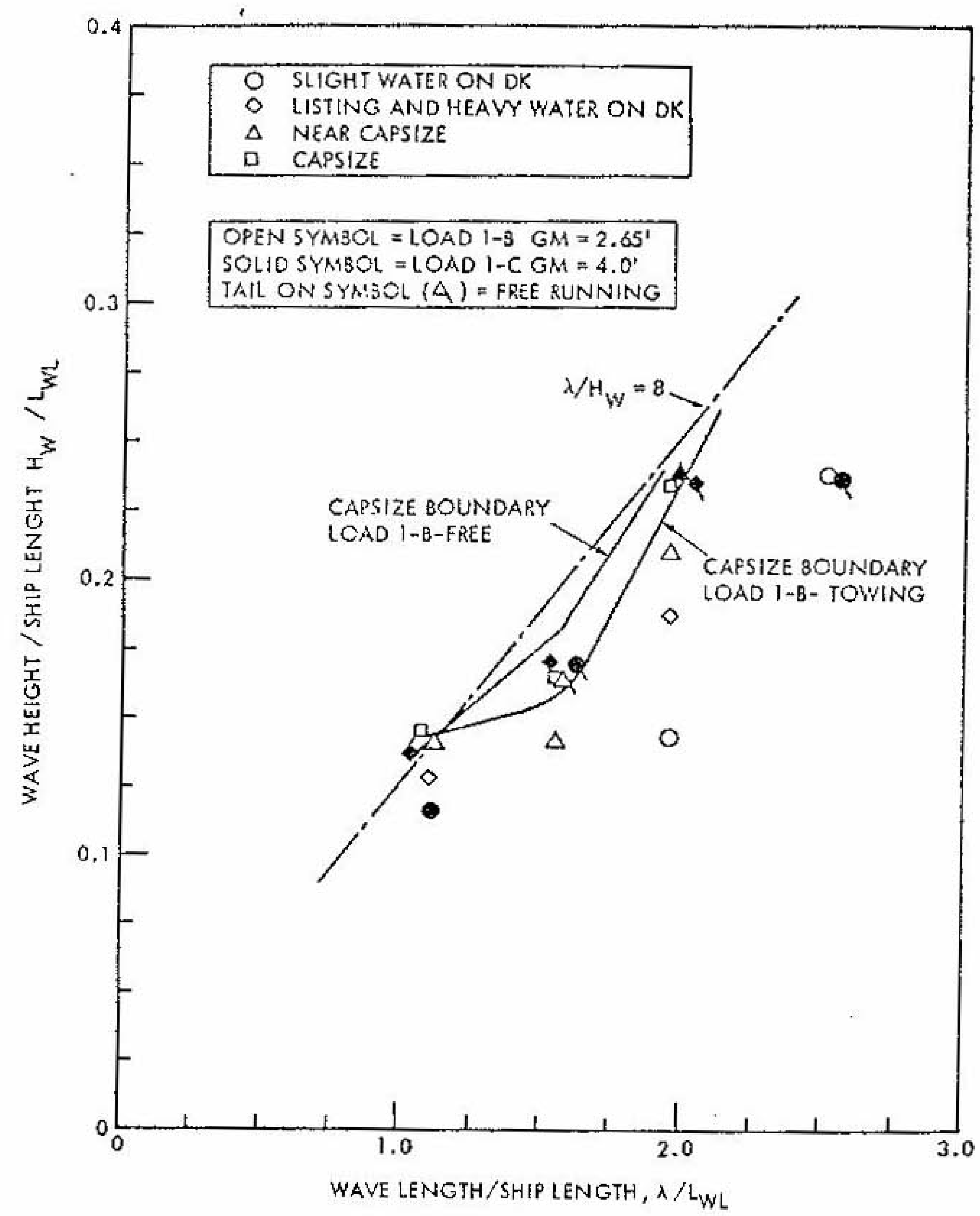

Fig. 11 Capsize boundary for T-14 at $V/\sqrt{L_{BP}} = 0.25$ in head seas

Hazard situations

A basic requirement in the development of a set of specific intact stability criteria is to define the various situations in which a vessel could be capsized so that criteria can be developed to protect against these situations. A danger in the use of specific criteria is that the set will not be complete so that a vessel may not have sufficient stability to survive in a situation which was not anticipated. However, it is believed possible to define a set of capsizing situations which are complete for towing, fishing, and supply vessels. The basis for this set of situations is the model experiments and the literature survey described in the foregoing.

Tripping of towing vessels in calm water. In this type of casualty, forces applied by the towline heel the vessel, causing it to flood through openings or to capsize. The forces on the towline can be generated by the actions of the tow or of the towing vessel. The former can be described as tow-tripping and the latter as self-tripping. Both are operational hazards which occur in ship handling situations if an error is made. The calm-water case is most dangerous since doors tend to be open. In the tow-tripping casualty the towline is led over the beam of the tug with the tow on the other end pulling the towing vessel laterally. The tow could be a ship or barge which is moving, other tug or a relative velocity at the tug caused by strong currents or propeller wash. The towing vessel may aggravate the situation by trying to maneuver under the towline by use of rudder action and power. The tow-tripping casualty is the most common type of intact stability casualty in the U. S. towing vessel fleet.

The self-tripping casualty is caused by the action of the rudder and propeller generating towline forces with the towline leading over the side. The forces applied in this way are largest at zero speed since the bollard thrust is larger than the available thrust underway. The causes of this type of casualty are directly under the control of the towing vessel crew and, as a result, it is much less common than the tow-tripping casualty. The greatest danger seems to be to vessels which are re-engined with much higher power than the crew is used to.

Water on deck in low-speed head or following sea operation. This hazard occurs when a vessel is operating in steep head or following seas at low speeds. The frequency of encounter and relative motions with the waves are high and the waves continually wash over the deck. The buildup of water on deck results in heeling moments which can cause capsize. The phenomenon is quasi-static in that a buildup in heel angle takes place over several wave encounters and the rolling motion is small compared with the mean heel angle. The situation can be aggravated by heeling moments caused by a towline and possibly by wind. This hazard is sensitive to freeboard and bulwark height, which will influence the amount and retention of water on deck.

Loss of stability in high-speed operations in following seas. This hazard occurs in operations in steep following waves when the vessel is operating at speed-length ratios above 0.7. The vessel spends significant time poised on a wave with the crest about amidships. This results in a loss of stability. In an extreme case the vessel may capsize directly from loss of stability. The cyclical reductions in stability can also result in resonant rolling at one-half the wave encounter frequency, which builds to capsizing in three to five cycles. The vessel rolls alternately to port and starboard in successive wave crests. A capsizing in this manner occurs when a group of steep waves of about the same frequency is encountered.

This capsizing phenomenon has been studied in detail for large cargo vessels and the results are reported in reference [11]. The model tests were conducted to study the behavior of towing and fishing vessels in these conditions. The capsizings which resulted are as described in the foregoing. The major difference in response between large cargo vessels and the smaller towing and fishing vessel was that water on deck contributed to the capsizing of the smaller vessels by increasing their roll period.

Rolling with wind heel and water on deck in beam sea operations. This hazard occurs in beam seas with the vessel subjected to wind gusts and is the condition which is implied in the classic wind heel criteria. If the freeboard is low, as is typical of many towing and fishing vessels, water will tend to build up on deck. A major difference between larger ships and towing and fishing vessels is that the buildup of water on deck should be considered. The water on deck can result in a quasi-static heel angle which may be to windward or to leeward depending on vessel characteristics, sea conditions, and external heeling moments. In the model tests it was determined that the quasi-static heel angle could be large and would in some cases result in capsizing. Other experimental programs such as those reported in [12] and [13] have shown similar results.

Proposed stability criteria

Stability criteria to meet the capsizing hazard situations described are presented in this section. In all cases, unusual loading conditions such as topside ice should be included in the stability studies. Also, intact stability under special operating conditions, such as lifting heavy weights over the side, should be checked if appropriate. In all cases, criteria are based on *GZ* curves calculated assuming a constant trim moment rather than constant trim with heel.

Tripping of towing vessel in calm water

The intact stability criterion for towing vessels is intended to provide reasonable protection from the operational hazards in normal towing and ship handling operations. The criterion has two parts. The first is directed at the hazard caused by action of the tow or assisted vessel relative to the tug. The second is directed at hazards caused by the improper application of power and rudder angle by the tug. This criterion is intended to apply to conventional towing and towing/supply vessel types with single- or twin-screw propulsion, with or without nozzles. It does not apply to towing vessels with paddle wheels or vertical-axis propellers. Special consideration should be given to vessels which are equipped with systems to limit line tension or position of force application if it can be shown that these systems are effective under all conditions.

Tow-tripping. The basic concept for the criterion to prevent tow-tripping is to require that the heeling moment generated as the vessel is pulled sideways be less than that necessary to submerge any openings or to capsize the vessel. A study of the videotapes and time histories of the tow-tripping tests indicated that the most serious conditions occur when the towline is initially over the beam at an angle of 90 deg to the centerline. This condition can occur when the vessel is at zero speed or when the vessel is underway with low initial tension in the line. If the vessel is underway, large steady tension in a towline over the side cannot be generated by actions of the towing vessel alone. As a result, combinations of tow and self-tripping with the vessel underway are not as serious as a simple tow-tripping case because the towline forces act in such a way as to reduce the angle of the towline with the centerline of the vessel.

The tow-tripping criterion is of the "moment balance type" (that is, it requires the righting moment to be equal to the heeling moment at some angle) rather than an "energy" type (that is, requiring the net area under the righting arm curve to exceed the net area under the heeling arm curve at some angle). In a very idealized case, the energy-type criterion could give an indication of the maximum instantaneous heel angle in response to an impulse-type loading. Although the most serious case will occur when the towline is initially slack, the load cannot come on the line as a pure impulse because of the spring-like behavior of any real line. Also, the idealized assumptions of the energy-type criteria neglect real effects due to hydrodynamic damping and coupling of the modes of motion. An analysis of model test data for slowly applied loads and impluse-type loads indicated that it was satisfactory to use a static moment balance-type criterion.

In order to develop a criterion, it is necessary to determine a formulation for the heeling moment and to define the lateral towing speed which will be used. The model test data were used to develop a formulation for the tow-tripping heeling moment. The time history records from the model tests were reviewed to obtain the steady-state values of towline tension, heel angle, sideways towing speed, and towline angle relative to the centerline for the various models tested. The righting moments were obtained from the GZ curves for each model. These data were used to calculate the effective drag coefficient and heeling arm in accordance with the following equations:

$$C_D = T/\frac{\rho}{2} A_P V_T^2 \qquad (1)$$

where

C_D = effective drag coefficient
T = measured towline tension
ρ = mass density of water
A_P = underwater profile area
V_T = lateral towing speed

$$\text{Heeling arm} = (h_{\text{Bitt}} \cos(\varphi) + C_3 H) = M_R/T \qquad (2)$$

where

h_{Bitt} = height of towing point above waterline
H = draft, ft
M_R = righting moment, ft-lb
T = towline tension
C_3 = location of center of lateral force as a fraction of draft below waterline
φ = heel angle, deg

It is realized that these are very simple equations with which to represent the complex phenomena which occur when a towing vessel is in a tripping situation. It is felt, however, that the basic factors in the determination of forces and moments are represented and the formulation is simple enough for use in a generally applied criterion.

It was expected that the effective drag coefficient would be a function of the longitudinal location of the towing bitt since this influenced the orientation of the model as it was towed sideways. The effective drag coefficient was also expected to be a function of the heel angle since the drag will increase as the deck edge is submerged. The effective drag coefficients

Nomenclature

A = linear damping coefficient
A_{DK} = deck area, sq ft
A_P = projected underwater area, sq ft
A_{Pa} = projected above-water area, sq ft
B = beam of vessel, ft; or quadratic damping coefficient
C = factor related to deck wetness
C_y = wind sideforce coefficient
C_D = effective drag coefficient = $C_1 \times C_2$
C_1 = drag coefficient for small heel angles (Fig. 10)
C_2 = correction to drag coefficient for other than nominal heel angle (Fig. 11)
C_3 = coefficient for center of lateral force as a fraction of draft below waterline (Fig. 12)
C_4 = 0.70 = effective fraction of bollard thrust to be expected from towline over beam
C_5 = correction factor for longitudinal location of towing bitt
C_6 = 0.52 = effective center of lateral resistance as a fraction of draft below waterline
D = depth of vessel, ft
E_{40} = area under righting arm curve up to 40 deg, ft-deg
FB_{avg} = average freeboard, ft
h_{Bitt} = distance from waterline to towing bitt, ft
h_{dist} = distance between center of wind pressure and center of underwater area, ft
H = draft, ft
H_w = wave height, ft
I = total roll moment of inertia
K = heeling moment, ft-lb or ft-tons
K_{wind} = wind heeling moment, ft-lb
L = vessel length overall, ft
L_{WL} = vessel length on waterline, ft
L_{BP} = vessel length between perpendiculars, ft
M_c = moment due to water, on deck, ft-lbs
M_R = righting moment, ft-lb
M_W = moment due to wind, ft-lb
T = towline tension, lb
T_B = bollard thrust, tons
U = towing speed, fps
V = vessel speed, knots
V_0 = freestream wind velocity, fps
V_T = lateral towing speed, fps
V_{wind} = designated wind speed, knots, = 70
Y_{wind} = lateral wind force, lb
ζ_x = wave slope
λ = wave length, ft
ρ = mass density of water, lb-sec^2/ft^4
ρ_a = mass density of air, lb-sec^2/ft^4
φ = roll angle, deg
φ_M = mean heel angle, deg
φ_R = range of stability, deg
φ_{rms} = rms roll angle, deg
ψ = heading relative to wind, deg
Δ = displacement, long tons

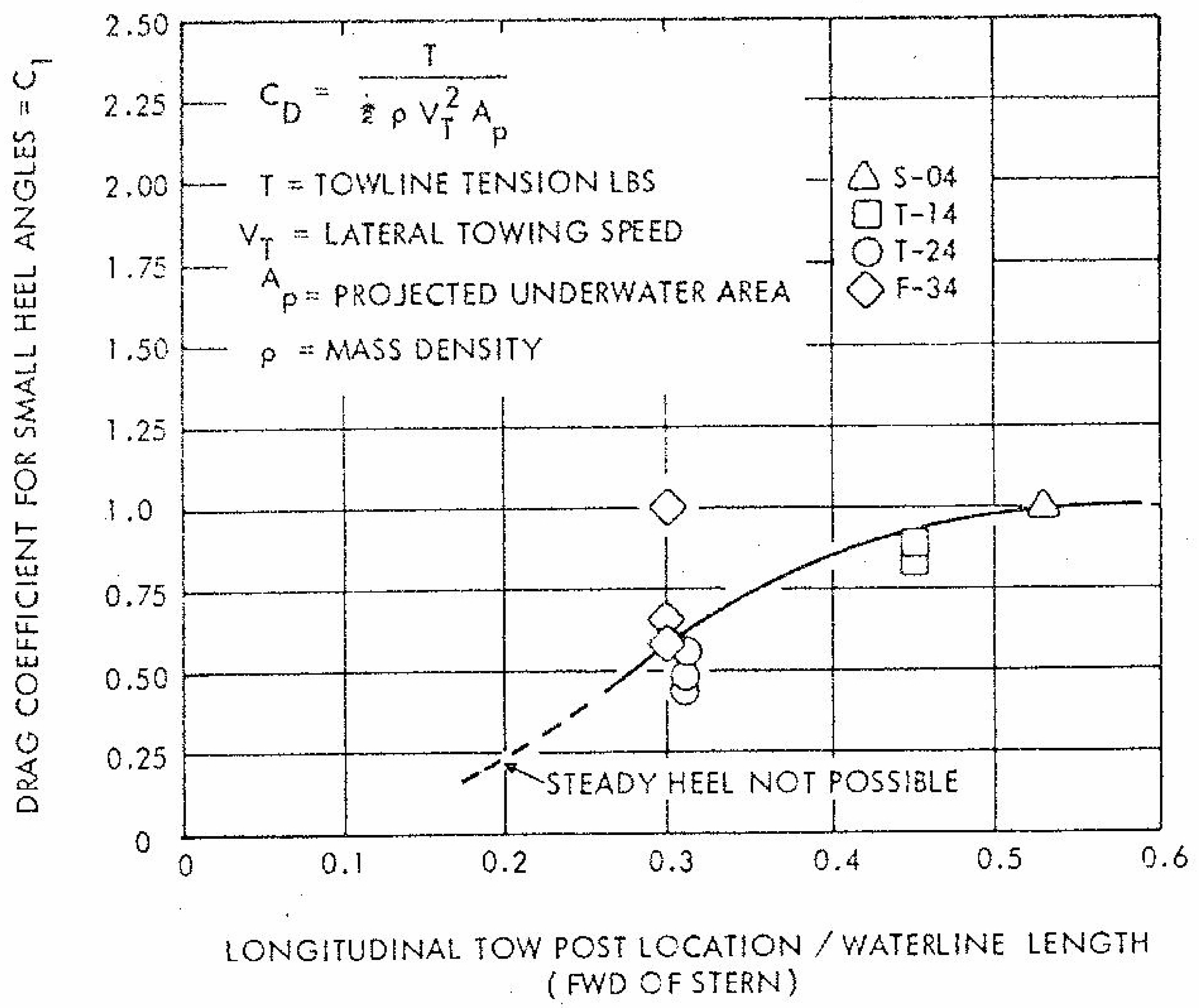

Fig. 12 Drag coefficient from tow tripping tests

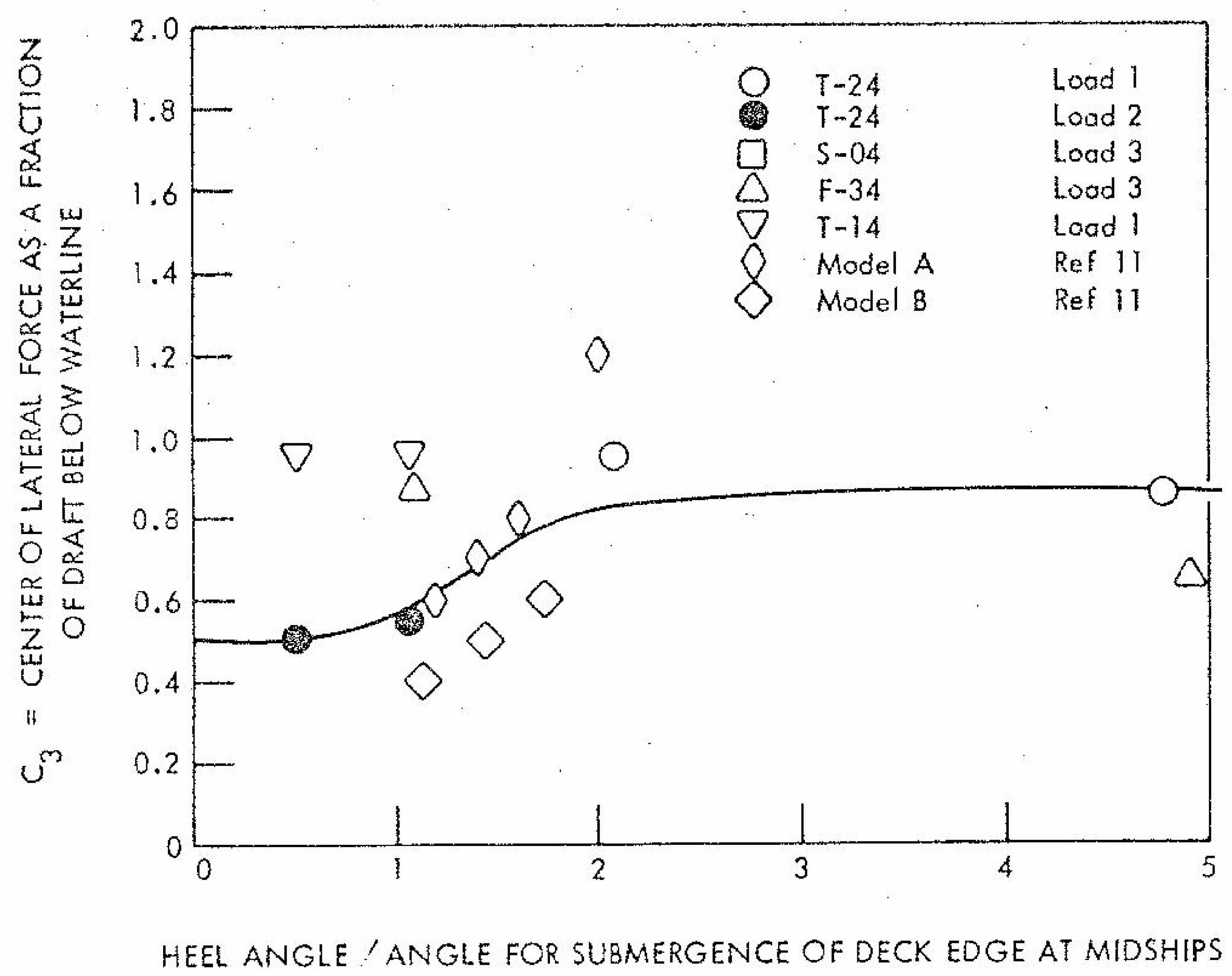

Fig. 14 Depth of center of lateral force as a function of heel angle

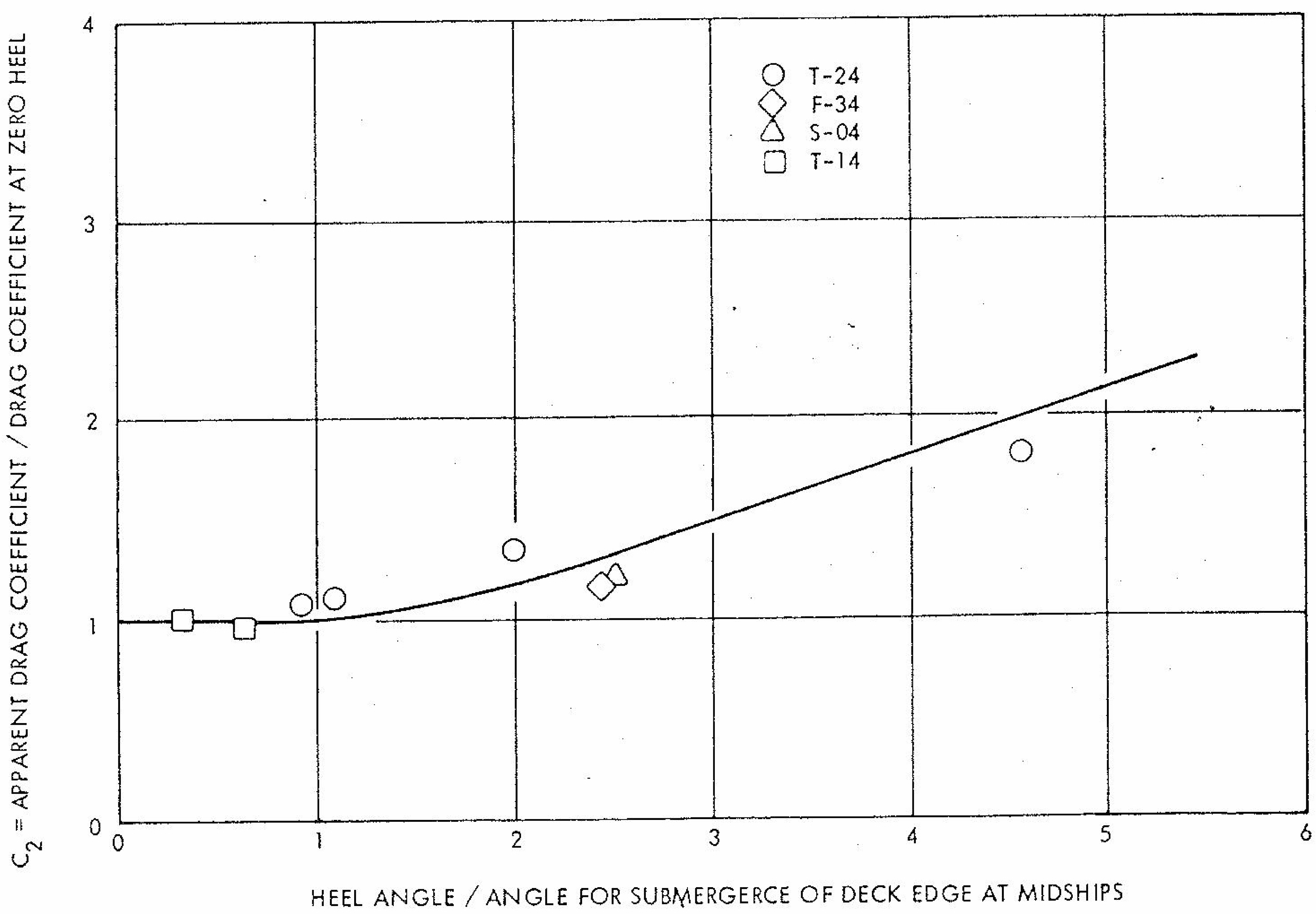

Fig. 13 Drag coefficient ratio versus normalized heel angle

were plotted as a function of the towing bitt's longitudinal location and the heel angle/angle to submerge the deck edge at midships. The results are presented in Figs. 12 and 13. It is of interest to compare the values obtained from the model tests with similar data for different hull forms reported in [10]. In the reference [10], tests, the apparent drag coefficient ranged between 1.0 and 0.8. This compares favorably with the data in Fig. 12 for cases with the towing bitt near midships which most closely approximate the test conditions of [10].

The vertical location of the center of hydrodynamic side force showed considerable scatter among models both for the data from the model tests and the tests reported in [10]. Typical data are presented in Fig. 14. . The scatter at small heel angles is not of concern since the forces are small and thus subject to large experimental error. There is a trend for the depth of the center of side force below the waterline to increase with heel angle. This seems reasonable since the deck edge is submerged and the underwater hull shape changes considerably. There does not seem to be a consistent trend in the available data for the location of side force as a function of hull proportions. In the development of a criterion, the conservative approach is to select the deepest locations of vertical center of side force.

The other factor in the development of a tow-tripping criterion is to determine the lateral towing speed for use in the criterion. This determination requires a considerable amount of judgment and should be the subject of further operational studies. The casualty records reviewed during the fleet census and the casualties described in Reference [10] indicate that there are several classic patterns which are repeated in tow-tripping casualties. Typical examples are as follows: .

Table 6 Speeds in tow-tripping situations

Situation	Range of absolute speeds, knots	Range of relative speeds, knots	Comments
Ship handling	0 to 8	0 to 6	towing vessel may change position when absolute speed is low, 0 to 4 knots; allowance should be made for propeller wash of assisted ship
Barge towing	4 to 10	0 to 5	barge is assumed to sheer off on a course 30 deg from the towing vessel's course
Assisting grounded vessels	. . .	0 to 5	relative speed depends on situation; assuming total bollard thrust/grounded vessel displacement = 0.02, 3 knots is possible in 10 sec and 5 knots in 20 sec

- Several towing vessels are assisting a ship which has way on. A towing vessel at the stern or bow tries to change position and the towline leads over the side. From this position, the towing vessel is pulled over by the towline to the ship being assisted. The situation may be made worse by the propeller wash from the assisted ship.
- Several towing vessels are assisting a grounded vessel. The grounded vessel comes free unexpectedly and pulls a poorly positioned towing vessel over. The grounded vessel is accelerated by the towline forces of the other towing vessels and possibly its own engines.
- A towing vessel is towing one or more barges which yaw to one side of the tug under the action of wind and waves. The towline comes over the beam and the motion of the barge causes the towing vessel to be pulled sideways.

These types of casualties often occur in relatively calm water so that the towing vessel will have its deckhouse doors open. Although the towing vessel may not capsize, it fills and sinks.

It must be realized that if the lateral towing speed is high enough, any towing vessel would be lost. For the purposes of a criterion, a speed must be chosen which is realistic but which is large enough to provide a margin for error. There is insufficient information available from casualty reports and operational studies to absolutely justify the selection of lateral speed. Thus, the selection must be made from qualitative considerations of the type of casualty situations just described. Table 6 presents the range of speeds that might be expected in these casualty situations.

A value of 5 knots is about the upper limit of relative speed which might be expected and thus seems reasonable for use in a criterion. A similar value proposed in [10] is also based on qualitative considerations of typical casualties.

Based on the foregoing analysis of forces and moments which result during tow-tripping, and consideration of possible lateral towing speeds, the following tow-tripping criterion is proposed.

When subjected to the specified heeling moment, a vessel shall not have a static heel angle which would result in downflooding or a capsizing. This heeling moment is given by the following formula:

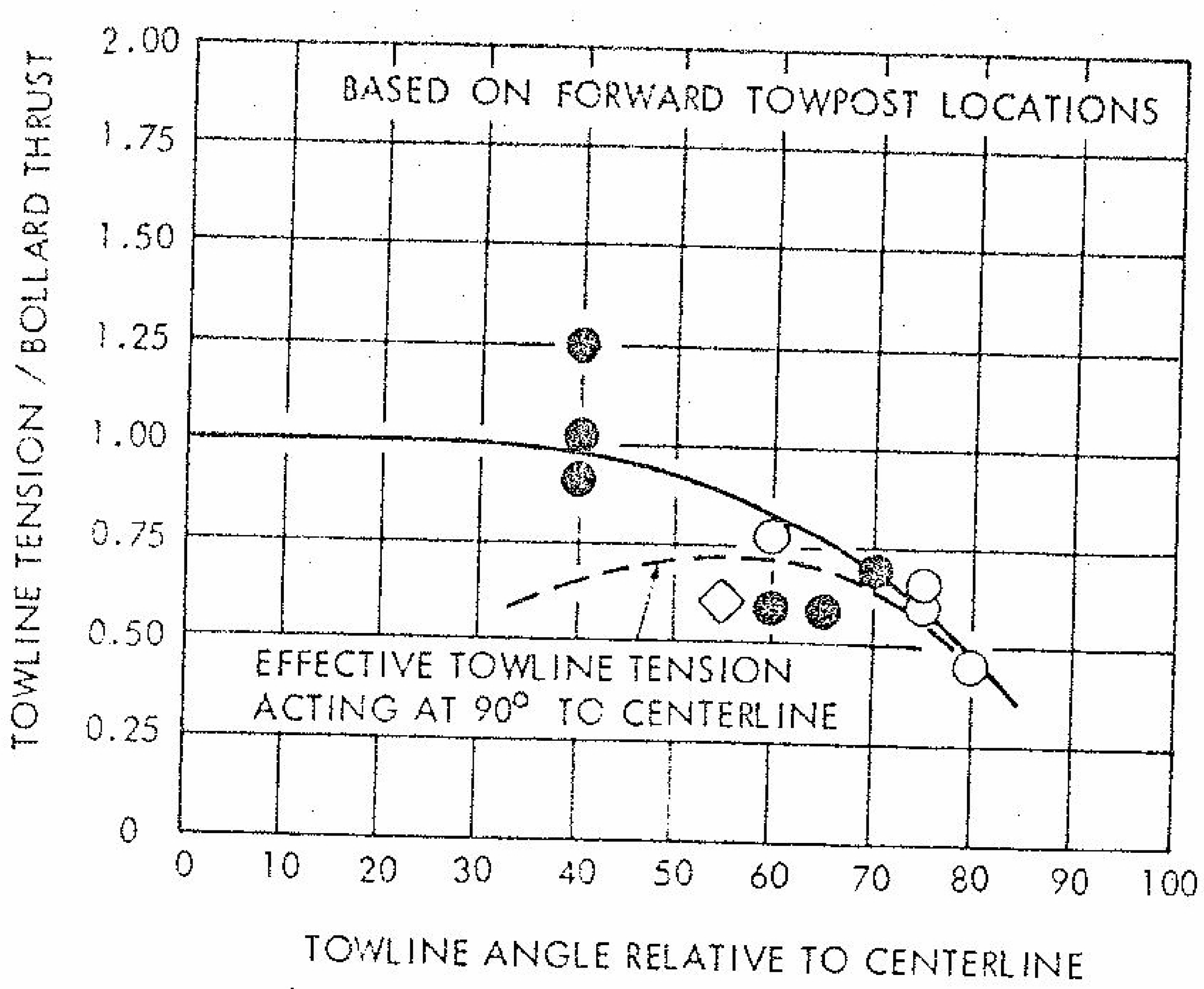

Fig. 15 Variation in towline tension with towline angle in self-tripping tests

$$K = C_1 \cdot C_2 \frac{\rho}{2} V_T{}^2 A_P (h_{\text{Bitt}} \cdot \cos(\varphi) + C_3 H) \qquad (3)$$

where

K = heeling moment, ft-lb
C_1 = drag coefficient (from Fig. 12)
C_2 = correction to drag coefficient for heel angle (from Fig. 13)
ρ = mass density of water
A_P = projected underwater lateral area, sq ft
h_{Bitt} = height of towing bitt above waterline, ft
C_3 = location of center of lateral force as fraction of draft below waterline (from Fig. 14)
H = draft, ft
V_T = designated towing speed = 8.45 fps
φ = heel angle, deg

Self-tripping. The basic concept for a criterion to prevent self-tripping is to require that the heeling moment generated by extreme action of the rudder and propulsion system while towing not be sufficient to submerge any openings or cause a capsizing. The largest heeling moments are generated when the vessel is pulling against a towline at bollard conditions with maximum thrust and the rudders are suddenly put hard over. Even in this case, the heel angle takes some time to develop and the resulting phenomenon is basically static in nature. This suggests that the criterion should be of the moment balance type.

An expression for the maximum heeling moment which can be obtained was developed from an analysis of the time history records from the models tests. These showed that as the angle of the towline relative to the centerline increased, the towline tension as a function of the bollard thrust decreased. The maximum effective fraction of the bollard thrust which could act to heel the vessel was found to be about 0.7. Figure 15 presents the relevant data. This fraction did not seem to be very sensitive to the size and location of the rudder or propeller for the models tested. The effective center of the lateral force was determined to be about 52 percent of the draft below the waterline. It was noted in the model tests that as the location of the towing bitt was moved aft, the effective towline angle relative to the centerline which could be maintained was reduced. This has the effect of reducing the effective portion of the bollard thrust in heeling the vessel. This effect is presented in Fig. 16.

It should be noted that the mechanism by which the side force is generated is different in tow-tripping and self-tripping. This accounts for the difference in the percentage of the draft

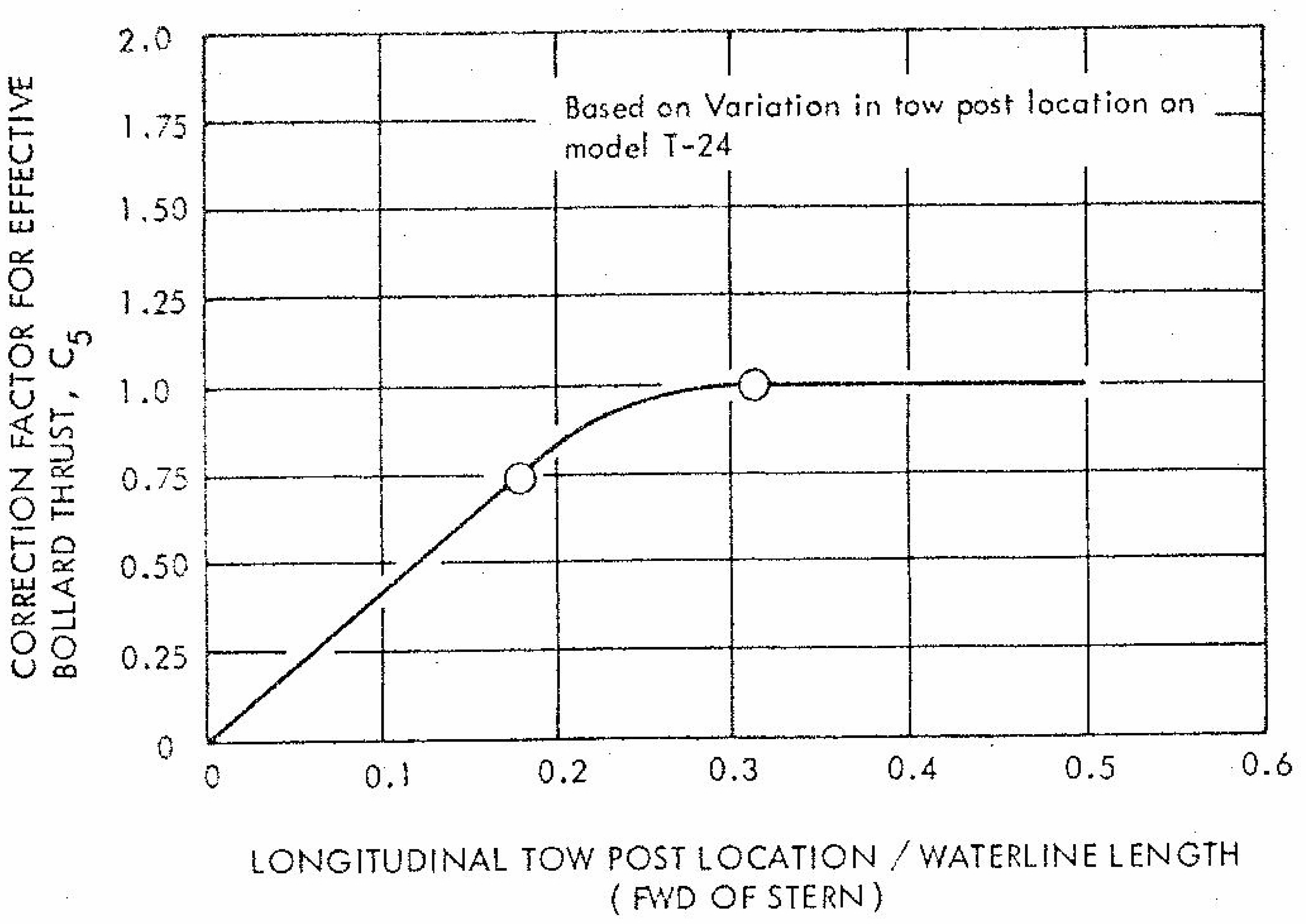

Fig. 16 Reduction in effective heeling moment versus longitudinal towpost location in self-tripping tests

at which the side force acts. In self-tripping, the side force is generated by the rudders, propellers, and flow on the aft part of the hull. The effective center in self-tripping is at a smaller fraction of the draft than the effective center of the side forces generated on the complete hull as the vessel is moved sideways in the tow-tripping case. The difference in the way the side force is generated also accounts for the difference in the variation of effective drag coefficient or effective bollard thrust as the towpost location is moved aft. In the self-tripping case, the rudder and propeller forces are far aft and thus can generate turning moments until the towpost is moved near the stern. In the tow-tripping case, the side forces, which act near midships, tend to align the towing vessel with the towline as the tow point is moved aft.

Based on the foregoing analysis of forces and moments which result during a self-tripping maneuver, the following self-tripping criterion is proposed.

When subject to the specified heeling moment, a vessel shall not have a static heel angle which will result in downflooding or capsizing. The following formula gives the heeling moment:

$$K = C_4 \cdot C_5 \cdot T_B \cdot (h_{\text{Bitt}} \cdot \cos(\varphi) + C_6 \cdot H) \qquad (4)$$

K = heeling moment, ft-lb
C_4 = effective fraction bollard thrust which can be expected on towline over beam = 0.70
C_5 = correction factor for longitudinal location of towing bitt (Fig. 16)
T_B = bollard thrust, lb
h_{Bitt} = height of towing bitt above waterline, ft
C_6 = effective center of resistance as fraction of draft below waterline = 0.52
H = draft, ft
φ = heel angle, deg

Water on deck in low-speed operations in head or following waves

The intact stability criterion for vessels developed in the following is intended to provide protection from the hazards of operations at low speed in head and following seas. The model tests showed that a significant hazard can exist during slow-speed (speed-length ratio ≤ 0.25) operations in steep head or following sea. This is due to a succession of waves washing on deck when the wave lengths are one to two times the vessel's length. The frequency of encounter is high enough that the water does not have time to run off the deck. The resulting buildup of water on the deck may cause a large angle of heel to develop. The time history records from the model tests show that this moment takes several wave encounters to develop and that the resulting heel angle is basically static in nature.

The details of the phenomenon of water buildup on deck are very complex and the only approach possible at this time is to develop an empirical criterion based on the model test data. The following general observations can be made based on the test results:

- The heeling moment is a function of the amount of water on deck. Thus, a criterion should take into account factors which influence this, such as freeboard and relative motion.
- The heeling moment is developed slowly and is quasi-static in nature. Thus, a criterion can be of the static moment balance type.
- The heeling moment is a function of heel angle and at large heel angles decreases rapidly. Some of the models were observed to develop quasi-static heel angles greater than the angle for maximum righting moment. For stable equilibrium the heeling moment must decrease more rapidly with heel angle than does the righting moment.
- The influence of bulwark height and freeing port area is not well defined. In some cases increasing the freeing port area allowed water on the deck faster than it could run off, thus making capsizing more likely.

An empirical criterion was developed for relationships between the wetness (relative motion-freeboard) versus the heeling moment, and heeling moment versus heel angle. This was done using model test data for several stability levels and a range of wave lengths and heights. A relationship for the variation in heeling moment, due to water on deck, as a function of heel angle was obtained as follows. Data on the mean heel angle were obtained from the time history records from the tests for runs with the same wave condition but different *GM*'s. The mean heel angle was less for the higher-*GM* case. To obtain the heeling moment at the mean heel angle, the righting moment versus heel angle curves for each *GM* were entered using the observed mean heel angle. This assumes that the mean heeling moment due to water on deck is equal to the righting moment at the mean heel angle. Moments due to the towline were removed based on the measured towline tension and angle, and assuming the moment arm extended from the towing bitt to half the draft. The resulting curves are shown in Fig. 17. The curve at larger angles was well defined since for stable equilibrium the slope of the heeling moment curve must be steeper than that of the righting moment curve. No data points were available at small angles, so the curve resulting from Fig. 17 was extended to zero heel angle arbitrarily.

The next step was to determine a relationship between the heeling moment caused by water on deck and some measure of the amount of water on deck. It was assumed that the heeling moment would be proportional to the product of an effective head of water and area of the deck which provides a measure of the weight of water on deck. This quantity times a moment arm, which should be proportional to some fraction of the beam, gives the heeling moment. The final step was to relate the effective head of water on the deck to a predictable quantity. It was assumed that the effective head would be proportional to the difference between the relative motion and the average freeboard, that is, the wetness. The ratio between effective head and wetness must be determined from the model test data. To do this, the wetness must be estimated and the heeling moment, expressed as the dynamic head, must be calculated from the test data. Since it has been shown that the heeling moment is a function of mean heel angle, it is necessary to correct the data points back to a common heel angle. If it can be shown that the relation between dynamic head and wetness is reasonably constant, then the basic empirical analysis can be regarded as reasonable.

The details of this empirical analysis are too long for inclusion here but are reported in detail in [14]. The result of the empirical analysis was the following relationship for the heeling moment due to water on deck:

$$K = 0.70\left(\frac{L_{WL}}{C} - FB_{\text{avg}}\right)\cdot\frac{A_{DK}B}{280}\cdot f(\varphi) \qquad (5)$$

where

K = heeling moment, ft-tons
L_{WL} = waterline length, ft
C = 20 for following seas, 10 for head seas
FB_{avg} = average freeboard[5] of exposed weather deck, ft
A_{DK} = planform area[5] of exposed weather deck, sq ft
B = beam, ft
$f(\varphi)$ = variation of heeling moment with heel angle as given in Fig. 15

If $(L_{WL}/C) - FB_{\text{avg}}$ is negative, $K = 0$.

For vessels that tow at sea, it must be assumed that the tow will tend to yaw or sheer off to the side. The heeling moment caused by this is minimized by running the towline through a fairlead aft. Even in this condition with a load on the towline, however, the model tests indicate that towline angles up to 20 deg from the centerline with full tension are possible. The additional heeling moment which results should be included in the criterion since it can reasonably be expected to occur at the same time that water is building up on deck. The model tests also indicate that the fluctuations in the towline tension due to waves are of a short enough period that the vessel does not have time to respond. Thus, a static towline moment can be used for the purposes of a criterion.

Based on the foregoing analysis, the following criterion for intact stability, to protect against water on deck in low-speed operation in head or following seas, is proposed.

The heeling moment curve defined here shall intersect the stillwater righting moment curve at less than 85 percent of the maximum righting moment and at an angle less than the downflooding angle for openings not fitted with closures. If the vessel tows at sea, the second term, which is a function of bollard thrust, must be included:

$$K = 0.70\left(\frac{L_{WL}}{C} - FB_{\text{avg}}\right)\cdot\frac{A_{DK}B}{280}\cdot f(\varphi) + T_B \cdot (h_{\text{Bitt}} + H/2)\cdot\sin(20\text{ deg}) \qquad (6)$$

where

K = heeling moment, ft-tons
T_B = bollard thrust, tons
L_{WL} = waterline length, ft
FB_{avg} = average freeboard[5] of exposed weather deck, ft
A_{DK} = planform area[5] of exposed weather deck, sq ft
B = beam, ft
C = 20 for following seas, 10 for head seas
$f(\varphi)$ = function of heel angle; see Fig. 17
h_{Bitt} = height of towing bitt above waterline
$H/2$ = ½ draft, ft

It is clear from the discussions presented in the foregoing that the analysis developed for the hazards due to water on deck is very empirical and subject to considerable uncertainty. Because of this, in a criterion it is prudent to require a significant

[5] The definition of average freeboard and planform area of the deck is illustrated in Fig. 18.

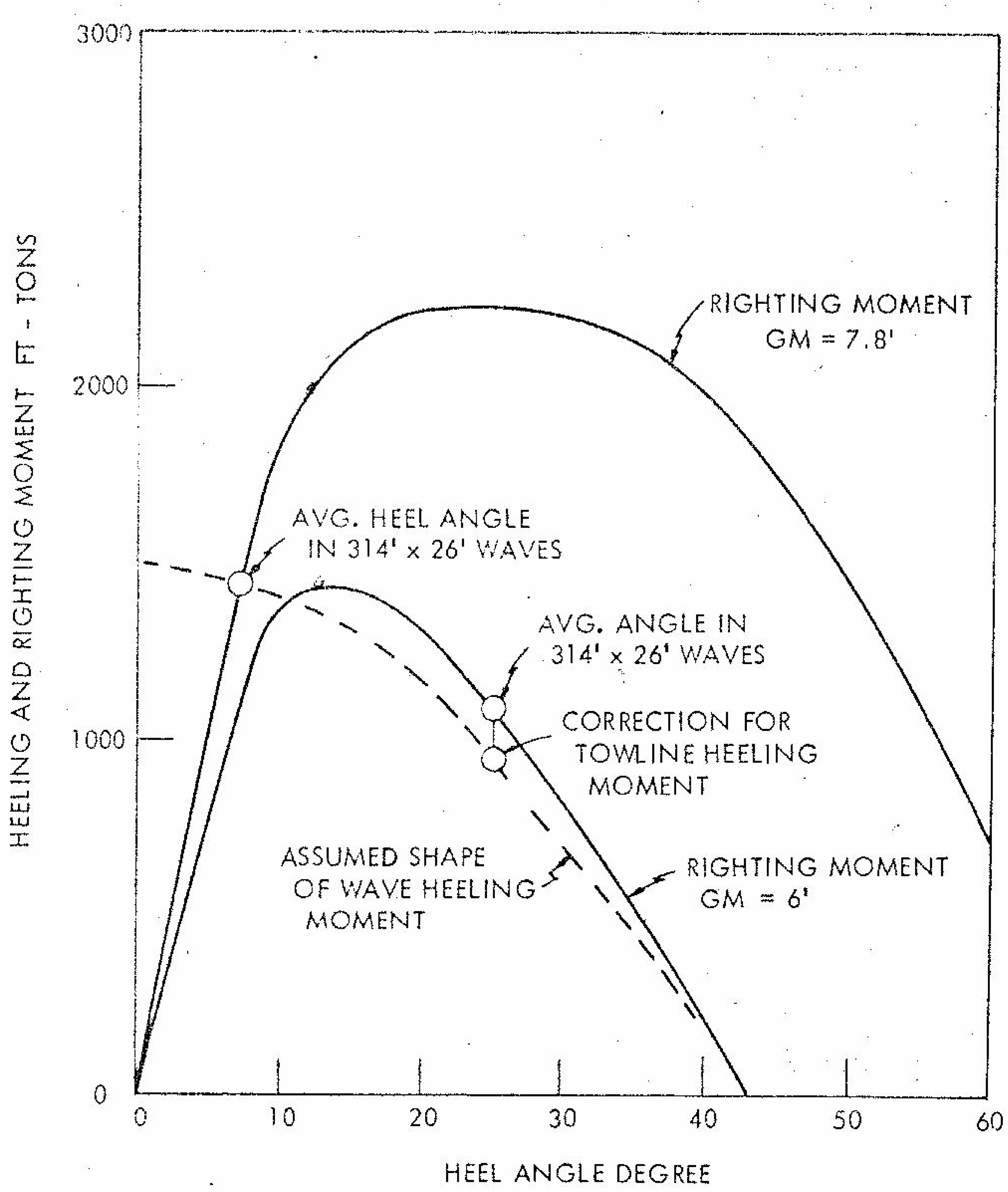

Fig. 17 Heeling moment due to water on deck versus heel angle for Model S-04

righting moment margin over the calculated heeling moment. Thus it is proposed that the intersection of the heeling and righting moment curves must occur at less than 85 percent of the maximum righting moment. It could be argued that wind heel could also occur with water on deck in head or following seas. To some extent this is covered by the margin in righting moment proposed. If this is not considered sufficient, a wind heel term can be added to the criterion.

As noted earlier, the influence of bulwark height and freeing port area is not known. The model tests were conducted on models in which the bulwark height/beam ratio ranged between 0.085 and 0.14, with freeing port area equal to that suggested by IMCO (Appendix 3). It would be reasonable to give special consideration to vessels with no bulwarks or very large freeing ports.

Operation in following seas at moderate and high speeds

The intact stability criterion for vessels developed in the following is intended to provide protection from the hazards of operation in following and quartering seas at speed-length ratios of about 0.8 and higher. Under these conditions the stability is greatly reduced when the vessel is poised with the wave crest at midships. This is most serious when the vessel encounters groups of steep waves with lengths between 1 and 2.5 times the vessel's length. It is a well-known phenomenon which was investigated in the model tests of this study and discussed in references [7] and [11]. If the reduction of stability is very large, the vessel can capsize when poised on a single wave, due to the direct loss of stability. Another possibility is that the alternate reduction of stability on wave crests and increase in stability in wave throughs will excite a resonant rolling at half the wave encounter frequency. The vessel rolls alternately to port in one crest and to starboard in the next crest. This can result in large roll angles which may build to capsize in three to five wave encounters. The third possibility is that

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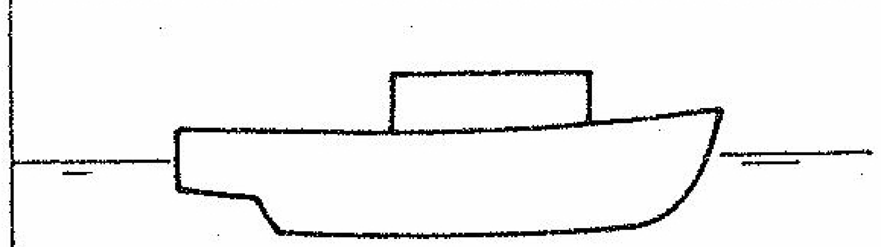
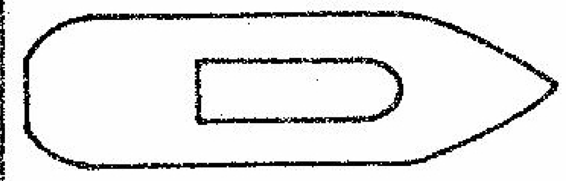
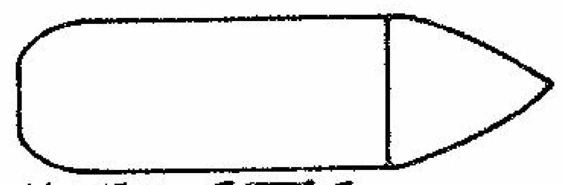
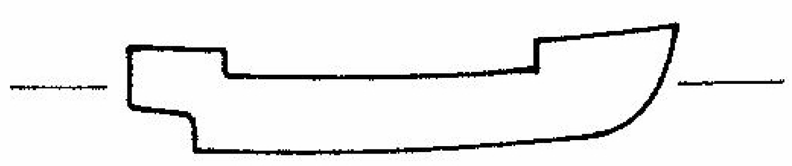
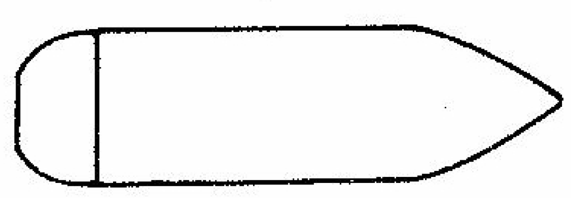
	
FOLLOWING SEAS DECK AREA Deck Area Included to 2/3 of LWL Forward of Stern Exclude Area of House FREEBOARD Average of Freeboard at Stern and at Midships	HEAD SEAS DECK AREA Entire Deck Area Except area of House FREEBOARD Average of Freeboard at Bow and at Midships
RAISED FO'C'SLE VESSELS	
	
FOLLOWING SEAS DECK AREA Deck Area Included to Aft End of Fo'c'sle Exclude Area of House FREEBOARD Average of Freeboard at Stern and at Midships	HEAD SEAS DECK AREA Deck Area is Area of Fo'c'sle Deck or Area of Forward Third of Vessel Which ever is Larger. In Order to be Considered a Raised Fo'c'sle, its Height Must be 4 Ft. Exclude Area of House on Fo'c'sle FREEBOARD Average of Freeboard at Fore and Aft End of Fo'c'sle. If Height Less than 4 Ft. Use Average Freeboard at bow and Midships.
RAISED POOP VESSELS	
	
FOLLOWING SEAS DECK AREA Deck Area to Include Poop Deck or Area to 1/3 of Length FWD of Stern. To be Considered a Raised Poop its Height Must Exceed 2 Ft. FREEBOARD Average Freeboard at Aft and FWD End of Raised Poop if Height Exceeds 2 Ft. if Lower, Average at Stern and Midships	HEAD SEAS DECK AREA Entire Area Excluding House Aft to Poop. FREEBOARD Same as for Flush or Raised Fo'c'sle as Appropriate

Fig. 18 Definitions for use in water-on-deck criterion

the vessel will broach on a wave crest and then capsize.

For towing, supply, and fishing vessels, the model tests, in addition to quantitative data, indicated several important qualitative points. One was that it was necessary to be running at a fairly high speed ($V\sqrt{L_{BP}} > 0.7$) before this type of capsizing would occur. Another was that water on deck played an important role in inducing large rolling or capsizing. The water on deck increased the roll period so that resonant rolling into alternate wave crests was possible. The final observation was that models tested did not show a tendency to uncontrollable broaching. This may be due to their relatively large rudders, as compared with larger vessels, and to the fact that

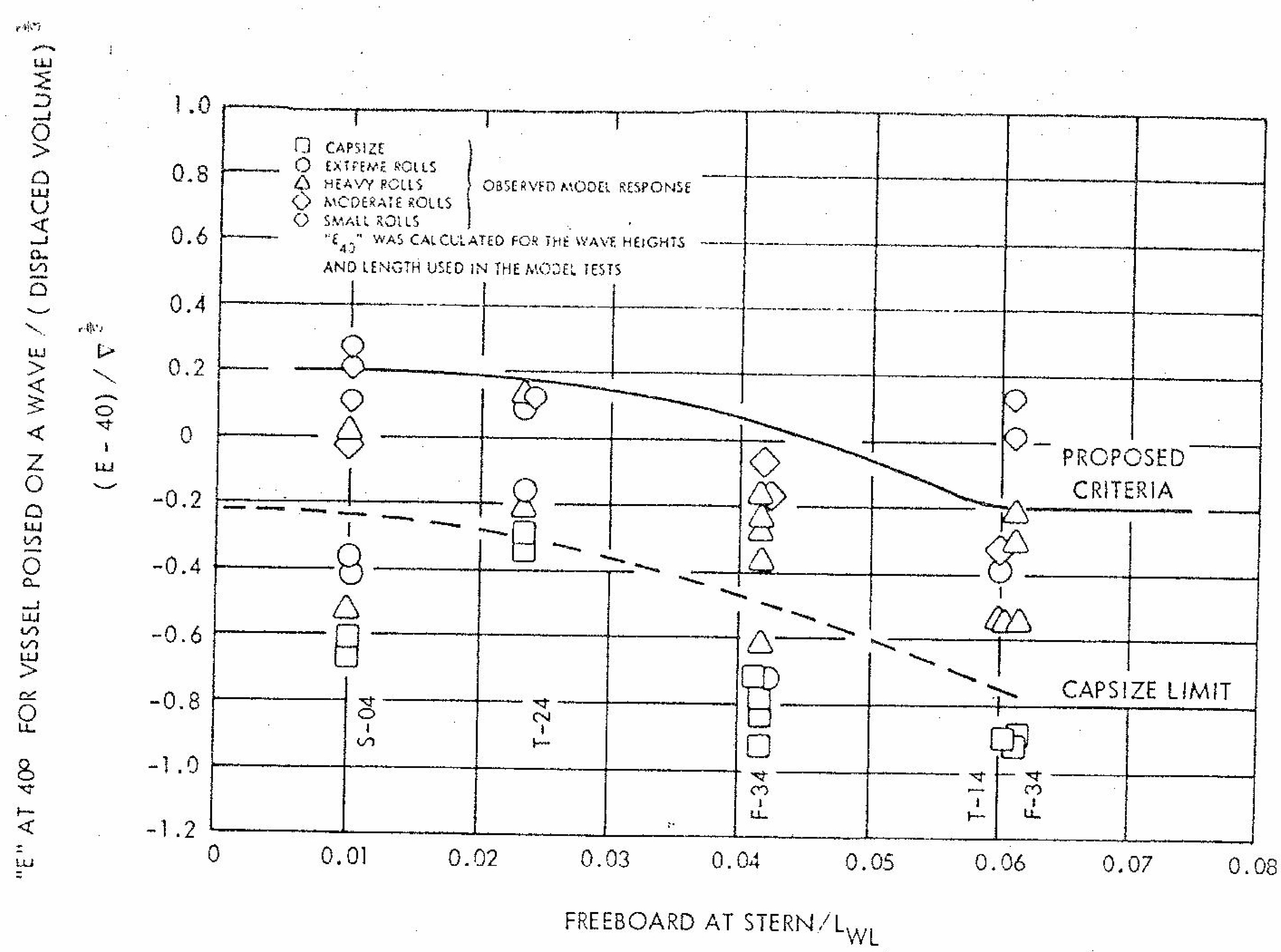


Fig. 19 Model response in following seas versus stability poised on a wave

tests were not carried out at extremely high speeds.

It was assumed that the tendency to capsize or develop extreme rolling in following waves was related in some way to the stability when poised on a wave crest. The model test data provided information on the response in regular waves of different heights and lengths. The approach used was to calculate the stability when poised on the crest of waves which had been used in the model tests and then to correlate the model response with the stability. As noted earlier, water on deck was important, so that the relative freeboard at the stern was considered to be an important parameter.

The results of the correlation are presented in Fig. 19. The measure of stability chosen for the correlation was the E value (that is, the area under the GZ curve) up to an angle of 40 deg in ft-deg. This was divided by the cube root of the displaced volume. It may be observed that an approximate capsizing limit in terms of $E_{40}/\nabla^{1/3}$ can be defined as a function of freeboard at the stern/waterline length. It seems desirable to define a criterion so that extreme rolling is avoided and that a margin is allowed for uncertainties in the empirically defined capsizing limit. The proposed criterion in terms of E_{40} when poised on a wave crest is also shown in Fig. 19.

One important qualification must be placed on this empirical correlation. In extreme light load conditions, when the KG is large relative to the draft, large sway-roll coupling moments may exist which could cause capsizing. The importance of this is discussed in [15]. Thus, for E_{40} when poised on a wave, the criterion presented in the foregoing, may not be conservative when the ratio of KG/H exceeds 1.4. This ratio of KG/H is the limit within the model test sample. Special consideration should be given to cases in which KG/H exceeds 1.4.

The final step in the formulation of a criterion is to select the wave condition for which the prescribed value of stability must be obtained. To this end, a study of wave groups was carried out to determine the possibility of occurrence of groups of waves with extreme heights and critical wave lengths [14]. The results of this study indicated that under some conditions, most likely a developing sea driven by very high winds, groups of waves with critical heights and lengths could occur. Thus, for a criterion applicable to all oceans, the critical wave length (wave length to waterline length of 1.8) and a wave height near the limit of breaking (wave height/wave length of 0.12) were chosen. For vessels which are expected to operate only in areas of good weather or where shelter is near, a smaller ratio of wave height/wave length could be used. This should be decided on a case-by-case basis. Also, the extreme wave steepness proposed for the criterion would not be sensible for vessels longer than about 250 ft.

Based on the foregoing analysis, the following criterion for intact stability, to protect against capsize when running at moderate and high speeds in following or quartering seas, is proposed:

The value of E at a heel angle of 40 deg calculated from the GZ curve with the vessel poised on a wave with its crest amidships shall equal or exceed the values given in Fig. 19. The ratio of wave length/waterline length shall be 1.8 and the wave height shall be 0.12 × wave length. E is the area under the GZ curve up to an angle of 40 deg expressed in the units of ft-deg.

This criterion applies to conventional towing, towing/supply, and fishing vessels with a value of KG/H less than 1.4. If this ratio is larger, the stability will have to be increased to account for the large rolling moments due to sway-roll coupling. If the vessel carries a cargo which can trap water (for example, open pipe on the deck of a supply vessel) or has a well or deck structure which can trap water for significant periods, the weight of trapped water should be accounted for in the KG and displacement values used in the calculation of stability.

Wind heel with rolling

One of the classic types of intact stability criterion now in use is the dynamic wind heel criterion. This type of criterion is intended to provide sufficient stability for a vessel to withstand the dynamics of being subjected to a wind gust while rolling. The classical form of such a criterion is shown in Fig. 20. For satisfactory stability, the "work" done by the righting levers must exceed the "work" done by the heeling levers. The extent to which the righting work must exceed the heeling work and the initial heel depends on the particular formulation of the criterion.

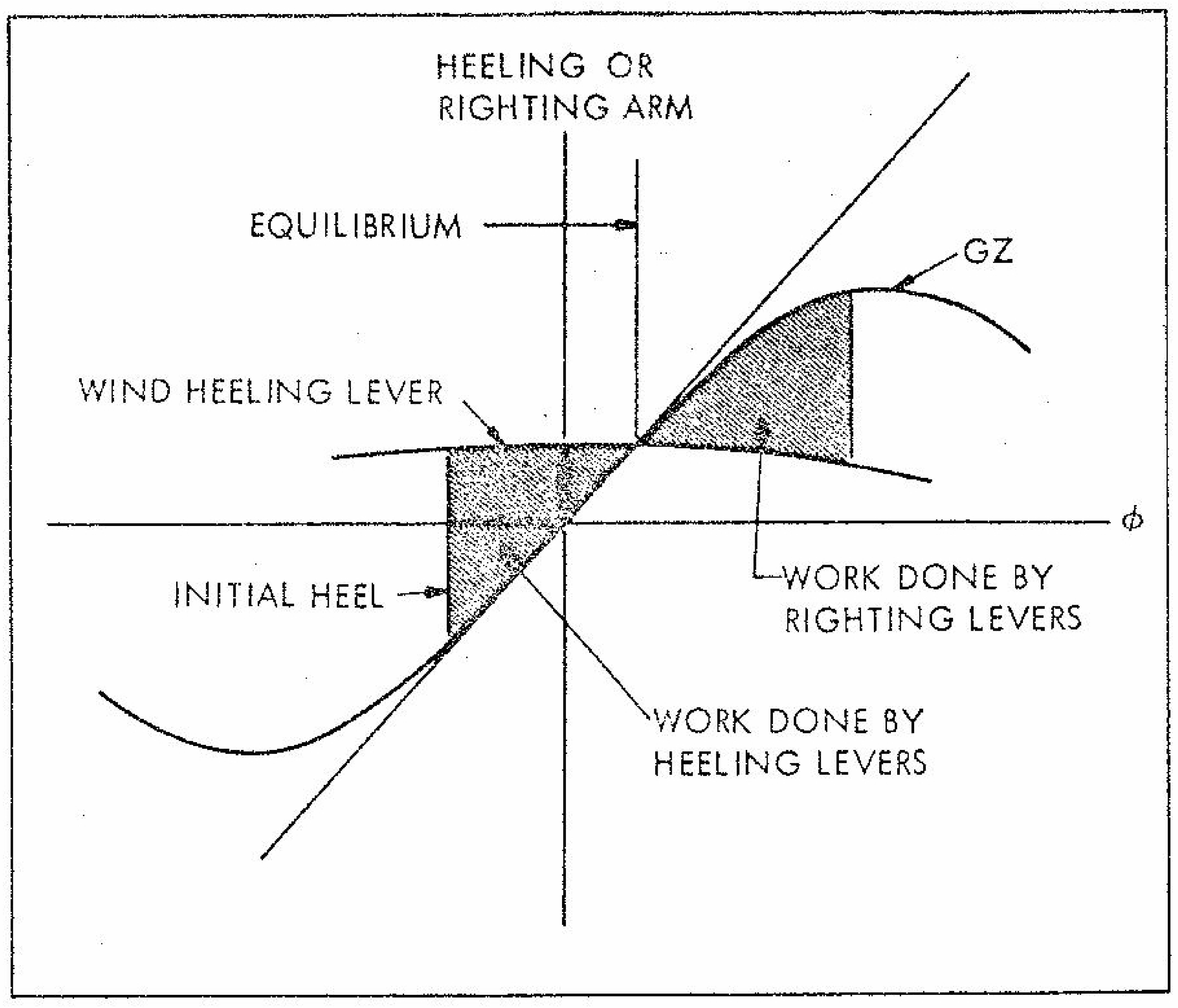


Fig. 20 Classical dynamic wind heel analysis

In fact, this classic wind heel criterion does not relate to the real dynamics of a ship rolling in gusting winds. It is highly idealized and very arbitrary in the selection of the initial heel angle. In order to develop a better understanding of rolling with a gusting wind it was necessary to conduct an analysis of the dynamics of the phenomenon. To date, such an analysis does not seem to have been reported in the literature and no model tests were conducted with wind. Thus, within the limited scope of this project, an analysis of rolling in gusting wind was conducted. It was clear that the response of the ship in roll would be very nonlinear in many realistic cases. Therefore, the method of analysis chosen was to solve the nonlinear roll equation of a ship in irregular waves and a gusting wind. Because the problem is nonlinear, the calculations must be carried out in the time domain.

The general form of the rolling equation used was

$$I\,\ddot{\varphi} + A\,\dot{\varphi} + B\,\dot{\varphi}|\,\dot{\varphi}| + \Delta\cdot f(\varphi,\zeta_x) = M_w + M_c \qquad (7)$$

where

φ = roll angle
ζ_x = effective wave slope
M_w = wind moment
M_c = constant moment due to water on deck
I = total roll moment of inertia
A = linear damping
B = quadratic damping
Δ = displacement
$f(\varphi,\zeta_x)$ = GZ curve as a function of $(\varphi - \zeta_x)$

In the usual case, the excitation due to the wave slope is put on the right-hand side. In this case, however, since the GZ curve is nonlinear, it is easier to include the effective wave slope on the left-hand side.

The effective wave slope for irregular waves was calculated from the summation of ten sine waves with random phases, amplitudes, and frequencies to approximate a Pierson-Moskowitz wave spectrum.

Surprisingly, there is very little reliable quantitative information about wind loads, especially as they vary in time. The available information on this problem is summarized in [14], which reviewed most available data on wind descriptions and ship wind loadings. From [16], the lateral wind force is given by

$$Y_{\text{Wind}} = \tfrac{1}{2}\rho_a V_0^2 \left(\frac{V_{VCA}}{V_0}\right)^2 A_{pa} C_y \sin\psi \qquad (8)$$

where

ρ_a = mass density of air
V_0 = freestream wind velocity
V_{VCA} = wind velocity at height of vertical center of area
A_{pa} = profile area
C_y = sideforce coefficient = 0.871
ψ = heading angle to wind

Available empirical formulations for the spectrum of wind gustiness were used to generate a time history of the wind gusts. The wind rolling moment was determined to be simply

$$M_{\text{Wind}} = Y_{\text{Wind}} \cdot h \qquad (9)$$

where h is the distance between the center of wind pressure and center of the underwater profile.

Equation (9), which was used in the analysis, assumes the wind moment to be independent of the roll angle. In the U. S. Navy wind heel criterion, the wind moment is assumed to vary as the cosine of the heel angle. This results in zero moment at 90 deg of heel. This is not realistic, since the vessel will still have an exposed profile and, as shown in the discussion of tow-tripping, the vertical center of hydrodynamic resistance is located at a greater fraction of the upright draft as the heel angle increases. Of course in this case the vessel is blown sideways rather than dragged sideways by a towline. Some limited wind tunnel data on wind force as a function of heel angle for a small vessel are presented in [17]. These data indicate some decrease in wind force with heel angle but not as rapidly as the cosine of the heel angle. Thus, because of the lack of sufficient data to define the variation of wind heeling moment with heel angle, the conservative assumption of a constant wind heeling moment was made for this study. The results of a typical computer simulation of a time history of roll, wave height, and wind speed are shown in Fig. 21.

Calculations were carried out for three vessels for which stability data were available. They were S-04, a supply vessel; T-24, an ocean towing vessel; and F-49, a side trawler. In Condition 1, these vessels do not satisfy the U. S. Navy wind heel criterion with a 60-knot wind. Vessel F-49 was selected since it is one of the few fishing vessels which does not satisfy the classic wind heel criterion in the full-load condition. These vessels' characteristics are given in Table 7 and their GZ curves are presented in Fig. 22. The results of the calculations are given in Fig. 23, which presents the region in which capsizing could be expected as a function of wind speed at the center of pressure and the significant wave height.

A number of interesting points were noted from the study of these vessels:

- The U. S. Navy wind heel criterion with a 60-knot wind does not provide a uniform level of protection to vessels which just satisfy it. In calm water S-04 could survive 200-knot winds, T-24 90-knot winds, and F-49 only 70-knot winds. In high waves, S-04 could capsize from waves alone (at least according to the mathematical model) and T-24 and F-49 could barely survive 60-knot mean winds with significant wave heights of 25 ft. This is not an unrealistic condition and thus it is implied that a 60-knot mean wind speed is too low for a criterion.
- The root-mean-square (rms) roll angle is not greatly affected by the wind gusts in high sea states. This implies that the frequency of the wind gusts does not couple effectively with the roll frequency. The roll is dominated by the waves which do have frequencies which excite rolling. In calm water, gusts do excite some rolling with rms roll angles about 65 percent of the mean heel angle.
- The time histories of the capsizings do not show the behavior assumed in the classical dynamic wind heel analysis. The capsizings do not necessarily occur when the vessel is

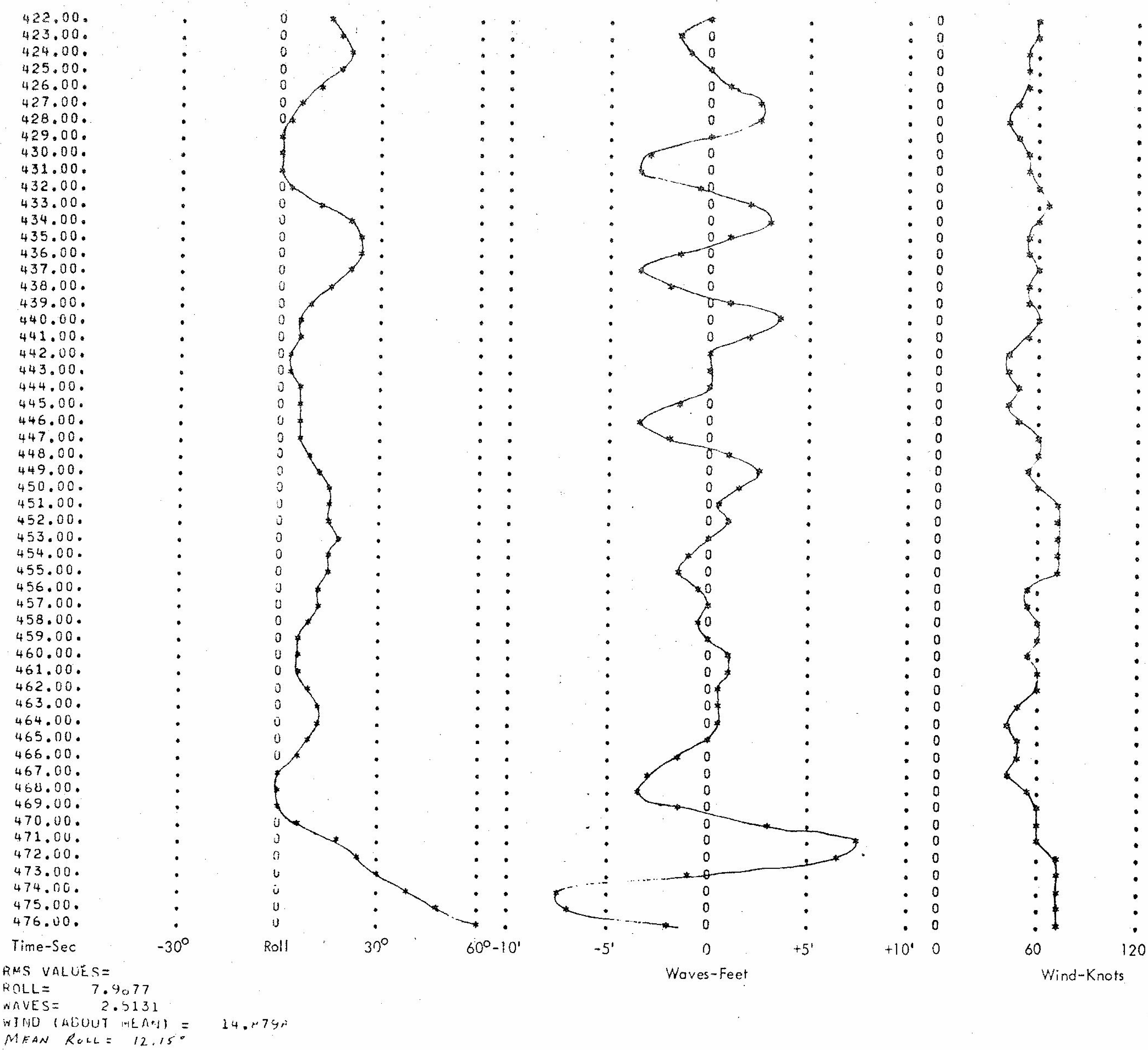


Fig. 21 Time history of capsize in waves and wind; Vessel F-49

subjected to a sharp wind gust after a large roll to windward. Rather a capsizing seems to be a random event which depends on the phasing of the roll, wave slope, and wind gust.

This last observation is most important for the formulation of a simplified wind heel criterion. It may be assumed that the probability of occurrence of an extreme roll is in some way related to the rms roll angle. Also, capsizing will occur when the effective roll angle exceeds the range of stability. Based on the calculated data, it was found that capsizing would occur if the rms roll angle exceeded about one quarter of the range of stability to leeward. This provided a much better prediction of capsizing than some type of balance between the "work" done by heeling and righting levers as suggested in Fig. 20.

It would be difficult to specify the use of nonlinear time domain computer simulation studies of wind heel with rolling during the design of typical towing and fishing vessels. Therefore, the following simplified criterion, based on the computer studies reported in the foregoing, is proposed:

The vessel shall have a range of stability to leeward in excess of 4.5 times the rms roll angle. Rms roll angle = 10 deg for open water and = 0.65 × mean heel angle for protected water. The mean heel angle may be calculated from the heeling moment due to wind and defined by

$$K_{\text{Wind}} = 0.004(V_{\text{Wind}})^2 \cdot A_{pa} \cdot h \tag{10}$$

where

Table 7 Characteristics of vessels used in wind heel study

Vessel type	S-04 Supply Vessel	T-24 Ocean Towing Vessel	F-49 Side Trawler
L_{WL}, ft	171	116	115
Beam, ft	37.5	31.5	26.6
Draft, ft	12.6	16.3	10.8
Displacement, tons	1507	8.85	484
C_B	0.65	0.52	0.51
Profile area, sq ft	1918	1765	2019
Heeling arm, ft	15.2	18	14.5

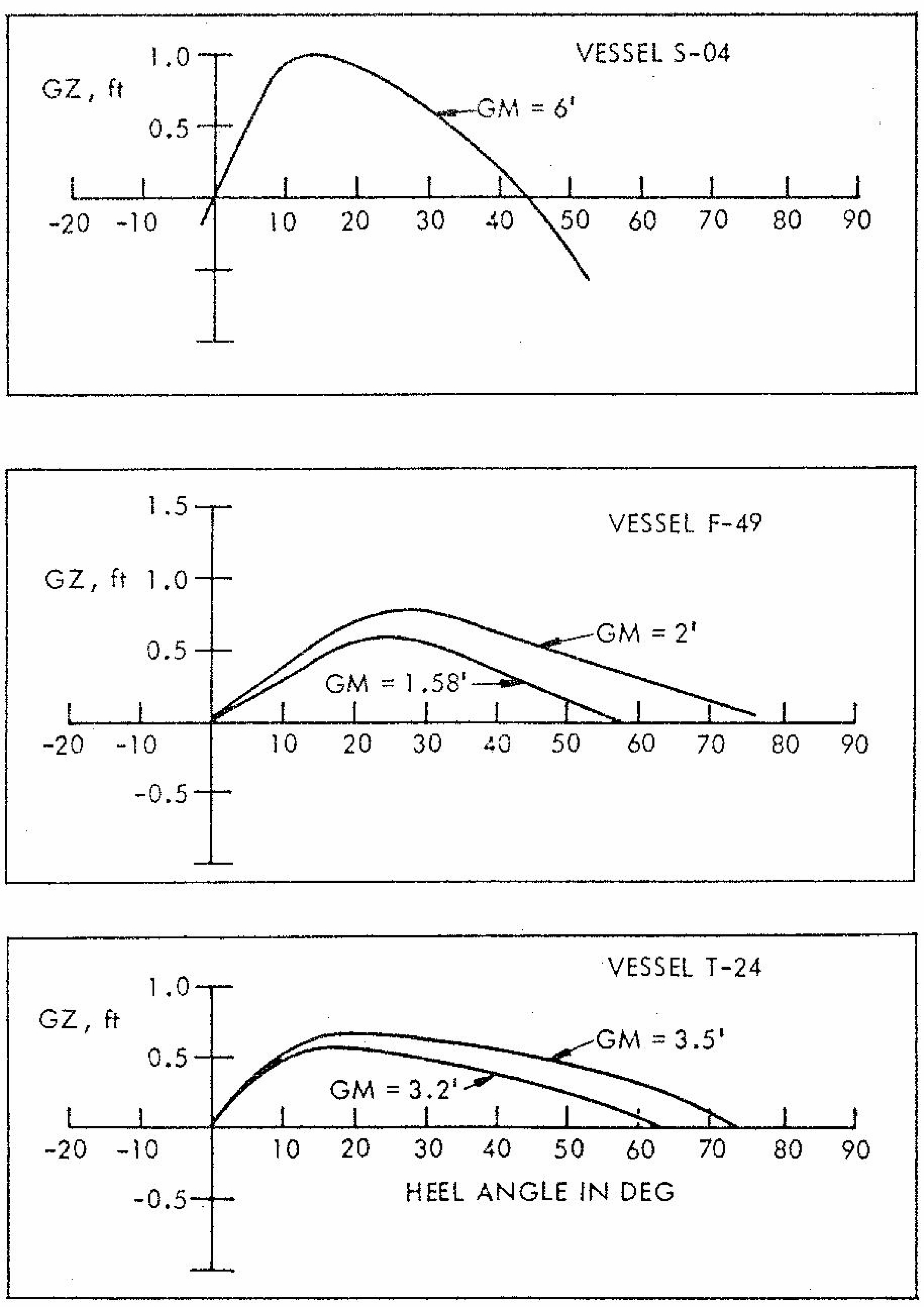


Fig. 22 GZ curves used in wind-wave heel with rolling analysis

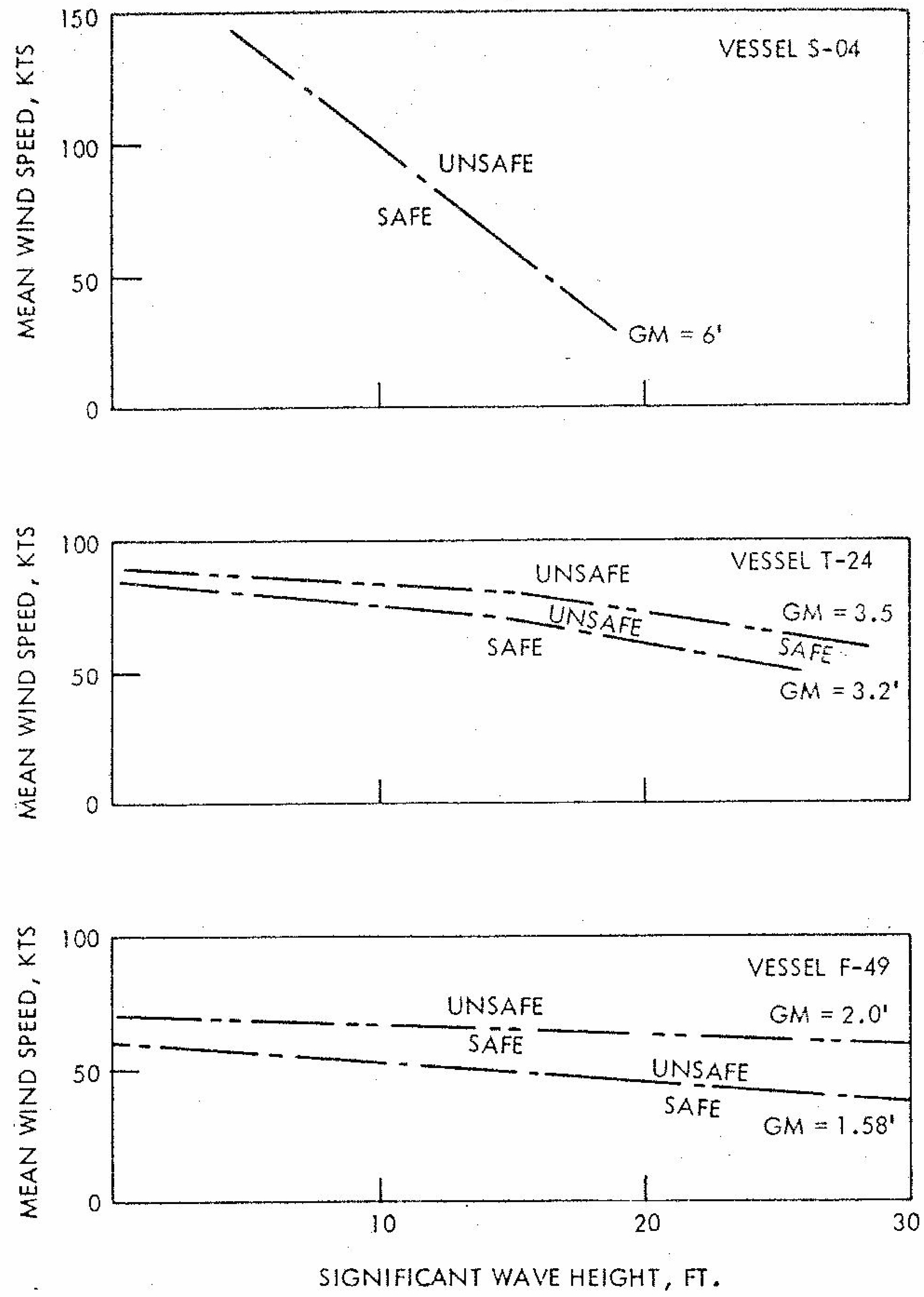


Fig. 23 Calculated capsize zones for wind heel and rolling in beam seas

K_{Wind} = wind heeling moment, ft-lb
V_{Wind} = wind speed, knots = 70
A_{pa} = projected lateral area above waterline, sq ft
h = moment arm = distance between centers of above and below water lateral areas, ft

If the vessel is expected to trap water on the leeward deck, the mean heeling moment due to this should be added to the wind heeling moment.

The requirements of this criterion are illustrated in Fig. 24.

A number of comments should be made about this simplified criterion. The wind pressure coefficient of 0.004 is higher than the value used for the calculations of the instantaneous wind force in the computer studies. This is to account for the fact that the mean wind force in a gusting wind is larger than the wind force in a steady wind of average velocity because wind force increases as the square of the wind speed.

The wind speed for wind heel criteria now in use is typically taken as 60 knots. For U. S. Naval vessels a wind speed of 100 knots is used. It is clear that in winter conditions in the North Atlantic and North Pacific, vessels will be subjected to winds in excess of 60 knots. A wind speed of 70 knots would seem to be a realistic minimum for open-water service. Since the center of above-water area of small vessels is lower than the 32.8 ft (10 m) used in wind speed reports, a 70-knot wind in the criterion is approximately equal to a wind of 82 knots at 32.8 ft. The most arbitrary assumption in this criterion is the selection of the rms roll angle. The value selected was based on a limited series of calculations for vessels at various GM's. In principle this should be a function of the actual sea spectrum, hull shape, roll natural period, damping devices such as bilge keels, and the roll restoring moment at large heel angles. In practice many of these factors may be of secondary importance because of the very large damping which results from the submergence of the deck edge and the sloshing of water on deck. The selection of an rms roll angle for use in a criterion deserves further study, including experimental verification.

Utilization of results

Potential fleet impact

The potential impact on the U. S. fleet of the set of intact stability criteria described in the foregoing and of the existing criteria was evaluated. The evaluation determined the percentage of the fleet which satisfies the criteria and the magnitude of the changes in stability needed to bring the vessels into compliance. The fleet in this context is defined as the 51 vessels listed in Table 1 on which detailed analyses were made. The actual U. S. fleet percentages may differ.

The basic fleet impact is presented in Table 8 in terms of the percentage of the 51 vessels in the sample which satisfies the various criteria. Details of the U. S. Coast Guard's towing vessel, the "Murphy," and the IMCO dynamic stability criteria are given in Appendix 3. For the evaluation of the self-tripping criterion it was assumed that vessels with open propellers produced 25 lb of bollard thrust per horsepower; vessels with nozzles were assumed to produce 30 lb/hp. In the calculation of the GM required to prevent self-tripping for Vessel S-04, it was assumed that the ship had 5000 shp installed. The following-sea criterion was evaluated for Vessels T-01 to T-11, S-03, S-04, and F-01 to F-29. A number of important observations with respect to fleet impact can be made from the comparisons made. For towing vessels in the full-load condition, the proposed tripping criteria are not as stringent as the U. S. Coast Guard towing vessel criterion. Only 31 percent of the sample satisfies the U. S. Coast Guard's towing vessel criterion, whereas 60 percent satisfies the proposed tow and self-tripping criteria. Considering the complete set of proposed criteria, 45 percent of the towing vessel sample passes.

Table 9 presents data showing the extent to which the initial stability would have to be changed to meet the various towing vessel criteria. The data in the table are presented in terms of the average of the ratio of *GM* required by a specific criterion to that required by the Murphy criterion. For the full-load condition, the proposed tripping criteria require, on the average, 85 percent of the *GM* required by the U. S. Coast Guard's towing vessel criterion. Considering the complete set of proposed criteria, the average required *GM* is 92 percent of that required by the U. S. Coast Guard's criterion. It is of interest to note that for the full-load condition, the average actual *GM* ratio of the towing vessel sample is the same as that required by the complete set of proposed criteria.

For the towing vessels in the full-load condition, the water-on-deck criterion is the most stringent. This criterion is very sensitive to freeboard, so a small reduction in displacement or increase in freeboard would bring a substantial number of the vessels in the existing fleet into complicance. For vessels which satisfy the proposed tripping criteria but not the water-on-deck criterion, the average increase in *GM* required to satisfy the water-on-deck criterion is 14 percent. These same vessels could satisfy the water-on-deck criterion with no increase in *GM* and an average increase in freeboard of less than 30 percent.

The two supply vessels in the full-load condition do not satisfy any of the proposed seakeeping criteria or the current IMCO criteria. They do satisfy the tripping criteria. The following sea criterion requires the largest increase in *GM*. This criterion is also the most difficult to satisfy by a reduction in displacement or an increase in freeboard. The following-seas criterion applies to only limited sea conditions, so it may be possible to relax its requirement if the operators are adequately instructed about the dangers of running at moderate or high speed in steep following seas. The water-on-deck and the wind heel criteria are sensitive to reduction in displacement with the resulting increase in freeboard. Thus, a reduction in the weight or height of the deck cargo will result in compliance. The detailed stability data for other load conditions were not available within the scope of this project, so no quantitative assessment could be made.

For towing vessels in the light-load condition, the complete set of proposed criteria is slightly less stringent than the current USCG towing vessel criterion. The proposed tripping criteria require, on the average, 92 percent of the *GM* required by the USCG towing vessel criterion. The complete set of proposed criteria, however, is more stringent for load condition 2. This is because of the wind heel and the following-seas criteria. On the average, the complete set of proposed criteria requires 19 percent more *GM* than the USCG towing vessel criterion. On the average, the fleet has 22 percent more *GM* than required by the USCG towing vessel criterion.

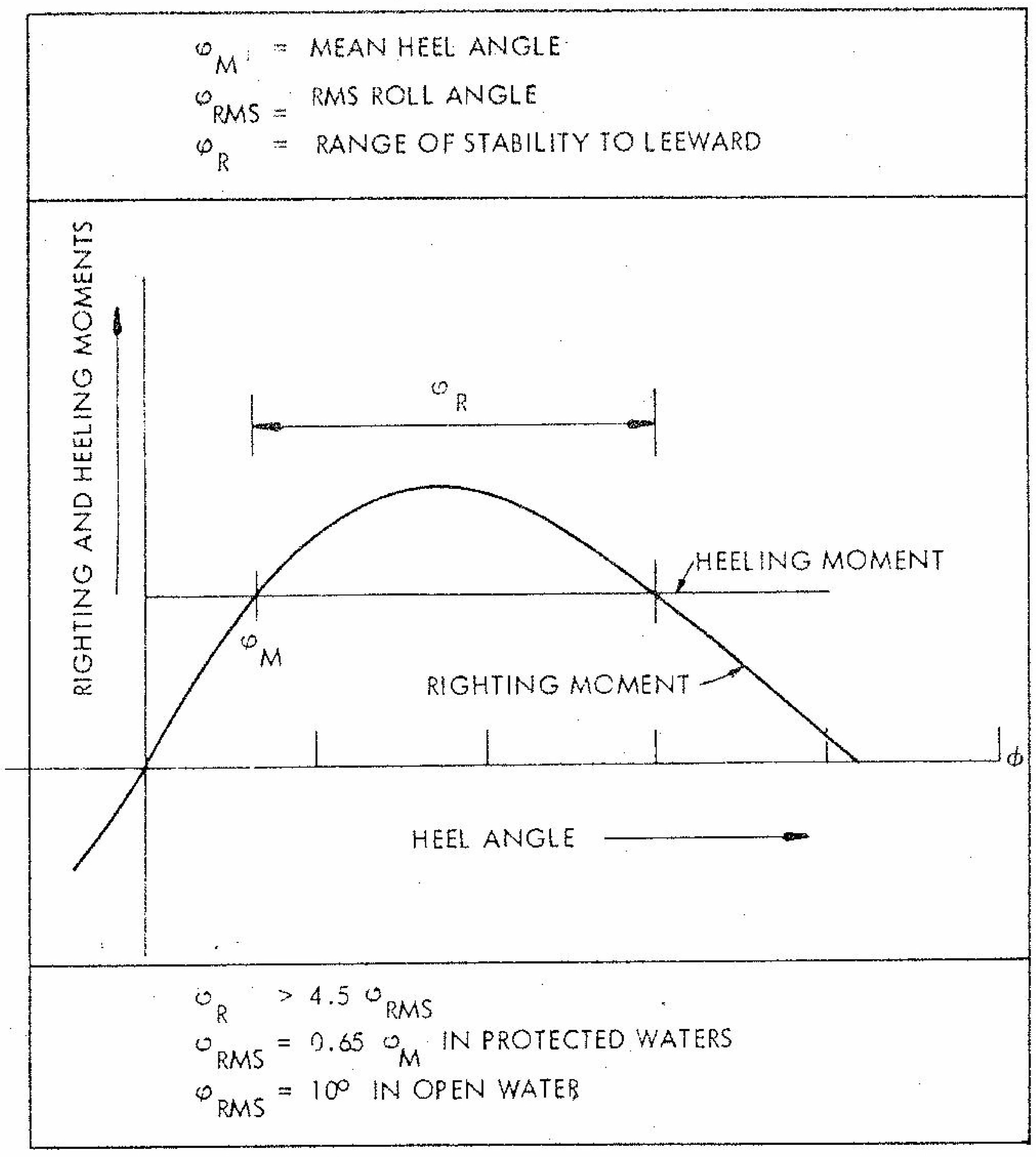


Fig. 24 Stability requirements for rolling with wind heel

For the supply vessels in load condition 2, the following-seas criterion is most stringent. Both vessels in the sample satisfy the proposed tripping criteria and the water-on-deck criteria. The wind heel criterion is satisfied in one case, and an 11 percent increase in *GM* would satisfy it in the other case.

For fishing vessels in load condition 1, the stringency of the proposed criteria is about the same as for the IMCO criteria. However, for fishing vessels in load condition 2, the proposed set is more stringent than the current IMCO criteria. The wind heel criterion is limiting in most cases. In many cases, however, the increase in *GM* required for compliance is not large. For example, an average increase in *GM* of 16 percent for those vessels which do not satisfy the proposed wind heel criterion would increase the level of compliance to 86 percent, the same as for the current IMCO criteria.

Based on the foregoing observations, it may be expected that the proposed set of criteria and the current USCG towing criterion would have a significant impact on the towing vessel fleet. The impact of the proposed set of criteria would be less, since a smaller increase in *GM* is required and the designer has more parameters that can be altered. Assuming that power plant and propulsion arrangements were fixed, the variables

Table 8 Percentages of U.S. towing, fishing, and supply vessel fleets meeting existin[...] ...ed criteria
(dashes indicate vessel types were not evaluated under listed crite[...]

	Vessels	Tow tripping	Self-tripping	Water on deck	Following seas	Wind heel (70 knots)	Total set
Load condition 1	Towing	65%	84%	50%	90%	85%	45%
	Supply	100%	100%	0%	0%	0%	0%
	Fishing	---	---	83%	78%	82%	69%
Load condition 2	Towing	84%	94%	94%	75%	53%	53%
	Supply	100%	100%	100%	0%	50%	0%
	Fishing	---	---	100%	75%	54%	50%

Table 9 Average of ratios of *GM* required for towing vessels by various stability criteria

Load condition	Murphy criterion	Present USCG towing vessel criterion	Proposed tripping criteria	Complete set of proposed criteria	Actual available *GM*
1	1.0	2.0	1.70	1.84	1.85
2	1.0	2.0	1.83	2.38	2.44

NOTES:
Based on sample of 20 towing vessels.
Table presents average of ratio of *GM* required by specific criterion divided by *GM* required by Murphy criterion.

include *KG*, freeboard, downflooding angle, and towing bit location as compared with only *KG* and freeboard in the current USCG criterion.

The proposed set of criteria would have a significant impact on the supply vessel fleet. The existing vessels would not be allowed to load as much deck cargo, and new designs would most likely need more freeboard aft. A more quantitative assessment of this should be made but was beyond the scope of this study. A larger number of supply vessels than the two included in the sample should be studied.

The proposed set of criteria would have only a limited impact on the fishing vessel fleet in load condition 1. In load condition 2, wind heel is the limiting criterion in most cases. A small increase in *GM* will bring a substantial percentage of the fleet into compliance.

U. S. Coast Guard regulations

In April 1976, the Coast Guard published an advance notice of proposed rulemaking in the Federal Register stating that the Coast Guard is considering rules on towing vessel stability based upon the research described in this paper. Interested persons were invited to participate in the determination of whether or not the study should be used as a basis for proposed rules. Comments received by July 1, 1976 were to be considered.

At the time of the writing of this paper, it is expected that the Coast Guard will publish in the Federal Register sometime early in 1977 a notice of proposed rulemaking on the minimum intact stability requirements for towing vessels and offshore supply vessels engaged in towing. Interested persons will then be invited to comment on the proposed regulations.

IMCO activities

A report of this research has been submitted to the IMCO Sub-Committee on Subdivision, Stability and Load Lines. The Sub-Committee is presently developing an intact stability criterion for offshore supply vessels. The results of this research will be used as guidance by the United States and other countries in modifying the existing IMCO criterion for passenger and cargo ships under 328 ft (100 m) for application to offshore supply vessels.

The International Convention on Fishing Vessels, which is expected to convene in the spring of 1977, will have intact stability standards as one item on its agenda. The results of this research will enable U. S. delegates to present factual evidence of the stability characteristics of U. S. fishing vessels.

Conclusion

Although not defintive, this research, in our opinion, advanced the knowledge of capsizing phenomena for small vessels. A number of specific conclusions can be drawn from the test results:

1. Three capsizing modes in waves were observed: (*a*) Low-speed operations in steep head or following seas, possibly with a tow, in which water on deck causes capsizing; (*b*) high-speed operation in following seas in which the loss of stability when the vessel is on the wave crest causes capsizing; and (*c*) beam sea operations in which rolling combined with heeling moments due to wind and water on deck cause capsizing.
2. Some towing and fishing vessels with stability levels which may realistically occur are vulnerable to capsizing by wave-induced forces.
3. Capsizing when running free in following seas will occur only if the speed-length ratio is high; that is, about 1.
4. The buildup of water on deck is a primary or contributing factor in all of the seakeeping capsizings observed in the test program. This is a dynamic phenomenon, and is not necessarily eliminated by lowering the bulwark heights or increasing freeing port area.
5. Towing vessel tripping casualties are mostly due to tow tripping as opposed to self-tripping. The stability required to protect against tow tripping is generally larger than that required to protect against self-tripping.

A set of intact stability criteria can be developed which protect against specific capsizing hazard situations with their associated sea conditions. The set of proposed intact stability criteria were formulated from a generalization of model test results and other analyses. These criteria are generally empirical in nature and are simple enough to be evaluated without excessive computational effort.

The impact of the proposed set of criteria would be significant on the towing vessel and offshore supply vessel fleets. The impact on the fishing vessel fleet would be small for the full-load case.

Acknowledgment

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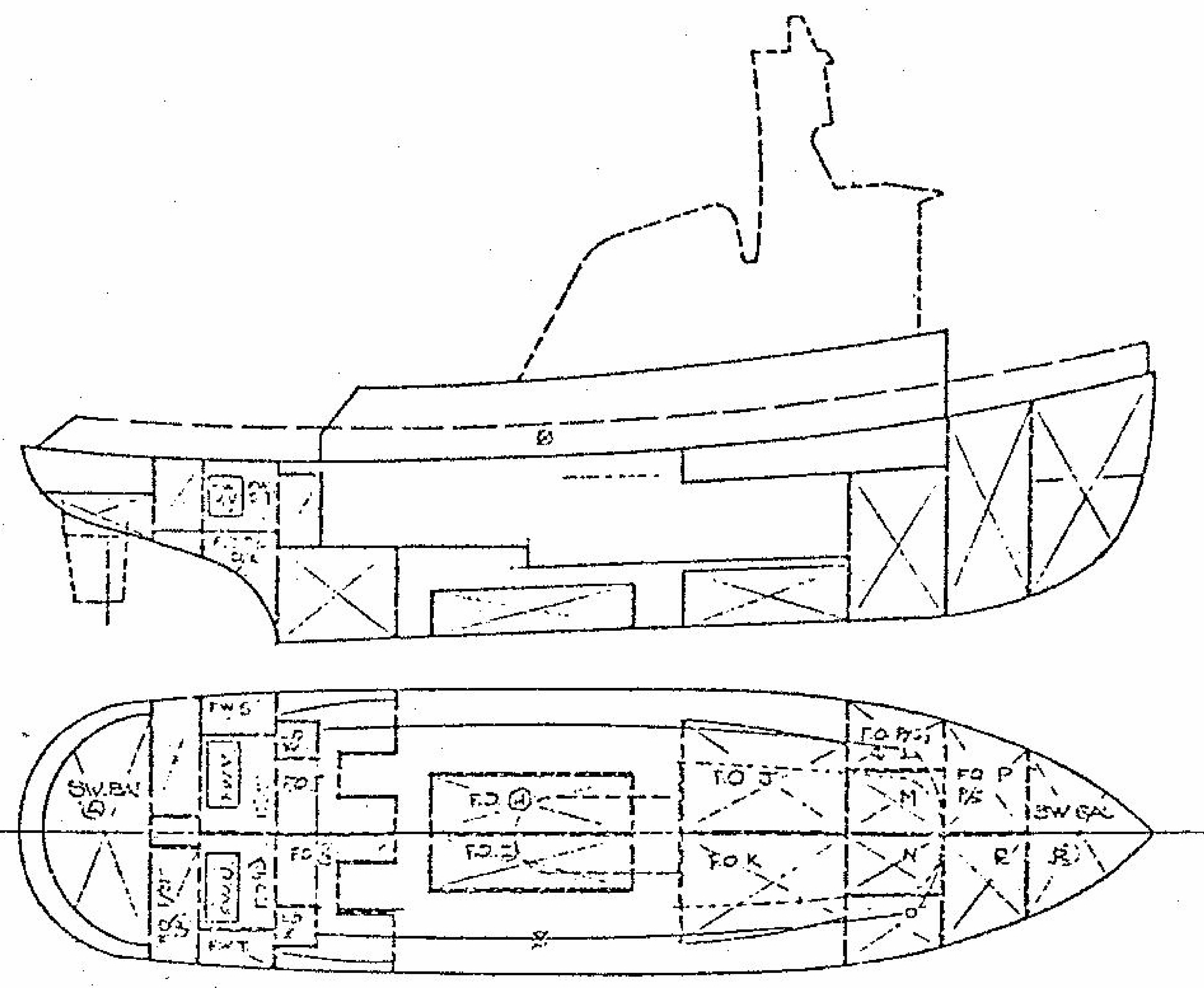
Appendix 1

Sample characteristic booklet



PRINCIPAL CHARACTERISTICS

LENGTH OVERALL	120.50 FEET
MOLDED BREADTH	31.500 FEET
MOLDED DEPTH AMIDSHIPS	18.726 FEET

PROPERTIES AT IMCO STANDARD DRAFT

WATERLINE LENGTH	118.61 FEET
BEAM AT SECTION OF MAXIMUM AREA	31.867 FEET
DISPLACEMENT	862.0 TONS

CONDITION 1 - FULL LOAD

	PCT	WEIGHT
FUEL OIL TANKS B & C	96	25.92
FUEL OIL TANKS D & E	96	12.50
FUEL OIL TANKS F & G	96	22.82
FUEL OIL TANKS H & I	96	26.98
FUEL OIL TANKS J & K	96	35.38
FUEL OIL TANKS L & O	96	22.94
FUEL OIL TANKS M & N	96	35.42
FUEL OIL TANKS P & Q	96	53.44
WASH WATER TANKS S & T	96	19.14
FRESH WATER TANKS U & V	96	10.04
LUBE OIL TANKS W & X	96	5.14
LIGHTSHIP		615.91
TOTAL DISPLACEMENT		885.63

T-01, BASIC DATA

AMIMCO 408.90	AWIMCO 3129.00	BHOB .0952	BHP 0.0	BIMCO 31.867
BIT 23.004	BOD 1.682	BOTS 2.002	BRDTH 31.500	CAMBR 0.0
CAPZ NO	CBS .5015	CHINE 0	CLASS TOWING	CMS .8061
CPS .6221	CWS .8278	DAFT 21.449	DEPTH 18.726	DFWD 25.464
DIA 10.000	DISK .333	DISPS 862.06	DLRS 516.6	DMIN 18.635
DOWN(1) 64.873	DOWN(2) 10.250	DOWN(3) 19.934	DRAG 2.795	FMINS 2.326
FOBS .0738	FOCSL(1) 0.0	FOCSL(2) 0.0	FPOL 0.0	FREE 18.630
GUARD 1.250	HITE 3.000	HOUSE(1) 47.430	HOUSE(2) 20.340	HOUSE(3) 0.0
HOUSE(4) 0.0	LSP 116.700	LIMCO 118.611	LOA 120.500	LOBS 3.722
LOD 6.435	NPK 11	NPM 31	NPS 31	OPER GULF
POOP(1) 0.0	POOP(2) 0.0	PRFCG 18.124	PROF 3610.300	PROPS 2
RDRCG 7.347	RUDR 89.120	SHAFT 5.221	SHEER 8.670	SHIFT(1) -1.013
SHIFT(2) 1.196	SHIFT(3) 0.0	SHP 0.0	SLOL .3936	SPEED 60.00
STERN SHIP	SWOB .6457	TIMCO 15.917	TODS .8500	TYPE OCEAN

REQUIRED FREEING PORT AREA, (IMCO) = 19.10

T-01, CONDITION 1
DATA AND CRITERIA

LWL 118.264	BEAM 31.810	DRAFT 16.264	TRIM -2.846	DISP 885.63
LCG 1.387	VCG 14.164	GM 3.519		
AC 1596.49	ACG 8.792	AM 420.00	AW 3157.00	BOT 1.956
CB .5066	CM .8118	CP .6241	CW .8392	DLR 535.4
FMIN 2.375	FOB .0747	GMOB .1106	HAO .248	KGOD .756
LOB 3.718	NPP 40	TOD .8685	XI(1) -.309	XI(2) 117.921

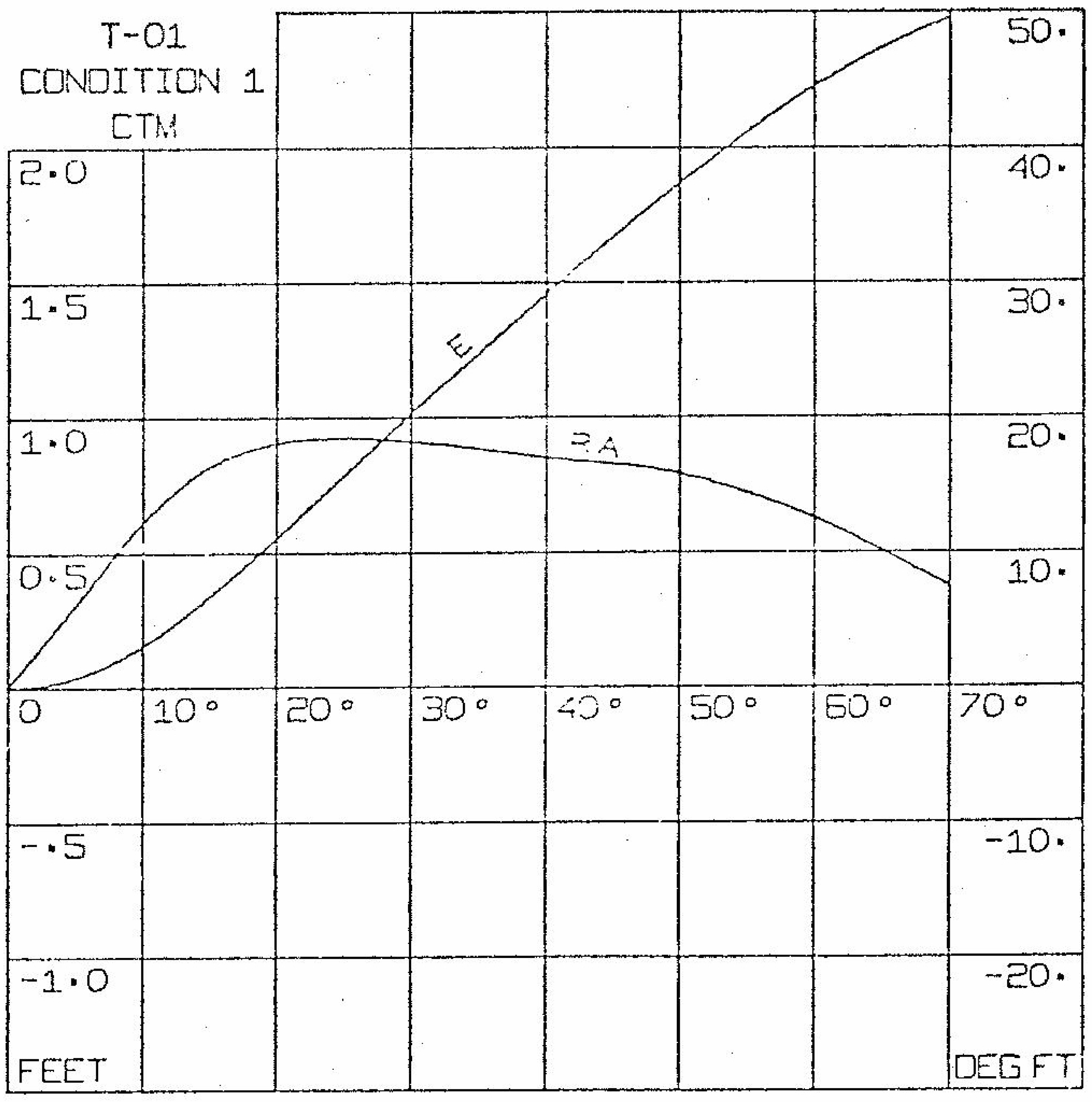
STATIC CRITERIA, (GM REQUIRED)

ARGYR 9.363	JAPAN 2.768	MURPHY 1.832	NORWAY 4.108	POLNSS 2.921
POLSIM 3.579	ROACH 6.840	ROOPDA 1.890	SIMCO 3.523	SOVIET 1.775
TOWNSL 2.785	USCGTV 3.664	WINDHL 2.556	WOOD 8.712	

DYNAMIC CRITERIA, (WHETHER SATISFIED)

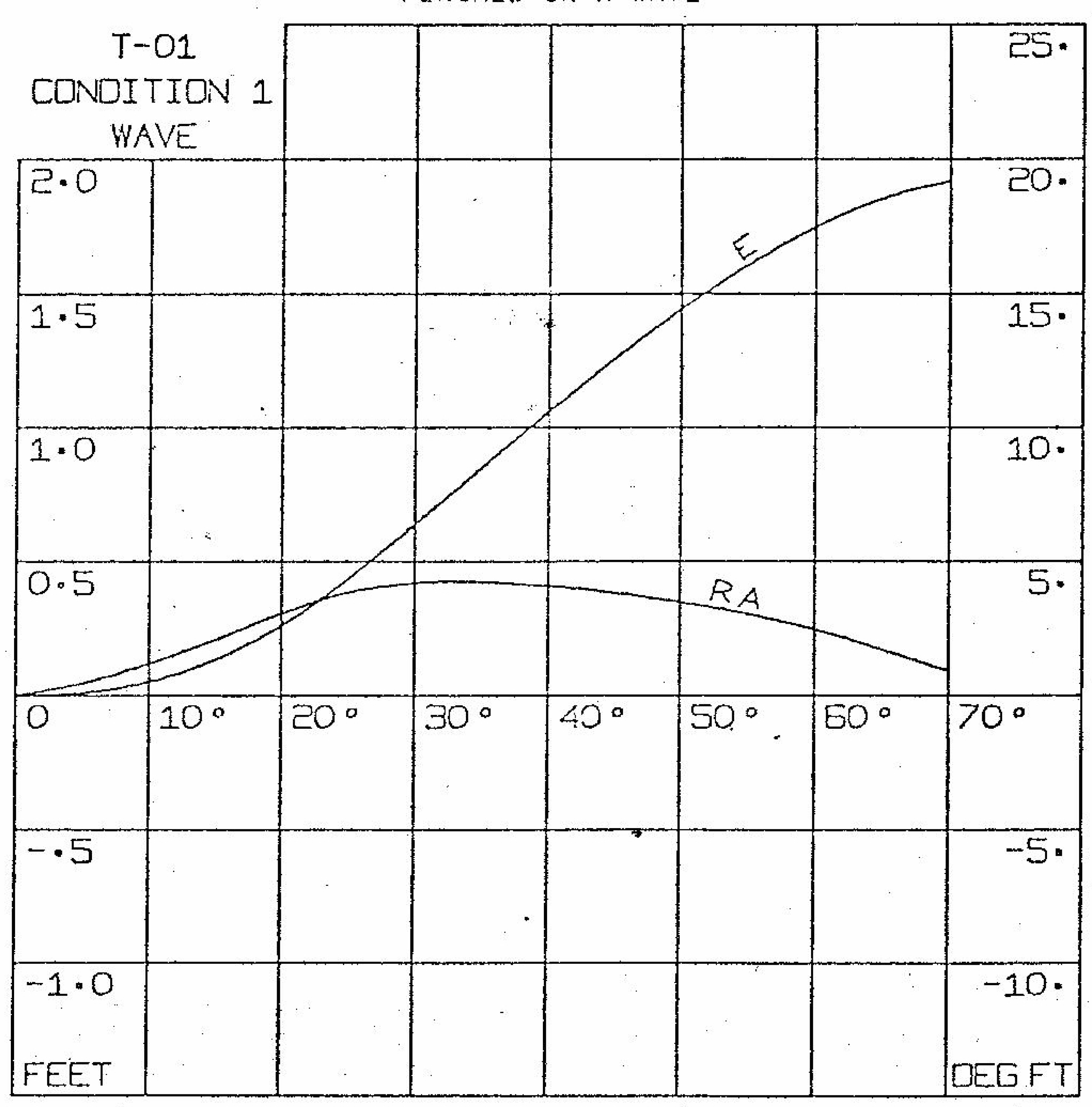
GERDYN CT N A CTM YES	IMCO CT N A CTM NO	LEATRD CT N A CTM NO	NAVY CT N A CTM YES	POLDYN CT N A CTM YES
RAHOLA CT N A CTM NO	SOVDYN CT N A CTM NO	USOTV CT N A CTM YES	USDYN CT N A CTM NO	

T-01, CONDITION 1
CONSTANT TRIM MOMENT



GMO	ANGDN	EDWN	ANGMX	GZMAX
3.519	19.72	10.82	25.25	.926
EMAX	E30	E40	WAVEHT	
15.88	20.25	29.05	0.0	
GZ05	GZ10	GZ15	GZ20	GZ25
.307	.612	.817	.905	.926
GZ30	GZ40	GZ50	GZ60	GZ70
.911	.851	.790	.626	.373

T-01, CONDITION 1
PERCHED ON A WAVE



GMO	ANGDN	EDWN	ANGMX	GZMAX
.532	0.0	0.0	33.00	.426
EMAX	E30	E40	WAVEHT	
7.67	6.40	10.61	11.880	
GZ05	GZ10	GZ15	GZ20	GZ25
.047	.120	.208	.307	.385
GZ30	GZ40	GZ50	GZ60	GZ70
.420	.409	.349	.247	.092

Appendix 2

Definitions

ACRONYM	DEFINITION
AC	CENTERLINE PLANE AREA UP TO THE WATERLINE.
ACG	HEIGHT ABOVE BASELINE OF CENTROID OF CENTERLINE PLANE AREA.
AM	MAXIMUM IMMERSED SECTION AREA.
AMIMCO	MAXIMUM IMMERSED SECTION AREA AT IMCO STANDARD DRAFT.
ANGDN	ANGLE OF DOWNFLOODING.
ANGMX	ANGLE OF MAXIMUM RIGHTING ARM.
ARGYR	STATIC STABILITY CRITERION PROPOSED BY ARGYRIADIS, (GM REQUIRED). SEE APPENDIX B.
AW	WATERPLANE AREA.
AWIMCO	WATER PLANE AREA AT IMCO STANDARD DRAFT.
BEAM	BEAM AT SECTION OF MAXIMUM AREA.
BHOB	BULWARK HEIGHT OVER THE BREADTH = HITE / BRDTH.
BHP	TOTAL BRAKE HORSEPOWER.
BIMCO	IMCO STANDARD WATERLINE BEAM AT SECTION OF MAXIMUM AREA.
BIT	HEIGHT OF TOWING BITT ABOVE BASELINE.
BOD	BREADTH TO DEPTH RATIO = BRDTH / DEPTH.
BOT	BEAM TO DRAFT RATIO = BEAM / DRAFT.
BOTS	BEAM TO DRAFT RATIO FOR IMCO STANDARD DRAFT = BIMCO / TIMCO.
BRDTH	MAXIMUM MOLDED BREADTH.
CAMBR	CAMBER IN MAIN DECK AT MAXIMUM BREADTH, (FEET).
CAPZ	CAPSIZE INDICATOR, (YES)-THE VESSEL HAS CAPSIZED, (NO)-THE VESSEL HAS NOT CAPSIZED.
CB	BLOCK COEFFICIENT = CP*CM.
CBS	BLOCK COEFFICIENT AT IMCO STANDARD DRAFT = CPS * CMS.
CHINE	NUMBER OF CHINES.
CLASS	VESSEL CLASS, (TOWING,FISHING,SUPPLY).
CM	IMMERSED MIDSHIP SECTION AREA COEFFICIENT = AM / (BEAM*DRAFT).
CMS	MAXIMUM SECTION COEFFICIENT AT IMCO STANDARD DRAFT = AMIMCO / (TIMCO*BIMCO).
CONDN	CONDITION NUMBER.
CP	PRISMATIC COEF = DISP*35. / (AM*LWL).
CPS	PRISMATIC COEFFICIENT AT IMCO STANDARD DRAFT = DISPS * 35. / (AMIMCO*LIMCO).
CW	WATERPLANE AREA COEFFICIENT = AW / (LWL*BEAM).
CWS	WATERPLANE COEFFICIENT AT IMCO STANDARD DRAFT = AWIMCO / (BIMCO*LIMCO).
DAFT	DEPTH AT AFTER PERPENDICULAR.
DEPTH	AMIDSHIPS DEPTH.
DFTRM	THE DRAFTS AND TRIMS AT EACH ANGLE OF HEEL.
DFWD	DEPTH AT FORWARD PERPENDICULAR.
DIA	PROPELLER DIAMETER IN FEET.
DISK	FRACTION OF PROPELLER DISC AREA BLANKED OUT BY RUDDER TURNED TO 45 DEGREES.
DISP	MOLDED DISPLACEMENT TO THE WATERLINE
DISPS	DISPLACEMENT AT IMCO STANDARD DRAFT.
DLR	DISPLACEMENT LENGTH RATIO = DISP / ((.01*LWL)**3).

ACRONYM	DEFINITION
DLRS	DISPLACEMENT LENGTH RATIO AT IMCO STANDARD DRAFT = DISPS / ((.01*LIMCO)**3).
DMIN	MINIMUM DEPTH AT SIDE.
DOWN	COORDINATES OF DOWNFLOODING POINT.
DRAFT	AMIDSHIPS DRAFT TO IMCO KEEL LINE
DRAG	DRAG OF KEEL MEASURED OVER LBP.
DTANG	DIFFERENCE IN THE VALUE OF ANGMX CAUSED BY TRIM.
DTEMX	DIFFERENCE IN THE VALUE OF EMAX CAUSED BY TRIM.
DTE30	DIFFERENCE IN THE VALUE OF E30 CAUSED BY TRIM.
DTE40	DIFFERENCE IN THE VALUE OF E40 CAUSED BY TRIM.
DTGZM	DIFFERENCE IN THE VALUE OF GZMAX CAUSED BY TRIM.
DWANG	DIFFERENCE IN THE VALUE OF ANGMX CAUSED BY A WAVE.
DWEMX	DIFFERENCE IN THE VALUE OF EMAX CAUSED BY A WAVE.
DWE30	DIFFERENCE IN THE VALUE OF E30 CAUSED BY A WAVE.
DWE40	DIFFERENCE IN THE VALUE OF E40 CAUSED BY A WAVE.
DWGMO	DIFFERENCE IN THE VALUE OF GMO CAUSED BY A WAVE.
DWGZM	DIFFERENCE IN THE VALUE OF GZMAX CAUSED BY A WAVE.
EDWN	AREA UNDER THE RIGHTING ARM CURVE UP TO THE ANGLE OF DOWNFLOODING.
EMAX	AREA UNDER THE RIGHTING ARM CURVE UP TO THE ANGLE OF MAXIMUM RIGHTING ARM.
E30	AREA UNDER THE RIGHTING ARM CURVE UP TO AN ANGLE OF HEEL OF 30 DEGREES.
E40	AREA UNDER THE RIGHTING ARM CURVE UP TO AN ANGLE OF HEEL OF 40 DEGREES.
FMIN	MINIMUM ACTUAL FREEBOARD.
FMINS	MINIMUM FREEBOARD AT IMCO STANDARD DRAFT.
FOB	MINIMUM FREEBOARD TO BEAM RATIO = FMIN / BEAM.
FOBS	FREEBOARD OVER BREADTH RATIO FOR IMCO STANDARD DRAFT = FMIN / BRDTH.
FOCSL	LENGTH AND HEIGHT OF FORECASTLE.
FPOL	COMBINED LENGTH OF THE FORECASTLE AND POOP DIVIDED BY THE VESSEL'S LENGTH. TO BE INCLUDED THE HEIGHT MUST BE GREATER THAN 5.9055 FEET.
FREE	FREEING PORT AREA.
FREEPT	FREEING PORT AREA REQUIRED BY IMCO. SEE APPENDIX B.
GERDYN	GERMAN DYNAMIC STABILITY CRITERIA, (YES)-IF SATISFIED, (NO)-IF NOT SATISFIED, (N A)-IF DATA IS NOT AVAILABLE. SEE APPENDIX C.
GM	UPRIGHT TRANSVERSE METACENTRIC HEIGHT.
GMOB	METACENTRIC HEIGHT TO BEAM RATIO = GM / BEAM.
GMO	SLOPE OF THE RIGHTING ARM CURVE AT AN ANGLE OF HEEL OF ZERO DEGREES.
GUARD	DISTANCE THAT THE GUARD EXTENDS BEYOND THE MOLDED LINES.
GZMAX	VALUE OF THE MAXIMUM RIGHTING ARM.
GZ05	RIGHTING ARM AT 5 DEGREES HEEL.
GZ10	RIGHTING ARM AT 10 DEGREES HEEL.
GZ15	RIGHTING ARM AT 15 DEGREES HEEL.
GZ20	RIGHTING ARM AT 20 DEGREES HEEL.
GZ25	RIGHTING ARM AT 25 DEGREES HEEL.
GZ30	RIGHTING ARM AT 30 DEGREES HEEL.
GZ40	RIGHTING ARM AT 40 DEGREES HEEL.
GZ50	RIGHTING ARM AT 50 DEGREES HEEL.
GZ60	RIGHTING ARM AT 60 DEGREES HEEL.

ACRONYM	DEFINITION
GZ70	RIGHTING ARM AT 70 DEGREES HEEL.
HAO	THE NAVY WIND HEELING ARM AT ZERO DEGREES.
HITE	AVERAGE HEIGHT OF BULWARK.
HOUSE	DIMENSIONS OF DECK HOUSES, 1,2-LENGTH AND BREADTH OF FORWARD HOUSE, 3,4-LENGTH AND BREADTH OF AFTER HOUSE.
ID	VESSEL IDENTIFICATION.
IMCO	IMCO DYNAMIC STABILITY CRITERIA, (YES)-IF SATISFIED, (NO)-IF NOT SATISFIED, (N A)-IF DATA IS NOT AVAILABLE. SEE APPENDIX C.
JAPAN	JAPAN FISH BOAT RULES, (GM REQUIRED). SEE APPENDIX B.
KGOD	KG OVER DEPTH RATIO = VCG / DEPTH.
LBP	LENGTH BETWEEN PERPENDICULARS, (AS DEFINED BY THE DESIGNER).
LCG	LONGITUDINAL CENTER OF GRAVITY, MEASURED FROM MIDSHIPS, (POSITIVE FORWARD).
LEATRD	DYNAMIC STABILITY CRITERIA PROPOSED BY LEATHARD, (YES)-SATISFIED, (NO)-NOT SATISFIED, (N A)-IF DATA IS NOT AVAILABLE. SEE APPENDIX C.
LIMCO	IMCO STANDARD WATERLINE LENGTH.
LOA	LENGTH OVERALL.
LOB	LENGTH TO BEAM RATIO = LWL / BEAM.
LOBS	WATERLINE LENGTH OVER BEAM RATIO FOR IMCO STANDARD DRAFT = LIMCO / BIMCO.
LOD	LENGTH TO DEPTH RATIO = LOA / DEPTH.
LWL	LENGTH ON WATERLINE.
METHOD	CALCULATION METHOD INDICATOR, (CT)-CONSTANT TRIM, (CTM)-CONSTANT TRIM MOMENT, (WAVE)-PERCHED ON A WAVE.
MURPHY	STATIC STABILITY CRITERION PROPOSED BY MURPHY, (GM REQUIRED). SEE APPENDIX B.
NAVY	NAVY DYNAMIC WIND HEEL STABILITY CRITERIA. (YES)-SATISFIED, (NO)-NOT SATISFIED, (N A)-IF DATA IS NOT AVAILABLE. SEE APPENDIX C.
NORWAY	PROPOSED NORWEGIAN STANDARD CRITERION, (GM REQUIRED). SEE APPENDIX B.
NPK	NUMBER OF POINTS CODED FOR FLAT PLATE KEELS OR SKEGS.
NPM	NUMBER OF POINTS CODED ALONG THE MOLDED CENTERLINE.
NPP	NUMBER OF POINTS CODED ALONG THE ABOVE THE SHEER PROFILE.
NPS	NUMBER OF POINTS CODED ALONG THE SHEER.
OPER	AREA OF OPERATION, (ATLANTIC,GULF,PACIFIC).
POLDYN	POLAND DYNAMIC STABILITY CRITERIA, (YES)-IF SATISFIED, (NO)-IF NOT SATISFIED, (N A)-IF DATA IS NOT AVAILABLE. SEE APPENDIX C.
POLNSS	POLISH NOT SO SIMPLIFIED CRITERION, (GM REQUIRED). SEE APPENDIX B.
POLSIM	POLISH SIMPLIFIED CRITERION, (GM REQUIRED). SEE APPENDIX B.
POOP	LENGTH AND HEIGHT OF POOP.
PRFCG	HEIGHT ABOVE BASELINE OF CENTROID OF WHOLE PROFILE AREA.
PROF	AREA OF WHOLE PROFILE ABOVE AND BELOW WATER LINE.
PROPS	NUMBER OF PROPELLERS.
RAHOLA	DYNAMIC STABILITY CRITERIA PROPOSED BY RAHOLA, (YES)-SATISFIED, (NO)-NOT SATISFIED, (N A)-IF DATA IS NOT AVAILABLE. SEE APPENDIX C.
RDRCG	HEIGHT ABOVE BASELINE OF CENTROID OF RUDDER AREA.
ROACH	MINIMUM GM REQUIRED BY ROACH TOWLINE PULL CRITERION. SEE APPENDIX B.

ACRONYM	DEFINITION
ROORDA	STATIC STABILITY CRITERION PROPOSED BY ROORDA, (GM REQUIRED). SEE APPENDIX B.
RUDR	TOTAL RUDDER AREA.
SHAFT	HEIGHT ABOVE BASELINE OF PROPELLER CENTERLINE AT RUDDER STOCK CENTERLINE.
SHEER	DIFFERENCE BETWEEN MAXIMIM AND MINIMUM HEIGHTS OF FREEBOARD DECK.
SHIFT	CONVERSION FROM DESIGNER'S BASELINE TO IMCO BASELINE.
SHP	TOTAL SHAFT HORSEPOWER.
SIMCO	IMCO SIMPLIFIED CRITERION, (GM REQUIRED). SEE APPENDIX B.
SLOL	COMBINED LENGTH OF THE HOUSES OVER THE VESSEL'S LENGTH.
SOVDYN	SOVIET UNION DYNAMIC STABILITY CRITERIA, (YES)-IF SATISFIED, (NO)-IF NOT SATISFIED, (N A)-IF DATA IS NOT AVAILABLE. SEE APPENDIX C.
SOVIET	SOVIET SIMPLIFIED CRITERION, (GM REQUIRED). SEE APPENDIX B.
SPEED	WIND SPEED USED TO CALCULATE THE NAVY WIND HEELING MOMENT.
STERN	TYPE OF STERN, SHIP TYPE-(SHIP), TRANSOM-(TRAN), COMBINATION-(COMB).
SWOB	AVERAGE WIDTH OF THE HOUSES OVER THE VESSEL'S BREADTH.
TIMCO	IMCO STANDARD DRAFT.
TOD	DRAFT TO DEPTH RATIO = DRAFT / DEPTH.
TODS	DRAFT TO DEPTH RATIO FOR IMCO STANDARD DRAFT = TIMCO / DEPTH.
TOWNSD	STATIC STABILITY CRITERION PROPOSED BY TOWNSEND, (GM REQUIRED). SEE APPENDIX B.
TRIM	TRIM OF THE VESSEL RELATIVE TO IMCO STANDARD WATERLINE, (POSITIVE BY THE STERN).
TYPE	VESSEL TYPE, A TERM OR NAME TO IDENTIFY A PARTICULAR TYPE OF VESSEL WITHIN A CLASS OR DESCRIBE THE INTENDED USE OF THE VESSEL.
USCGTV	USCG TOWING VESSEL CRITERION, (GM REQUIRED). SEE APPENDIX B.
USDTV	USCG DYNAMIC TOWING VESSEL CRITERIA, (YES)-IF SATISFIED, (NO)-IF NOT SATISFIED, (N A)-IF DATA NOT AVAILABLE OR NOT APPLICABLE. SEE APPENDIX C.
USDYN	USCG DYNAMIC STABILITY CRITERIA, (YES)-IF SATISFIED, (NO)-IF NOT SATISFIED, (N A)-IF DATA IS NOT AVAILABLE. SEE APPENDIX C.
VCG	VERTICAL CENTER OF GRAVITY, MEASURED FROM THE IMCO BASELINE.
WAVEHT	THE WAVE HEIGHT USED IN CALCULATING THE RIGHTING ARM CURVE.
WINDHL	COAST GUARD WIND HEEL CRITERION, (GM REQUIRED). SEE APPENDIX B.
WOOD	STATIC STABILITY CRITERION PROPOSED BY WOOD, (GM REQUIRED). SEE APPENDIX B.
WVOL	VOLUME OF THE DECK WELL AT ZERO HEEL AND TRIM.
XI	X COORDINATES OF THE INTERSECTION OF THE WATERLINE WITH THE MOLDED CENTERLINE.

Appendix 3

"Static" stability criteria

1. ARGYRIADIS

```
GMR = SHP * (BIT-ACG)/(100 * DISP * (FMIN/BRDTH))
```

2. JAPAN FISH BOAT RULES

For seiners,GM is to be the larger of:

```
GMR = (BRDTH/23.0) + .8858
GMR = (LIMCO/120.0) + .8858
```

For other fishing vessels:

For BRDTH less than 22.966' GM is to be the larger of:

```
GMR = (BRDTH/25.0) + .3937
GMR = (LIMCO/150.0) + .3937
```

For BRDTH greater than or equal to 22.966' GM is to be the larger of:

```
GMR = ((BRDTH/3.28083  - 7.0)/12.0 + .4) * 3.28083
GMR = (LIMCO/3.28083 - 4.2)/72.0 + .4) * 3.28083
```

3. MURPHY

```
GMR = A/B
WHERE A = PROPS * ((SHP*DIA/PROPS)**0.667)*DISK*(BIT-SHAFT)
      B = 76.0*DISP*FMIN/BRDTH
```

4. PROPOSED NORWEGIAN STANDARD

```
GMR = ((BIT - DRAFT/2.0)/5.0*FMIN)*3.28083
```

5. POLISH NOT SO SIMPLIFIED CRITERION

```
GMR = 1.3123-2.0*BRDTH*(XMS+XMS2)
WHERE XMS = -0.061+.376*FMIN/BRDTH-.831*(FMIN/BRDTH)**2.0
      XMS2 = .007*BRDTH/DMIN +.028*(FOCSL+POOP)/LIMCO
```

6. POLISH SIMPLIFIED CRITERION

```
GMR = DMIN *(.105-.706*FMIN/BRDTH+.083*BRDTH/DMIN)
```

7. ROACH

```
GMR = BHP*15.0*(BIT-ACG)/(DISP*(FMIN/BRDTH)*2240.)
```

8. ROORDA

```
GMR = .06*BRDTH
```

9. IMCO SIMPLIFIED CRITERION

```
GMR = 1.7388+2.0*BEAM*(GM1+GM2)
WHERE GM1 = .075-.37*FMIN/BEAM+.82*(FMIN/BEAM)**2.
      GM2 = -.014*BEAM/DMIN -.032*(FOCSL+POOP)/LWL
```

FORECASTLE AND POOP ARE TAKEN INTO ACCOUNT ONLY IF THEY HAVE HEIGHTS OF AT LEAST 5.9055'

10. SOVIET SIMPLIFIED CRITERION

```
GMR = DMIN *(-0.47-0.35*FMIN/BRDTH+.35*BRDTH/DMIN)
```

11. TOWNSEND

```
GMR = 0.08*(BRDTH**2.0)/(12.0*FMIN)
```

12. USCG TOWING VESSEL CRITERION

```
GMR = A/B
WHERE A = PROPS*((SHP*DIA/PROPS)**.6667)*DISK*(BIT-SHAFT)
      B = 38.0*DISP*FMIN/BRDTH
```

13. WIND HEEL

```
GMR = XP*(PROF-AC)*H/(DISP*FMIN/BRDTH)
WHERE XP = .005+((LBP/14200.)**2.0)
      A = PROF-AC
```

H = (PRFCG*PROF-ACG*AC)/(PROF-AC)-ACG
(FMIN/BRDTH) is not to be taken as greater than 0.24933

14. WOOD

GMR =((SHP*DIA/PROPS)**.667)*(BIT-SHAFT)/24.*DISP*(FMIN/BRDTH)

15. IMCO FREEING PORT AREA

XL is the length of the well, and is not to be taken as greater than 0.7* LIMCO

WHERE XL is 65.617' or less, the basic required area
AR = 7.535 + .115*XL

WHERE XL is greater than 65.617'
AR = .23*XL

If HITE is greater than 3.937' a correction
COR = .04*XL*(HITE-3.937)
is added to AR

If HITE is less than 2.953' a correction
COR = .04*XL*(2.953-HITE)
is subtracted from AR

Appendix 4

"Dynamic" stability criteria

1. 1. GERMAN DEMOCRATIC REPUBLIC STABILITY CRITERION

GZ30 not less than 0.82 ft.
GZ60 must be positive

2. 2. IMCO DYNAMIC STABILITY CRITERION

E30 not less than 10.3 Ft-Deg.
EDWN not less than 16.9 Ft-Deg.
E40 not less than 16.9 Ft-Deg.
E40-E30 not less than 5.6 Ft-Deg.
EDWN-E30 not less than 5.6 Ft-Deg.
ANGMX not less than 25 deg.
GZ not less than .656 Ft. at an angle of heel equal to or greater than 30°
GM not less than 1.148 Ft.

3. LEATHARD

GM = 1.+ .02*LIMCO
GZMAX = 0.00833*LIMCO+.25
GZ60 must be positive
FMIN not less than .02*LIMCO+.5
2.0*FIM/BRDTH not less than 0.1763
ANGMX must be greater than 30°

4. NAVY CRITERION

The heeling arm at the intersection of the heeling arm and righting arm curves is to be not greater than 0.6 GZMAX

The area between the heeling and righting arm curves in the range between their two intersections is to be at least 1.4 times the area between the curves in the range from their first intersection to 25° to windward of that point.

5. POLISH DYNAMIC CRITERION

GZ30 not less than 0.656 Ft.
GZ60 must be positive
GM must be positive

6. RAHOLA

GZMAX not less than 0.656 ft.
ANGMX not less than 30 deg.
EMAX not less than 15.038 deg.ft.

7. SOVIET UNION DYNAMIC STABILITY CRITERION

GZMAX not less than 0.82 ft.
ANGMX not less than 30 deg.
GZ60 must be positive

8. U.S. DYNAMIC TOWING VESSEL

Applied against the righting arm curve is a heeling moment arm HA = 2*PROPS*DISK*(BIT-SHAFT)*COSØ*((SHP*DIA/PROPS)**0.667)/38.0*DISP)

Equilibrium must be reached before the angle of downflooding. The residual righting energy up to the maximum righting arm, 40 degrees, or the angle of downflooding, whichever is least, must be at least 2 ft-degrees.

9. U.S. DYNAMIC CRITERION

E value to ANGMX, ANGDN, or 40 degrees, whichever is least, must be at least 16.9 ft-degrees.

E40-E30, or EDWN-E30 if ANGDN is less than 40 degrees, must be at least 5.6 ft-degrees.

ANGMX to be at least 25°

GZ60 must be positive.

Discussion

Corning Townsend III,[6] Visitor

The authors acknowledge that this specific type of criterion cannot be applied to vessels which are drastically different than those investigated. This is especially true when trying to generalize ship dynamics from the results of just a few tests. What then are the limits of the important parameters, such as bulwark height, bilge keels, beam draft ratio, brake horsepower, and length, that are considered acceptable for the proposed criteria?

The authors suggest that a less severe criterion for following seas could be used when designing vessels expected to operate in areas of good weather. However, righting energy (or E_{40} value) is only slightly changeable after a vessel is built, which might jeopardize the future use and/or resale of that vessel.

[6] Townsend Marine Consultants, Georgetown, Connecticut.

Perhaps a single wave height to wave length ratio in conjunction with a loadline which already varies with seasonal and world location would produce the same degree of safety and stability that the authors desire.

It surprises me that in the development of a criterion for stability with water on the aft deck, freeboard at the transom is essentially inconsequential. For instance, with a 120-ft vessel the required E_{40} obtained from Fig. 19 is the same if the designed freeboard at the transom is 0 in. or 27 in. This does not seem realistic and encourages low freeboard aft, which is dangerous for a working platform. Also, the required E_{40} is 0 ft-deg for a 120-ft vessel having a transom freeboard of 5.4 ft, for instance, a GZ curve with a value of 0 ft from 0 to 40 deg. Some other criteria would obviously govern, but why is a criterion like this created? Perhaps too many types of vessels are incorporated into one set of rules.

In the fleet impact study, it was found that on the average the complete set of proposed criteria required 19 percent more *GM* than the existing USCG criteria. This would mean stiffer boats with higher roll accelerations and reduced crew comfort.

Is it possible to form a meaningful safety criterion which would incorporate an upper limit on roll acceleration experienced in normally occupied areas of the vessel? This would put an upper limit on the stiffness and indirectly on *GM*. Consequently, an absolute minimum on range would have to be enforced. For *this* criterion, I would suggest adopting the IMCO definition of downflooding and require a range from 0 deg to downflooding of about 75 deg.

Odo Krappinger, Member

First I should like to expatiate a bit on the statement the authors have made in the Introduction of their paper on previous work in the general area of intact stability. In former times many papers dealt with suggestions for better ways to calculate curves of stability. Many of them procured the impression that safety against capsizing depends only on the improvements of these calculations. The availability of computers for stability calculations has stopped this kind of paper as well as the idea that a more accurate calculation of the righting levers can solve the problem. Nowadays papers on intact stability of ships mostly deal with the physical phenomenon of capsizing. Although some of them have largely extended our insight into some aspects of the problem, they do not provide practical solutions. Because of the complexity of the problems, theoretical approaches have to be restricted to artificially bounded cases. Therefore, they are not suited to judge the actual safety against capsizing in spite of the fact that some experts mistake the sophistication of calculations for their actual validity.

In a recent paper[7] I tried to indicate in more detail all the reasons why we cannot expect to find a comprehensive and physically correct procedure for dealing with safety against capsizing in the foreseeable future. As a consequence I suggested in rather general terms a procedure that is very similar to the one the authors have chosen in their paper. It is the explicit definition of various hazard situations and the development of simple mathematical models (that is, criteria) for specific situations which allow discrimination between safe and unsafe cases.

To my knowledge the authors are the first to have successfully applied this philosophy in a comprehensive manner. Moreover, they have demonstrated how model tests combined with other information can most efficiently be used. I am glad that they have submitted a report of their research to IMCO; it may well have a pilot effect for the further work of this body. In the proposed frame for criteria development it should be possible to include also the results of other investigations in order to provide a more detailed definition of hazard situations as well as a broader base for specific criteria. As an example I would like to mention that capsizing experiments recently carried out in the Hamburg Ship Model Basin with a model of a fishing vessel in an irregular sea have led to a quite different conclusion than that reached in the paper with regard to the effect of water on deck: With increasing open deck area, the vessel became safer. At the same time the safety decreased with increasing freeboard-to-draft ratio for all investigated variations of the deck area.

In more complex cases the formulation of criteria may be facilitated by using the discriminant analysis. Its application to stability problems has been described by Sharma and the discusser.[8]

A. Morrall,[9] Visitor

The authors have presented a detailed and informative paper on the subject of intact stability. They have identified dangerous capsize situations and developed stability criteria for towing and fishing vessels. This paper will undoubtedly have an influence on the forthcoming International Fishing Vessel Convention.

As capsizing may occur as a result of numerous possible situations, it is practically impossible to establish a model for each configuration. Moreover, the degree of safety associated with each situation would depend in part on the prevailing sea conditions. Although the main reasons for capsizing can be expected to be similar for vessels of a certain type, it would be useful to know how to characterize the range in which the dominant situation is appropriate. Could the authors comment on this point and indicate the ship parameters that are most relevant to the stability criteria formulated?

The authors have investigated the complex problem of water on deck that may cause a substantial decrease in the vessel's stability. It is surprising that no mention is made of the dynamic influence of water trapped between deckhouse and bulwark on the 'pseudo-static' angle of heel, or that intense flooding of the deck in beam waves occurs at particular values of wave frequency as found by other researchers.

The vigorous treatment of ship response to wind and waves is to be commended and the finding that the classic wind heel criterion does not relate to the real dynamics of the situation is most relevant. However, the simple wind criterion formulated implies that the range of stability must be greater than 55 deg, a requirement that is not always possible for fishing and towing vessels. The most arbitrary assumption in this criterion is in the selection of the rms roll angle as stated, and this requires further study before any implementation. Could the authors therefore recommend this simple criterion to the International Fishing Vessel Convention?

In a sense the experiments are contrived events that would normally happen in nature. The authors have enlarged on the repertoire of these events and suggested possible stability criteria to prevent capsize. Could they comment on whether the criteria formulated would have been different if the experiments had been conducted in irregular waves instead of regular waves? It would be of interest to know the margins of safety implied in stability criteria and more importantly the range of ship parameters over which the criteria are valid.

N. Hamlin, Member

This discussion is directed at the rolling-in-beam-seas question.

As a senior thesis at Webb Institute in 1975, Messrs. Ostrowski and Wendel built a one-thirtieth scale, fiberglass, compartmented model of a 166-ft off-shore supply vessel, and tested it in the Robinson Model Basin at zero speed in waves from abeam to the point of capsize. Regular waves were used for most tests. Some findings which may be of interest in the search for stability criteria are as follows:

- As designed, the vessel had inherently large stability. At the design draft of 10.1 ft, with the $\overline{GM}$ required for the ship of 6.6 ft, capsizing could not be produced by any combination of wave height and period available. With *GM* reduced to 3.8 ft by raising the center of gravity, capsizing took place when

[7] "Stability of Ships and Modern Safety Concepts," *Proceedings*, International Conference on Stability of Ships and Ocean Vehicles, Glasgow, 1975.

[8] Krappinger, O. and Sharma, S. D., "Sicherheit in der Schiffstechnik," *Jahrbuch der Schiffbautechnischen Gesellschaft*, 1974, pp. 329–355.

[9] National Maritime Institute, Middlesex, England.

heavy rolling occurred with shipping of water on deck and with the model in waves of approximately twice the model's natural roll frequency—that is, rolling to port and then to starboard on successive crests.

- The wave height to cause capsize then decreased slightly as $\overline{GM}$ was increased by lowering the center of gravity. Thus, there may be a $\overline{GM}$ for minimum wave height to cause capsize, although this point was not explored in depth.
- When capsizing occurred, it always took place to windward.
- Capsizing took place at two drafts with a wave height representing about 13 ft when the $\overline{GM}$ was adjusted to give a scaled righting arm of 0.3 ft at a heel angle for deck edge immersion. This condition was tested for possible use in studies relating to the damage stability of passenger vessels, inasmuch as it represents a reference point in the equivalent 1960 SOLAS Rules, presented to the Society in 1974.
- The effect of bulwarks was detrimental in high waves; capsizing occurred with a lower wave height with the bulwarks in place (freeing ports open) than with the bulwarks removed. With the freeing ports closed, the wave height for capsize was further reduced. This suggests that, in writing regulations, some thought be given to freeing port configuration to assure that they not be blocked by deck cargo.
- Free water, whether trapped on deck by the bulwarks or in slack tanks below deck, frequently behaved as does the water in a passive antirolling tank, building up a 180-deg out-of-phase component which tended to reduce the roll.
- Under equal loading and deck conditions, capsizing occurred in irregular waves of a higher significant height than was needed to capsize the model in regular waves. This was believed to result from the continuity of shipping water on deck in regular waves, compared with the more sporadic shipping of water—albeit temporarily more pronounced—that took place in irregular waves.

The author's equation (7), and its manifestation, Fig. 21, represents a commendable study, but could they tell us how ζ_x, effective wave slope, was determined?

Robert Stanley, Member

I compliment the authors on this discrete, scientific approach to the problem of towboat and fishboat stability.

My observations are limited to the topic of operation in following seas. I think that an oversimplification has been made about the work done at U.C. Berkeley [11] on capsizing in following seas. That work noted, among other things, that hulls poised with wave crest at midship suffered dramatic loss of *GM* and deterioration of the static *GZ* curve. Further, when wave encounter frequency was twice the model roll frequency, rapid increase in roll amplitude followed by capsizing sometimes occurred within a few oscillations. The simplification that I am concerned about is the authors' attempt to relate their model response data principally to the stability of a hull poised on a wave crest. This relationship may be adequate for analysis of a family of geometrically similar hull forms, but I question its adequacy when applied to disparate hull forms such as S-04 and F-34.

The authors may have found otherwise, and I welcome their response. However, Fig. 19 indicates to me that a more rigorous examination is in order for the damped spring and mass system excited by an oscillating forcing function, which is a simplified analogy to the ship in following seas. The damping is a function of roll velocity, wave profile, hull shape, freeboard, etc. The spring is time variant, dependent on a changing center of buoyancy and waterplane shape. The forcing function is the seaway, wind, and towline or fishnet input to the ship. My concern is with the time-dependent damping and spring constants, which are functions of the entire hull shape rather than just the underwater characteristics when a wave crest is at midship. As reference [11] has shown, the critical case of following-sea operation often results in the large roll amplitudes occurring when the wave trough is at midship. Hence, the characteristics of the fore and afterbody, at large heel angles, appear to be important in allowing or preventing capsize. These characteristics may be amenable to analysis through comparison of three *GZ* curves: for crest at midship, trough at midship, and still water.

In lieu of calling for a new program to investigate roll damping and spring constant behavior in the context of a nonlinear dynamic situation, I urge the authors to reexamine the assumption that extreme rolling in following seas is dependent only on area under the *GZ* curve up to 40 deg when a wave crest is at midship. I suspect that Rahola [6] and others were on to something when they suggested that maximum *GZ* at some large heel angle, and some percentage of total "righting energy" between moderate and large heel angles, was desirable to prevent capsize. I do not doubt that the criteria presented in Fig. 19 are adequate to provide good safety. However, in the context of proposed rulemaking which the authors have shown will have great impact on the supply boat industry especially, I believe that they will need a more detailed analysis to back up their criteria.

John W. Gilbert, Member

The authors are to be commended on this highly informative paper. The stability criteria for towing and fishing vessels are of the utmost importance to those of us engaged in the design of these vessels. We have been involved in the design of all classes of towing and fishing boats, covering the complete range developed in the paper. In the absence of definitive stability criteria, certain standards have been used in establishing the required stability for certain types of vessels, particularly fishing vessels. New regulations resulting from studies such as this paper outlines are of serious concern to the industry.

It is significant that in the New England fishing industry there has not been a loss due to capsizing by either the standard New England side trawler/dragger or stern trawler, since the loss of the *Belle* in 1946, that can be ascribed to loss of stability due to action of the sea. One of the causes of tug losses on the East Coast has been the increased horsepower of new tugs, as well as the repowering of older tugs. It has been our practice to use several criteria, including the U.S. Coast Guard formula and Rahola. In modern tugs, increased freeboard is most beneficial, and is increased over that in common practice, as it is felt that the existing rules are inadequate.

On fishing vessels the stability criteria depend a great deal on the type of vessel and where it fishes. We presently use Canadian stability criteria for large fishing vessels, which are essentially IMCO, incorporating the accumulated winter ice for all operating conditions, as well as the worst operating condition. A concerted effort is also made to provide a seakindly vessel when meeting criteria, as they can often result in an overly stiff vessel that is difficult to work on. Shrimpboats generally exceed IMCO by a sizeable margin because of their heavy departure displacement for long trips. Menhaden fishing boats meet IMCO and are among the most difficult because of their shallow draft and small freeboard in the fully loaded condition.

The fishing vessel F-34 selected for analysis is a typical West Coast crab boat. These are not considered typical of good fishing vessel practice, and have suffered a relatively high casualty rate. Those brought to the East Coast for use in the herring fishery have suffered large numbers of capsizings. On vessels designed for similar service on the East Coast, it has been our practice of have greater freeboard and stability throughout the operating range. The East Coast hull form tends to have less deadweight capacity, be somewhat finer forward, with greater deadrise aft. The authors state that F-34 is a similar hull form to Atlantic Coast stern trawlers, which is only partly true. The maximum allowable draft over depth on the East Coast to which this type of vessel would be permitted loading would be approximately 0.8. Trawler designers today have to review the effect of free surface of flooding the fishhold, as these vessels often change fisheries from penned or boxed fish to crab, lobster, or herring in refrigerated seawater.

In Table 1, the bhp for some of the vessels we designed is as follows:

Vessel	Bhp
F-16	365
F-18	765
F-19	1500
F-20	425
F-28	665

In Table 2, it should be noted that the coefficients such as L/B are based on length on the waterline.

The waves used in the model test, although quite steep, are not unusual on the fishing grounds. On Georges Bank, breaking waves are not uncommon, particularly where the bottom shelves onto the banks. It is traditional practice, especially on wooden fishing boats, to lay to and drift with the wind and sea. Conventional trawler forms tend to lay broadside to, often with steadying sail to damp rolling. The wind criterion of 100 knots is reasonable. On a 100-ft fishing vessel in a 100-knot wind, the wind heel in gusts could be as high as 10 deg superimposed on a 20-deg roll. Stern trawlers tend to lay stern to, with the sea on the quarter. In this condition, they are reasonably comfortable and safe.

Small stern trawlers have posed new problems, particularly with regard to water on deck. With the fishing gear snagged on the bottom, the usual procedure to free it is to back over the gear while hauling back. In a following sea, the vessel will often board a sea completely over the stern and bury the after deck over the bulwarks. Stern gates help; however, there is still a wedging action produced by the stern ramp. In addition, shallow stern ramps found on larger trawlers with slope angles of 35 deg or less have, on occasion, been found to develop synchronous surging up the ramp that will fill the after deck rail to rail. The winter ice criterion usually insures sufficient additional stability to compensate for a flooded main deck. The small stern trawlers have increased sheer aft to provide freeboard at the head of the ramp and transom.

The regulatory requirements for scuppers have not really been accepted by the industry, as open scuppers contribute to flooding under certain conditions. The usual option on scuppers is to have vertical sliding gates over fairly large, deep scuppers that permit selection by the crew of the least flooding arrangement.

It would be appreciated if the authors could further develop how the capsize boundaries were established in Figs. 8, 9, and 11. The hazard of accumulated seawater on deck, described in the paper as one of the major contributions to capsizing, points out the need for a long range in righting arms under this condition, as larger angles of heel with a reasonable freeboard should permit the deck to drain over the rail, as well as through the scuppers. Openings, particularly through superstructure on a stern dragger, are kept as high as possible with weather covers.

Access openings are kept as close to centerline as possible. Under the proposed fishing vessel criteria, stability should be sufficient for cargo hoists to lift the maximum weight of fish to be brought aboard in one lift. On side trawlers, the current practice is to design for a hoist of 20 tons pulled from the hounds of the mast, due to limits of the winch and nets. Small stern trawlers are designed for a maximum lift up the ramp of 40 tons, which adds to the deck load.

The criteria were reviewed and found to be most informative; however, application to a number of vessels would have to be tried to fully evaluate their effects. From the paper it appears that none of the models were fitted with bilge keels, which is standard practice on most fishing vessels and tugs. With the increased vessel stiffness, roll damping will become more important. Oil supply boats are inherently self-damping by virture of large beam-to-draft ratio. Round-bottom tugs with high initial stability are bad performers in any kind of seaway.

The model testing utilized in this study was most thorough; however, it would be beneficial if additional hulls were used. The capabilities of both fishing vessels in the paper are limited; left unexplored is the behavior of many of the other types of fishing boats. Modern fishing techniques have evolved a number of boat types such as the king crab boat, herring seiner, and stern dragger which have not had the benefit of years of design evaluation found in the East Coast wooden dragger and traditional steel trawler. For this reason, the criteria proposed by this paper will serve as a guideline for design development where this experience is lacking and tradition is nonexistent.

As a contributor to some of the vessels considered in the study, I can think of many vessels that it would be desirable to study, if for no other reason than to have another parameter in understanding the stability criteria developed here.

Yingkei Mok, Member

While serving on the stability committee of the Offshore Marine Service Association, I had the opportunity to study the research reports in this paper, namely, references [7] and [14], as well as the Task Two Report earlier this year. It was decided that each member of the stability committee would study these reports and apply the proposed criteria to one or two of his latest designs in order to determine the impact of these proposed criteria to vessels of current design.

The committee members reported studies of eight vessels, four tugs, and four supply vessels. Three of the supply vessels did not meet the water-on-deck criterion and two of the supply vessels failed to meet the following-sea criterion. The tugs had less trouble meeting the criteria although they all failed the original tow-tripping criterion in reference [14] because the fraction ½ was left out.

I studied the effect of these proposed criteria on a 110-ft seagoing tug of typical Gulf of Mexico design with no forecastle. The position of the towpost on this vessel was 37 percent of the waterline length from the stern. It was during this study that I felt the authors had placed too much importance on the position of the towpost on the tow-tripping forces.

It was mentioned in the paper that towing point locations were varied during the tow-tripping tests. However, the authors did not present the effect of varying towing point locations on the same model. Instead of drag coefficient, C_1 of four models with different towing point locations was plotted in Fig. 12 as part of the criterion. These models had different hull forms and proportions, noticeably the beam/draft ratio.

It was highly possible that the high drag coefficients of Models S-04 and T-14 were due more to the high beam/draft ratio than to the towing point locations. Vessels with high beam/draft ratio have smaller projected underwater lateral area A_p in the at-rest condition. When these vessels heel to one side, the projected underwater lateral area increases faster than on vessels with small beam/draft ratio. Since the at-rest A_p was used to determine the drag coefficient, this explains the high drag coefficients for Models S-04 and T-14.

To illustrate my point, data from Fig. 12 are plotted in Fig. 25 in terms of drag coefficient C_1 versus beam/draft ratio.

I hope the proposed regulations will not force designers to compromise good design and place the towing posts of a tug close to the rudderstocks.

As to the problem of supply vessels meeting the water-on-deck criterion, it appears from equation (6) where

$$\frac{A_{DK}B}{280} = \frac{A_{DK}}{2} \cdot \frac{B}{4} \cdot \frac{1}{35}$$

that the authors assume that the water on deck is distributed on one side of the vessel only while the deck on the other side of the vessel is dry. The result is that the heeling moment arm is equal to $B/4$ as shown in Fig. 26. A triangular-shaped water distribution on deck may be more realistic. In that case the heeling moment arm would be equal to $B/6$. If such is the case, some of the supply vessels that we studied would have met the criterion.

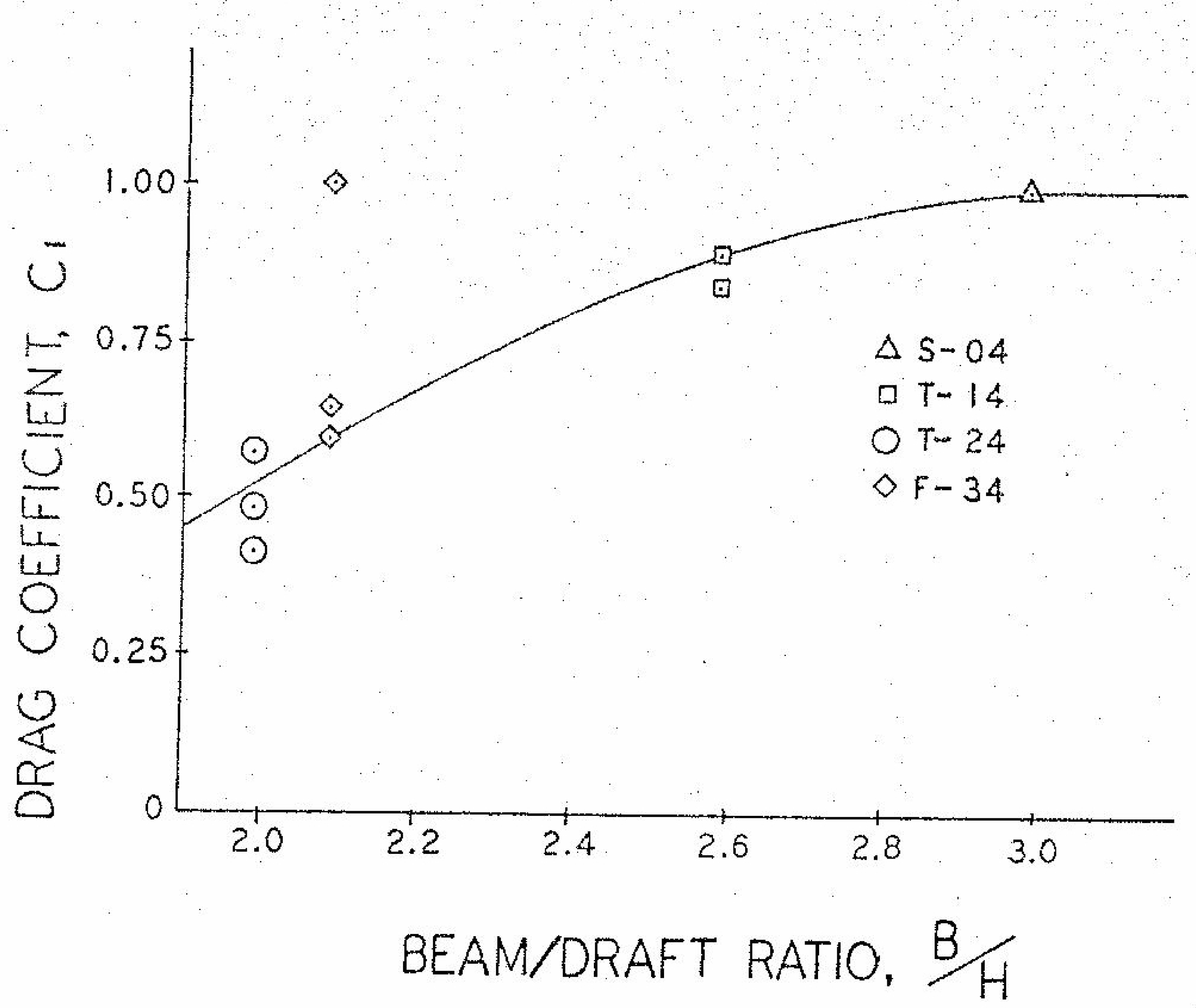


Fig. 25 Drag coefficient C_1 versus beam/draft ratio

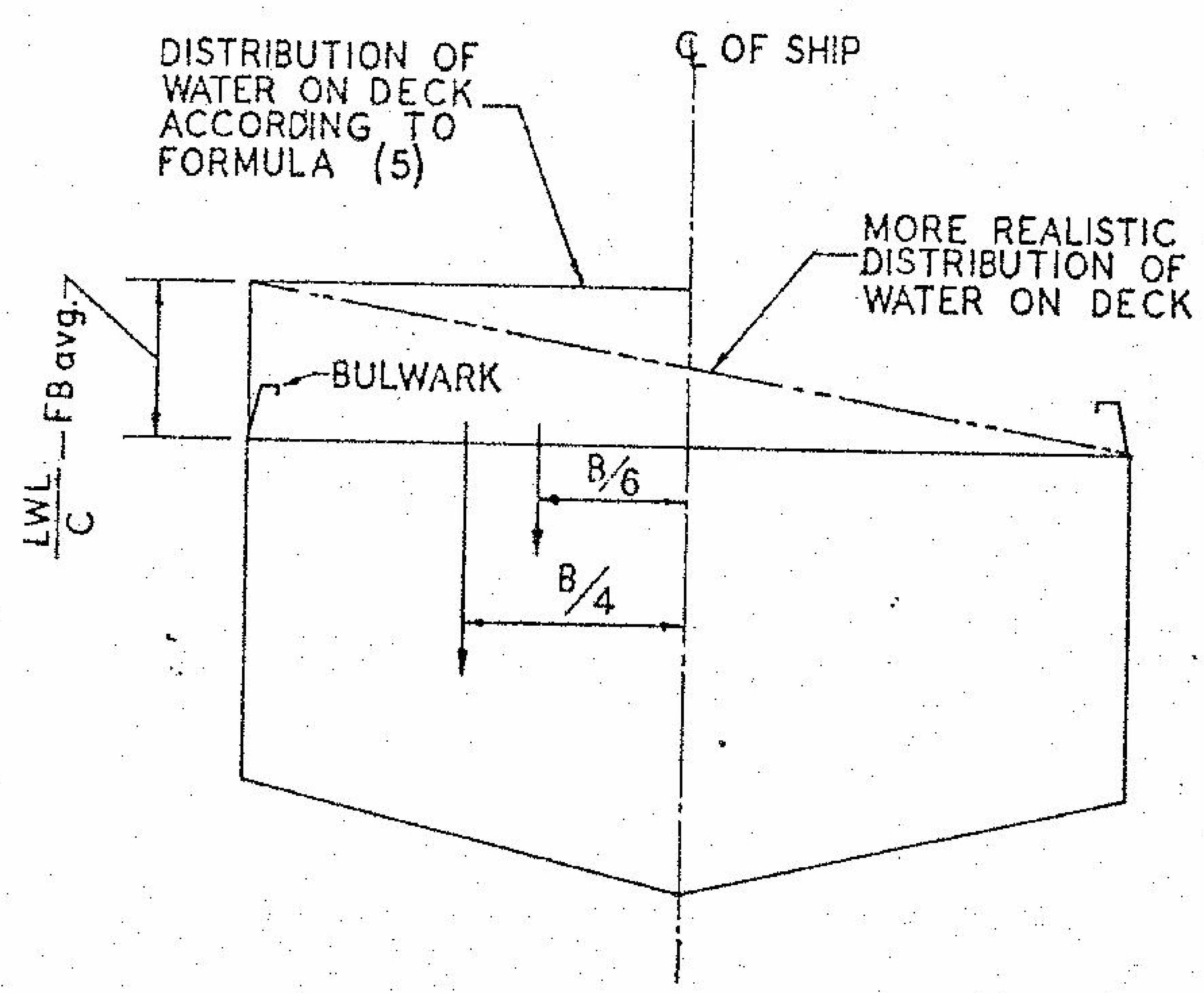


Fig. 26 Water distribution on deck

George M. Kapsilis, Member

The long list of criteria in use or under proposal presented at the end of the paper testifies to the need for a unified and rationally developed set of intact stability criteria for towing and fishing vessels. These standards should encompass all possible modes of ship loss. The criteria proposed by the authors are, therefore, an important contribution in this direction.

The following specific questions are raised:

1. With regard to the water-on-deck criterion, the authors mention the inclusion of the effect of wind heel as an optional addition. Since wind and wave directions do not necessarily coincide in an irregular short-crested sea, the possibility exists for beam wind heeling moments. If this factor is included in this criterion, then what is an appropriate wind speed/heeling moment to be used?
2. In the criterion for wind heel and rolling, what ship load condition is assumed?
3. With regard to the downflooding angle, what types of openings define this angle?
4. If the vessel is equipped with roll stabilizing devices—remote a possibility as it may seem—should the roll criteria be reduced?

The proposed criteria along with the existing USCG and U.S. Navy criteria were applied to a towing and salvage boat in a feasibility study we conducted two years ago. The principal characteristics of this boat are presented in Table 10. The selected hull form is typical of the offshore supply boat type, with a double chine and raked stem.

Table 10 Principal characteristics of a towing and salvage ship

LOA, ft-in.	224–9
LWL, ft-in.	204–9
Beam, ft-in.	42–0
Depth (main deck at side), ft-in.	20–0
Design draft, ft-in.	14–3
Displacement at design draft, long tons	2056.6
Installed horsepower	7200
Propellers (controllable pitch in nozzles)	2
Propeller diameter, ft-in.	9–6
Bollard pull, total, lb	157,000

Figure 27 shows the righting and heeling arm curves for the full-load towing condition. Unfortunately, time did not permit the evaluation of the following-seas criterion with the ship poised on the wave crest. It is seen that all criteria shown are satisfied. It may be noted that the beam wind speed used with the U.S. Navy criterion is 100 knots.

Figure 28 shows the rolling criteria for full-load and minimum-operating salvage conditions. In this mode, the ship is deck-loaded for salvage and deep-dive operations but not for towing. Again, the criteria are met. It may be noted that the USCG static criteria (required *GM*) were met with wide margins for all conditions.

By varying the *KG* until the proposed rolling criterion (ϕ_R = 45 deg) is just met, the corresponding beam wind to just satisfy the U.S. Navy wind heel criterion was determined to be 90 knots. This computation confirms the authors' findings that the 60-knot wind speed allowed for these boats by the U.S. Navy criterion is probably too low.

Eugene C. Haciski, Member

[The views expressed herein are the opinions of the discusser and not necessarily those of the U.S. Coast Guard.]

I would like to congratulate the authors of this excellent paper, showing the most important results of the multiyear research program. Having had an opportunity to look, in full scope, at research reports including the videotapes of most tests, I would like to make some small amplification of this paper and to stress certain characteristics of ship rolling motions just before the capsizing point.

A short analysis of the capsizing mechanism of about 30 test runs shows three basic types of ship rolling motion, which are depicted on the simplified histograms, Fig. 29, 30, and 31.

Figure 29 shows a classical case, where the amplitude of heel

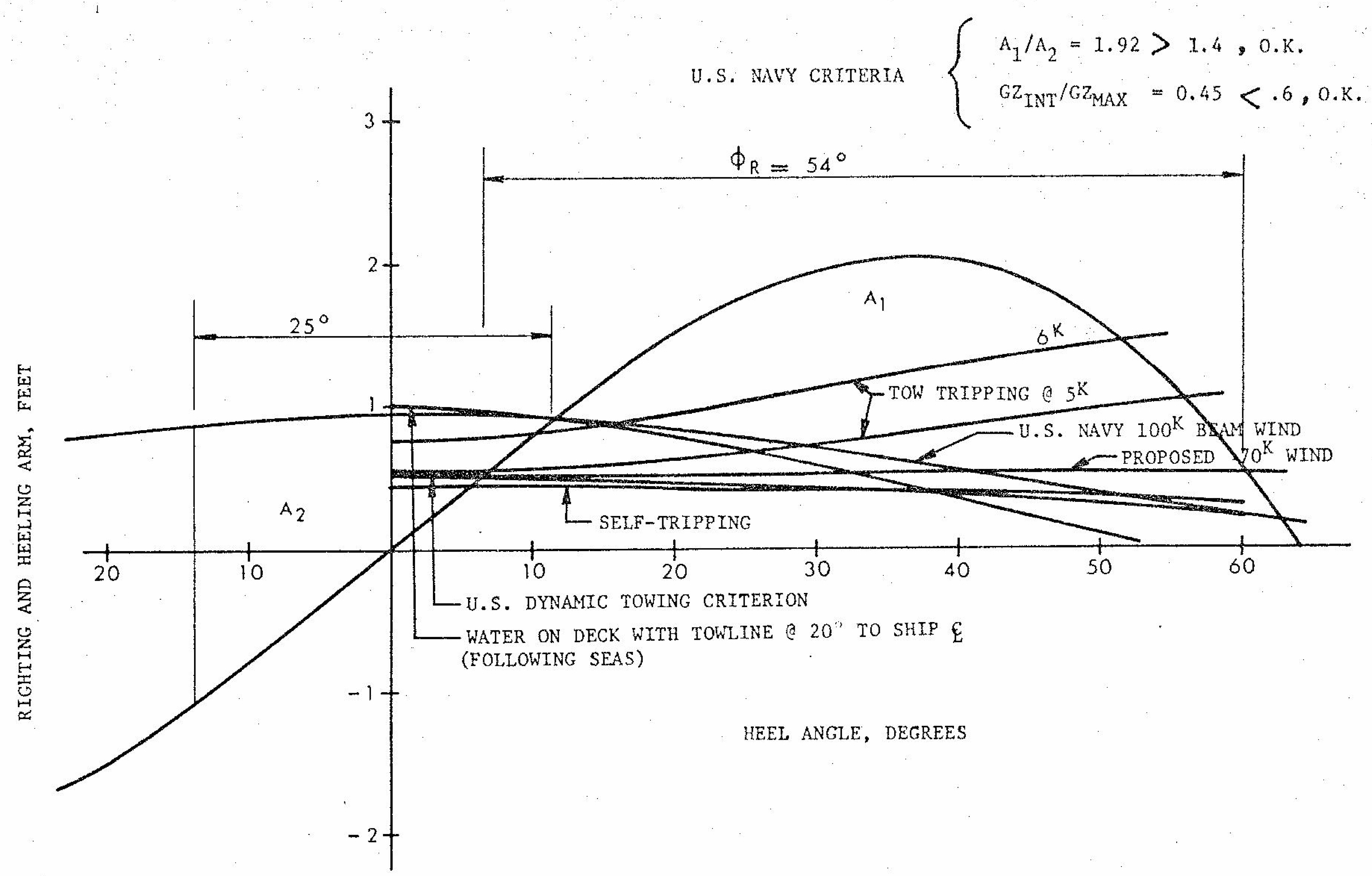


Fig. 27 Full-load towing condition

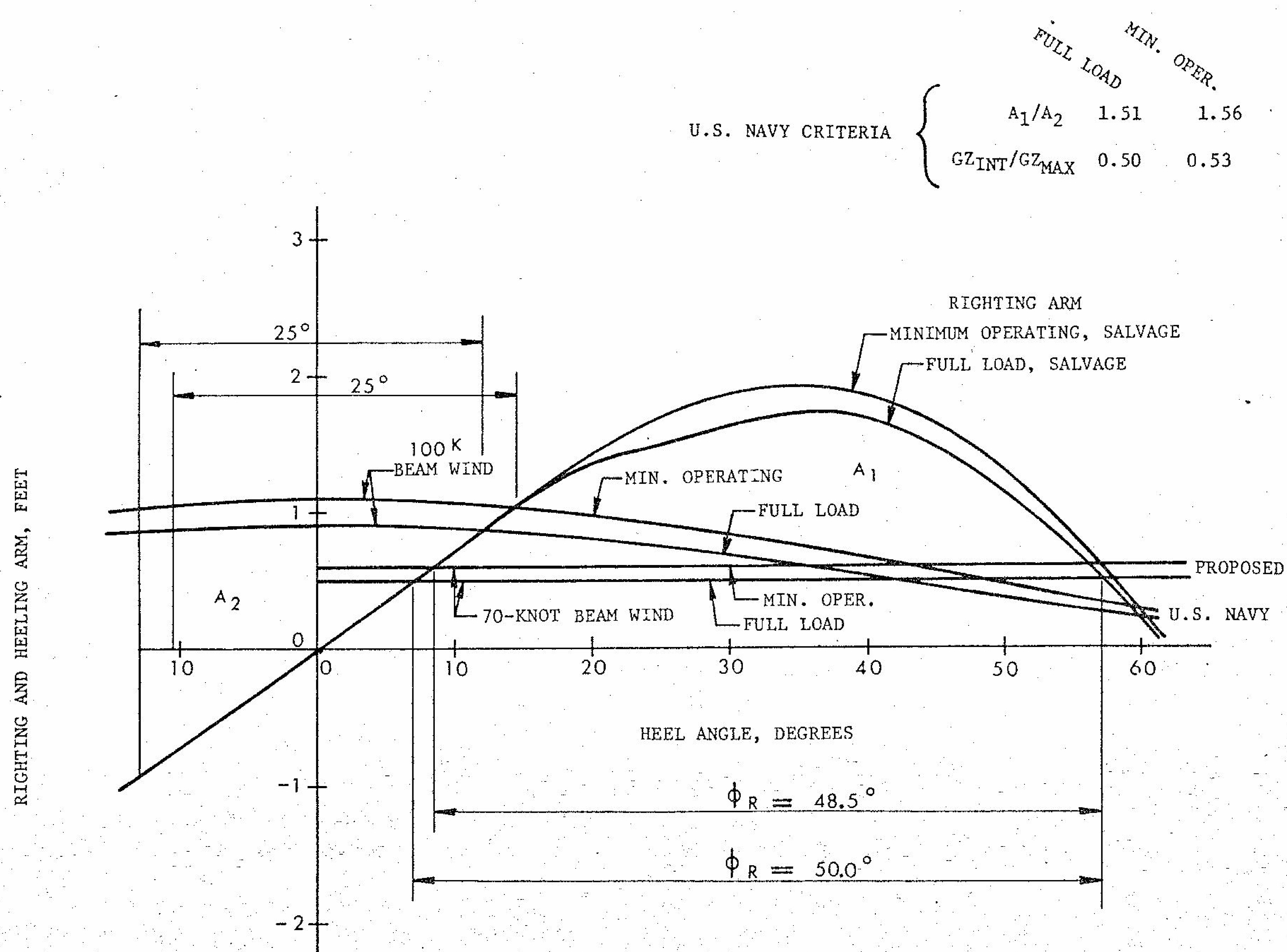


Fig. 28 Salvage condition

angle increases gradually up to the critical point, after which the vessel capsizes. It should be noted that rolling motion is symetrical, in other words, the ship returns to the upright position in each period of roll. In this case, the ship motion is probably in resonance with wave-induced forces, and damping moments are not effective.

Figure 30 illustrates another typical group of ship rolling motions. It is characterized by a gradual increase of amplitude with the centerline of oscillations diverging from the zero line, with steady or variable slope.

Figure 31 shows a very interesting group of ship rolling motions with semi-steady heel angle. This characteristic phenomenon of ship roll is also known as the pseudo-static heel angle, or the quasi-static heel angle.

The principal characteristic of this group of histograms is that the oscillations of the vessel become asymetrical, that is, the inclination to one side is larger than to the other, and the centerline of oscillations is about parallel to the zero heel line. This semi-steady heel has also been found by other researchers around the world. These model experiments have been reported to the various IMCO subcommittees. It should be noted that this angle is caused mainly by the presence of green water trapped on deck. All other time-history diagrams of rolling motion could be presented as a combination of this group of three basic types of rolling.

In conclusion, I propose that studies of ship stability with consideration of ship motions on the waves should be continued. Detailed analyses of time history, especially ship rolling, in conjunction with other significant dynamic parameters like wind force, could determine the exact causes of ship capsizing.

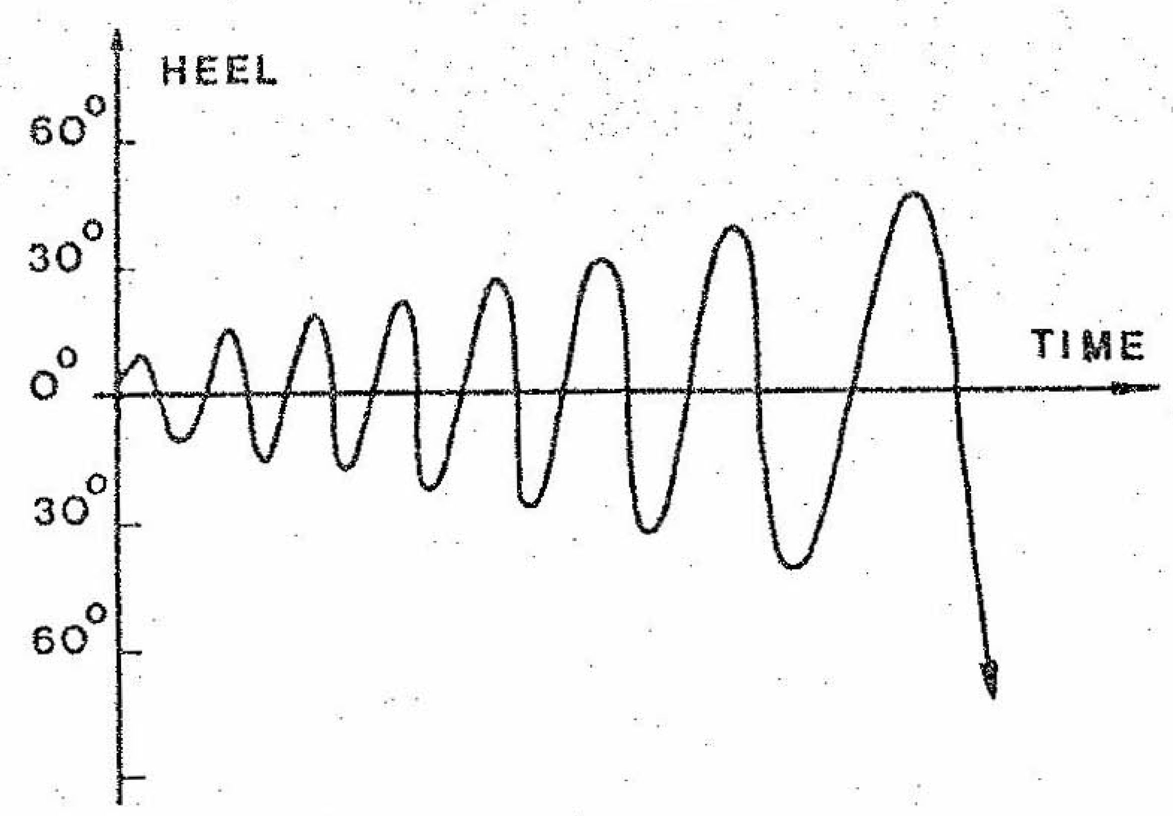


Fig. 29

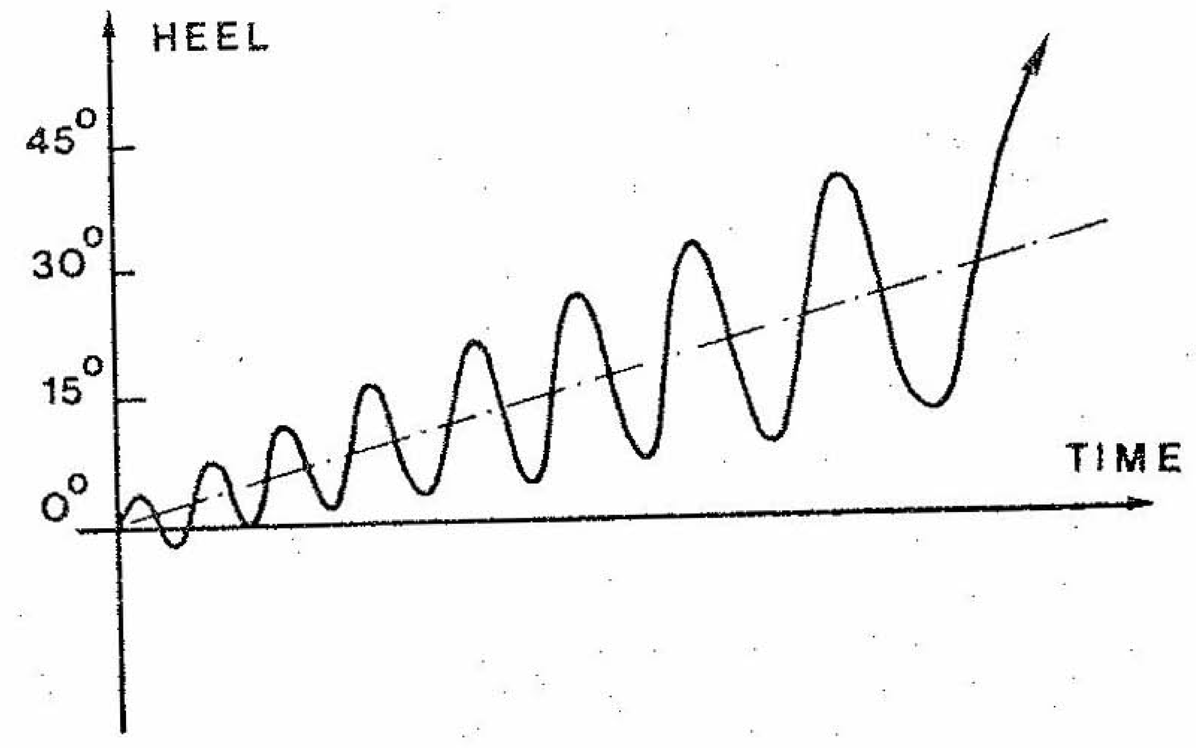


Fig. 30

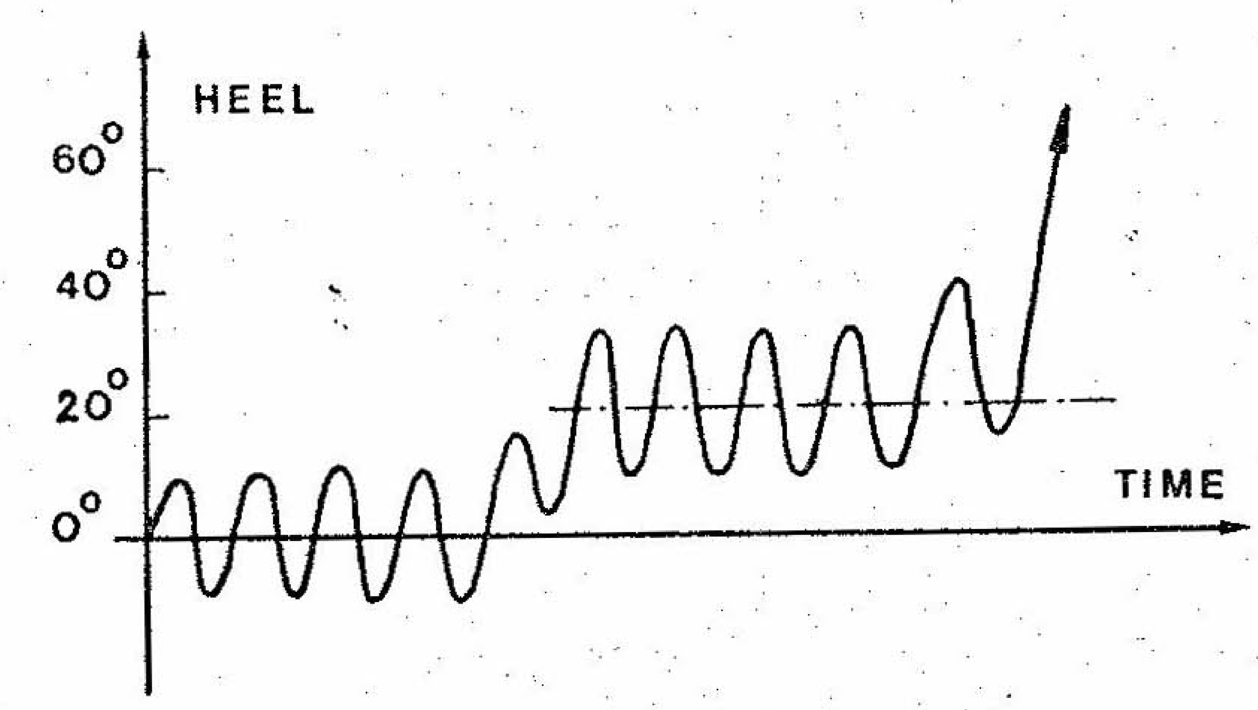


Fig. 31

George C. Nickum, Member

This is an interesting paper on a fascinating subject. The paper reports on a Coast Guard-sponsored study which is one of a number of recent studies conducted by various maritime agencies throughout the world—all aimed at finding a definitive answer to the question, "What forces are exerted on vessels by the infinitely varying shape of the ocean's surface?" This is the fundamental problem confronting the naval architect in assessing the adequacy of the vessel's stability. We know a great deal about the ability of a ship to resist capsizing but, with a few limited exceptions, for example, heeling moments due to high-speed turns, we cannot as yet predict accurately what capsizing forces the ocean will exert. The data reported in the study are of value and add incrementally to the material being assembled and studied all over the world which one day, hopefully soon, will lead to a breakthrough that will permit naval architects to say, "These are the capsizing forces that the ocean will exert on this vessel and these, therefore, are the resistive characteristics that the vessel must possess in order to be safe at sea."

While admitting the value of the data obtained in the study and partially reported in this paper, I cannot agree that the data warrant the development and use of five new specific criteria for towboats and fishing vessels. I do not believe that the assumptions derived by the authors from the model tests described are sufficiently valid to be used as the base for formulating these new criteria. I regret that space does not permit a detailed discussion and analysis of the assumptions made by the authors in developing their criteria. One example will have to do: The water-on-deck criterion assumes that there is no difference between a vessel having bulwarks and one having no bulwarks. This assumption is patently invalid and destroys the credibility of the water-on-deck criteria.

While I applaud the authors in their attempt to develop more precise and rational criteria, I have to regretfully say that I do not feel that they have been successful in their attempts. Until we can validate all of the assumptions that have to be made in developing new or specific types of criteria, I believe we must stick with the basic Rahola principle which was used in the development of the IMCO criteria. This principle says; Find the stability parameters of vessels that have been lost and establish parameters that are higher than these as the minimum acceptable parameters to be used in evaluating stability. With only two unexplained exceptions, the IMCO fishing vessel criteria which have been in general use since 1968 appear to have provided adequate stability for the world's fishing fleet and, with one unexplained exception, to the world's fleet of freighters and other vessels under 100 meters in length.

One important point brought up by the authors is the inherent danger to vessels operating with KG/H values of greater than 1.4 due to the large rolling moments caused by sway-roll coupling. This undoubtedly was the reason for the loss of a Danish coaster in the Baltic when operating in a light condition. Further research is needed on this point so that naval architects can properly protect small vessels which must travel at sea frequently while in a light condition.

A. Yücel Odabaşi,[10] Visitor

I would like to commence by paying tribute to the authors

[10] The British Ship Research Association, Wallsend, Tyne & Wear, England.

for the amount of valuable experimental work presented in this paper. The wealth of material used in the preview of the subject is quite impressive and both their data analysis and their results of the systematic experiments will no doubt make an important contribution to the overall understanding of capsizing phenomena. Having studied the paper with due care I wish, however, to express reservations about the authors' conclusions and hence about the proposed intact stability criteria for towing and fishing vessels.

The basic disagreement between the authors and this discusser stems from a difference in the basic understanding and definition of the concept of stability. In order that a stability criterion be established, one needs to define the meaning of intact ship stability in terms of symbolic notation, because there exists a variety of stability definitions, each employing a different norm and measure, cf [18],[11] and, consequently, leading to different conclusions and criteria. In the paper it is hard to perceive consistency and rationality as far as the basic concept of stability is concerned. Although the authors frequently refer to dynamical phenomena observed during experimentation, they somehow reduce the problem to a statical one. Furthermore, they use alternatively the initial metacentric height and the area under the righting arm curve for settling different moments which are reduced to statical form in an identical manner. It is, therefore, very hard to judge the proposed intact ship stability criteria on the basis of any rational stability theory of ships which has been developed during the last two decades.

Before going into the critical examination of the paper, I would like to make a few remarks on the concept of motion stability. A ship, being subject to persistent disturbances due to its environment, executes a motion which is neither self-oscillation around a stable equilibrium nor steady state-oscillation of a forced system. Consequently, techniques which yield results for the self-oscillations—for example, stability of equilibrium position in small and in large; and for steady-state oscillations, for example, perturbation methods—cannot provide a satisfactory answer to the question. In an attempt to overcome these difficulties, the discusser adopted La Salle's eventual stability definition [19], which states that if the system is structurally stable and, for a given persistent disturbance, the motion is bounded, the bound being within the limits of the domain of attraction, then the motion is eventually stable and as the time passes the oscillations tend to act more and more like self-oscillations around a stable equilibrium position. Derivation of stability criteria, based on this definition, for both deterministic and random cases has been presented in reference [20], and application of the deterministic criteria to analysis of the capsizing of the Danish tanker MT *Edith Terkol* predicted two possible mechanisms of capsizing [21]. Although the basic theoretical treatment is complicated, the final results are fairly simple and do not require information additional to the ship-environmental system parameters. Therefore it is not correct to conclude, as the authors do, that a dynamic systems analysis is over-complicated if not impossible.

From the analysis contained in this paper, it is understood that the paper consists of four sections: data collection and analysis, experimentation, analysis of experimental findings, and formulation of the criteria. As mentioned earlier, the first two sections contain an impressive amount of work and deserve the highest appreciation. The authors' conclusions and their criteria give cause for concern, and here each criterion will be considered separately.

(i) Effect of water on deck. The authors seem to be of the impression that the effect of water on deck can be treated as, or reduced to, a simple heeling problem. This is certainly not the case, as various published studies, cf [22–25], and practical experience prove. To verify the foregoing statement, we refer to the theoretical findings of Tamiya [22] where, under the assumption of constant amounts of water, it is found that the dynamic moment created by the water on deck has two components, one in phase with the roll angular velocity and the other with the roll angle. Secondly, there exists a natural frequency of the water on deck, defined by the relationship

$$\omega_{mn}{}^2 = \frac{g\pi}{ab}\sqrt{m^2b^2 + n^2a^2}\tanh\frac{nh}{ab}\sqrt{m^2b^2 + n^2a^2} \qquad (11)$$

which can give rise to resonance phenomenon. Here g is the magnitude of gravitational acceleration, a and b the length and beam of the free water surface, respectively, h is the depth of water, and m and n are integers. The pseudo-static angle referred by Dudziak [8] is also a natural consequence of the dynamics of motion and cannot be explained within the limits of the statical treatment adopted in the paper. On the basis of kinetic energy, if we define a sloshmass, then the ratio of sloshmass to the mass of the water on deck, for a rectangular deck form, has been derived as

$$\frac{M_{\text{slosh}}}{M} = \frac{8b}{\pi^3 h}\sum_{\lambda=1}^{\infty}\tanh\frac{(2\lambda-1)\pi h}{b}\Big/(2\lambda-1)^3 \qquad (12)$$

and for low (h/b) values the sloshmass approaches 80 percent of the total mass. This, again, proves that to assume a statical treatment for water on deck is misleading.

If we now also consider that the amount of water on deck is not constant but varies with time, depending on the frequency of encounter, heading, freeboard, speed, etc., the dynamics of motion will have more pronounced effects on stability because in this case the system parameters undergo instantaneous changes depending on the instantaneous shipping of water. Such an occurrence, by itself, may cause instability, depending on the previous motion history. Further information on this subject may be found in reference [26].

(ii) Effect of wind and waves. In estimating the lateral wind force the authors seem to have difficulty in finding literature. Here I will refer to publications by Wagner [27] and Wieghardt [28] where a thorough review of the subject may be found. As to the dependence of lateral wind force on the angle of roll, some additional information may be found in [29].

The determination of wind heeling moment is another source of arbitrariness. Although the authors seemingly use the classical approach in their computations, when taken together with their equation (7), one may raise the following question: "As is well known from theoretical hydrodynamics, the so-called water resistance force is a fluid-reactive force to the ship's swaying motion and therefore related to the sway velocity. Consequently, the fluid reactive force will vary with time, depending on the time variation of the sway velocity, and hence will give rise to coupling between roll and sway motions. Furthermore, the so-called water resistance force need not be equal to the lateral wind force since the latter will be in equilibrium with both inertial and fluid forces for swaying motion (including drift). Therefore, how can the authors consider that their equation (9) is valid?"

In spite of the foregoing criticism, equation (7) of the paper is still a good approximation to the large-amplitude rolling motion of a ship. The authors' numerical solution method, however, does not necessarily give the correct answer to the stability question. This is because of the fact that in nonlinear systems, depending on the choice of initial conditions, more than one solution may exist and hence a numerical or an analytical approximation method only yields a branch of the solution. The non-uniqueness becomes very significant in resonance (ordinary, subharmonic, superharmonic, and combination tones) zones. A more detailed discussion of the subject

[11] Additional references follow the discussion.

may be found in reference [30]. A method of overcoming this difficulty is to employ the methods of stability assessment directly from the equations of motion. In fact it is not necessary to solve the equations of motion in order to assess the stability of motion. Application of such methods to the intact ship stability problem may be found in references [20, 21].

Before closing the discussion I would like to distinguish between the criteria needed for ship designers and regulatory bodies, and those needed for masters of small ships. The former should be comprehensive and need not be oversimplified whereas the latter should be expressed only in terms of directly measurable quantities, such as freeboard and trim. When looked at from this point of view the criteria proposed in the paper are neither comprehensive nor rational enough to satisfy the designers and the regulatory bodies, nor are they simple enough to be used by shipboard personnel.

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Authors' Closure

The authors would like to thank all the discussers for their contribution to the paper. Our comments follow the order in which the discussions appear.

Mr. Townsend asked what are the important parameters for application of the proposed criteria. The limits of the criteria are related to the range of hull forms tested. The particulars of the four models can be found in Table 2. Throughout the section on criteria development, we have given parametric limitations whenever possible. As stated in the second paragraph under Fig. 17, the model tests were conducted on models in which the bulwark height/beam ratio ranged between 0.085 and 0.14, with freeing port area equal to that suggested by IMCO. The lower limit in length is probably 80 ft. Below this length the deck geometry of vessels changes significantly; for example, wells and no forecastle or sheer. The upper limit is around 250 ft. Above this length, the wave steepness used in the model testing would not be expected in the actual ocean environment.

Mr. Townsend's statement that righting energy (or E_{40} value) only slightly changeable after a vessel is built is not always true. On offshore supply vessels and fishing vessels which have a variable deck load, the E_{40} value can be changed depending on area of operation. Concerning his comments on Fig. 19, we would like to point out that as freeboard increases at the stern the E_{40} value required decreases. This should encourage increased freeboard at the stern. Also, the E_{40} value is measured with the vessel perched on a wave. An E_{40} value of 0.0 from Fig. 19 does not mean an E_{40} value of 0.0 for the vessel in calm water.

Although the complete set of proposed criteria requires 19 percent more GM than the existing Coast Guard criteria, it was found that, on the average, the fleet already has 22 percent more GM than required by the Coast Guard criteria. The authors do not feel that the proposed criteria will mean stiffer boats.

We would be interested in seeing the details of the capsizing experiments carried out by Prof. Krappinger at the Hamburg Ship Model Basin. Although water on deck can have a damping effect on the roll motions of a flush-deck vessel without bulwarks, this positive effect is more than offset by the negative effect of trapping water on vessels with bulwarks or other obstructions.

In answer to Dr. Morrall's question concerning dangerous capsizing situations, the authors feel that the proposed stability criteria cover the hazards encountered by a tugboat or fishing vessel. Each criterion should be given equal weight and, for a given design, anyone of the criterion may become the predominant design limitation. As stated in the paper, freeboard and displacement seem to be the governing parameters for most existing vessels. Figure 10 shows the influence of water trapped on deck. The roll record indicates a "pseudo-static" angle of heel between 20 and 30 deg before capsizing. However, no experiments were performed on deck wetness versus wave frequency.

The proposed criteria are a complete set. We would not recommend the wind heel with rolling criterion alone. We would recommend the entire set to the International Fishing Vessel Convention. The proposed criteria have approximately a 20 percent margin of safety. A part of the research not included in the paper was a theoretical wave group analysis using the JONSWAP spectra. This analysis indicated that critical wave groups of three or more waves, all with heights greater than 0.16 times ship length, could be expected once per hour. Based on this analysis, we consider that tests in irregular waves would not be significantly different.

The results reported by Prof. Hamlin confirm the fact that water on deck frequently acts as a passive antirolling device. However, the results concerning bulwarks and freeing ports must be carefully analyzed. As reported under Fig. 7, in one case, when the freeing port area was doubled, the model seemed to capsize sooner under the same wave conditions due to water entering through the freeing ports. The scale effects of modeling trapped water and the trade-off between trapping water and allowing water to enter through freeing ports must be considered before any conclusions can be drawn. The effective wave slope, equation (7), was determined from the geometric wave slope with a correction for the "Smith" effect.

Although capsizing in waves is a very complex problem and involves more than perching a vessel on a wave crest as stated by Mr. Stanley, the test results from the different hull forms indicated that a generalization could be made. Any one or combination of stability parameters could have been used. However, for simplicity of the criterion, righting energy (E_{40}) on a wave crest versus freeboard at the stern divided by ship length was chosen. Within the ship parameters tested, the authors consider that Fig. 19 provides adequate protection against capsizing in following seas.

Mr. Gilbert has presented a most informative discussion. It is of great interest to know the types of criteria and design practices now being used by active boat designers. In the introduction to the proposed stability criteria, we have noted that careful attention should be given to unusual loading conditions such as topside ice and the lifting of heavy weights over the side. Mr. Gilbert noted these two conditions in particular. His description of freeing snagged gear and the resulting water on deck of small stern trawlers in following seas is a classic case in which the proposed water-on-deck criterion should provide protection. We would rather consider this situation directly than to depend on the winter ice criterion to insure sufficient stability.

With respect to the selection of capsize boundaries in Figs. 8, 9, and 11, the procedure used was somewhat judgmental. The boundaries were drawn to pass between conditions in which capsize resulted and conditions in which extreme rolls and large heel angles were observed. For wave lengths in which wave heights large enough to cause capsizes were not tested, the extension of the boundaries was based on the qualitative behavior of the model in the conditions tested. Repeated viewing of the videotapes was most useful for this.

We agree that Model F-34 is an example of a type of fishing vessel with a poor casualty record and marginal stability characteristics. This was one of the reasons that F-34 was chosen for the test program rather than one of the New England-type vessels. We hope that in the not-too-distant future funds can be found to test models of additional vessel types.

Mr. Gilbert's observations with respect to scupper or freeing port size are most interesting. As we have noted, the effects of water on deck are very complex, and in some cases simply increasing freeing port area or lowering bulwark height may not have the desired effect.

The authors do not agree with Mr. Mok that the drag coefficient C_1 (Fig. 12) may be more a function of beam/draft ratio than a function of towing point location. In reference [10], Models A and B were towed sideways with the towing bit near midships. Model A with a beam/draft ratio of 2.43 had a drag coefficient of about 1.0 while Model B with a beam/draft ratio of 2.60 had a drag coefficient of about 0.9 for small angles of heel. If one plots the drag coefficients for Models A and B on Mr. Mok's figure, it can be readily seen that the drag coefficient is not necessarily a function of beam/draft ratio. For small angles of heel, the beam/draft ratio probably does not effect the rate of underwater lateral area increase.

With respect to Mr. Mok's statement that the proposed criterion may force designers to place towing posts close to rudderstocks, the reason for including the coefficient C_1 was to recognize existing designs that have towing posts aft of amidships and to give these designs credit. One could always simplify the criterion by making $C_1 = 1.0$ for all cases. It would be unfortunate if a naval architect would obtain approval for a design with marginal stability by moving the towing bitts aft rather than correcting the fundamental problem.

Equation (6) does not assume any static distribution of water on deck. The constant 0.7/280 is an arbitrary constant derived from an empirical analysis of the test results. The constant 280 was arrived at by the logic noted but was only included to make the numerical value of the constant reasonable. If one was assuming static conditions in the criterion, a triangular shape for the water distribution on deck would be a reasonable assumption and indeed this would result in a constant of 0.67/280.

The authors do not have any definitive answer for Mr. Kapsilis on what wind heeling moment should be added to the water-on-deck criterion. A study would have to be conducted on what wind speeds could be expected. For the present we suggest assuming a 60-knot wind on the quarter. This would give an approximate 45-knot wind from the beam. The wind heel and rolling criterion should be applied at all loading conditions. Downflooding depends on the capsizing situation. For the free running case, all watertight doors and hatches on the main deck may be considered closed. However, for towing situations where the capsizing moment may be applied suddenly, doors and hatches should be considered opened. In both cases small openings fitted with automatic closing devices would not be considered downflooding. Again, concerning roll stabilizing devices, the authors do not have an answer. These devices introduce another parameter which was not considered in the research.

The authors would like to thank Mr. Haciski for his analysis of the histograms recorded during the model testing. A detailed analysis of these capsizing phenomena was not conducted by the authors; however, the resulting capsizing hazard has been considered in developing the proposed criteria. We agree more work needs to be done on the capsizing modes of small vessels in waves.

The authors do not agree with Mr. Nickum that the results of the model tests are not sufficient for formulating the proposed criteria. We would like to point out that these are specific criteria and not a general criterion like Rahola or IMCO. Therefore, there are parametric limitations to the criteria. Mr. Nickum states that the water-on-deck criterion assumes that there is no difference between a vessel having bulwarks and one having no bulwarks. This is not true. The criterion assumes that the vessel has bulwarks and, as stated in the second paragraph under Fig. 17, special consideration should be given to vessels without bulwarks.

The IMCO fishing vessel criterion is a general criterion and does not cover all capsizing hazards seen by a fishing vessel or tugboat. Two specific hazards not addressed are tow tripping and self-tripping. Furthermore, the IMCO fishing vessel criterion makes no distinction between a vessel with no bulwarks and one with bulwarks. The authors feel that the proposed criteria will provide the designer with more flexibility in design while assuring that vessels are protected against all capsizing hazards expected.

Dr. Odabasi raises a number of points. It is not clear to the authors that the use of a particular symbolic notation is necessary to establish intact stability criteria. In all cases, dynamical phenomena occur in capsize situations. We have consistently tried to express criteria in static terms and have used model test results and more complete analysis to relate the dynamics of the capsize to some static measure. This approach was adopted because we felt it was the only one which could realistically be expected to provide criteria in a form which could be widely used.

Dr. Odabasi's comments on the effect of water on decks again illustrate how complex this phenomenon is. Our approach was not to neglect these complexities but rather to accept that only testing of physical models would begin to include all of these complexities. The problem was then to present and generalize the results of the model tests in a form suitable for a criterion. It was in this step that we found that a static approximation with empirical constants to account for dynamic effects could be used as a criterion. There are uncertainties in this approach, as noted in the paper, and we would agree that work should proceed on a more rigorous analysis.

Given that equation (7) is a good approximation of the large-amplitude rolling motion of a ship, we believe that the numerical solution method used will give the correct result. After a reasonably short period (say 3 to 5 times the natural roll period) the initial conditions will have little effect on the motions calculated for an irregular input. We have not been able to review Dr. Odabasi's references [20] and [21] but we wonder if a practical assessment of stability can be made for complex cases without solving the equations of motion.