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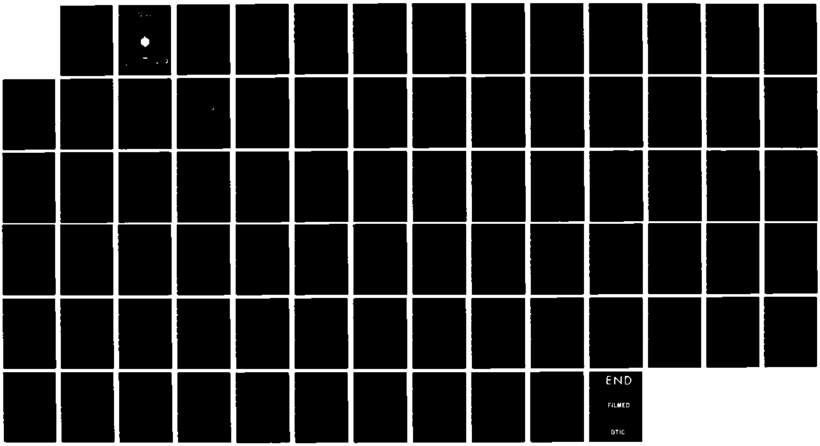

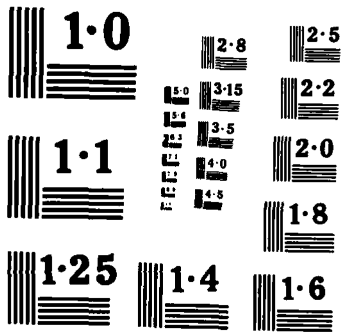

NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

A TRIDENT SCHOLAR PROJECT REPORT

NO. 132

UNITED STATES NAVAL ACADEMY
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"OPTIMIZATION OF BOW-BULB FORMS FOR RESISTANCE AND SEAKEEPING CHARACTERISTICS: A COMPARISON OF EXISTING COMPUTER SOFTWARE PREDICTIONS METHODS WITH EXPERIMENTAL RESULTS"

A TRIDENT SCHOLAR PROJECT REPORT

by

MIDSHIPMAN JEFF W. HOYLE, '85

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20 May 1985
Date

ABSTRACT

This report presents the results of an investigation of bulbous bows for fine form ships conducted as a Trident Scholar research project. Nine different bulbs were designed for the OLIVER HAZARD PERRY (FFG-7) Class of Ships. These bulbs varied primarily in length and breadth and were designed using a Naval Sea Systems Command application of the Kracht bulb design curves. Resistance predictions were obtained for the FFG-7 appended with eight of these bulb forms from the XYZ Free Surface Program. Seakeeping characteristics were predicted for the appended FFG-7 with the aid of the Navy Standard Ship Motions Program. Resistance and seakeeping predictions were also obtained for the unappended PERRY hullform and the FFG-7 appended with an existing bow bulb similar to that found on the Italian frigate, MAESTRALE. Finally, model tests were performed at the U. S. Naval Academy in calm water and irregular, head seas on six different configurations of the PERRY hullform: unappended, appended with MAESTRALE-style bulb, and appended with four newly designed bow bulbs. The FFG-7 hull form was also appended with a fifteen degree stern wedge during all computer runs and model tests. A comparison of the computer predictions and model test results is presented, along with a determination of the applicability of the bulb design method utilized to develop the bulb forms. The effects of changes in bulb length and breadth are also investigated.

PREFACE

As a Trident Scholar report, this paper was written in such a manner as to be understood by a broad audience. However, as a result of the nature of the research presented, this report was written in a technical format and the use of terms and phrases familiar only to those who have studied naval architecture was unavoidable. Therefore, in order to aid the reader who has not had the benefit of such study, a concentrated effort has been made by the author to define such terms and phrases with footnotes in the body of the report. Most of these footnotes are written in a non-technical, rather general manner and are probably unnecessary reading for anyone who is familiar with the field of naval architecture.

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INTRODUCTION

Since the turn of the century, naval architects have realized that reduction in the overall resistance of a ship can be achieved by the addition of a bulbous bow to the hull form. Admiral David W. Taylor first recognized these effects when he fitted a bulbous bow to the battleship, DELAWARE, to increase her speed at constant power. (Kracht, SNAME, 1978, p. 197) Today, nearly eighty years later, the bow bulb is utilized routinely in the design and construction of surface ships. However, knowledge of optimal design and power prediction for ships with bulbous bows has progressed very little since the time of Taylor. Furthermore, the research which has been conducted in this area has concentrated primarily on low speed, full form ships such as naval auxiliarys and amphibious ships. Thus, design of bulbous bows for high speed, fine form vessels such as destroyers and frigates is a relatively unknown art. To date, the only full-scale application of a bulbous bow to such a hull form is that found on the Italian frigate, MAESTRALE. In this paper, results of a year-long investigation of bulbous bows for the USS OLIVER HAZARD PERRY (FFG-7) class of ships are presented. It is the ardent hope of the author that knowledge gained from this study will aid designers of future ships in the selection and/or rejection of bulbous bows for their hull form.

OBJECTIVES

The objectives of this Trident research project were three-fold:

(1) Comparison of computer predictions of resistance and seakeeping characteristics of the FFG-7 appended with vari us bow bulbs to actual model test results.

(2) Determination of the applicability of the NAV EA interpretation of the Kracht bulb design charts to fine form, high speed vessels such as the FFG-7.

(3) Investigation of the effects of changes in bulb length and breadth on the resistance and seakeeping performance of the FFG-7 hull form.

BOW BULB THEORY

The reductions in resistance caused by the addition of a bulbous bow to a hull form are derived primarily through attenuation of the ship's bow wave system. This results in a reduction of the wave-making resistance of the ship. Furthermore, there is reason to believe that a bulb acts to reduce frictional resistance as well, by smoothing the flow around the forebody. (Kracht, SNAME, 1978, p. 197) Since the beneficial action of a bulbous bow depends heavily on the waves it produces and the flow around it, it is quite obvious that the size, position, and form of the bulb body will have a marked impact on the resistance characteristics of the ship.

Recognizing the importance of the bulb form in reducing a ship's resistance, it is necessary to classify bulbs according to some geometric parameter. Alfred M. Kracht has differentiated bulbs into three main categories according to the shape of the bulb's cross section at the forward perpendicular.[1] These three classes are presented below and are depicted graphically in Figure 1.

"a) △- Type: Figure 1 (a) shows the drop-shaped sectional area of the delta-type with the center of area in the lower-half part. This shape indicates a concentration of the bulb volume near the base. The Taylor bulb and the pear-shaped bulbs belong to this type.

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[1] The forward perpendicular is defined as that point along the length of the ship where the stem of the ship intersects the design water line.

b) O-Type: This type (Figure 1 b), with an oval sectional area and a center of area in the middle, has a central volumetric concentration. All the circular, elliptical, and lens shaped bulbs as well as the cylindrical bulbs belong to this type.

c) ▽ - Type: The Nabla-Type also has a drop-shaped sectional area (Figure 1 c), but its center of area is situated in the upper-half part, indicating a volume concentration near the free surface. Because of its favorable seakeeping properties, this type is the most common bulb in use today." (Kracht, SNAME, 1978, p. 198)

Kracht also divides bulbs into two types according to their lateral contours:

a) Those bulbs which do not change the outline of the stem of the ship.

b) Those bulbs which protrude forward, thereby altering the ship's stem profile.

This classification is unnecessary however, since bulbs such as the Taylor bulb which do not change the stem outline do not have favorable properties and are no longer in use. Lastly, bulbs can be described as "additive" or "implicit". An "additive" bulb is one which is added to an existing ship configuration, thus increasing the displacement volume of the ship. For an "implicit" bulb application a portion of the displacement volume of the ship is shifted forward to create the bulb, thus changing the bulbless ship configuration. (Kracht, SNAME, 1978, p. 198-199) All bulbs designed during the course of this study can be described as "additive" and are of the Nabla-type.

In addition to reducing the resistance of a hull form, bulbous bows also influence other properties of a ship. For instance, model tests have shown that bulbous bows can influence the quasi-propulsive coefficient,[2] wake fraction[2] and thrust deduction fraction.[2] However, in SNAME, 1978, Kracht is quick to

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[2] The Quasi-Propulsive Coefficient, Wake Fraction, and Thrust Deduction Fraction are all quantities which affect a ship's ability to propel itself through the water.

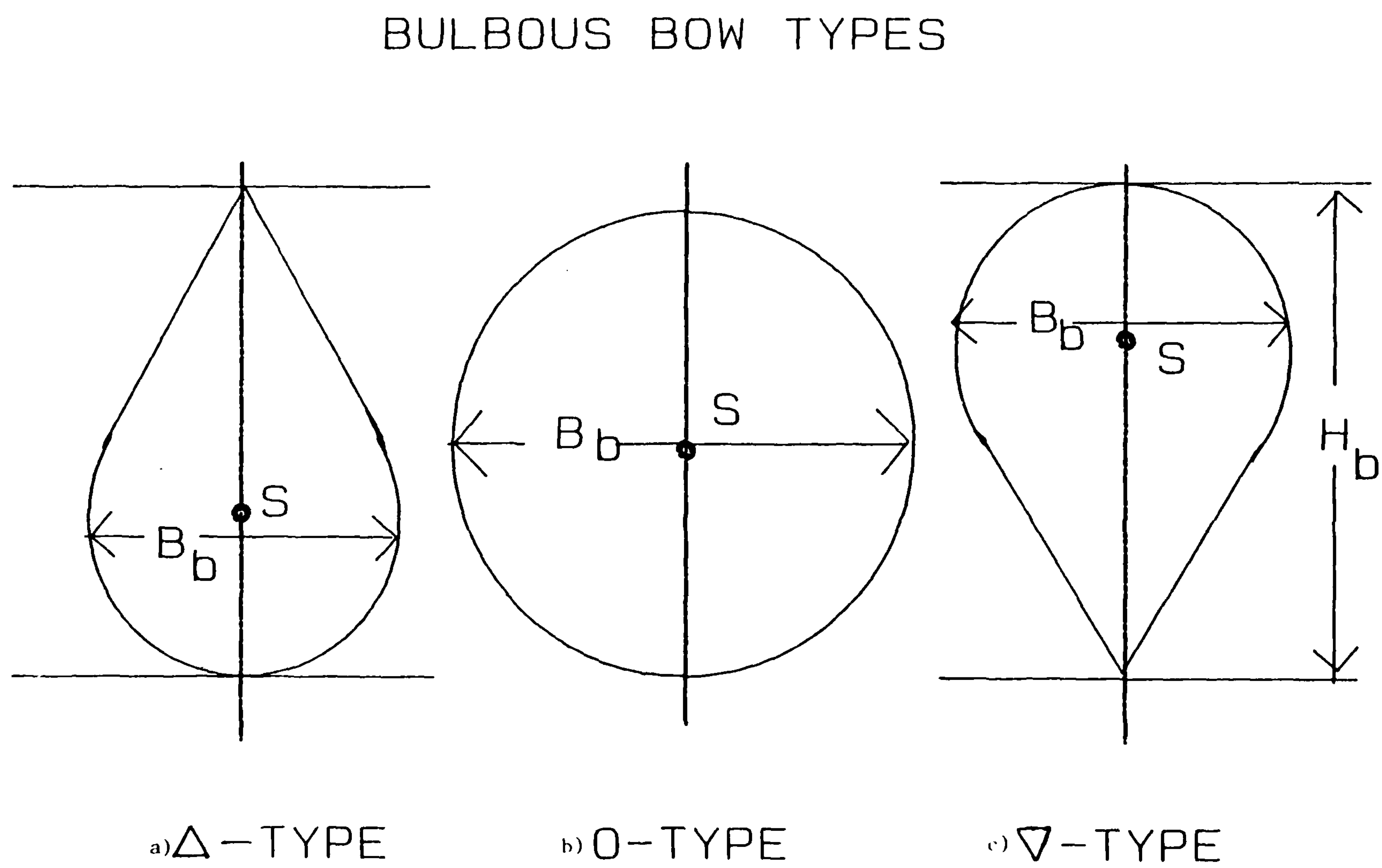


FIGURE 1

point out that it is not certain if these bul. effects are present in the full-scale ship because of the importance of scale effects on the expansion of model test results. Bulbous bows do not seem to significantly influence course stability or maneuverability, and model tests in regular waves tend to indicate that the "bulbous ship is the best ship regardless of seakeeping aspects" up to a wavelength to ship's length ratio of 0.8. For ice navigation, ships equipped with bulbous bows have a definite advantage. The bulbs tend to tip the ice floes so that they slide along the ship's hull on their wet side, which has a smaller friction coefficient. Thus, the speed loss of a ship equipped with a bulbous bow in ice is less than that of the same ship without a bow bulb. As these factors present no reasons sufficient to prevent the utilization of a bulbous bow, it appears that bulb design may be completed in view of the calm water characteristics only. (Kracht, SNAME, 1978, pp. 199-200)

MODEL SELECTION

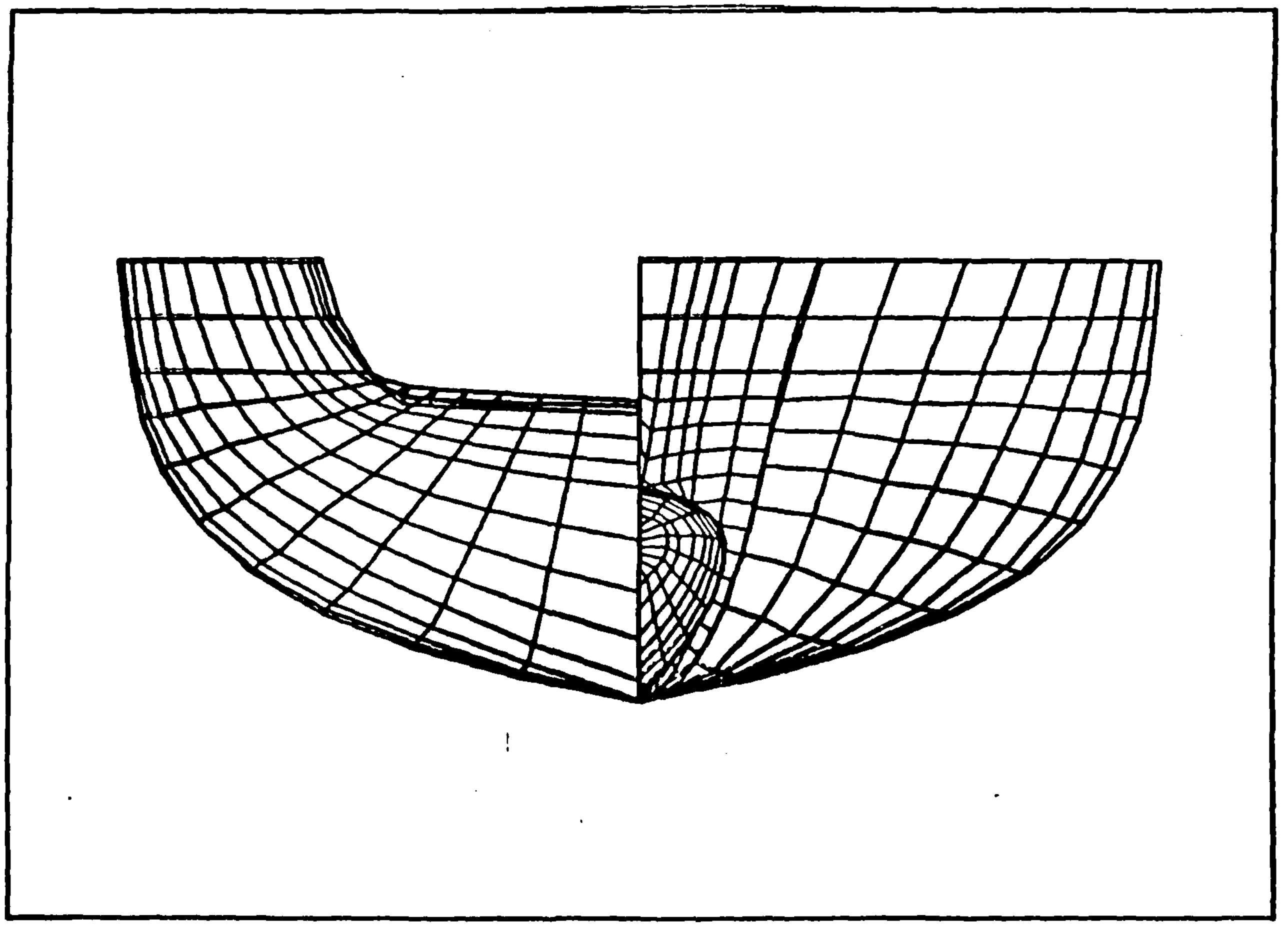
The model chosen for use in this study was a 1/24.75 scale model of the FFG-7, USS OLIVER HAZARD PERRY. The selection criteria employed to make that decision were three-fold. First, the excellent resistance characteristics of this hull form have been well-documented. (Woo, 1983 and Zseleczky, 1984) Thus, reduction of the required effective horsepower by adding a bulbous bow presented a great challenge to the designer of that bulb. Secondly, the FFG-7 model was already in the possession of the U. S. Naval Academy Hydromechanics Laboratory, thereby lowering the overall cost of the project. Lastly, the model of the FFG-7 had been fitted with a removable bow section during an earlier study conducted by Zseleczky and Johnson (Zseleczky, 1984), which facilitated the removal and addition of various bulb forms. That research effort looked into the effects of a bow bulb similar to that found on the Italian frigate, MAESTRALE, on the resistance characteristics of the FFG-7. Also incorporated into that study was a comparison of the effects of various stern wedges on the FFG-7's calm water resistance. That report concluded that when used in conjunction with a bulbous bow, a 15° stern wedge seems to be optimum for reducing the overall resistance of the FFG-7 model. Therefore, the 15° stern wedge was appended to the FFG-7 model for all computer runs and tank tests conducted during this Trident research effort. The body plan of the FFG-7 with stern wedge and bow bulb, is shown in Figure 2.

BOW BULB DESIGN

In order to begin the task of bow bulb design for a particular hull form, it is necessary to decide upon a suitable bulb design methodology for the ship under consideration. Hagen and Fung (Hagen, 1983) suggest that any such methodology must be empirical in nature, as the present knowledge of the hydrodynamic interactions between the bulb and main hull are much too complex to develop an analytical approach to bulb design. That report also depicts two differing methods of bulbous bow design:

1) Bulb design without use of design charts.
2) Bulb design using design charts.

The first method is described as "art", and it should be utilized only by designers who are thoroughly familiar with guidelines present in the literature and whose experience and judgement can be relied upon to provide acceptable initial bulb designs. (Hagen, 1983) Owing to this designer's lack of experience and insufficient time to sift through the numerous, and often contradictory, guidelines present in the literature, the bow bulbs developed during the course of this project were designed with the aid of design charts discussed in Kracht, SNAME, 1978 and found in Kracht, VWS, 1978. These charts



BODY PLAN WITH BULB AND WEDGE

FIGURE 2

were developed by Alfred M. Kracht from a large number of model tests of ships with and without bulbs, having block coefficients[3] which range from 0.56 to 0.82. This range of block coefficient is indicative of larger, slower displacement ships such as tankers and naval auxiliaries. Since the goal of this project was to design bow bulbs for the small, fast FFG-7 hull form (block coefficient equal to 0.45), the necessity of verifying the applicability of Kracht's design charts became readily apparent. To accomplish this task, a trend study was initiated which attempted to detect changes in the optimum value of the major bulb parameters defined by Kracht as a function of changing block coefficient and Froude number. This trend study is presented as Figures 3 through 6 in Appendix A. The results of this study were encouraging since they indicated that most of the optimum parameter values vary only slightly with block coefficient. Thus, it was determined that the range of the Kracht bulb design charts could be extrapolated downward, and the design charts corresponding to the smallest block coefficient (C_B = 0.56) were used to develop bow bulb parameters for the FFG-7 hull form.

These bulb parameters, described by Kracht in SNAME, 1978 and VWS, 1978 are defined as follows:

" a) Breadth Parameter (C_{BB}) - The maximum breadth (B_B) of bulb area (A_{BT}) at the forward perpendicular divided by the beam at amidships (B_{MS}) of the ship: $C_{BB} = B_B/B_{MS}$

b) Length Parameter (C_{LPR}) - The protruding length (L_{PR}) divided by the length between perpendiculars (L_{PP}) of the ship: $C_{LPR} = L_{PR}/L_{PP}$

c) Depth Parameter (C_{ZB}) - The height (Z_B) of the foremost point of the bulb over the baseline divided by the draft (T_{FP}) at the forward perpendicular: $C_{ZB} = Z_B/T_{FP}$

---

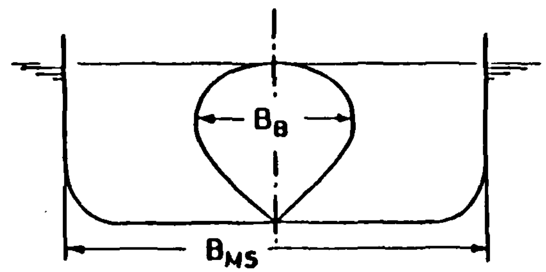
[3] The block coefficient (C_B) is a measure of the fullness of a hull form. It is defined as the volume of displacement divided by the product of length, beam, and draft:

$$C_B = \frac{VOLUME}{L \times B \times T}$$

BOW BULB PARAMETERS

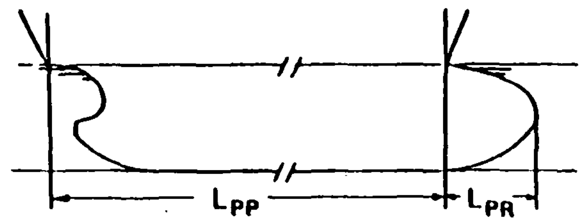
1. BREADTH PARAMETER

$$C_{BB} = B_B / B_{MS}$$



2. LENGTH PARAMETER

$$C_{LPR} = L_{PR} / L_{PP}$$



3. DEPTH PARAMETER

$$C_{ZB} = Z_B / T_{FP}$$

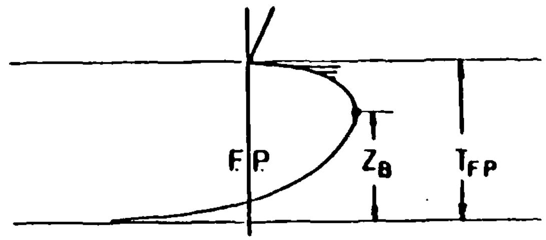
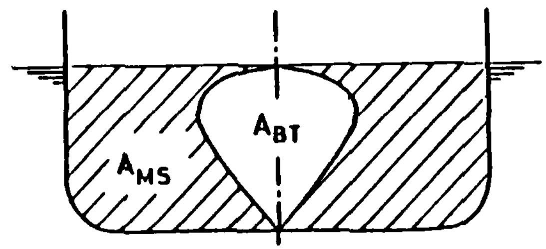


FIGURE 7

BOW BULB PARAMETERS

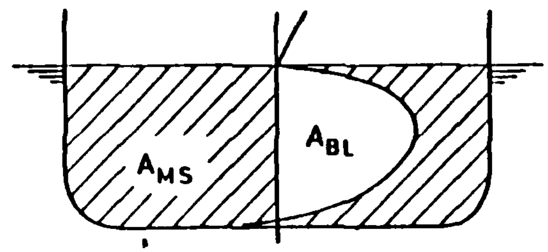
4. CROSS-SECTION PARAMETER

$C_{ABT} = A_{BT}/A_{MS}$



5. LATERAL PARAMETER

$C_{ABL} = A_{BL}/A_{MS}$



6. VOLUMETRIC PARAMETER

$C_{VPR} = V_{PR}/V_{WL}$

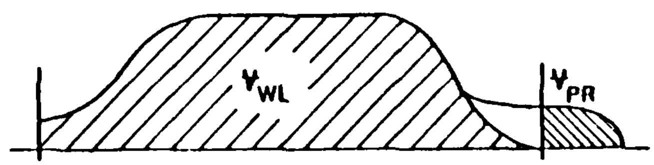


FIGURE 7

d) Cross-Section Parameter (C_{ABT}) - The cross-sectional area (A_{BT}) of the bulbous bow at the forward perpendicular divided by the midship section area (A_{MS}) of the ship: $C_{ABT} = A_{BT}/A_{MS}$

e) Lateral Parameter (C_{ABL}) - The area (A_{BL}) of the protuding bulb in the longitudinal plane divided by the midship-section area of the ship (A_{MS}): $C_{ABL} = A_{BL}/A_{MS}$

f) Volumetric Parameter (C_{VPR}) - The volume (V_{PR}) of the protruding part of the bulb divided by the volume of displacement (V_{WL}) of the ship: $C_{VPR} = V_{PR}/V_{WL}$ " (Hagen, 1983, p. 41)

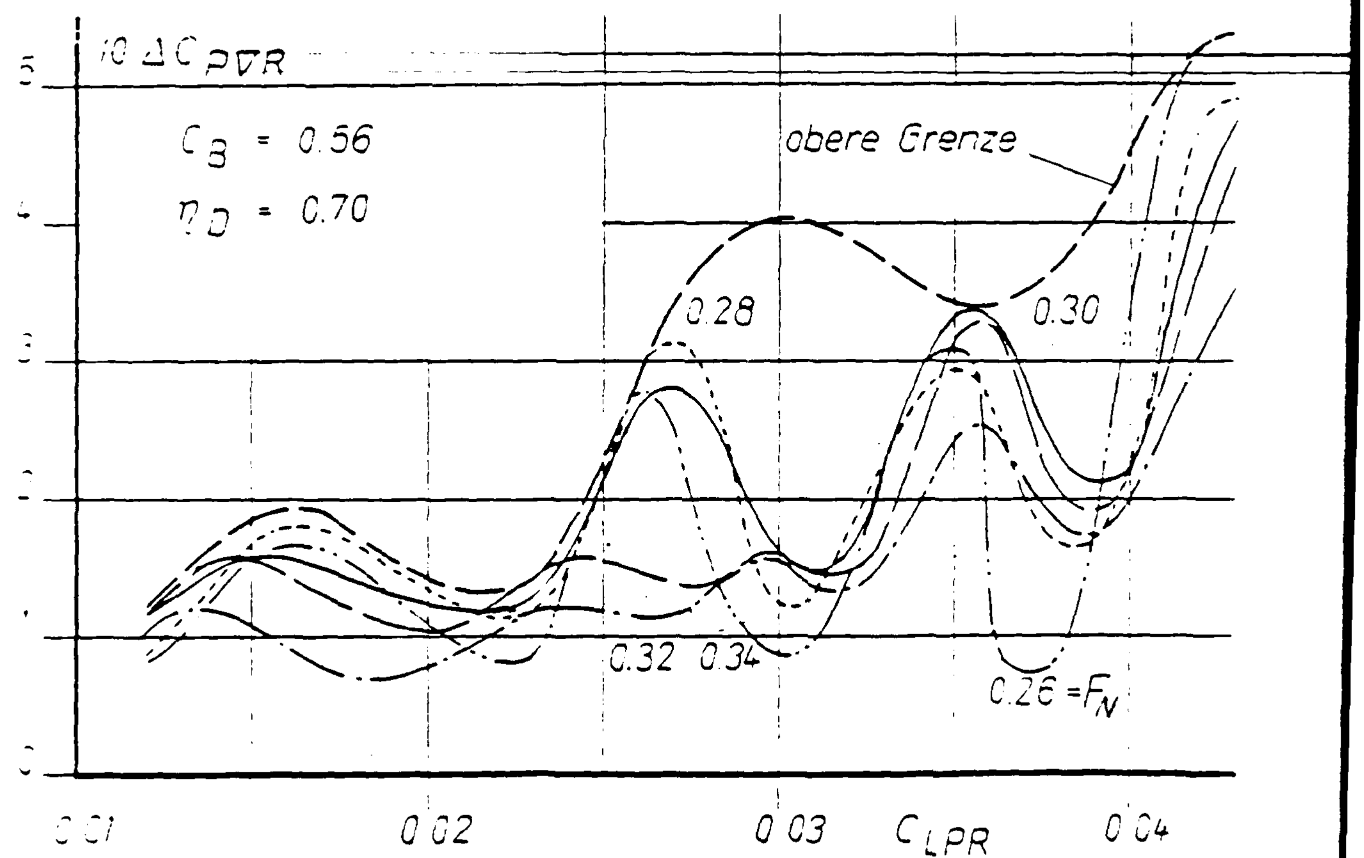
Note: Protruding is used here to mean that part of the bulb which extends forward of the forward perpendicular.

A graphical representation of these bulb parameters can be found in Figure 7, also taken from Hagen, 1983.

Utilization of design charts to derive near-optimum values of the parameters defined above is the goal of the bulb design methodology put forth by Hagen and Fung. These design charts were provided by Kracht in VWS, 1978. Each chart shows the residual power reduction coefficient ($\triangle C_{P\nabla R}$)[4] as a function of Froude number and one of the bulb shape parameters defined above for a particular block coefficient. This gives a total of six charts for each value of block coefficient. A representative design chart showing the residual power reduction coefficient ($\triangle C_{\nabla R}$) as a function of the length parameter (C_{LPR}) is shown in figure 8 (taken from Hagen, 1983). The wavy shape of this curve is typical of all the design charts, thus a given value of the residual power reduction coefficient can be achieved at more than one value of the bulb parameter. This further complicates the problem of finding near-optimum values for each of the six parameters.

The method developed in Hagen, 1983 to utilize the design charts differs somewhat from that advocated by Kracht in VWS, 1978. For the purposes

REPRESENTATIVE KRACHT DESIGN CURVE



NOTE: OBERE GRENZE IS GERMAN FOR UPPER LIMIT

FIGURE 8

of this design, the guidelines set forth in Hagen, 1983 were followed to define the parameters of the first bulb produced in the study. Subsequent bulbs resulted from making methodical variations to this initial bulb form. An outline of the chart utilization procedure (taken from Hagen, 1983) together with notes peculiar to this project is presented in Appendix B.

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[4]The residual power reduction coefficient is a measure of the percent reduction in power necessary to drive a ship equipped with a bulbous bow as compared to the same ship without a bow bulb. It considers only that power which is necessary to overcome the residuary resistance of the hull form (total resistance minus frictional resistance) and is quantitatively defined in Hagen, 1983 as:

$$\Delta C_{P\nabla R} = C_{P\nabla R_o} \text{ (without bulb)} - C_{P\nabla R} \text{ (with bulb)} \; / \; C_{P\nabla R_o}$$

where $C_{P\nabla R} = P_O / \left[(\rho/2)\, v^3\, (\nabla_{WL}^2)^{0.333}\right] \quad C_F S / \left[\eta_D\, (\nabla_{WL}^2)^{0.333}\right]$

P_D = Delivered Power

ρ = Mass density of water

V = Speed

∇_{WL} = Displacement volume

C_F = Frictional resistance coefficient

ITTC Standard: $C_F = 0.075/(\mathrm{LOG}R_N - 2.0)^2$

S = Wetted surface

η_D = Quasi-propulsive coefficient

Maximizing the residual power reduction coefficient is desirable since a large $\Delta C_{P\nabla R}$ indicates a large reduction in residuary resistance as a result of the addition of a bulbous bow.

Despite the desirability of a systematic approach to bulbous bow design, the method outlined in Appendix B does have significant limitations. Perhaps the most important disadvantage of this method is that it fails to provide a way to join the bulb to the rest of the hull. The methodology concerns itself only with that portion of the bulb forward of the forward perpendicular, as is apparent from the definitions of the bulb geometry parameters. The integration of the bulb into the rest of the ship's hull is left entirely to the designer's discretion, although Hagen and Fung do offer some guidelines on this topic taken from "various experimental investigations". Their report goes so far as to suggest that "simply continuing the bulb aft using longitudinal elements parallel to the ship's axis is probably as good a solution to the problem as any". (Hagen, 1983, p. 54) In light of this recommendation and in the interest of keeping factors other than bulb form constant throughout this study, this guideline was followed explicitly for all bulbs designed for this project.

As was previously stated, the bulb designated as bulbous bow no. 1 was developed by following the design methodology advocated in Hagen, 1983 as closely as possible. For all of the remaining bulb forms designed in the course of this project, methodical variations to the shape of bulb no. 1 were made by assuming specific values of the bulb parameters to be varied, specifically the length parameter (C_{LPR}) and the breadth parameter (C_{BB}). These variations were made according to the bulb design matrix presented in figure 9. The numbers inside the boxes on that figure correspond to the number assigned to the bulb which had that particular length and breadth. The design methodology put forth in Hagen, 1983 was then utilized to develop a bulb form with the required parameters. A complete listing of the parameters for each bulb designed, as well as the values for the existing MAESTRALE O-type bulb, is presented in Table 1 located in Appendix C. Figure 10 is a computer-generated profile view of

BULB DESIGN MATRIX

BULB LENGTH (FT. FWD OF FP)

BULB BREADTH (FT. AT MAX. WIDTH)

	4'	8'	12'	14'	16'
7'	8	7	2	1	3
9'			5	4	6

FIGURE 9

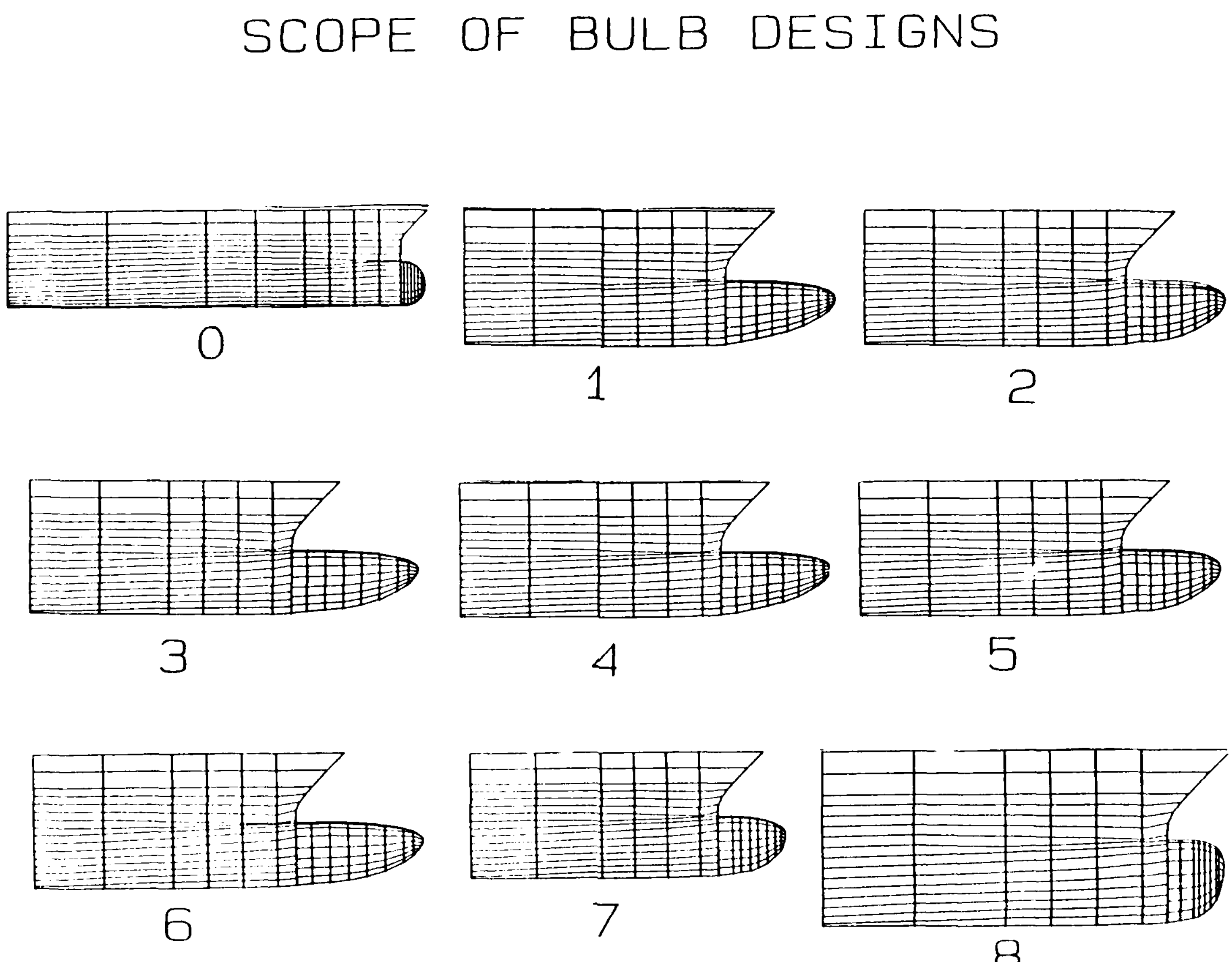

FIGURE 10

the scope of the bulb designs. Again, the numbers on figure 11 correspond to bulb number, with bulb 0 being the existing MAESTRALE 0-type bulb.

COMPUTER PREDICTIONS

Having completed the design of the bulbous bows as described above, the computer was then utilized to predict their performance. First, the XYZ free surface program was used to predict the calm-water resistance characteristics of the FFG-7 configured with and without bulb forms. Then, the Navy Standard Ship Motions Program was run to determine their seakeeping performance. An overview of the operation of these two programs is presented here. For a more detailed description of the computer programs and their operation, consult Cheng, 1984 and Meyers, 1981.

RESISTANCE

According to Mr. Bill H. Cheng and his fellow researchers at David Taylor Naval Ship Research and Development Center, the XYZ free surface program (XYZFS) "is a versatile ship design tool which can be used to predict the wave resistance characteristics of a wide variety of hull forms." (Cheng, 1984, p. 1) XYZFS computes three-dimensional steady potential flow about ships through a Rankine Source Panel Method. It obtains the local flow field, wave resistance, and wave patterns for hull forms moving at a constant speed. These speeds must correspond to Froude numbers[5] between 0.2 and 0.6. XYZFS can also estimate

---

5 Froude number is the non-dimensional speed of a ship. It is equal to the ship's speed divided by the square root of the product of the gravitational constant times the ship's length:

$$F_N = V/\sqrt{gL}$$

residuary resistance. Ships can be held fixed or allowed to sink and trim in response to hydrodynamic forces while the program is running. For a detailed explanation of the application of the XYZ Free Surface Program to this project, as well as figure 11 which shows a panelized bulb form used as input into XYZFS, see Appendix D. The results obtained from the XYS Free Surface Program are presented in figure 12 in the form of effective horespower (EHP)[6] ratios. For the purposes of this project, effective horsepower ratio is defined as the EHP of the FFG-7 configured with bulb and stern wedge to that of the FFG-7 with stern wedge only. Thus, whenever the EHP ratio is below 1.00, the bow bulb is reducing the resistance of the hull form.

SEAKEEPING

The other numerical analysis method used to predict performance of the bulb candidates, the Navy Standard Ship Motions Program (SMP), represents a combination of earlier computer programs "to provide motion predictions in both regular waves and irregular seas for any location on the ship." (Meyers, 1981, p.3) SMP can be used to obtain any or all of the following:

1) Rigid body motions, including displacements, velocities, and accelerations for the surge, sway, heave, roll, pitch, and yaw motions.

2) Longitudinal, lateral, and vertical motions at up to ten user-defined locations.

3) Relative motions for another ten arbitrary points.

4) Probability and frequency of slamming, emergence, and submergence at those points defined for relative motion calculation. (Meyers, 1981, p. 4)

---

[6] Effective horsepower is defined as the power necessary to tow a hull form at constant speed. It is equal to the total resistance of the ship multiplied by the ship speed and divided by a constant (550):

$$EHP = R_{TS} \cdot V_S / 550$$

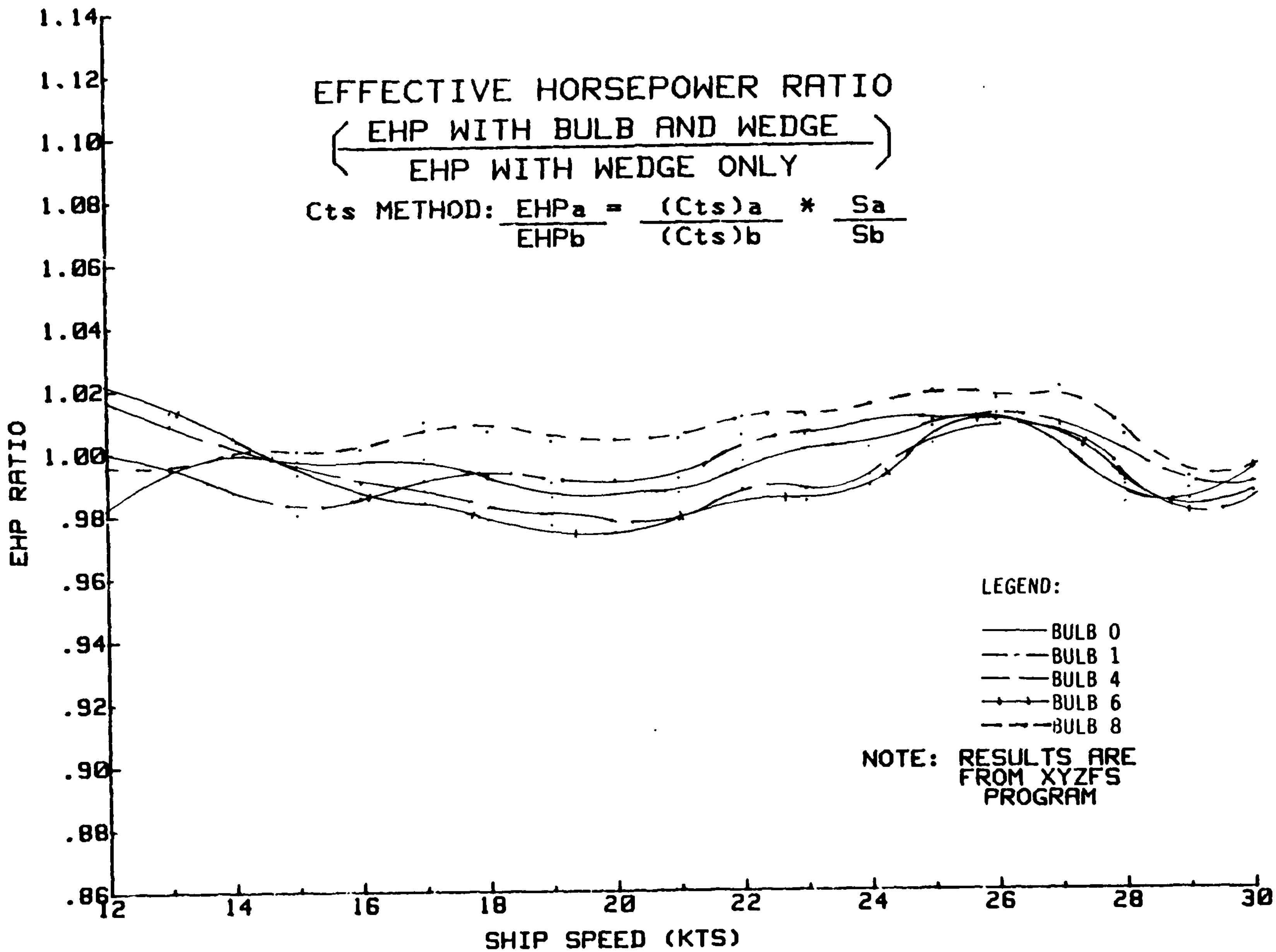
EFFECTIVE HORSEPOWER RATIO
(EHP WITH BULB AND WEDGE / EHP WITH WEDGE ONLY)
Cts METHOD: EHPa / EHPb = (Cts)a / (Cts)b * Sa / Sb
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
.98
.96
.94
.92
.90
.88
.86
EHP RATIO
12
14
16
18
20
22
24
26
28
30
SHIP SPEED (KTS)
LEGEND:
BULB 0
BULB 1
BULB 4
BULB 6
BULB 8
NOTE: RESULTS ARE FROM XYZFS PROGRAM

FIGURE 12

For an explanation of the adaption of the Ship Motions Program to this project, consult Appendix E.

The results obtained from the Ship Motions Program are presented as plots of significant heave[7] amplitude, significant pitch[7] amplitude, and probability of slamming[7] at station two in figures 13 through 15. All of these outputs are plotted versus ship speed. These figures indicate that SMP detects very little difference in the seakeeping performance of the FFG-7 with and without bow bulb, and even less of a difference between two different bulb configurations. Thus, it was unnecessary to execute SMP for all of the bulbs designed.

MODEL TEST PROGRAM

In order to experimentally determine the resistance and seakeeping characteristics of the FFG-7 appended with bulbous bows and to verify the results obtained in the computer predictions phase of this project, an extensive series of model tests was performed in the United States Naval Academy Hydromechanics Laboratory 380 foot towing tank. The test program consisted of three parts: (1) bulb construction and model preparation, (2) effective horsepower testing to determine resistance characteristics, and (3) head seas testing in irregular waves to assess seakeeping performance. Each of these portions of the test program are discussed separately, and the general arrangement of the data acquisition system used during the model tests is depicted graphically in figure 16 located in appendix F. Also contained in appendix F is table 2 which provides information about the sensors utilized during the model testing portion of this Trident project.

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[7] Heave, pitch, and slamming are terms associated with seakeeping performance. Heave and pitch are vertical plane motions which result as the ship responds to wave action, while slamming is characterized by impacting the free surface of the water forcefully at a given point along the length of the ship.

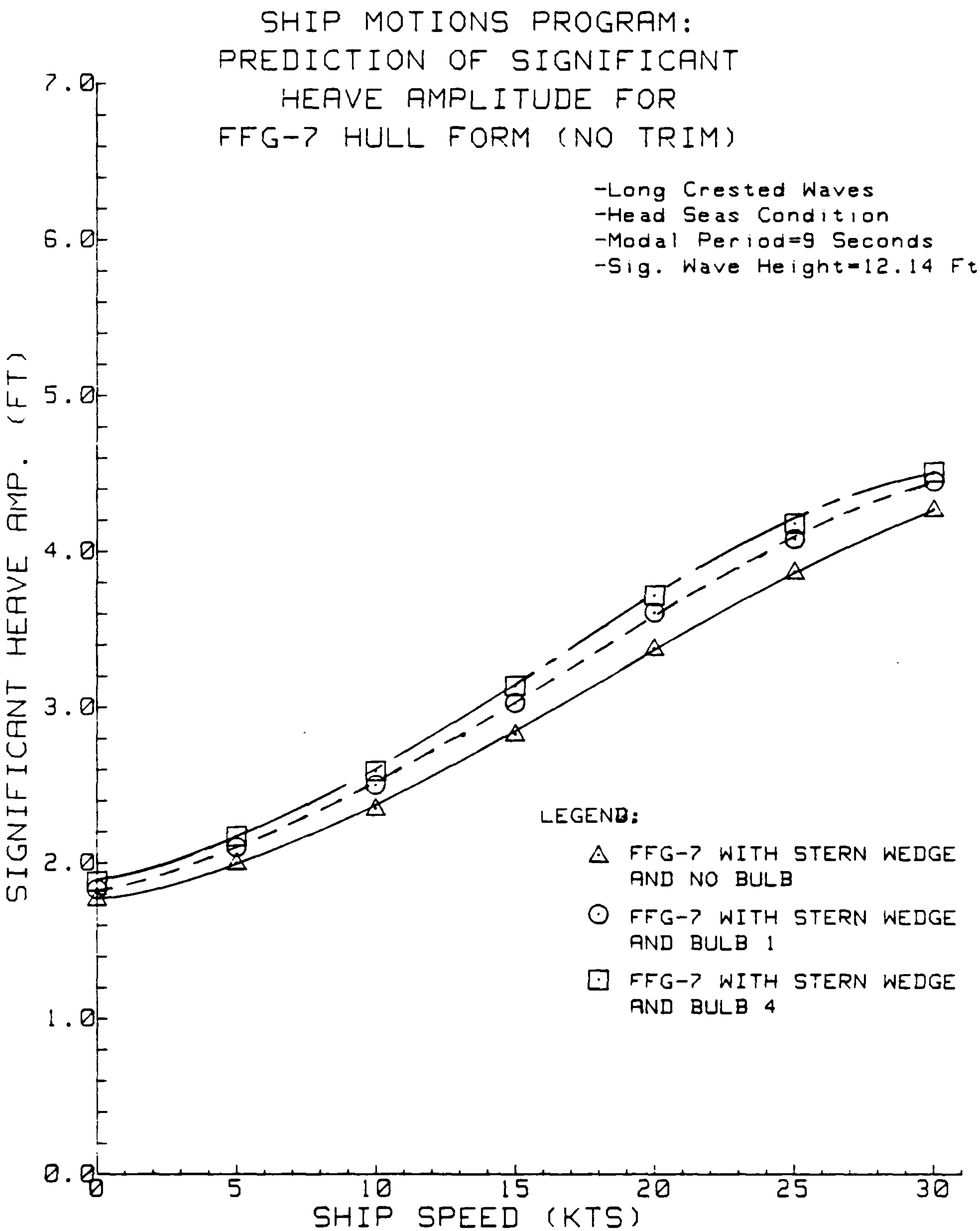
SHIP MOTIONS PROGRAM:
PREDICTION OF SIGNIFICANT
HEAVE AMPLITUDE FOR
FFG-7 HULL FORM (NO TRIM)
-Long Crested Waves
-Head Seas Condition
-Modal Period=9 Seconds
-Sig. Wave Height=12.14 Ft
SIGNIFICANT HEAVE AMP. (FT)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
5
10
15
20
25
30
SHIP SPEED (KTS)
LEGEND:
FFG-7 WITH STERN WEDGE AND NO BULB
FFG-7 WITH STERN WEDGE AND BULB 1
FFG-7 WITH STERN WEDGE AND BULB 4

FIGURE 13

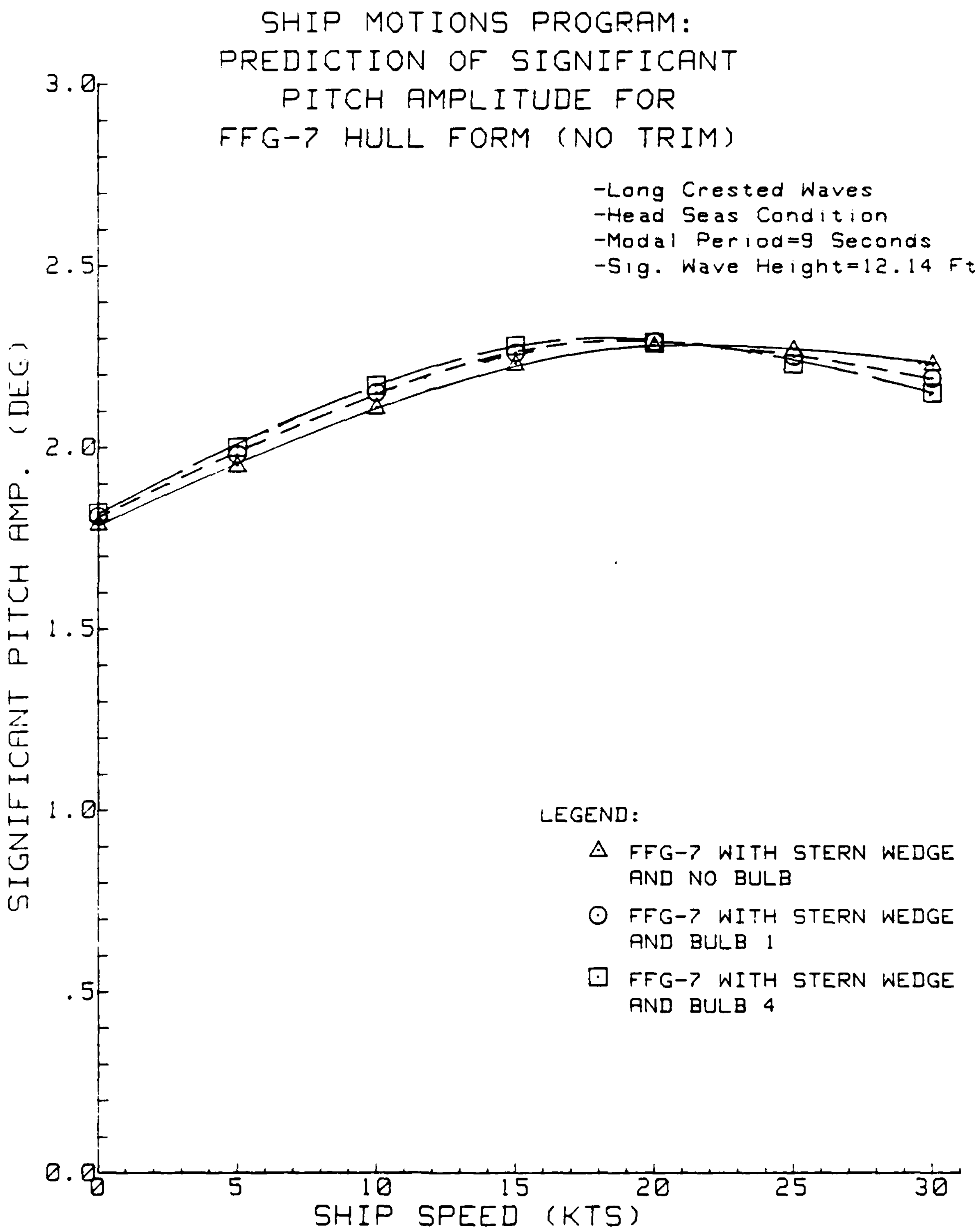
SHIP MOTIONS PROGRAM:
PREDICTION OF SIGNIFICANT
PITCH AMPLITUDE FOR
FFG-7 HULL FORM (NO TRIM)
-Long Crested Waves
-Head Seas Condition
-Modal Period=9 Seconds
-Sig. Wave Height=12.14 Ft
SIGNIFICANT PITCH AMP. (DEG)
3.0
2.5
2.0
1.5
1.0
.5
0.0
0
5
10
15
20
25
30
SHIP SPEED (KTS)
LEGEND:
FFG-7 WITH STERN WEDGE AND NO BULB
FFG-7 WITH STERN WEDGE AND BULB 1
FFG-7 WITH STERN WEDGE AND BULB 4

FIGURE 14

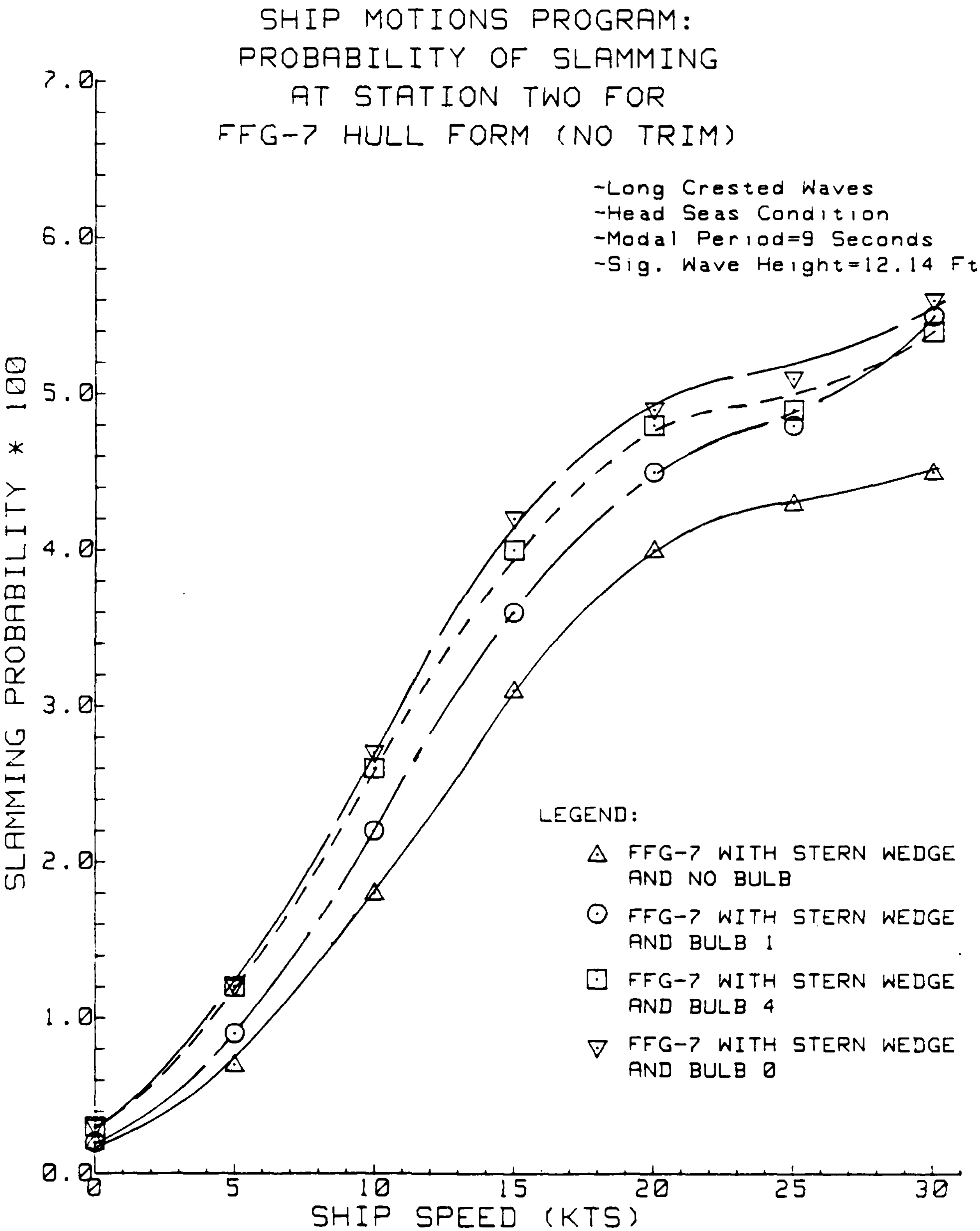
SHIP MOTIONS PROGRAM:
PROBABILITY OF SLAMMING
AT STATION TWO FOR
FFG-7 HULL FORM (NO TRIM)
-Long Crested Waves
-Head Seas Condition
-Modal Period=9 Seconds
-Sig. Wave Height=12.14 Ft
SLAMMING PROBABILITY * 100
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
0
5
10
15
20
25
30
SHIP SPEED (KTS)
LEGEND:
FFG-7 WITH STERN WEDGE AND NO BULB
FFG-7 WITH STERN WEDGE AND BULB 1
FFG-7 WITH STERN WEDGE AND BULB 4
FFG-7 WITH STERN WEDGE AND BULB 0

FIGURE 15

Bulb Construction and Model Preparation

In addition to the normal FFG-7 bow and Maestrale-style bulb which existed prior to this project, four of the nine bulbs previously described and analyzed on XYZFS were constructed and tested on the FFG-7 model fitted with a removable bow section and a 15 degree stern wedge. As previously noted, the decision to use this stern wedge was based on its favorable effects on the resistance characteristics of the FFG-7 hull form as reported by Zseleczky and Johnson in Zseleczky, 1984. The bulbs constructed during the course of this project were made from a high-density foam by Tom Price, an experienced model maker in the Technical Support Department at the U. S. Naval Academy. Each bulb was carefully cut and shaped to represent the lines developed by this designer. Decisions about which bulbs to produce resulted from careful consideration of the objectives of this program. Bulb 1 was chosen to validate the extrapolation of the Kracht method for initial bulb design to the lower block coefficient of the FFG-7 (C_B = 0.45). The decision to produce bulb 8 stemmed from the fact that its length was almost identical to that of the Maestrale-style bulb. This offered an opportunity to directly compare the results of an O-type bulb to a ∇- type bulb of similar length. Finally, bulbs 4 and 6 were produced because of the superior resistance characteristics predicted for them by the XYZ Free Surface Program.

Before testing began, each model configuration was ballasted to correctly represent the scaled displacement of the FFG-7 hull form in the same configuration. All models were ballasted to a constant waterline of 14.35 feet full-scale with zero degrees trim. Longitudinal gyradius[8] was set at the

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[8] The longitudinal gyradius is the radius of gyration of the ship about an axis which separates the ship into forward and after sections of amidships.

standard value of 25% of the length between perpendiculars by the bifilar suspension method[9]. Two rows of small studs were placed near the bow to stimulate turbulent flow about the model on all configurations which included a bulbous bow. One of these rows was located on the bulb at the point of maximum breadth. The other was placed four inches from the stem of the model with a one inch vertical separation (pitch). Only one row of studs was used for the no bulb condition. The model configured with Maestrale-style bulb and stern wedge was towed from the longitudinal location of the center of gravity, as is standard practice for the Naval Academy Hydro Lab. However, since the longitudinal location of the center of gravity varied only slightly for each bulb configuration and alteration of the towing point would have required much additional work, this towing point was used for all model configurations tested. For a comparison of the longitudinal position of the center of gravity, displacement, and wetted surface on each configuration, along with other relevant model parameters, see the table of model particulars (Table 3).

Resistance Tests

Calm-water resistance tests were performed on each model configuration to evaluate the effective horsepower necessary to tow the ship at speeds ranging from 12 to 30 kts full-scale. The variables measured during these tests included speed, drag, sinkage, and trim. The dynamometer used for both effective horsepower and seakeeping tests was a Netherlands Ship Model Basin air-bearing rig with single heave post. The model was free to pitch and heave only, with all other motions (yaw, roll, sway, and surge) being locked.

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9 The bifilar suspension method is used to determine the longitudinal gyradius. The longitudinal gyradius is assumed equal to the vertical gyradius, which is determined by suspending the model on two wires and timing its oscillations.

MODEL PARTICULARS OF FFG-7 CONFIGURATIONS

	NO BULB	BULB 0	BULB 1	BULB 4	BULB 5	BULB 8
WATERLINE LENGTH (FT.)	16.5	16.5	16.5	16.5	16.5	16.5
WETTED SURFACE (FT^2)	28.99	29.86	29.90	30.06	30.22	29.67
DISPLACEMENT (LBS.)	490.5	495.5	495.9	497.8	498.4	494.7
LCG (IN., +=FWD MIDSHIP)	-2.02	2.53	1.39	1.23	1.23	1.39
TANK TEMP. (DEG. F)	60	60	58	60	60	58

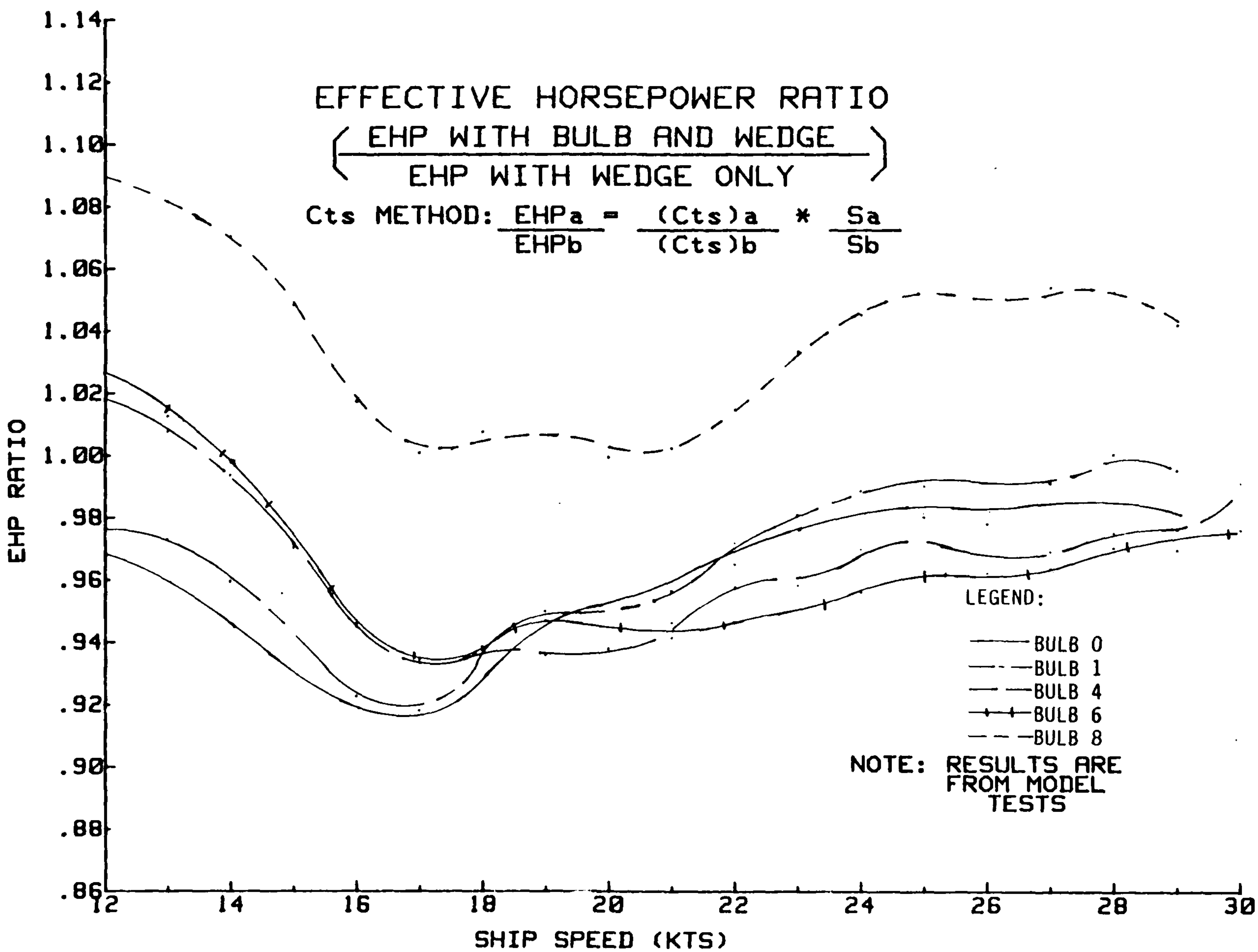
NOTE: CORRELATION ALLOWANCE OF 0.00045 WAS USED TO EXPAND ALL EFFECTIVE HORSEPOWER RESULTS TO FULL SCALE. THIS CORRELATION ALLOWANCE WAS SUGGESTED FOR THE FFG-7 HULL FORM IN WOO, 1983.

TABLE 3

Results of the effective horsepower tests are presented as effective horsepower ratios in figure 17. Again, an EHP ratio of less that 1.00 indicates that the bulb is lowering the ship's resistance. The EHP ratio of bulb 0 was derived from data which was manipulated to subtract the effects of a calibration error, while all other curves resulted from actual model test data.

Seakeeping Tests

In addition to the calm water resistance testing, head seas tests in irregular waves were performed on all model configurations in order to assess seakeeping performance. Waves used for this study were periodic encountered, irregular waves as described by Johnson, Anderson, Clark and Lund in Johnson, 1980. Three waves were constructed according to the methods developed in that paper, corresponding to ship speeds of 15, 20, and 25 knots. In this manner, each model configuration was tested in three identical irregular wave trains. For most configurations, the model was towed at each speed twice to collect data on resistance, pitch, heave, bow acceleration, and encountered wave height. Again, information about the sensors used to collect this data is provided in Appendix E. Unfortunately, the amount of data collected during seakeeping tests was not sufficient to provide statistically significant results, and therefore, this portion of the model test program was quantitatively inconclusive. However, videotapes made of all configurations and speeds tested allowed for a qualitative comparison of seakeeping performance. From these videotapes, it was apparent that the addition of a bulbous bow to the FFG-7 hull form tended to degrade its seakeeping performance to a small degree. This fact was evidenced by the more extreme motions and greater amount of water taken over the deck when the FFG-7 model was configured with a bow bulb. On the other hand, the videotapes also indicate that the bulbless hull form rises higher out of the water in response to the wave action. Although the hull form seems to take more water over the deck when configured with a bow bulb, the amount of water taken



EFFECTIVE HORSEPOWER RATIO
(EHP WITH BULB AND WEDGE / EHP WITH WEDGE ONLY)
Cts METHOD: EHPa / EHPb = (Cts)a / (Cts)b * Sa / Sb
EHP RATIO
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
.98
.96
.94
.92
.90
.88
.86
12
14
16
18
20
22
24
26
28
30
SHIP SPEED (KTS)
LEGEND:
BULB 0
BULB 1
BULB 4
BULB 6
BULB 8
NOTE: RESULTS ARE FROM MODEL TESTS

FIGURE 17

on seems to decrease with increasing bulb length. Overall, the small degradation in seakeeping performance resulting from the addition of a bulbous bow to the FFG-7 hull form is not sufficient to override the resistance advantages of the ship with bow bulb.

COMPARISON OF COMPUTER PREDICTIONS TO MODEL TEST RESULTS

As previously stated, the primary objective of this Trident research project was the comparison of computer predicted resistance and seakeeping. characteristics of the FFG-7 hull form with and without bow bulb to the results obtained from actual model testing. Comparisons for the resistance and seakeeping portions of the study are discussed separately here.

Resistance

The comparison of the resistance predictions of the XYZ Free Surface Program and the results obtained from calm water tank testing of the FFG-7 model was made on two separate bases. First, in an absolute sense, the XYZ Free Surface Program predicted approximately 10-15% lower resistance than the model tests for all configurations at all speeds. This fact is evident on the plots of total ship resistance coefficient[10] versus ship speed presented in figures 18 through 23. The multiplicity of points in the 18-20 knots speed range on the XYZFS curve results from the execution of two separate algorithims within the

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[10] The total ship resistance coefficient (C_{TS}) is simply the nondimensionalized resistance of the hull form. It is equal to the ship's total resistance divided by the product of one-half times the water density multiplied by the square of the velocity of the ship times the wetted surface of the hull form:

$$C_{TS} = R_{TS} / (\tfrac{1}{2}\rho V^2 S)$$

The total ship resistance coefficient can be used to obtain EHP ratios if the two hullforms in question are moving at the same speed in the same fluid:

$$\text{EHP RATIO} = \frac{EHP_A}{EHP_B} = \frac{(C_{TS})A}{(C_{TS})B} \times \frac{S_A}{S_B}$$

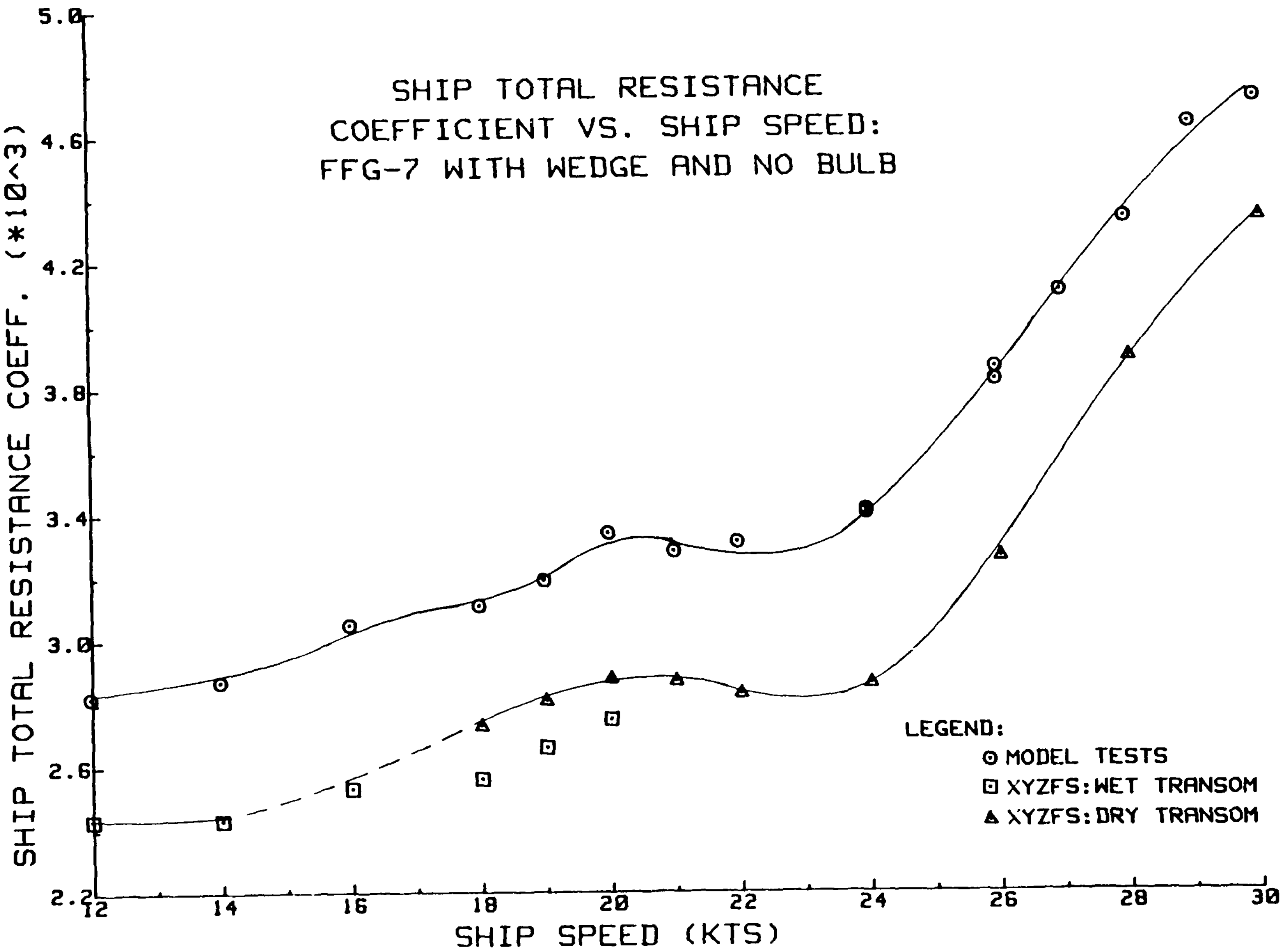
SHIP TOTAL RESISTANCE
COEFFICIENT VS. SHIP SPEED:
FFG-7 WITH WEDGE AND NO BULB
SHIP TOTAL RESISTANCE COEFF. (*10^3)
5.0
4.6
4.2
3.8
3.4
3.0
2.6
2.2
12
14
16
18
20
22
24
26
28
30
SHIP SPEED (KTS)
LEGEND:
MODEL TESTS
XYZFS:WET TRANSOM
XYZFS:DRY TRANSOM

FIGURE 18

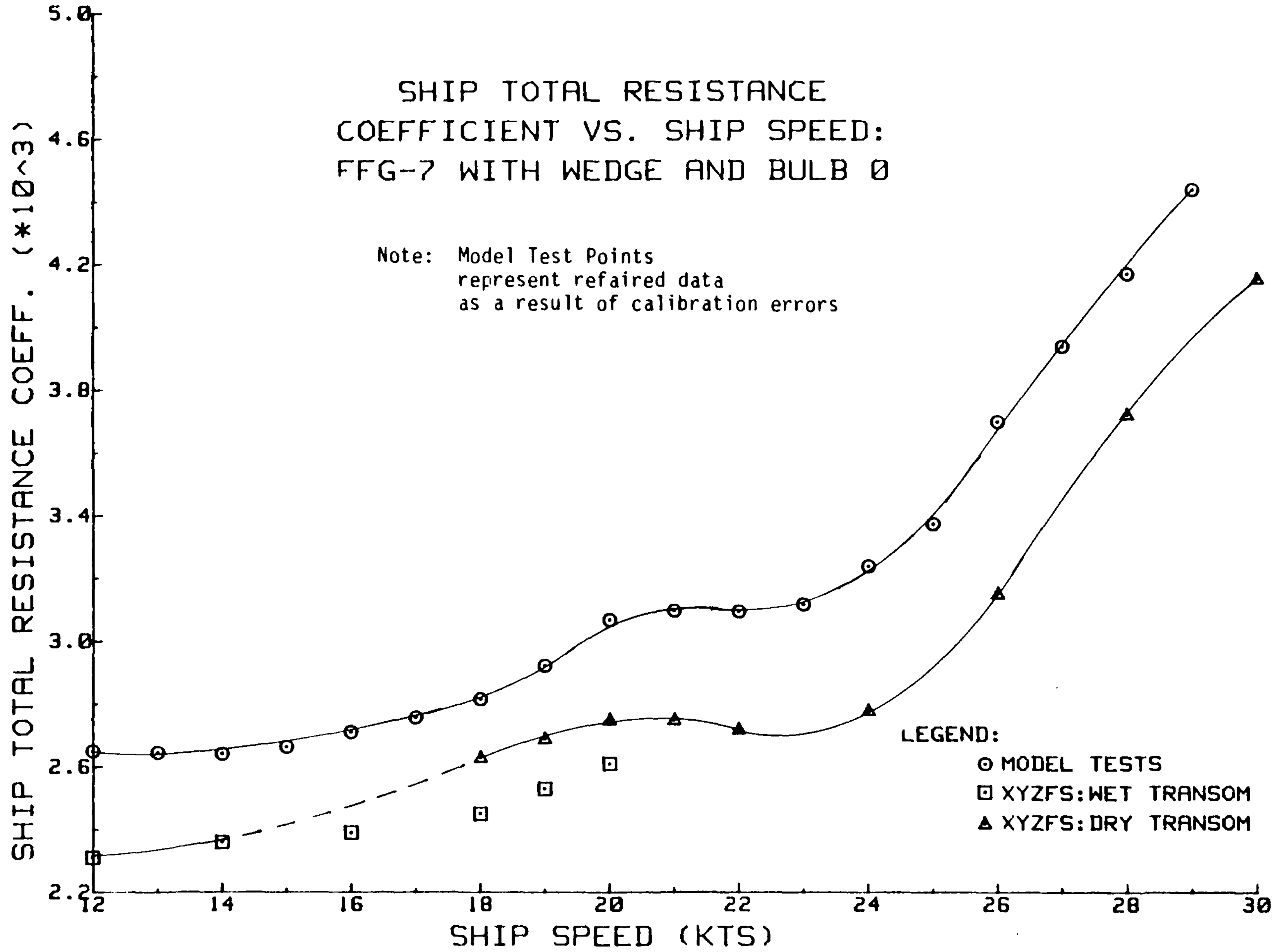
SHIP TOTAL RESISTANCE
COEFFICIENT VS. SHIP SPEED:
FFG-7 WITH WEDGE AND BULB 0
Note: Model Test Points
represent refaired data
as a result of calibration errors
LEGEND:
MODEL TESTS
XYZFS:WET TRANSOM
XYZFS:DRY TRANSOM
SHIP TOTAL RESISTANCE COEFF. (*10^3)
SHIP SPEED (KTS)
5.0
4.6
4.2
3.8
3.4
3.0
2.6
2.2
12
14
16
18
20
22
24
26
28
30

FIGURE 19

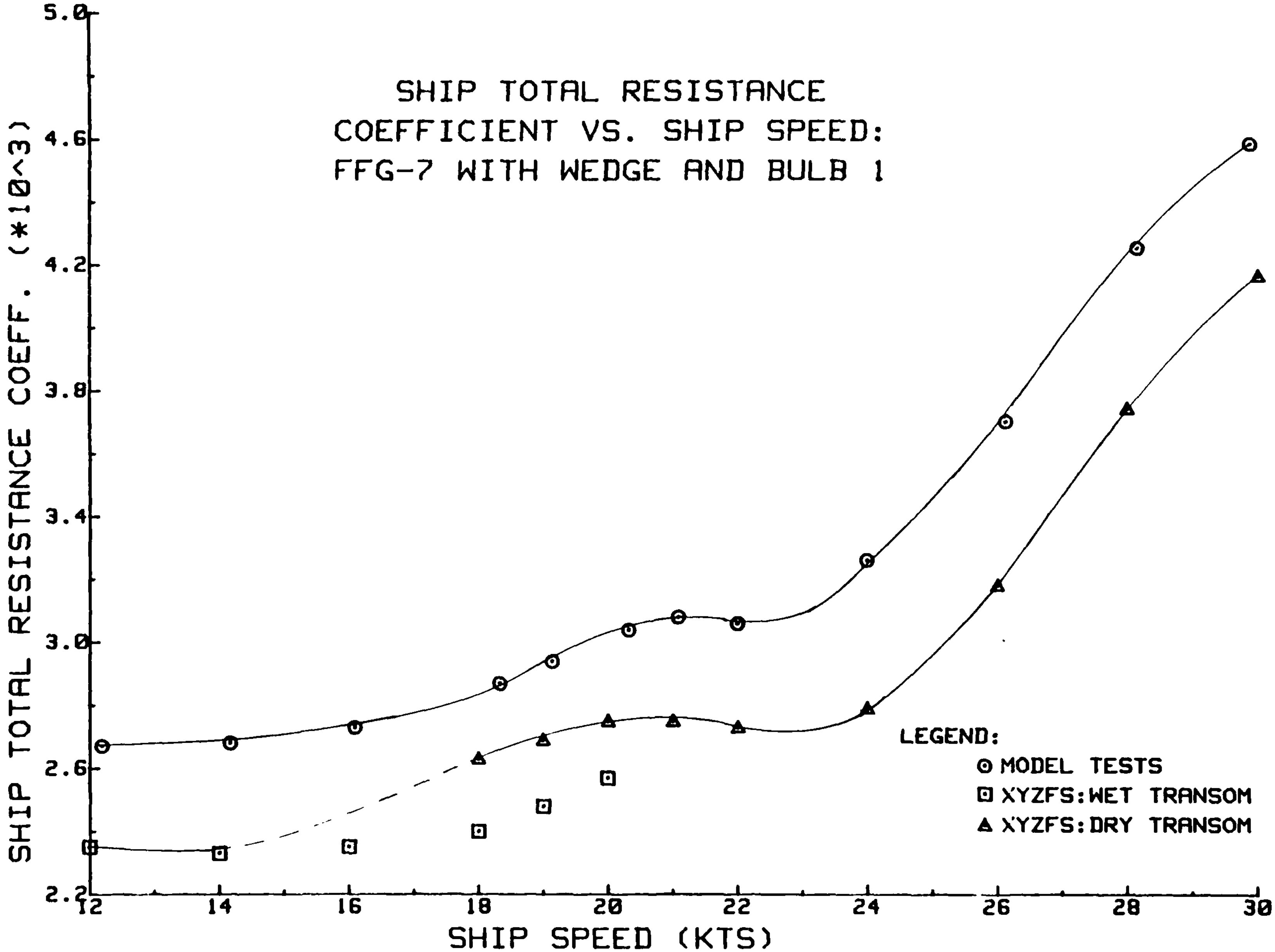
SHIP TOTAL RESISTANCE
COEFFICIENT VS. SHIP SPEED:
FFG-7 WITH WEDGE AND BULB 1
SHIP TOTAL RESISTANCE COEFF. (*10^3)
5.0
4.6
4.2
3.8
3.4
3.0
2.6
2.2
12
14
16
18
20
22
24
26
28
30
SHIP SPEED (KTS)
LEGEND:
MODEL TESTS
XYZFS:WET TRANSOM
XYZFS:DRY TRANSOM

FIGURE 20

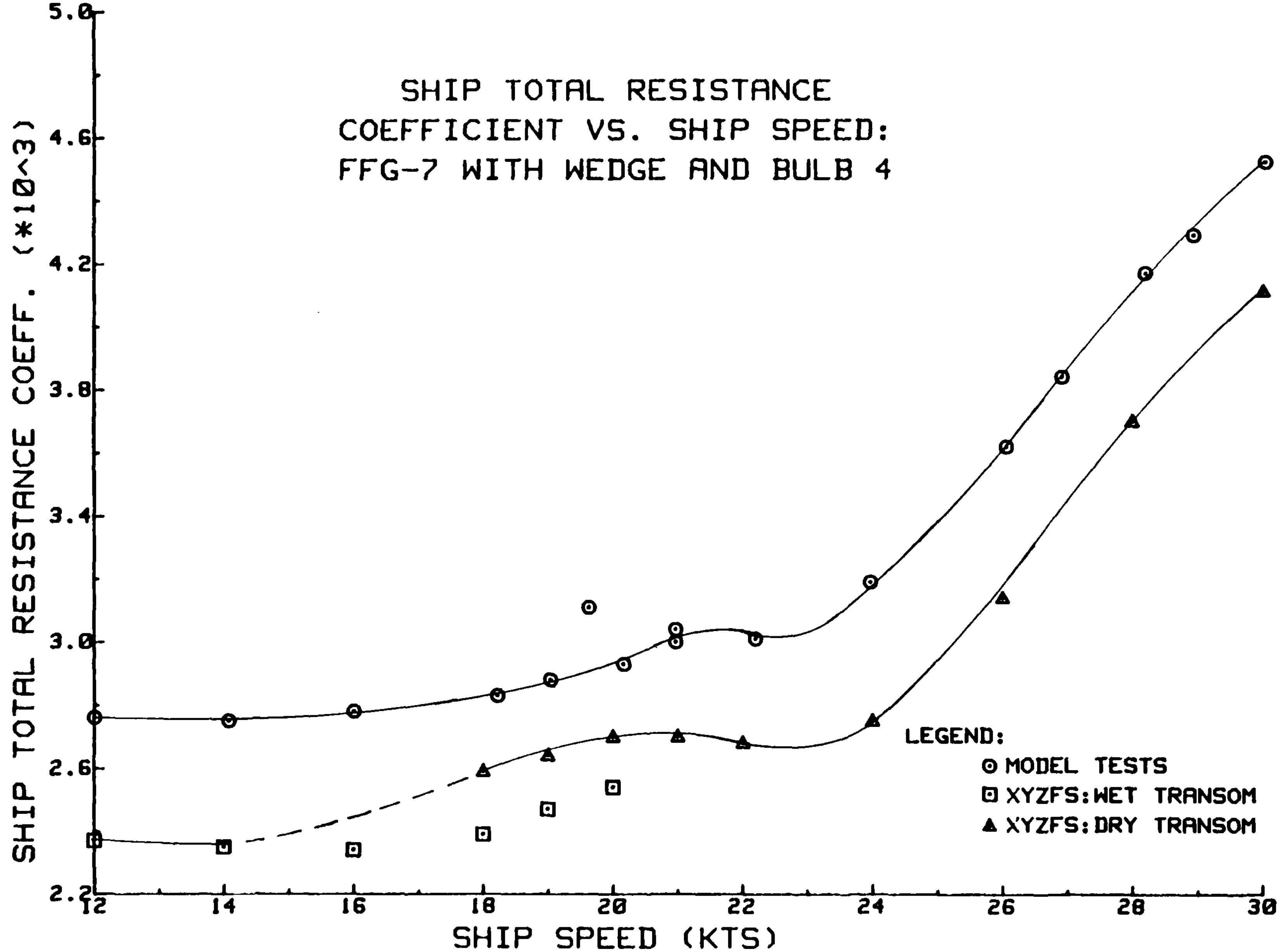
SHIP TOTAL RESISTANCE
COEFFICIENT VS. SHIP SPEED:
FFG-7 WITH WEDGE AND BULB 4
SHIP TOTAL RESISTANCE COEFF. (*10^3)
5.0
4.6
4.2
3.8
3.4
3.0
2.6
2.2
12
14
16
18
20
22
24
26
28
30
SHIP SPEED (KTS)
LEGEND:
MODEL TESTS
XYZFS:WET TRANSOM
XYZFS:DRY TRANSOM

FIGURE 21

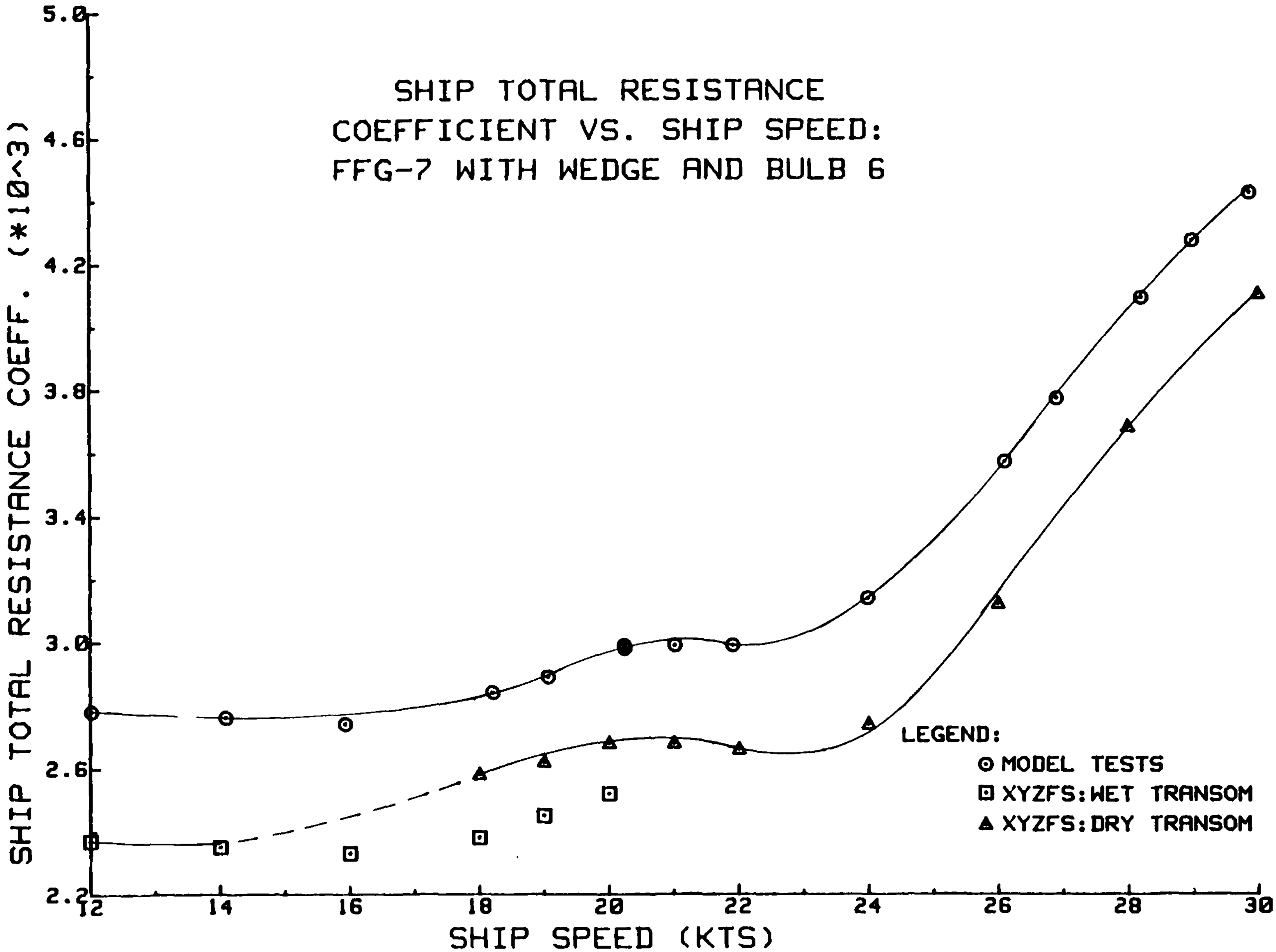
SHIP TOTAL RESISTANCE
COEFFICIENT VS. SHIP SPEED:
FFG-7 WITH WEDGE AND BULB 6
SHIP TOTAL RESISTANCE COEFF. (*10^3)
5.0
4.6
4.2
3.8
3.4
3.0
2.6
2.2
12
14
16
18
20
22
24
26
28
30
SHIP SPEED (KTS)
LEGEND:
MODEL TESTS
XYZFS:WET TRANSOM
XYZFS:DRY TRANSOM

FIGURE 22

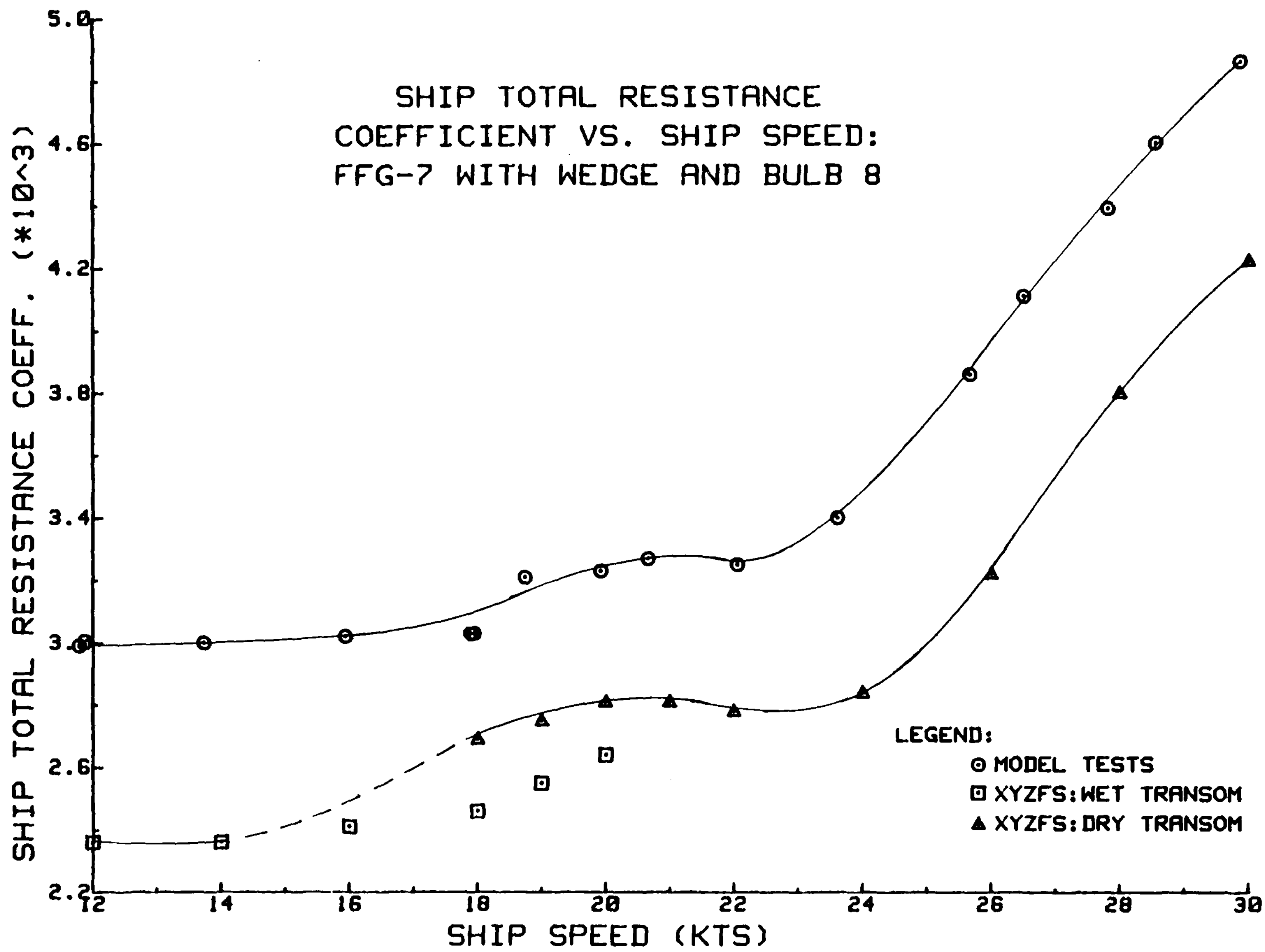
SHIP TOTAL RESISTANCE
COEFFICIENT VS. SHIP SPEED:
FFG-7 WITH WEDGE AND BULB 8
SHIP TOTAL RESISTANCE COEFF. (*10^3)
5.0
4.6
4.2
3.8
3.4
3.0
2.6
2.2
12
14
16
18
20
22
24
26
28
30
SHIP SPEED (KTS)
LEGEND:
MODEL TESTS
XYZFS:WET TRANSOM
XYZFS:DRY TRANSOM

FIGURE 23

program. One assumes a wetted transom stern while the other assumes the transom is completely dry. Since the model tests showed that the transom stern of the FFG-7 was dry at all speeds above 16 knots, the "wet-algorithm" points above that speed were ignored for the purpose of fairing those curves. The dashed line between 14 and 18 knots on the XYZFS curves represents the uncertainty which is present in the transition from the wet transom to a dry stern. From these curves, the EHP ratio curves described earlier were derived. As was the case with those EHP ratios, the total ship resistance coefficient curve from model test data for bulb 0 represents refaired data as a result of a calibration error. A comparison of EHP ratios from XYZFS output and model test results for each bulb is shown in figures 24 through 28 contained in Appendix G. Although similar trends are evident from these curves, the quantitative results still differ somewhat. Many plausible explanations can be advanced for the absolute differences between XYZFS predictions and model test results. First, a skeg[11] was present on the FFG-7 model when tested, but this skeg was not added to the hull form as paneled for XYZFS. Thus, the drag of the skeg is not included in the computer predictions but does add to the overall resistance of the model. Secondly, the running draft at the forward and after perpendiculars used as input to the XYZ Free Surface Program was not exactly the same as that obtained during model testing. Other possible sources of these differences include the questionable ability of XYZFS to predict form drag[12] and the program's inability to model wave-breaking resistance.[12] This latter difficulty with XYZFS could become a factor at high speed. Any or all of these explanations, acting together

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11 A skeg is an appendage normally located on the bottom of a ship at the centerline to enhance course-keeping ability.

12 Form drag and wave-breaking resistance are components of a ship's total resistance to motion.

or independently, might account for the absolute differences associated with the ship resistance coefficient curves obtained from the computer and model tests.

Notwithstanding the absolute quantitative differences between XYZFS and model test resistance computations, a relative comparison of bulb forms reveals identical rankings from both sources. Table 4 evidences this statement by providing relative bulb rankings from XYZFS and model tests. These rankings were developed from the EHP ratio curves presented earlier (Figures 7 and 11), concentrating on the 18-25 knot speed range. The rankings are arranged from best to worst, with best being that bulb which had the lowest EHP ratio over the speed range considered. These identical relative rankings indicate that the XYZFS program can be used with confidence to select the best alternative among competing bulb forms, when lowering a ship's resistance is the primary consideration.

From this relative ranking of bulb forms, several observations can be made. First, in general, the resistance advantages derived from adding a bulbous bow to the FFG-7 hull form seem to increase with increasing bulb volume. One noteworthy exception to this rule is the superior performance of the relatively small MAESTRALE O-type bulb which has a lower effective horsepower ratio than bulb 1 over the majority of the speed range of interest, despite having less volume. Notwithstanding this exception, larger bulb size seems to enhance a bulb's resistance reducing effect. Bulb 6 (the longest and broadest of all bulbs tested) illustrates this point by having the lowest EHP ratio over the 18 - 25 knot speed range. This last observation indicates that bow bulbs for fine form, high speed ships should be made as large as possible within the practical constraints associated with ship handling.

RELATIVE BULB RANKING

XYZFS	MODEL TESTS
BULB 6	BULB 6
BULB 4	BULB 4
BULB 0	BULB 0
BULB 1	BULB 1
BULB 8	BULB 8

TABLE 4

Seakeeping

Unfortunately, as previously stated, quantitative results were not obtained from the seakeeping model tests and therefore no direct comparison can be made between the Navy Standard Ship Motions Program output and model test results. The problem with drawing concrete conclusions on the basis of seakeeping model tests is that large amounts of data must be collected in order to statistically average the results. Although multiple runs down the tank were made at each speed of interest, the amount of data collected was insufficient to give confidence in the significance of the averaged results.

CONCLUSIONS

On the basis of the work outlined in this report, the following general conclusions can be drawn about the application of bow bulbs to fine form, hign speed ships:

1) The XYZ Free Surface Program can be used to provide an accurate relative ranking of bulbous bow configurations when lowering a hull form's resistance is the primary consideration.
2) Increases in bulb breadth and volume tend to enhance the resistance characteristics of the hull form, indicating that bow bulbs should be made as large as the practical constraints associated with shiphandling will allow.
3) The Kracht bulb design charts yield an acceptable initial bulb design in that it tends to reduce the overall resistance of the hull form. However, this design is not optimum, and adjustments can be made to improve the bulb form.
4) The existing MAESTRALE O-type bulb possesses excellent resistance characteristics as well as the practical advantages of short length and ease of manufacture.

5) Qualitatively, at least, bulbous bows tend to degrade the seakeeping performance of hull forms to a small degree. However, this degradation does not seem sufficient to override the resistance advantages of the hull form configured with a bulbous bow.

6) The reduction in resistance due to the bow bulbs designed for this project is not substantial enough to warrant retrofitting the FFG-7. On the other hand, the reductions realized with this hull form indicate that serious consideration should be given to the use of a bulbous bow for similar future ships.

The importance of the first conclusion to the naval architecture community cannot be overstated. The XYZ free surface program has been proven to be a reliable alternative to expensive and time-consuming model testing when choosing between initial bulb designs. However, model tests are still necessary once the optimum bulb form has become evident in order to quantify the magnitude of a ship's resistance and required horsepower. This method of utilizing the computer to optimize and then quantifying with model testing has enormous potential as a design tool for naval architects.

SUGGESTIONS FOR FUTURE WORK

As a follow-on to the research conducted during this project, future studies of bulbous bows for high speed, fine form vessels should consider:

1) Further optimization of the bulb form utilizing the XYZ Free Surface Program to rank competing designs.

2) Impacts of practical shiphandling factors such as anchoring and docking on the bulb design process.

3) Investigation of variations to the O-type bulb form.

4) Investigation of alternate methods of fairing the bulb form into the hull form.

5) Improvement of XYZ Free Surface predictions in terms of the absolute magnitude of the results.

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6) Darlene Batten, for clerical support throughout the project.
7) And most importantly, Dr. Bruce Johnson and Dr. Bruce Nehrling of the USNA faculty who served as principal adivsors for all facets of this Trident Project.

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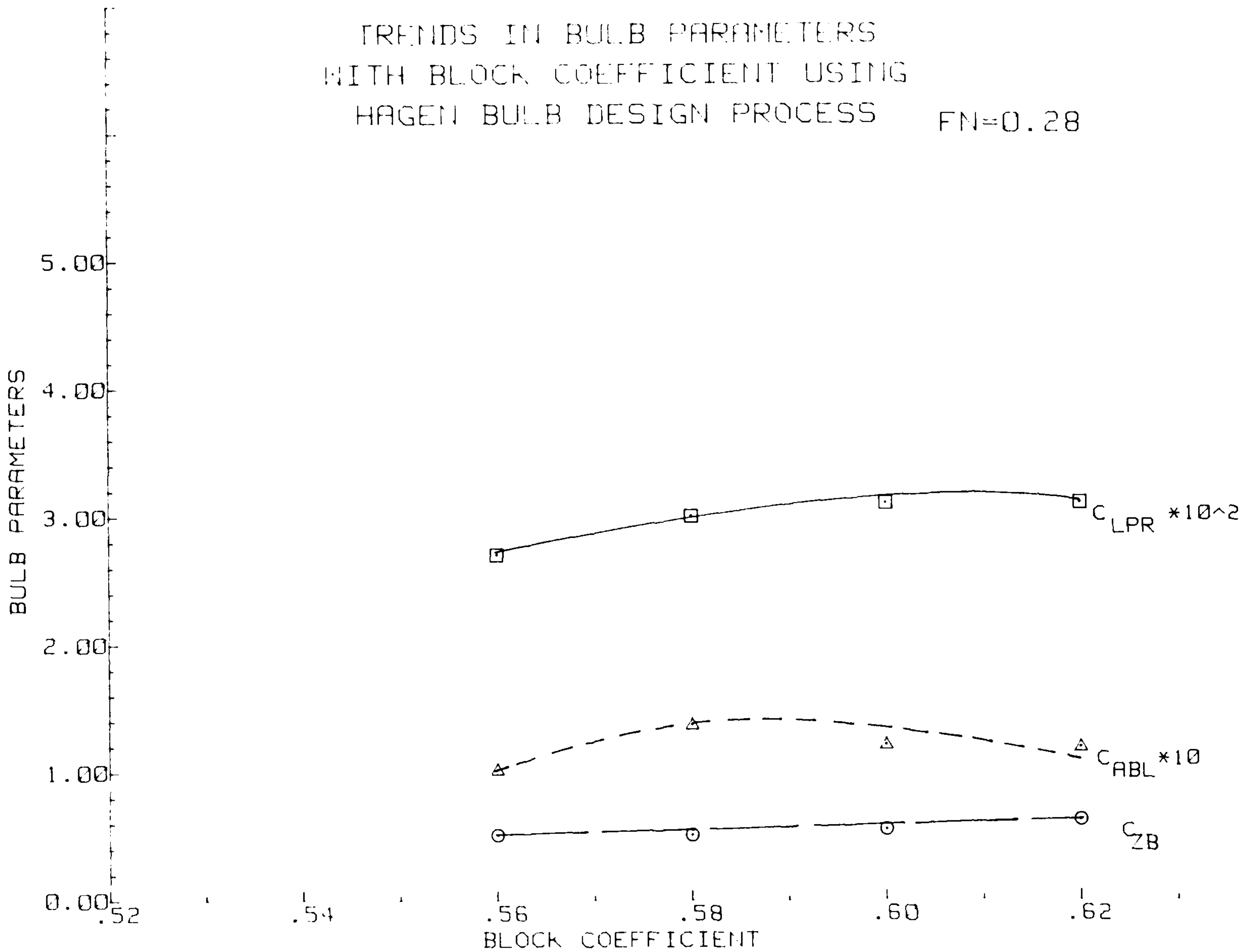
APPENDIX A:

Bulb Parameter Trend Study



TRENDS IN BULB PARAMETERS
WITH BLOCK COEFFICIENT USING
HAGEN BULB DESIGN PROCESS
FN=0.28
BULB PARAMETERS
5.00
4.00
3.00
2.00
1.00
0.00
.52
.54
.56
.58
.60
.62
BLOCK COEFFICIENT
C LPR *10^2
C ABL *10
C ZB

FIGURE 3

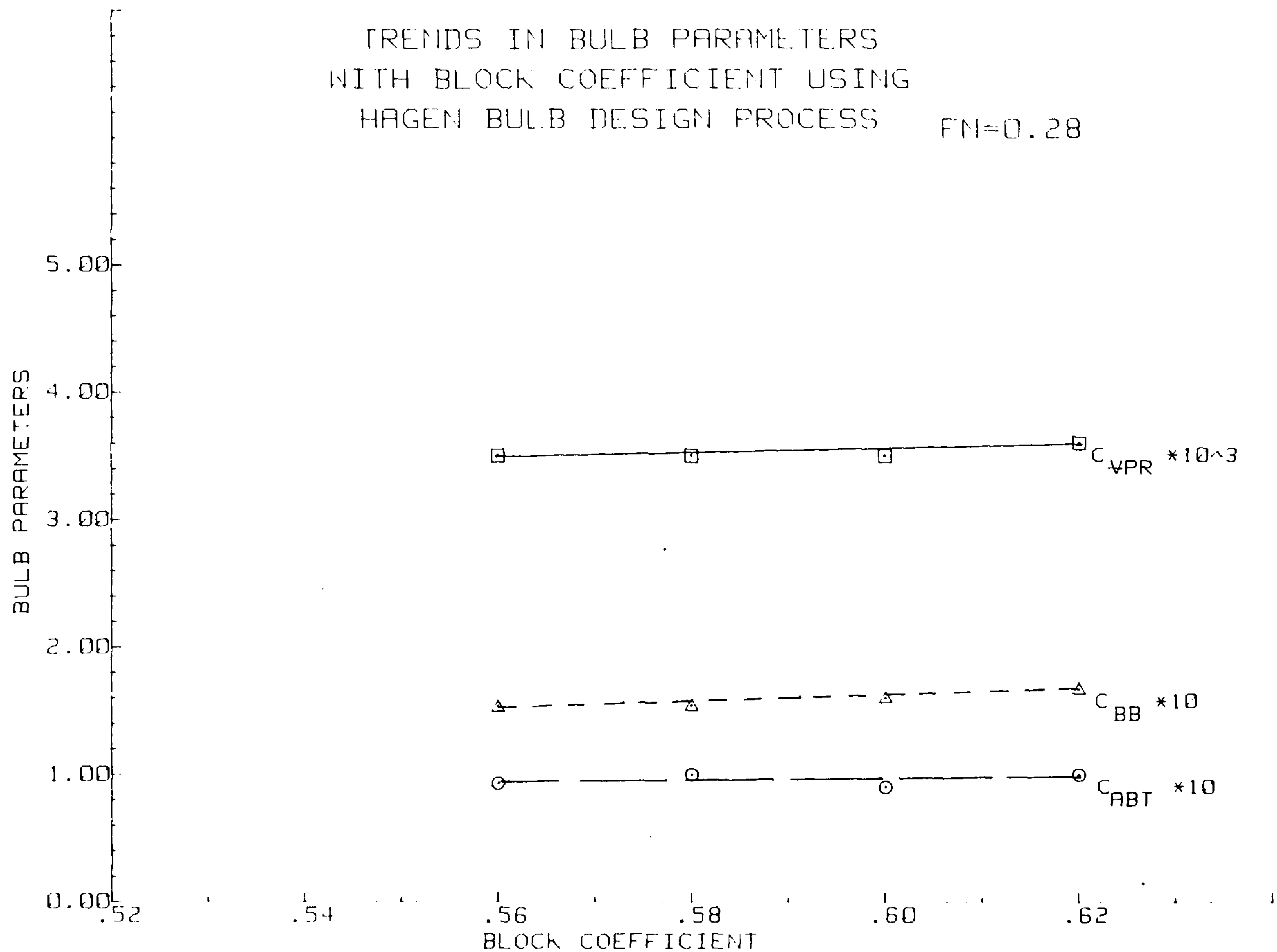

TRENDS IN BULB PARAMETERS
WITH BLOCK COEFFICIENT USING
HAGEN BULB DESIGN PROCESS
FN=0.28
BULB PARAMETERS
5.00
4.00
3.00
2.00
1.00
0.00
.52
.54
.56
.58
.60
.62
BLOCK COEFFICIENT
C VPR *10^3
C BB *10
C ABT *10

FIGURE 4

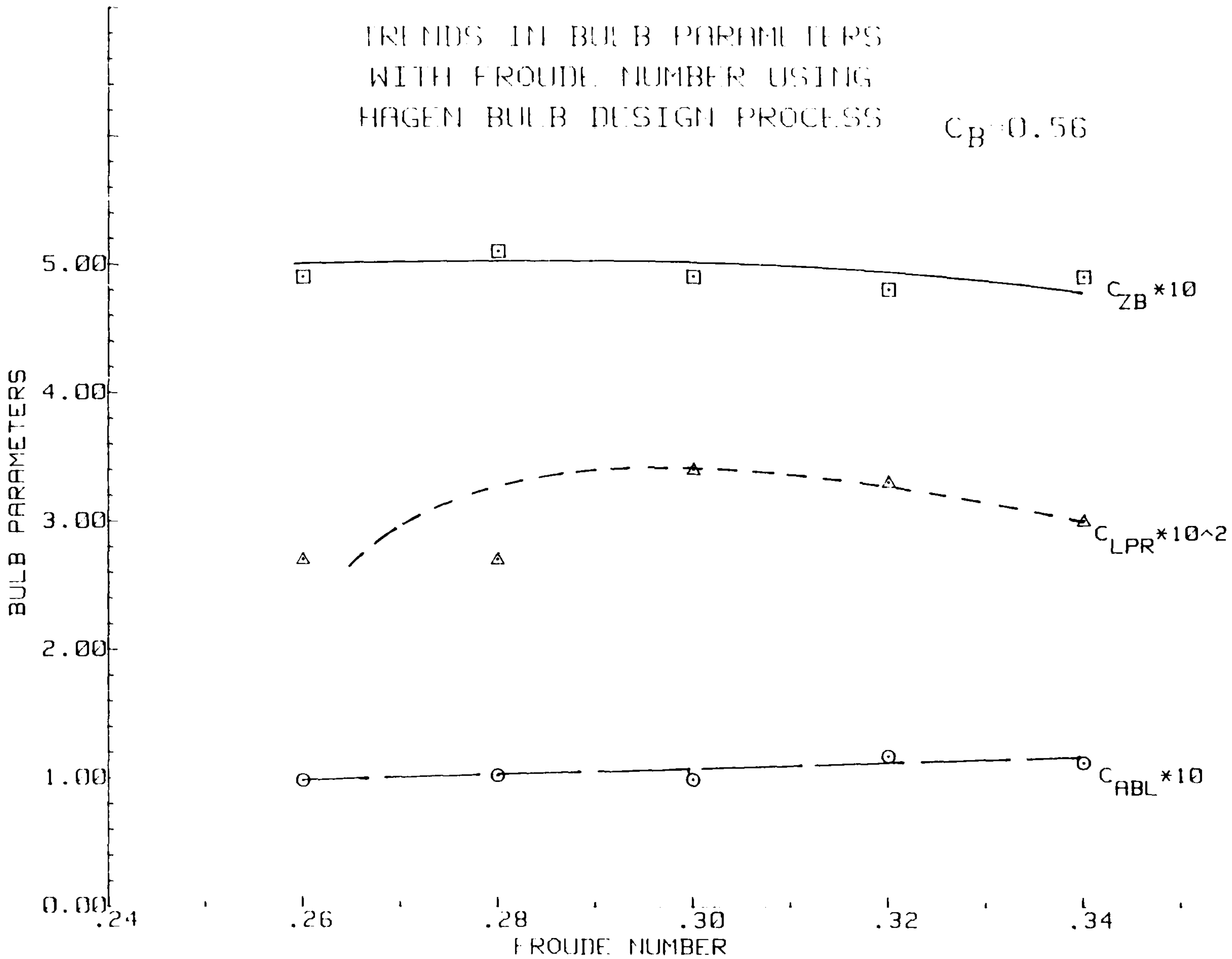

TRENDS IN BULB PARAMETERS
WITH FROUDE NUMBER USING
HAGEN BULB DESIGN PROCESS
CB=0.56
5.00
4.00
3.00
2.00
1.00
0.00
BULB PARAMETERS
CZB*10
CLPR*10^2
CABL*10
.24
.26
.28
.30
.32
.34
FROUDE NUMBER

FIGURE 5

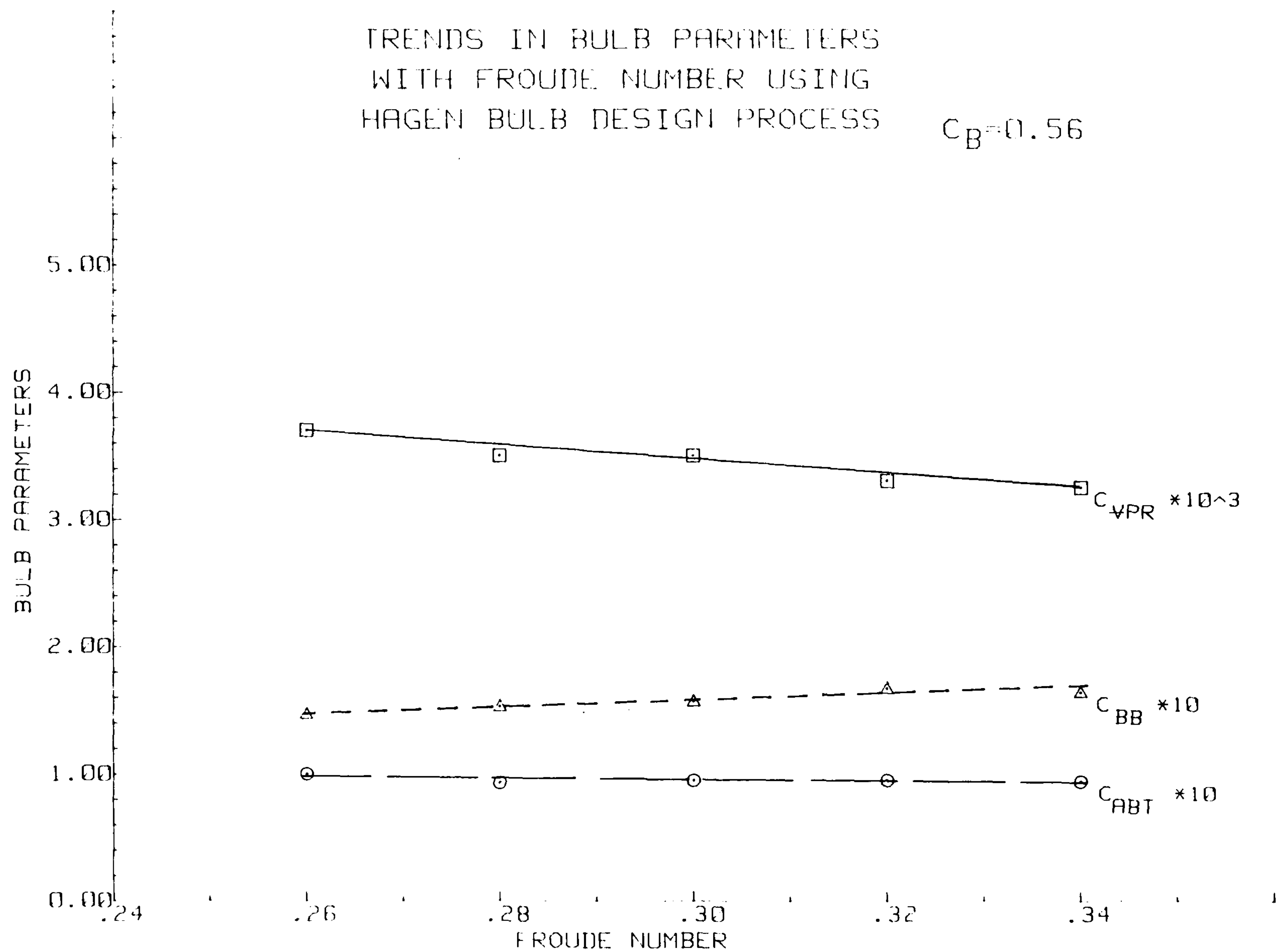

TRENDS IN BULB PARAMETERS
WITH FROUDE NUMBER USING
HAGEN BULB DESIGN PROCESS
C_B=0.56
BULB PARAMETERS
5.00
4.00
3.00
2.00
1.00
0.00
.24
.26
.28
.30
.32
.34
FROUDE NUMBER
C_∀PR *10^3
C_BB *10
C_ABT *10

FIGURE 6

APPENDIX B:

Detailed Outline and Notes on Bulb Design Method

DETAILED OUTLINE AND NOTES ON BULB DESIGN METHOD

Step a) Determine the block coefficient and the design Froude number for the candidate bulbless ship. Select the set of design charts in Kracht, VWS, 1978 appropriate for the block coefficient.

Note a) The block coefficient of the FFG-7 hull form is considerably smaller than the range of block coefficients found in Kracht, VWS, 1978. Therefore, the design charts corresponding to the smallest block coefficient available in Kracht, VWS, 1978 was selected. A Froude number of 0.30 (a ship speed of 20.4 kts) was chosen as the design Froude number for this project. This decision was based on the mission profile of the FFG-7 which reveals that 20 knots is the most common ship speed.

Step b) In each of the six design charts, locate the points on the appropriate Froude number curve where the maxima occur. Record the values of $\triangle C_{P\nabla R}$ associated with each of the maxima.

Note b) It was assumed that the authors of Hagen, 1983 intended for only the largest maxima from each of the design charts be recorded. This assumption was necessary in order to understand the intention of step C. Without this assumption, one might select a sub-optimal design value of $\triangle C_{PVR}$.

Step c) Select the smallest of the recorded values of $\triangle C_{PVR}$ as the design value for the bulb, and from each of the six charts determine the value of the bulb parameter which corresponds to that value of $\triangle C_{PVR}$. (Several guidelines are presented at this point to aid in parameter value selection in the almost unavoidable event that several values for a given bulb parameter can be found for the given value of $\triangle C_{PVR}$).

Note c) The ΔC_{PVR} chosen as the design value for the FFG-7 was 0.29, and the guidelines for resolving ambiguities arising from the undulations of the curves were closely followed.

Step d) Determine the height of the bulb at the forward perpendicular. Both the selected height and distance from the bottom of the bulb to the baseline are matters of judgement. However, the height of the bulb is constrained by at least two requirements:

1) It must be large enough to enable the required cross-section area (A_{BT}) to be developed.
2) The top of the bulb must be an appropriate distance below the design waterline. A tentative valve for bulb height can be obtained using the following formula:

$$H_B \simeq (4A_{BT}) / (\pi B_B)$$

Note d) The height of the bulb was determined to be 9.27' full scale by use of the formula shown above. An arbitrary value of 0.56' was assigned as the distance from the baseline to the bottom of the bulb giving an effective bulb height of 9.27' - 0.56' = 8.71'. These values were held constant for all bulbs produced by this study, and the effective bulb height was used in all further calculations required by the design methodology.

Step e) Lay out the upper portion of the longitudinal profile of the bulb by joining the point at the forward perpendicular (at height H_B above the bottom of the bulb) to the point at the nose (at height Z_B above the baseline) with an arbitrary curve (concave downward) having the general shape of an ellipse or parabola with vertex at the nose.

Note e) Quite obviously, the discretion of the designer impacts heavily on the choice of the "arbitrary curve" mentioned above. Thus, it is readily apparent that two designers utilizing exactly the same bulb parameters could develop completely different bulb forms.

Step f) Lay out the lower curve of the longitudinal profile by computing distances $y(x)$ below the upper curve at longitudinal distances, x, forward of the forward perpendicular according to the following formula:

$$y(x) \simeq \left[H_B^2 - x^2 \left(H_B / L_{PR} \right)^2 \right]^{0.5}$$

Note f) This step is relatively straight-forward and easy to implement. However, no mention is made in Hagen, 1983 as to how this formula was derived.

Step g) Perform an integration to determine the area A_{BL} for comparison with design chart. Make minor adjustments in the longitudinal profile to obtain approximate agreement with one of the values selected from the design chart.

Note g) The value of C_{ABL} developed by this method was approximately twice that selected as the near-optimum value from the design chart. Presumably, this occurred because of the appreciable downward extrapolation of the range of block coefficients in the design curves. Thus, the decision to disregard the value of C_{ABL} taken from the design charts in order to attain the correct value of other bulb parameters was necessary at this point.

Step h) Compute the approximate transverse areas of the bulb at selected longitudinal stations by the following formulation:

$$A_T(x) \simeq \left[y^2(x)\, A'_{BT} \right] / \left[H_B^{\,2} \right]$$

Where A'_{BT} is the actual designed transverse area of the bulb at the forward perpendicular. In general, A'_{BT} is likely to be equal to, or very nearly the same as, the design-chart value.

Note h) Again, no mention is made in Hagen, 1983 as to how this formulation was derived.

Step i) Perform an integration to determine the bulb volume.

Note i) Straight-forward application of Simpson's Rule to the transverse areas computed in step h was utilized to complete this step.

Step j) Starting with the derived approximate valves of the parameters which describe the bulb geometry, develop a faired bulb configuration (i.e., as is done with ship lines and body plans) and compute the values of its geometric parameters for comparison with those selected from the design charts. Although, it is not expected that exact agreement would be achieved, iterations on the design can be made, as appropriate to bring the actual values into better agreement with the design chart selections.

Note j) The discretion of the individual designer again plays a major role in the implementation of this step. After numerous iterations the final bulb form produced from this design methodology was designated as bulb no. 1.

APPENDIX C:

Kracht Bulb Parameters

FFG-7 TRIDENT BULB STUDY

KRACHT BULB PARAMETERS

BULB NUMBER	C_{LPR}	C_{BB}	C_{ZB}	C_{ABL}	C_{ABT}	C_{VPR}
0	0.011	0.194	0.293	0.064	0.125	0.0014
1	0.034	0.165	0.46	0.174	0.086	0.0028
2	0.030	0.165	0.46	0.165	0.088	0.0030
3	0.040	0.165	0.46	0.219	0.088	0.0039
4	0.034	0.200	0.46	0.174	0.106	0.0035
5	0.030	0.200	0.46	0.165	0.106	0.0036
6	0.040	0.200	0.46	0.219	0.106	0.0047
7	0.020	0.165	0.46	0.110	0.088	0.0020
8	0.010	0.165	0.46	0.056	0.088	0.0010
9	0.050	0.165	0.46	0.276	0.088	0.0049

TABLE 3

APPENDIX D:

Application of XYZ Free Surface Program to Trident Bulb Study

Application of XYZ Free Surface Program
To Trident Bulb Study

For each bulb configuration studied during that course of this Trident research project, the following steps were executed sequentially in order to obtain resistance predictions from the XYZ Free Surface Program.

Step 1) Bulb form was digitized at the U. S. Naval Academy's CADIG Facility and appended to digitized FFG-7 hull form.

Step 2) Digitized data was transferred to David Taylor Naval Ship Research and Development Center over ordinary phone lines.

Step 3) Digitized data was utilized to panel hull form at DTNSRDC for input into XYZFS. A figure representing a panelized bulb form is contained in this appendix.

Step 4) XYZ Free Surface Program run in Seattle, Washington on Boeing's Cray Computer.

Step 5) XYZFS results analyzed at DTNSRDC and USNA.

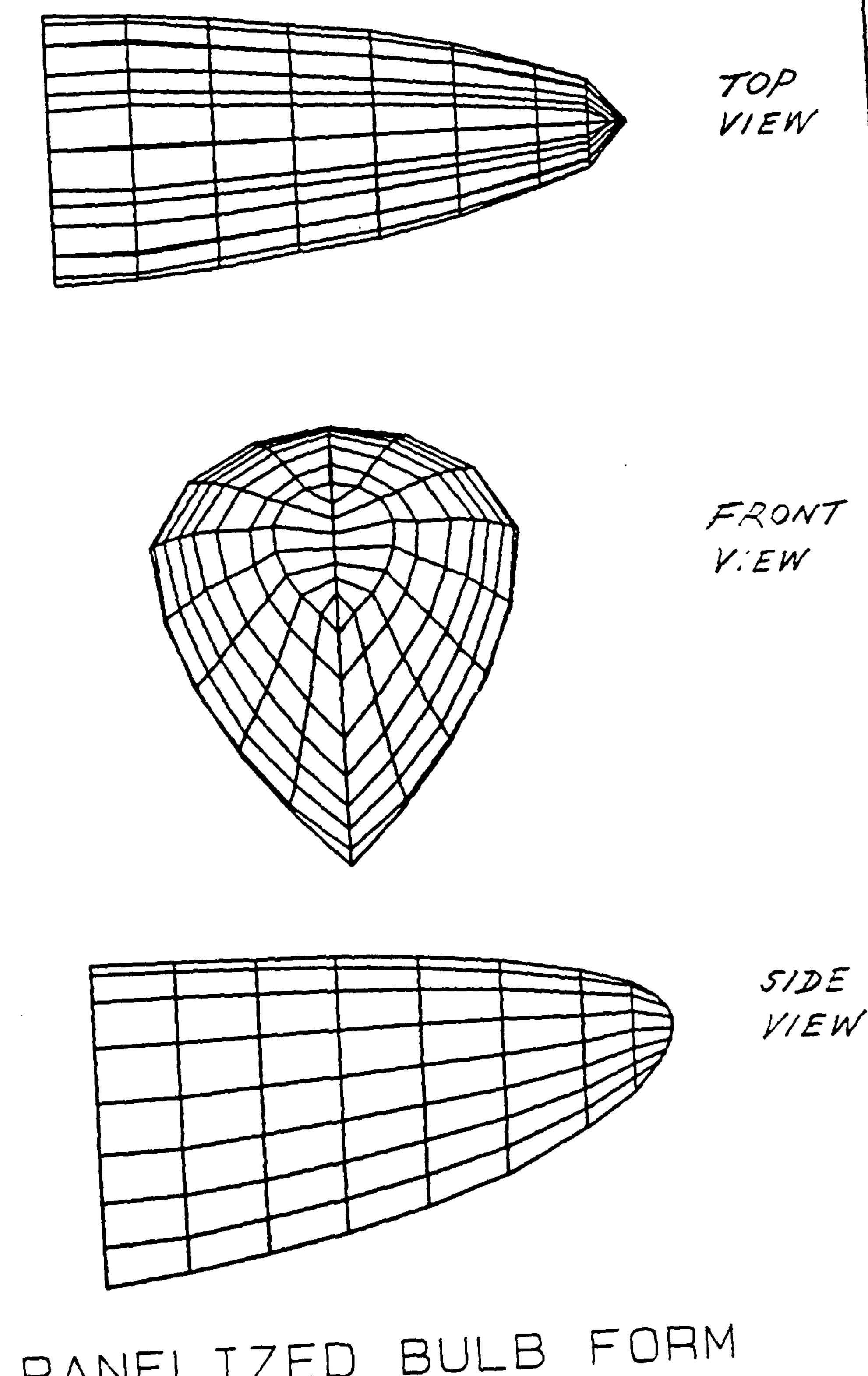


FIGURE 11

APPENDIX E:

Adaptation of Ship Motions Program to Trident Bulb Study

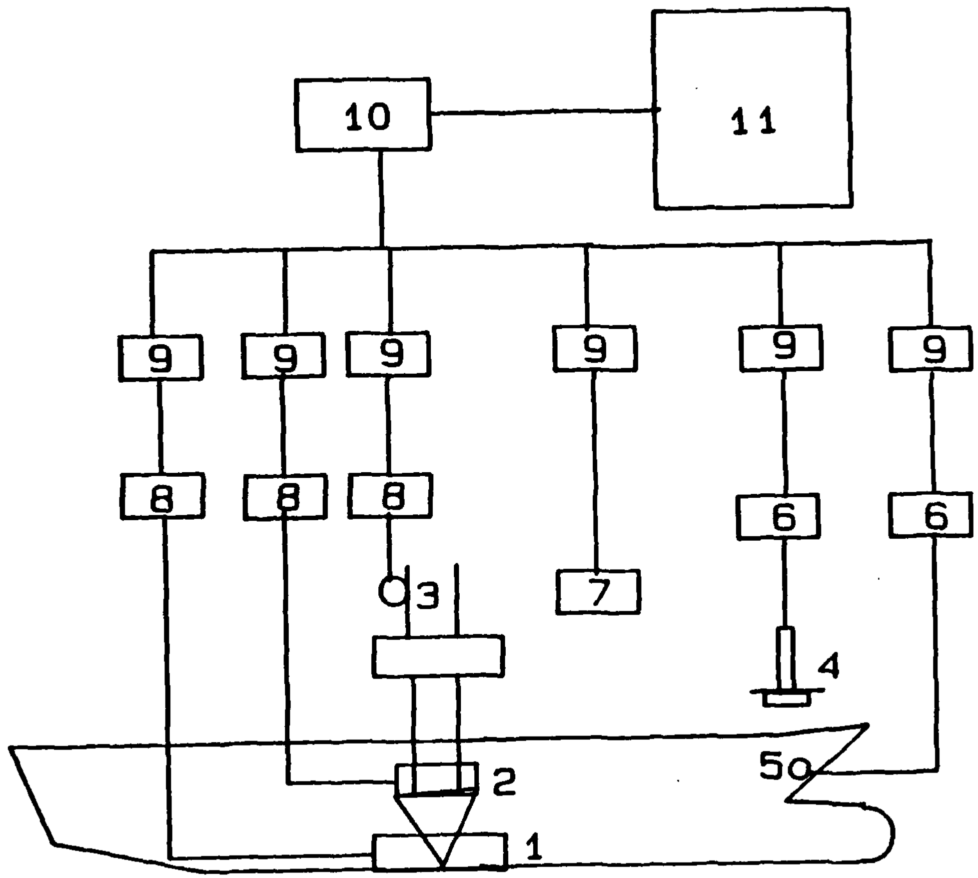
Adaptation of Ship Motions Program to Trident Bulb Study

The Navy Standard Ship Motions Program (SMP) was run on four configurations of the FFG-7 studied during this Trident Research Project. SMP was run on the VAX Computer at the Naval Sea Systems Command from the Naval Academy utilizing a phone link established for that purpose. In order to eliminate unnecessary results, the output of SMP was limited to rigid body motion calculations and probability of slamming and emergence of the bulb forms. These results were printed at NAVSEA and transported to USNA for analysis.

APPENDIX F:

Model Test Data Collection and Sensor Information

MODEL TEST DATA COLLECTION



1. BLOCK GAGE
2. PITCH POTENTIOMETER
3. HEAVE POTENTIOMETER
4. SONIC PROBE
5. ACCELEROMETER
6. POWER SUPPLY
7. CARRIAGE VELOCITY TACHOMETER
8. SIGNAL CONDITIONING UNIT
9. FILTER
   - RESISTANCE TESTS FILTERED @ 2 HZ
   - SEAKEEPING TESTS FILTERED @ 20 HZ
10. ANALOG-TO-DIGITAL CONVERTER
11. PDP 11/50 COMPUTER

NOTE: SONIC PROBE AND ACCELEROMETER PRESENT ONLY FOR SEAKEEPING TESTS

FIGURE 16

MODEL TEST SENSORS

QUANTITY MEASURED	TRANSDUCER	DESCRIPTION	TOLERANCE
DRAG	BLOCK GAGE	HYDRONAUTICS VARIABLE-RELUCTANCE MODULAR FORCE GAGE (50 lb DESIGN LOAD)	LINEARITY (% DESIGN LOAD) +0.25
PITCH	POTENTIOMETER	10-TURN, 10 k-OHM	TOLERANCE +10% FULL LOAD LINEARITY +5%
ACCELERATION	ACCELEROMETER	SCHAEVITZ 10g LINEAR SERVO ACCELEROMETER (+10g FULL LOAD)	LINEARITY 0.05% FULL LOAD REPEATABILITY 0.01% FULL LOAD
ENCOUNTERED WAVE HEIGHT	SONIC PROBE	WESMAR LM4000 ULTRASONIC PULSED SONAR SYSTEM (30" MEASURED RANGE) (60" FULL LOAD)	RESOLUTION (0.5% MEASURED RANGE) LINEARITY (0.5% FULL SCALE)

TABLE 2

APPENDIX G:

EHP Ratio Comparisons from XYZFS and Model Tests

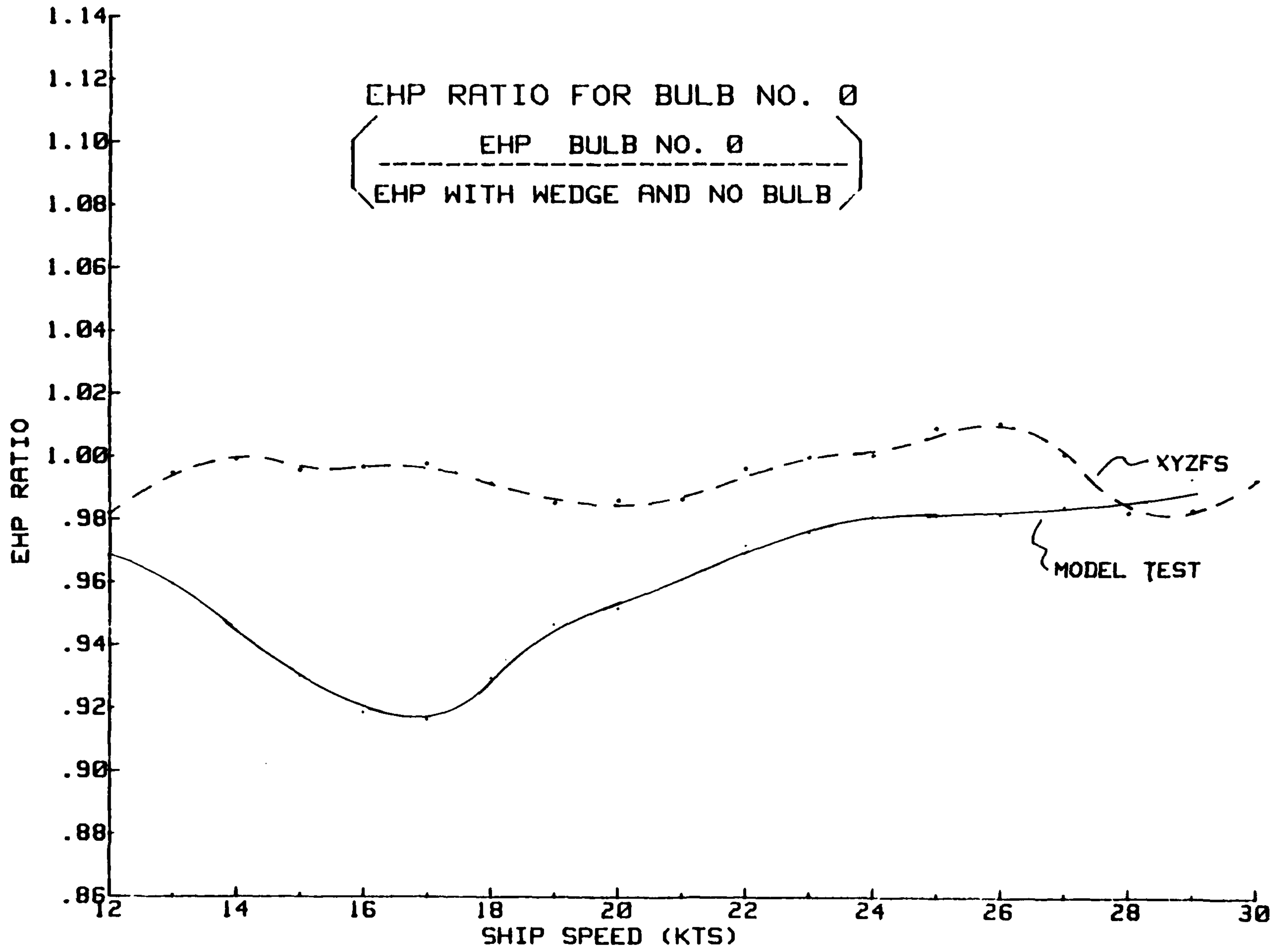
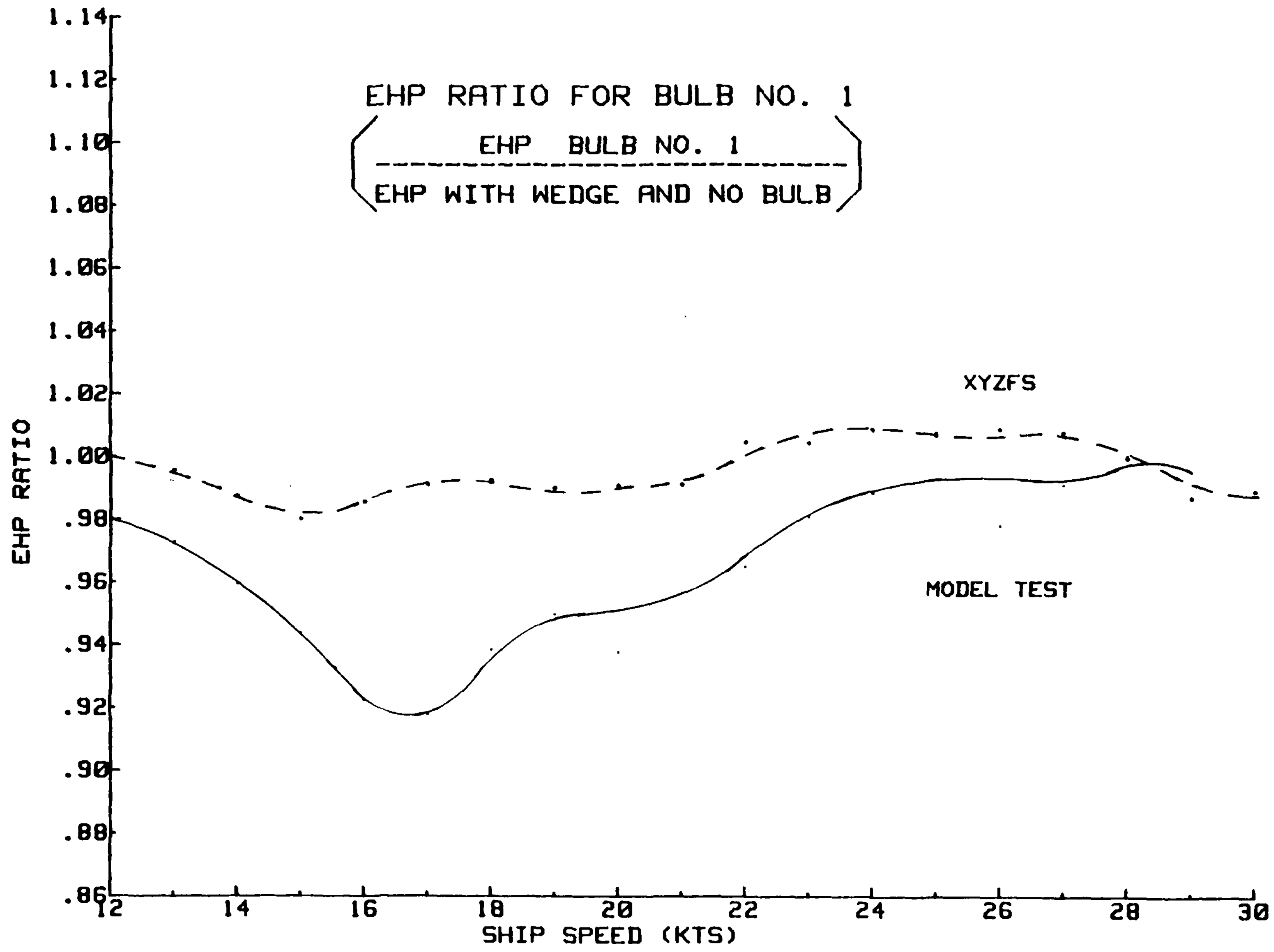

EHP RATIO FOR BULB NO. 0
EHP BULB NO. 0
EHP WITH WEDGE AND NO BULB
EHP RATIO
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
.98
.96
.94
.92
.90
.88
.86
12
14
16
18
20
22
24
26
28
30
SHIP SPEED (KTS)
XYZFS
MODEL TEST

FIGURE 24



EHP RATIO FOR BULB NO. 1
EHP BULB NO. 1
EHP WITH WEDGE AND NO BULB
XYZFS
MODEL TEST
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
.98
.96
.94
.92
.90
.88
.86
EHP RATIO
12
14
16
18
20
22
24
26
28
30
SHIP SPEED (KTS)

FIGURE 25

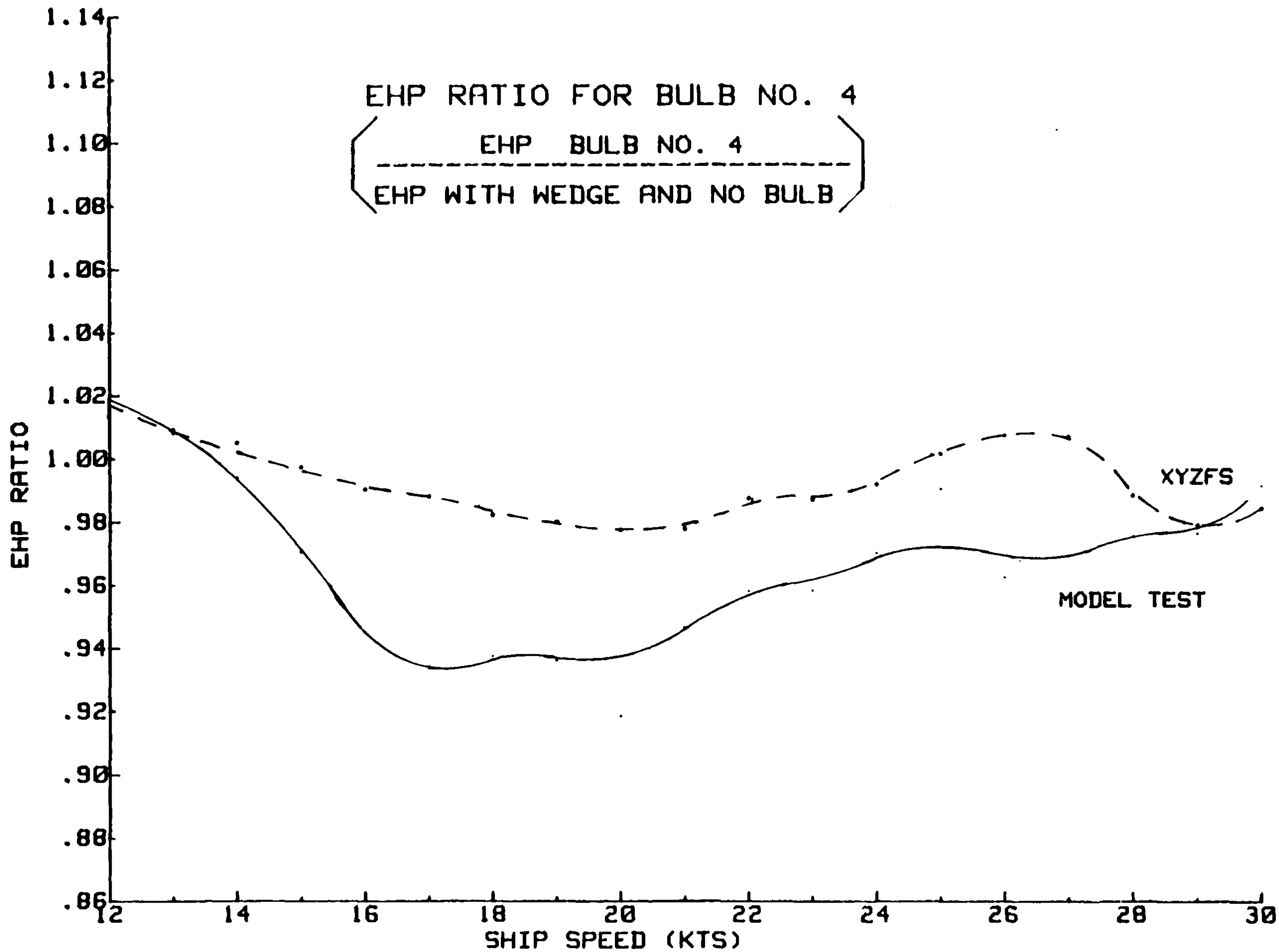

EHP RATIO FOR BULB NO. 4
EHP BULB NO. 4
EHP WITH WEDGE AND NO BULB
XYZFS
MODEL TEST
EHP RATIO
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
.98
.96
.94
.92
.90
.88
.86
12
14
16
18
20
22
24
26
28
30
SHIP SPEED (KTS)

FIGURE 26

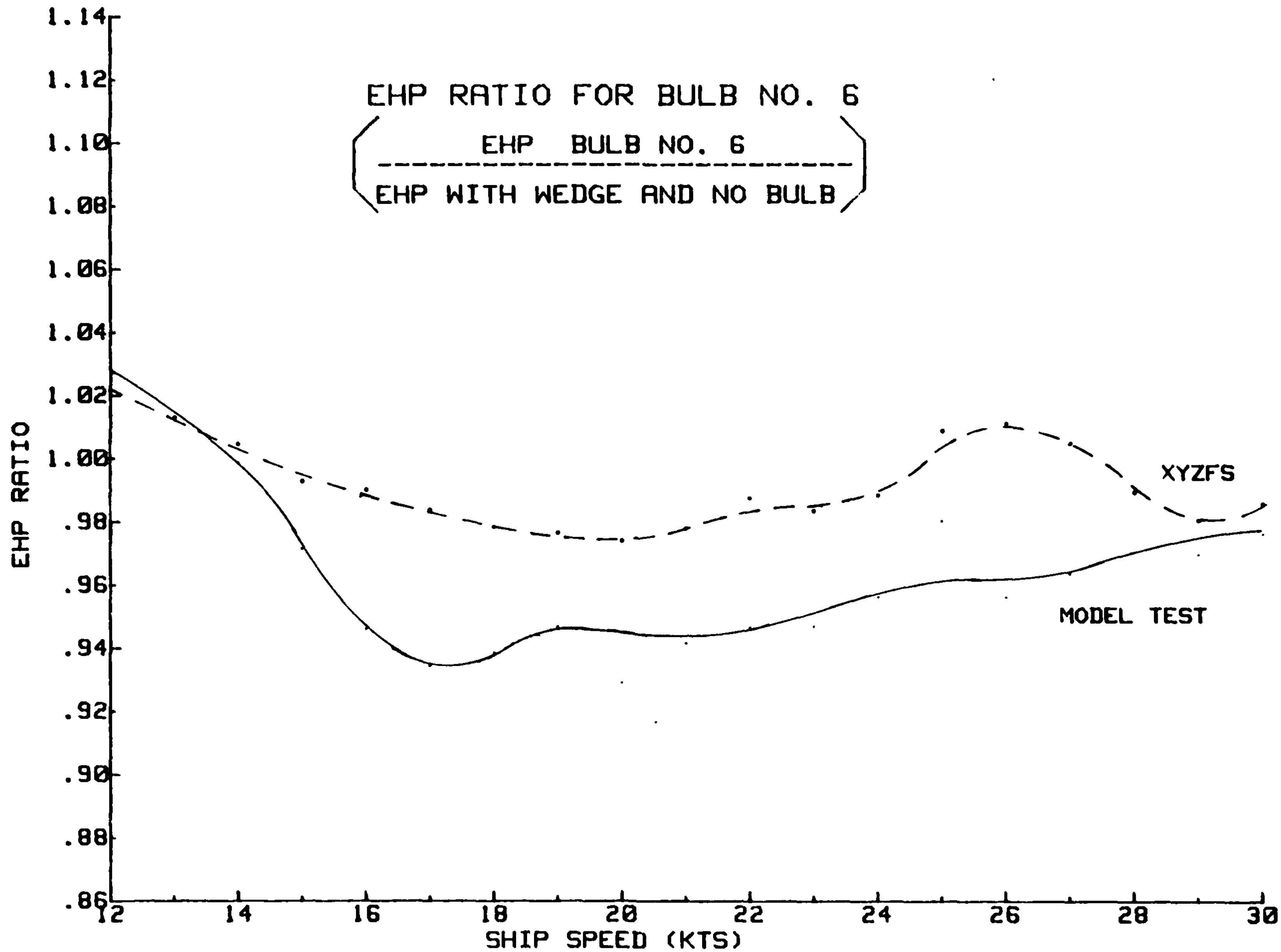

EHP RATIO FOR BULB NO. 6
EHP BULB NO. 6
EHP WITH WEDGE AND NO BULB
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
.98
.96
.94
.92
.90
.88
.86
EHP RATIO
12
14
16
18
20
22
24
26
28
30
SHIP SPEED (KTS)
XYZFS
MODEL TEST

FIGURE 27

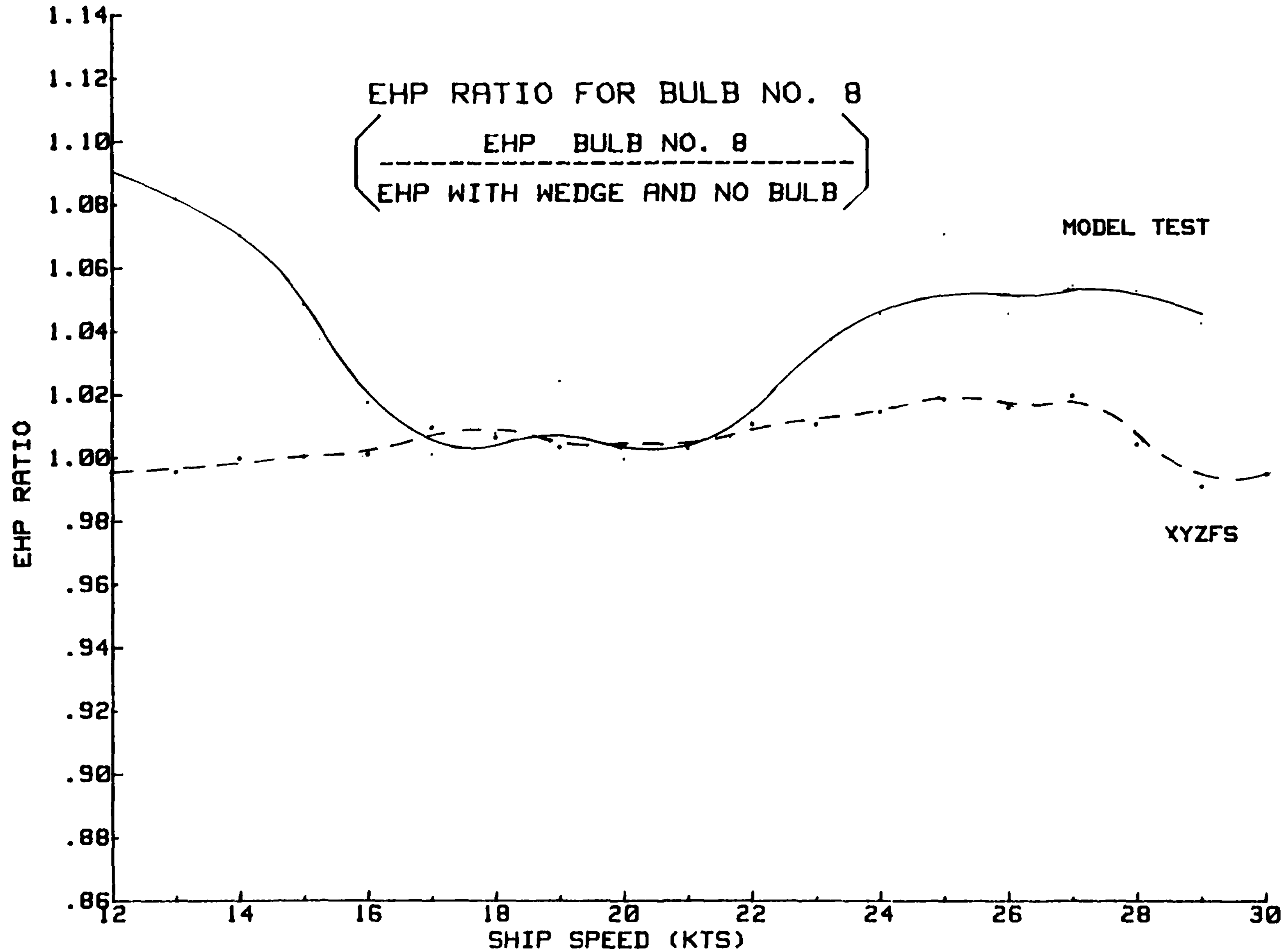

EHP RATIO FOR BULB NO. 8
EHP BULB NO. 8
EHP WITH WEDGE AND NO BULB
MODEL TEST
XYZFS
EHP RATIO
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
.98
.96
.94
.92
.90
.88
.86
12
14
16
18
20
22
24
26
28
30
SHIP SPEED (KTS)

FIGURE 28